Domestic Coal Supply Optimization Scenario towards Sustainable Development in Indonesia

(持続可能な開発に向けたインドネシア国内の石炭供給最適化シナリオ)

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Certification

This is to certify that the doctoral thesis dissertation entitled:

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is a series of research works by **Firly Rachmaditya Baskoro** during his doctoral study from April 1, 2018 to the February 16, 2022 in Production Systems Engineering Laboratory, Department of System Cybernetics, Graduate School of Engineering, Hiroshima University, Japan. This doctoral thesis dissertation has been accepted as a part of requirements in conferring in a **Doctor of Engineering/Philosophy** degree to him.

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Abstract

Energy is one of vital part to achieve the Sustainable Development Goals (SDGs). Coal is considered as one of the most abundantly and the cheapest available energy source, particularly in the developing country. Indonesia is one of a country that still heavily rely on coal to fulfill its national primary energy demand, particularly for electricity generation which in majority is generated by coal-fired power plants (CFPPs). Coal holds major role as raw material to generate power, as well as key component in metal production. However, coal utilization is facing greater challenges in terms of economic, environmental, and social concerns.

Indonesia plays an important role in the global coal market. In 2018, Indonesia ranked as the 5th largest coal producer and the 2nd largest coal exporter in the world. However, only 21% of the production volume is utilized in the domestic market. In the future, Indonesia's coal production is expected to continue to increase due to the growth in coal demand for electricity generation. This research aims to predict the future of coal production in Indonesia to support economic growth considering less damage to the environment and more benefits to the social community and examine its contribution to the national primary energy mix as a part of national energy policy.

System dynamics model is utilized, which simulates the future of coal supply and demand in relation to the availability of coal reserves, the interaction between coal and its substitutes, economic growth, and the price of commodities. Four scenarios are introduced to analyze the impact of coal utilization to the economy and environment, which are Business as Usual (BaU), Economic Growth Priority (EGP), Policy Regulation (PR), and Environmentally Oriented (EO) scenario. The results show that coal production in Indonesia will continue to increase in the future. The EO scenario will be the best alternative for future energy policy in Indonesia because of its ability to fulfill both economic growth and low carbon intensity target. Furthermore, the EO scenario also able to achieve the government target in primary energy mix in 2030 with 33.5% of coal, 19.4% of oil, 7.8% of gas, and 39.3% of renewable energy.

Indonesian coal is distributed in several islands, such as Sumatra, Kalimantan, Sulawesi, and Papua. Most of them are classified as low and medium rank coal, which is very suitable for coal-fired power plants. In the future, domestic coal demand will increase, driven by the government plans to increase the electricity generation capacity and primary energy demand. In the existing scheme, only a coal mining company whose coal quality is an exact match with the CFPP specification can be selected as a supplier, without considering a blending mechanism. This condition may have some issues for long-term supply, as the coal will be exhausted in time and tends to come at a high cost.

To improve the decision making for securing the long-term coal demand for electricity generation, optimization with coal blending should be considered. This research includes the consideration of the coal quality parameters; the power plant's requirement criteria; the location of the coal blending facility; and ship types. In order to optimize coal utilization in Indonesia, it is necessary to consider economic, environmental, and social factors which in the existing condition only economic aspect that has been considered. Therefore, economic-environment-social model is constructed to solve the problem. A multi-objective optimization using mixed-integer linear programming, consisting of linear inequalities in binary and continuous variables as the constraints, is introduced to find the optimal solution, with cost, carbon dioxide (CO_2) emission, and social benefits as the objective functions. In this study, cost represents the economic aspect, CO_2 emission represents the environmental impact, while social aspect will be represented by the corporate social responsibility (CSR) programs as well as the human development index (HDI) in several province with high coal dependency. In most research on optimization, social aspects were analyzed by using the number of workers, which often neglects the fact that the same job can have different social benefits in different regions. The utilization of HDI which consider education, healthiness, and economic level of a region may give better understanding on social impact from coal mining industry to the society. Prioritization for underdeveloped and fast-growing region is considered in this study.

Several scenarios, which are the baseline condition, chartered ship, and environmental consciousness, are analyzed. The results obtained by using the epsilon-constraint method show the benefits of the proposed schemes and scenarios, which are able to secure long-term demand with a more flexible solution, and reduce the total cost and carbon dioxide emission, as well as increase the social benefits. Furthermore, considering the parameter setting and modeling, the optimization can be considered as applicable for solving similar problems related to the transportation selection and supply chain for similar commodities in the greater area. The results of the research perhaps can be utilized by the decision makers to improve the coal utilization towards the sustainable development.

Keywords: carbon dioxide emission, coal, mixed-integer linear programming, multi-objective optimization, system dynamics, sustainable development

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List of Publication

1. **Journal Paper**
   a. **Baskoro, F. R.**, Takahashi, K., Morikawa, K., & Nagasawa, K. (2021). System dynamics approach in determining coal utilization scenario in Indonesia. Resources Policy, 73 (October 2021), 102209. https://doi.org/10.1016/j.resourpol.2021.102209
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   b. **Baskoro, F. R.**, Nagasawa, K., Morikawa, K., & Takahashi, K. (2019). Modelling new scheme on coal procurement for coal-fired power plants in Indonesia. 36th Annual International Pittsburgh Coal Conference: Clean Coal-Based Energy/Fuels and the Environment, PCC 2019, 160393.
   c. **Baskoro, F. R.**, Nagasawa, K., Morikawa, K., & Takahashi, K. (2021). Sustainable Development Model on Coal Supply for Coal-Fired Power Plants by using Multi-Objective Optimization with Economic, Environmental, and Social Aspects Consideration. 38th Annual International Pittsburgh Coal Conference: Clean Coal-Based Energy/Fuels and the Environment, PCC 2021.

Research and Publication Relation

Section	Title	Main Reference
1	Introduction	1a, 1b 2a, 2b, 2c
2	Coal utilization scenario in Indonesia	1a 2a
3	Optimization of coal supply for coal-fired power plants in Indonesia	1b 2b
4	Optimization of coal supply with economic, environmental, and social aspects consideration	2c
5	Conclusions	1a, 1b 2a, 2b, 2c

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1 Introduction

1.1 Background

Energy plays a vital role in the economy, both in terms of supply and demand. In terms of demand, energy is a commodity that needed by people to maximize their utility. In terms of supply, energy is a key production factor other than capital, labor, and raw materials. In addition, energy is a key factor in increasing economic growth and living standards. Based on the research from Fatai, Oxley, & Scrimgeour (2004), the increase amount of energy consumption in Indonesia will drives the national economic growth.

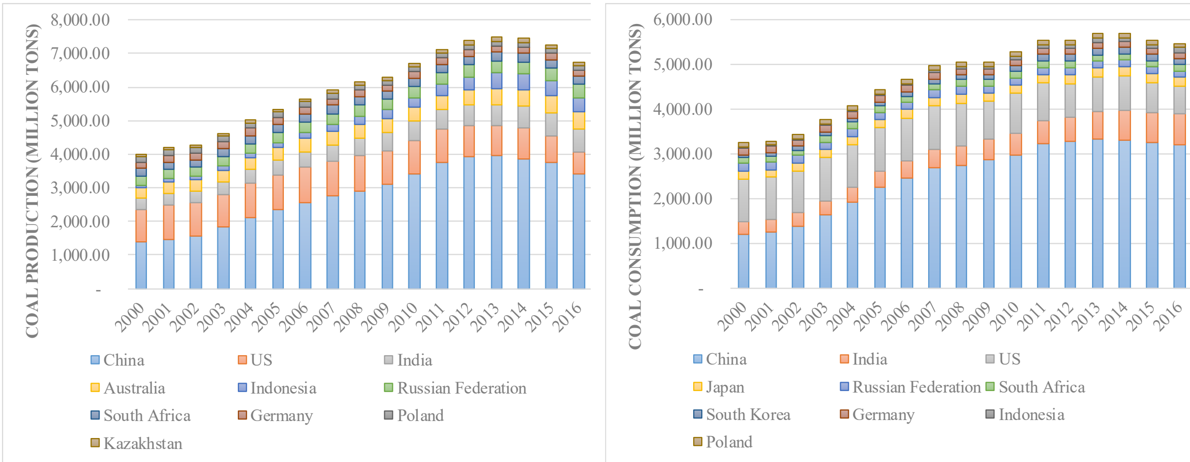
The sustainability of domestic energy supply is regulated in Presidential Decree No. 5 of 2006 concerning the National Energy Policy, which has the goal to achieve energy elasticity of less than 1 by 2025, and realizing an optimal energy mix in 2025. In 2025, there will be a change in the role of each types of energy in the domestic energy consumption with maximum portion of petroleum up to 20%, minimum portion of natural gas at least 30%, coal at least 33%, biofuel at least 5%, geothermal at least 5%, renewable energy at least 5%, and minimum portion of liquefied-coal at least 2%. The fulfillment of domestic energy sources is carried out with the main steps of providing, utilizing, stipulating energy pricing policies, and preserving the environment by applying the principles of sustainable development.

Considering the recent condition of the national primary energy mix, coal is considered as the main energy sources in Indonesia. Furthermore, Indonesia has also hold a vital role in the global coal market, indicated by its current status in 2017 as the 5th largest coal producer and the 2nd top coal exporter in the world. In addition, British Petroleum (2017) stated that the growth rate of Indonesia's coal production and consumption was the fastest among the top ten coal producer and consumer countries. In 2017, Indonesia has produced around 461 million tons of coal, which is only 97 million tons that accounted for domestic utilization. Based on the data from Ministry of Energy and Mineral Resources Republic of Indonesia (2018), the total coal resources in Indonesia is around 140.48 billion tons with 29.91 billion tons classified as coal reserves. Indonesia's coal reserves is only 2.2% compared to the total world's coal reserves. The contradiction between coal production and reserve status has raised a concern over the future of coal supply in the domestic market. Without any extensive efforts in exploration activity, coal expected will be exhausted in 55 years later. To overcome those issue, prediction on the future coal production in Indonesia is necessary. However, coal utilization in the domestic market will results on the increase of carbon dioxide emission. To find the suitable alternatives on coal policy considering the minimum impact to the environment, the influencing factors of coal production should be analyzed.

1.1.1 Roles of coal in Indonesia

Despite the large amount of coal production at the present time, the commercial coal production activity in Indonesia just really begins in 1990 (Friederich & van Leeuwen, 2017). Before 1990, the majority of primary energy demand in Indonesia was fulfilled by oil due to the price competitiveness (Lucarelli, 2015). The success of exploration program in first generation Coal Contract of Work (CCoW) scheme between the government and coal mining companies has affected the steady increase of coal production.

Significant growth of coal production in Indonesia begins in 2000 (see Figure 1-1). Latest data shows that the annual coal production in Indonesia is more than 450 million tons, and predicted continue to increase in the near future, mainly drift by the market demand.



(a) *(b)*

Figure 1-1: Historical coal production (a) and coal consumption (b) of top ten coal producer and consumer countries.

Indonesian coal is sold in both domestic and export market. From all of the total production within the last 5 years, only around 20.75% is utilized in the domestic market. The rest of coal production is sold to the foreign market in Asia, Europe, and America. According to the characteristic of coal reserves in Indonesia, which classified as low and medium rank, Indonesian coal is commonly utilized for direct combustion in coal-fired power plant, cement, metallurgical, pulp, textile, fertilizer, and other industry.

From all sectors, power plants consume around 81.79% of coal in the domestic market. Coal-fired power plant constitutes the largest portion of Indonesia's power plant, which is around 60% of total electricity generation. Cement and textile industry are the second and third biggest consumer of coal in the domestic market, with total consumption around 13.85 million tons (12.84%) and 2.59 million tons (2.40%) respectively in 2017.

In the future, the amount of domestic coal demand is expected to increase, primarily affected by the electricity generation. In 2017, PLN (state-owned electric company) announced a 35,000 MW program to install new power plants in order to support government's target on the electrification ratio. Moreover, the government also published a regulation on domestic market obligation (DMO). The DMO regulation requires coal mining company in Indonesia to sell their coal production at least 25% in the domestic market.

1.1.2 Coal resources and reserves in Indonesia

Indonesia coal resources and reserves have continued to increase over the past 10 years. The total coal reserves in 2007 was 18.65 billion tons compared to 29.91 billion tons in 2017 (Ministry of Energy and Mineral Resources Republic of Indonesia, 2018). Thus, the average growth of coal reserves in Indonesia is around 5.36% per annum. From the data, it shows that the significant growth of coal reserves occurred in 2011, mainly affected by the high coal price at that time.

Table 1-1 Distribution of coal resources and reserves in Indonesia

Region	Resources (billion tons)	Reserves (billion tons)
Sumatera	55.26	13.28
Java	0.10	0.00
Kalimantan	84.70	16.63
Sulawesi	0.28	0.00
Papua	0.14	0.00
Total	**140.47**	**29.91**

Indonesia's coal resources and reserves are distributed in several regions (see Table 1-1), mostly in Kalimantan and Sumatra. South Sumatra, which has 10.93 billion tons coal reserves, is a province with the highest coal reserves and followed by East Kalimantan as the second highest province with coal reserves, which has around 7.72 billion tons of coal reserves.

Majority of coal reserves in Indonesia is classified as low and medium rank coal, which is accounted for around 86.6% of the total coal reserves. This type of coal contains relatively high level of moisture content and volatile matter with low calorific heating value, therefore the utilization of this type of coal very suitable for direct combustion, both on coal-fired power plant (CFPP) and other industry.

Regarding the purpose of this research, which will try to optimize the domestic coal utilization in Indonesia by considering the coal blending activity, detail specification of coal should be known. Therefore, the data from MEMR cannot be used directly. The data of coal reserve should consist of calorific value, total moisture, ash content, and sulfur content. From the total 128.06 billion tons of coal resource and 28.46 billion tons of coal reserve, only 85.03 billion tons of coal resource and 20.35 billion tons of coal reserve which has all the specification data as can be seen in Figure 1-2.

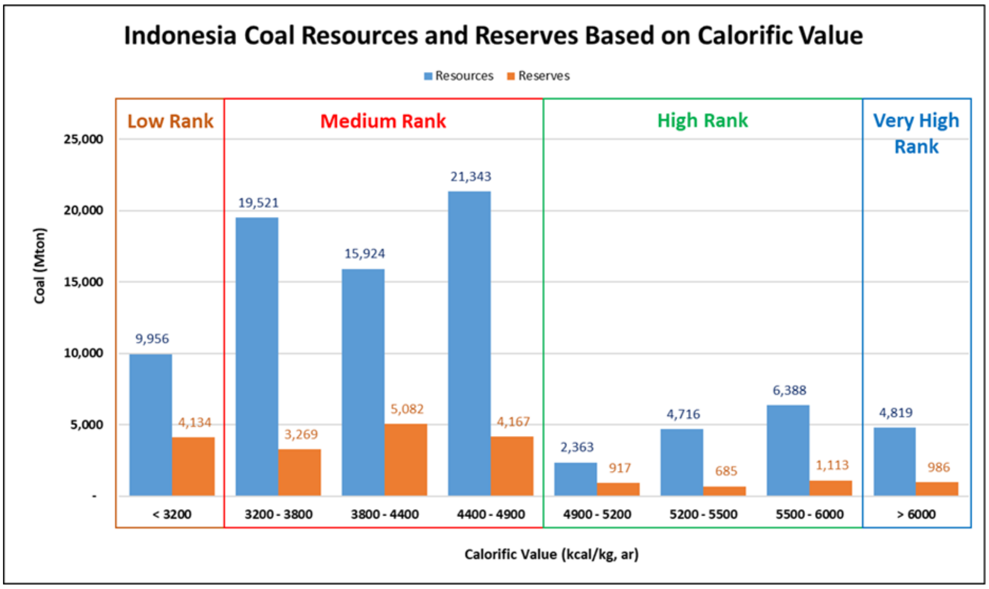


Figure 1-2: Indonesia’s coal resource and reserve classification based on its calorific value

Figure 1-2 shows that the majority of coal resource and reserve in Indonesia are classified as medium rank coal (3,200 – 4,800 kcal/kg in as-received basis) which very suitable for CFPPs. However, the specification varies differently in terms of calorific value, total moisture, ash content, and sulfur content. Moreover, each coal specification has a limited amount of available reserve. Therefore, to optimize the coal utilization in order to minimize procurement and transportation costs as well as guarantee the continuity of coal supply, coal blending activity should be considered.

Generally, coal mining activity involves several stages in the life of mine. There are four activities, which are prospecting, exploration, development, and exploitation (Hartman, 1987). Most of the time, prospecting and exploration activity are conducted collaboratively both by geologist and mining engineers to make sure the occurrences of coal deposit in certain location. The objective of exploration activity is to determine the amount and value of coal deposit, mostly conducted by using core drilling techniques.

After the coal deposit was determined as economically feasible, the development stage will begins. Development stage consist of construction work of mining facilities, as well as gain access for the coal deposit. There are two methods to access the coal deposit, by directly expose near-surface material or excavate openings from the surface to more deeply buried coal deposit to prepare for underground mining.

Development of underground coal mining is generally more complex and expensive, because it needs careful planning to ensure the safety aspects of mining activity. However, the mining methods selection in exploitation activity is defined mainly by the characteristics of the coal deposit and the limits imposed by safety, technology, and economics. Geological condition plays the most important role in selecting whether the coal mining will be carried out by using open pit or underground mining method.

Surface mining is the predominant exploitation method in Indonesia, most of coal mining companies in Indonesia are conducting the coal production activity by using open pit mining method. This method is less expensive and easier than the underground mining method, moreover the production rate in open pit coal mining method is significantly higher than underground coal mining method. Coal production from open pit mining method contributing more than 90% of total Indonesia's coal production (Ministry of Energy and Mineral Resources Republic of Indonesia, 2018).

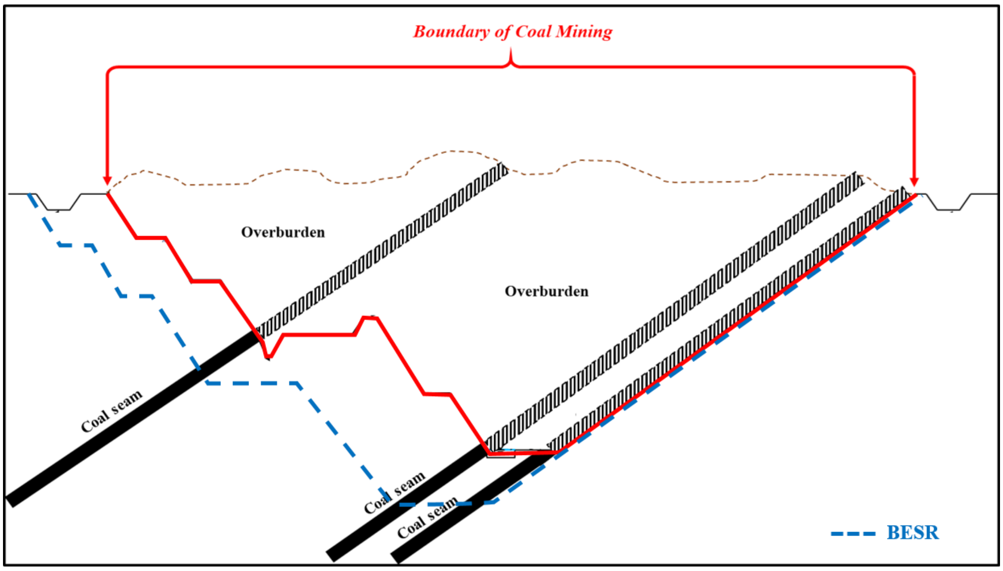


Figure 1-3: Vertical cross section of typical surface coal mining in Indonesia

In determining the amount of production or boundary in open pit coal mining, Break-Even Stripping Ratio (BESR) calculation was commonly applied by coal mining companies, as shown in Figure 1-3. The BESR value will be compared to the Stripping Ratio value, which is the ration between the amount of overburden removal in bank cubic meter (BCM) and the amount of coal getting in ton (see Eq. (1.1)). The boundary of coal mining should be inside the BESR line (SR < BESR) that will produce profits for the company. The equation of BESR is shown in Eq. (1.2) as follows. Revenue and cost of coal getting were stated in \$/ton, while the cost of overburden was stated in \$/BCM.

$$SR = \frac{Volume\ of\ Overburden}{Tonnage\ of\ Coal} \tag{1.1}$$

$$BESR = \frac{Revenue - Cost\ of\ Coal\ Getting}{Cost\ of\ Overburden\ Removal} \tag{1.2}$$

1.1.3 National primary energy demand

In Indonesia, the primary energy mix is regulated in Presidential Decree No. 5 of 2006 concerning the National Energy Policy as well as Presidential Decree No. 22 of 2017 concerning the General Plan of National Energy, which has the goal of achieving energy elasticity of less than one by 2025 and realizing an optimal energy mix in the same year. In 2025, there will be a change in the role of each type of energy in the domestic energy consumption, with a maximum share of petroleum of up to 25%, a minimum share of natural gas of at least 22%, coal at least 30%, biofuel at least 5%, geothermal at least 5%, renewable energy at least 10%, and a minimum share of liquefied coal of at least 3%. The framework of the energy systems and its impact in Indonesia can be seen in Figure 1-4.

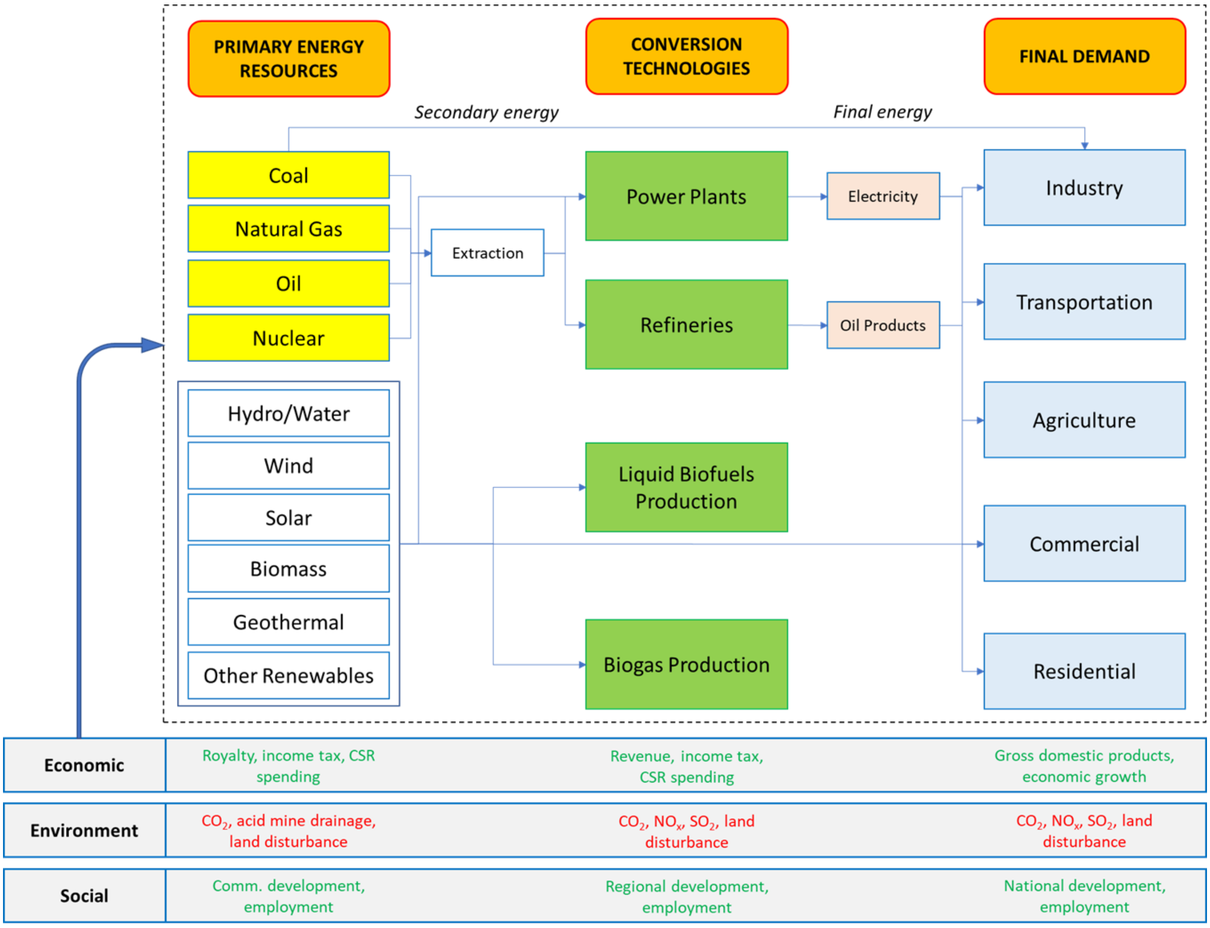


Figure 1-4: Framework of energy systems in Indonesia

Considering the recent condition of the primary energy mix and in respect to the regulation mentioned above, coal is considered as an important primary energy source in Indonesia (see Figure 2-1) and will become more important in the future. The contribution of coal to the national energy mix will increase every year, and coal will become the largest energy source in 2025. This can be achieved by increasing the amount of coal production or prioritizing domestic utilization by reducing the amount exported. Furthermore, Indonesia has also held a vital role in the global coal market, indicated by its status in 2018 as the 5th largest coal producer and the 2nd top coal exporter in the world. In addition, British Petroleum (2019) stated that the growth rate of Indonesia's coal production in 2018 was the fastest among the top ten coal producer and consumer countries. Indonesia has 18.94% of growth on coal production in 2018 and is the highest compared to other countries. Furthermore, the annual growth rate of coal production in Indonesia in the last 10 years is around 7.83% per year, which is the 3rd country with the most significant growth of coal production in the world after Mongolia and Uzbekistan. In 2018, Indonesia produced approximately 548.6 million tons of coal, of which only 114.55 million tons were for domestic utilization. Based on the data from the Ministry of Energy and Mineral Resource of the Republic of Indonesia (2018), the total coal resources (concentration or occurrence of coal in or on the Earth's crust in such form, quality, and quantity that there are reasonable prospects for eventual economic extraction) in Indonesia are around 140.48 billion tons, with 29.91 billion tons classified as coal reserves (the economically mineable part of the coal resource). Indonesia's coal reserves only account for 3.5% of the total world coal reserves (British Petroleum, 2019).

1.1.4 Electricity generation

Indonesia is one of developing country that try to accelerate the economic growth through vast development in industrial sector. The target plan of economic development acceleration has affecting to the electricity generation. In 2020, the electricity generation in Indonesia is around 275.2 TWh which increase 5.9% annually from 2009.

In 2020, thermal power capacity in Indonesia was 59.38GW making its share 85.6% in total power capacity. Indonesia produced 83.2% of its power generation from thermal sources. Thermal power capacity is expected to reach 92.53GW by 2030 maintaining its dominance in the country. During 2021-2030, thermal power generation will be dominated by coal-based electricity generation.

The electricity generation can be classified based on the energy sources, which are hydropower, geothermal, renewable energy, gas, oil, coal, and coal. In 2020, coal accounted for 198,1 TWh or 68.20% of total electricity generation. This condition shows the coal dependency for power generation in Indonesia, that will still increase in the near future considering the 35 GW project.

1.1.5 Challenges on coal utilization

Coal has constraints that put it in a weak position in respect of oil and gas. Being a solid and heavy material, it is bulky and needs large stockpile areas. With a lower calorific value than oil and gas, it does not have the ease of use of a liquid or gaseous fuel. It generates pollution at every stage of the production and utilization.

Using coal as the fuel for power plant will emit carbon dioxide (CO_2) and other gases. CO_2 is the main source of Greenhouse Gases (GHG) and these gases have very significant impact in the global warming. Combustion of coal contributes 37% of CO_2 emission globally. Furthermore, among other fossil fuels, coal is more carbon-intensive fuel per energy unit, therefore the increment in CO_2 emissions from its combustion is higher than the increment in emissions from other fossil fuels, such as natural gas and oil.

The utilization of coal can give benefits for the human and development, however the value of coal are partially offset by the environment issues occurred from its utilization. Some of these environmental issues also have impacts on human health. Table 1-2 summarizes the effect of coal utilization on the environment at the production and utilization stage.

Table 1-2 Main impacts of coal in each stage

Stage	Impacts
Mining	
• *Underground*	• Surface subsidence • Generation of gases (mainly CH_4) • Liquid effluent/Acid Mine Drainage • Hydrologic impact • Health effect of miner: respiratory diseases (e.q. pneumoconiosis or silicosis) caused by dust
• *Surface*	• Surface disturbance (e.q. changed of natural land surface) • Liquid effluent/Acid Mine Drainage • Hydrologic impact • Solid waste

Stage	Impacts
Beneficiation	• Water contamination from preparation plants • Air contamination from preparation plants • Refuse contamination from preparation plants
Transportation	• Air pollution • Surface disturbance
Combustion	• Fly ash, bottom ash, boiler slag, Flue Gas Desulfurization material • Sulfur Oxides • Nitrogen Oxides • Particulate matter • Carbon monoxide • Potentially toxic trace elements (Cr, Ar, Ld, Cd, etc.) • Carbon dioxide

Facing the environment challenges, at the moment coal mining industry is developing a roadmap into a cleaner coal utilization. Deploying cleaner coal utilization paradigm, which would improve the thermal efficiency of coal utilization and reduce emissions, could minimize investment risks and give a major improvement to prospects for coal demand. In electricity or power generation, this paradigm responses the environmental challenges through three ways which are: reducing emission of pollutants, increasing thermal efficiency, and reducing CO_2 emission to near zero level. While attention is focused on power generation technologies, continuous technological advances are being made along the entire coal chain.

New techniques have been developed for coal mining, preparation of coal for use in power stations, as well as for coal combustion, emissions control and the disposal of solid waste. These techniques are able to minimize the environment impacts. Technologies on the horizon such as carbon capture and storage (CCS) could achieve near-zero emissions of pollutants from coal-fired power plants (CFPPs).

1.2 Literature Review

The literature that was reviewed in this thesis are briefly explained in this section in order to point out the problems related to the coal mining industry in Indonesia. The topics are including: 1) economic aspects from coal utilization, 2) environmental aspects from coal utilization, and 3) social aspects from coal utilization.

1.2.1 Economic aspect from coal utilization

Economic growth in Indonesia shows a significant development in a decade. Indonesia is one of biggest economy in the world with more than 1 trillion USD of Gross Domestic Products (GDP), which also the biggest economy in the South-East Asian. After the world economy crisis in 2008, Indonesia belongs to the middle-income country with per capita GDP around USD 3,500 per capita.

Coal is the focus of energy policy in Indonesia since 1970. Indonesia has abundant coal reserves compare to the other energy source. Coal not only important for electricity generation, but also an export commodity for Indonesia. Indonesia is the second largest coal exporter in the world. Income from coal in the last 4 years was USD 2.17 billion or 80% from the total non-oil and gas income.

With the important role of coal to the economy, it is necessary to optimize the coal utilization to support the economic growth in Indonesia, particularly on how to optimize the supply between domestic and export market.

1.2.2 Carbon dioxide emission from coal utilization

A major environmental challenge facing the world today is the risk of global warming. Human activities, such as the combustion of fossil fuels, produce additional GHGs which accumulate in the atmosphere. Scientists believe that the increase of these gases is causing a greenhouse effect, which could cause global warming and climate change. The major greenhouse gases include water vapor, carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.

Coal is one of many sources of greenhouse gas emissions generated by human activities and the industry. Greenhouse gases associated with coal include methane, CO_2 and nitrous oxide (NO_2). Methane is released from deep coal mining. CO_2 and NO_2 are released when coal is used in electricity generation or industrial processes, such as steel production and cement manufacture.

1.2.3 Social impact from coal utilization

Coal mining has a long history as a prime mover for regional development, particularly in remote area. Coal resources exist in many developing countries, including those with significant energy challenges. Coal will therefore play a major role in supporting the development of base-load electricity where it is most needed. CFPP will be fed into national grids, and it will bring energy access to millions and support economic growth in the developing world.

The World Energy Outlook 2011 highlights that coal alone accounts for more than 50% of the total on-grid additions required to achieve the IEA's Energy for all case. This clearly demonstrates coal's fundamental role in supporting modern base load electricity. Many countries with electricity challenges are also able to access coal resources in an affordable and secure way to support the growth for the electricity supply. As nations develop, they seek secure, reliable, and affordable sources of energy to strengthen and build the economies – coal is a rational choice in many of developing countries because it is widely available, safe, reliable, and relatively low cost. This has been demonstrated in Indonesia, Vietnam, in China, in South Africa, and many other developing countries. Many developing countries have significant coal reserves. The fact that coal is expected to account for more than 50% of total on-grid additions demonstrates coal's continuing role as the backbone of our global electricity supply.

There is a huge opportunity to ensure that modern and clean coal technologies can be part of addressing the challenge of energy poverty. National and international policy frameworks and financing mechanisms must support the deployment of the most efficient and cleanest coal technology. If these frameworks are not in place, then less efficient technologies with greater environmental consequences are likely to prove more attractive on a cost basis than more expensive but also more efficient and cleaner technologies.

1.3 Problem Statements

Coal as one important energy sources is facing greater challenges in the future, particularly in terms of CO_2 emission. Indonesia still heavily relies on coal as the source for primary energy demand. It is important to analyze the future role of coal in the primary energy mix in order to support the national development as well as meet the global target to prevent the climate change.

However, the domestic coal supply problems in Indonesia also need to address, in order to bring optimal advantage from coal utilization. As an overview, the research will address the coal production trend in the future considering its factors, as well as optimizing the coal utilization considering the economy, environmental, and social aspects ().

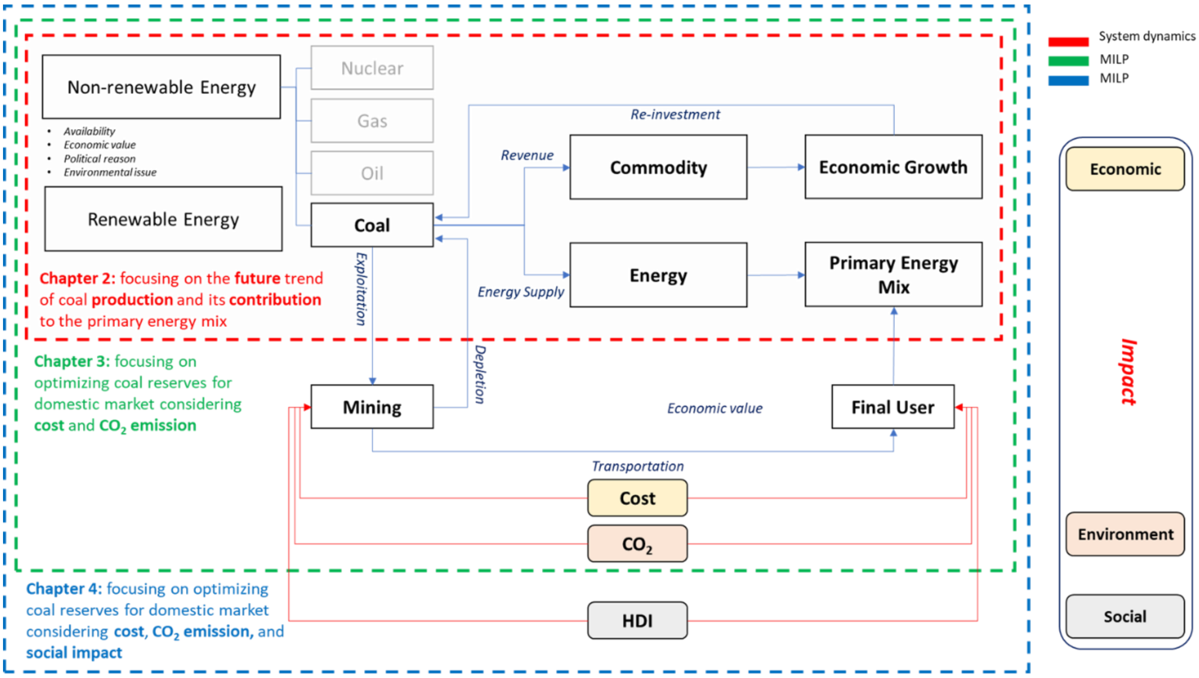


Figure 1-5: Problem statements and the research overview

1.4 Research Objectives

The future of coal industry in Indonesia is important to be analyzed considering the vital contribution of coal to the national primary energy mix. This research tries to analyze and optimize the current situation of coal mining and its utilization in Indonesia. As the first step in understanding and analyzing the current situation, a simulation model will be utilized in this research. Furthermore, by using a simulation analysis one of the objectives of this research is to forecast several scenarios of coal utilization in Indonesia considering economic, environmental, and social aspects. Having understood the actual and the future trend of coal utilization in Indonesia, it is hoped that the results of this research may contribute as a guideline for energy policy in Indonesia.

Fundamentally, there are four key questions that will be considered in this research, which are 1) Does Indonesia still need coal? 2) If coal demand still growing in the future, how should Indonesia optimize their coal utilization? 3) What should be done to diminish negative environmental impacts of coal mining and utilization? 4) Concerning the economic, environmental, and social aspects, what will the states of the coal mining industry in Indonesia the future?

1.5 Research Approaches

Three approaches will be utilized in this proposed study, which are an investigation analysis, simulation, and optimization. The purpose of the first analysis is to examine the present and future roles of coal in Indonesia and to seek answers to the research objectives mentioned in the above.

The simulation is conducted in order to analyze several scenarios for coal and energy utilization, particularly considering the environmental impact. Simulation will be conducted by using system dynamics model in order to understand the impact of each factor to the future coal supply and demand.

The last approach is conducted in order to optimize the coal utilization in Indonesia, after the role of coal utilization in the future has been known from the previous simulation. The purpose of optimization is to ensure the security of coal supply that also try to consider economic, environmental, and social aspects.

1.6 Thesis Outline

This doctoral thesis divided into five chapters, which are the introduction, system dynamics approach in determining coal utilization scenario in Indonesia, multi-objective optimization on total cost and carbon dioxide emission of coal supply for coal-fired power plants in Indonesia, multi-objective optimization model for coal supply with economic, environmental, and social aspects consideration, and conclusions.

2 Coal utilization scenario in Indonesia

2.1 Introduction

Energy plays a vital role in the economy, in terms of both supply and demand. In terms of demand, energy is a commodity needed by people to maximize their utility. In terms of supply, energy is key to production, along with capital, labor, and raw materials. In addition, energy is a key factor in increasing economic growth and living standards. Based on the research by Fatai et al. (2004), the increasing amount of energy consumption in Indonesia will drive national economic growth. In Indonesia, the primary energy mix is regulated in Presidential Decree No. 5 of 2006 concerning the National Energy Policy as well as Presidential Decree No. 22 of 2017 concerning the General Plan of National Energy, which has the goal of achieving energy elasticity of less than one by 2025 and realizing an optimal energy mix in the same year. In 2025, there will be a change in the role of each type of energy in the domestic energy consumption, with a maximum share of petroleum of up to 25%, a minimum share of natural gas of at least 22%, coal at least 30%, biofuel at least 5%, geothermal at least 5%, renewable energy at least 10%, and a minimum share of liquefied coal of at least 3%.

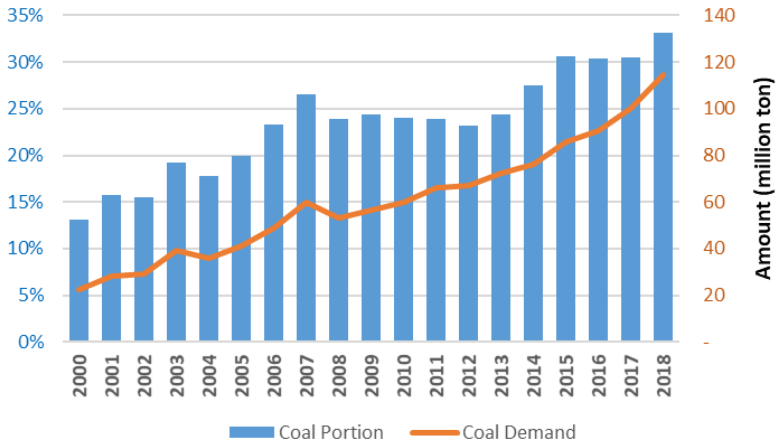


Figure 2-1: Indonesia's coal portion in the primary energy mix and coal demand (source: British Petroleum, 2019)

Considering the recent condition of the primary energy mix and in respect to the regulation mentioned above, coal is considered as an important primary energy source in Indonesia (see Figure 2-1) and will become more important in the future. The contribution of coal to the national energy mix will increase every year, and coal will become the largest energy source in 2025. This can be achieved by increasing the amount of coal production or prioritizing domestic utilization by reducing the amount exported. Furthermore, Indonesia has also held a vital role in the global coal market, indicated by its status in 2018 as the 5th largest coal producer and the 2nd top coal exporter in the world. In addition, British Petroleum (2019) stated that the growth rate of Indonesia's coal production in 2018 was the fastest among the top ten coal producer and consumer countries (see Figure 2-2). Indonesia has 18.94% of growth on coal production in 2018 and is the highest compared to other countries. Furthermore, the annual growth rate of coal production in Indonesia in the last 10 years is around 7.83% per year, which is the 3rd country with the most significant growth of coal production in the world after Mongolia and Uzbekistan. In 2018, Indonesia produced approximately 548.6 million tons of coal, of which only 114.55 million tons were for domestic utilization. Based on the data from the Ministry of Energy and Mineral Resource of the Republic of Indonesia (2018), the total coal resources (concentration or occurrence of coal in or on the Earth's crust in such form, quality, and quantity that there are reasonable prospects for eventual economic extraction) in Indonesia are around 140.48 billion tons, with 29.91 billion tons classified as coal reserves (the economically mineable part of the coal resource). Indonesia's coal reserves only account for 3.5% of the total world coal reserves (British Petroleum, 2019). As one of the most important coal suppliers in the world, Indonesia has many problems to solve, such as:

- How much coal is necessary to support national economic growth?
- What is the trend of Indonesia's coal supply and demand in the future?
- Is Indonesia able to fulfill its target on carbon dioxide emission reduction?

Considering this, it would be better for the utilization policy of coal in Indonesia if the future of coal production could be predicted scientifically.

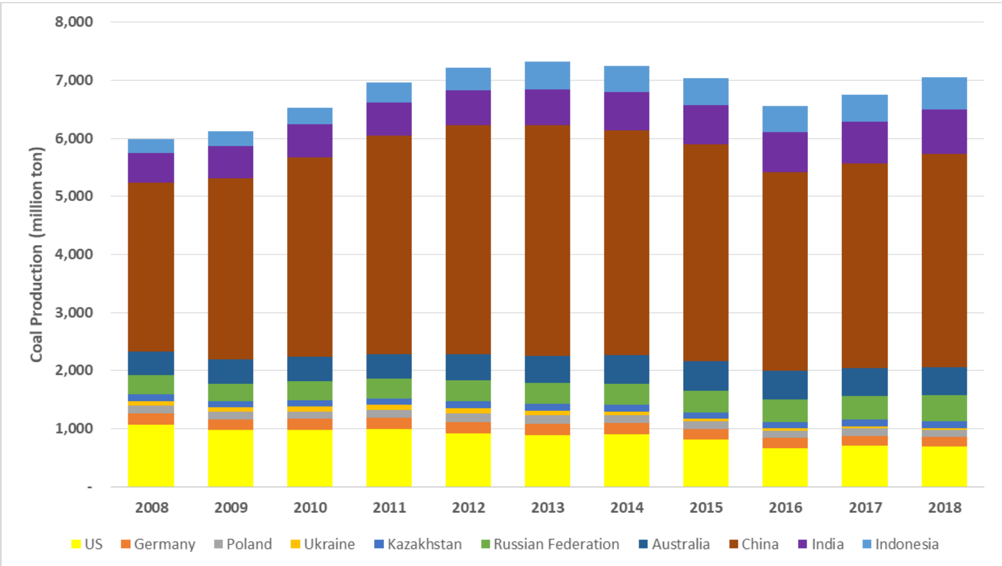


Figure 2-2: Coal production growth in the top ten coal reserves country (source: British Petroleum, 2019)

To answer several questions above, system dynamics model of coal production in Indonesia, which primarily refer to previous research on the scenario prediction of China's coal production conducted by Wang et al. (2018), will be constructed. Time series forecasting method cannot be used to analyze the impact of other factors in coal production, therefore system dynamics method will be utilized. Several modifications from Wang et al. (2018) will be applied, particularly considering the different conditions of the coal mining industry in Indonesia. The most important difference will be the incorporation of the oil and gas that is assumed to be a substitute for coal in Indonesia's primary energy mix. On their preliminary study, Baskoro et al. (2018) try to consider activity in the mining industry in order to predict the future of coal production in Indonesia. In their study, the introduction of coal substitution can improve the forecasting performance with smaller error of simulation results. In this study, it is also expected that the modification can be used to analyze several scenarios for the national energy policy.

2.2 Coal production

This research is conducted with a similar approach to that of Wang et al. (2018) because the similarity of both methodology and considered factors. However, the system dynamics model can be improved from Wang et al. (2018) by considering several modifications according to the actual condition of coal mining activity in Indonesia. In their study, coal production was built by assuming that the coal reserves will always decrease because of production activity without any addition from exploration activity. That kind of approach is not suitable for the current condition of coal production in Indonesia, in which exploration activities are still being continuously carried out by the coal mining companies. In such circumstances, the prediction could be better and utilized for a longer period by assuming that the reserves will also increase due to such exploration activity. Therefore, the transformation mechanism of coal resources into coal reserves, as mentioned in the JORC (2012), will be taken into consideration in this proposed research.

Wang et al. (2018) only consider coal in its system dynamics model, which will be modified in this research. This modification is motivated by the fact that Indonesia is also heavily reliant on oil and gas, as well as renewable energy as substitutes for coal. However, the oil and gas reserves in Indonesia are becoming scarce as a result of exploitation. Thus, the best option for fulfilling the primary energy demand is to utilize coal and renewable energy. In the future, the role of coal in the national primary energy mix will be more vital due to its increasing share, as targeted by the government. Considering the weaknesses of the above studies, the authors conduct a forecast for coal production and the impact of coal substitution in Indonesia. Therefore, oil and gas prices will be incorporated into the model.

2.3 System dynamics model

2.3.1 Model boundary and hypothesis

This research was carried out using a similar approach to that of Wang et al. (2018). Therefore, there will be several similarities in terms of the research structure and method. However, due to the different conditions in Indonesia's and China's coal mining, several parameters have been constructed differently according to the current situation in Indonesia (see Table 2-1).

Table 2-1 Research comparison

Parameters	Wang et al. (2018)	Proposed research
Supply–demand system		
Export market	-	√
Domestic market	√	√
Parameter variation		
Economy	√	√
Environment	√	√
Production factor	Reserve; Capital factor	Reserve; Price
Reserve	Exogenous	Endogenous
Energy substitution	-	√

Brief comparisons between Wang et al. (2018) and this proposed research are as follows.

- Wang et al. (2018) only considered coal in the domestic market for the modeling. In the proposed research, export market will be also considered because majority of coal production in Indonesia was sold to the export market.
- Both economy and environmental aspect will be similarly considered as Wang et al. (2018). Moreover, the primary energy mix will be also considered in the proposed research as a guideline for the national energy policy.
- One of the most important aspect in system dynamics modelling for coal production is its production factor, therefore this factor will be similarly considered in this proposed research. However, a different approach will be applied because Wang et al. (2018) constructs their model based on the coal production capacity. In this proposed research, the model will be constructed based on the production activity, therefore coal price will be the most important factor instead of capital factor.
- Coal reserves was assumed as exogenous variable in Wang et al. (2018), however in order to analyze the impact of exploration activity to the coal production, it is necessary to consider coal reserves as an endogenous variable.
- Wang et al. (2018) only focus on coal without considering other energy resources such as oil, natural gas, and renewable energy. However, the national energy demand in Indonesia was fulfilled not only by coal, but also oil, natural gas, and renewable energy. Each type of energy resources has its own characteristics. Therefore oil, natural gas, and renewable energy will be included in the model by considering the availability, cost, environmental impact, and other characteristics.

In this research, both the domestic and export markets were considered in the modeling. Moreover, to analyze the impact of exploration activity, the coal reserves were assumed to be an endogenous variable that will change depending on the discovery rate. The other major difference is the incorporation of energy substitutes for coal, such as oil and gas. By considering all these differences, it is expected that the model can represent the current situation in Indonesia very well.

To understand the behavior and predict the future coal production in Indonesia, the system dynamics of coal production was developed. The model development consists of several steps, such as the definition of the model boundary, model construction, parameter setting and calibration, model simulation, and scenario simulation. This paper aims to understand the feedback mechanism between the coal production rate and all the influencing factors, such as the coal price, substitution price, and available reserves, by investigating the modules of coal production, coal demand, carbon dioxide emissions, and gross domestic product (GDP) using system dynamics model based on Forrester (1961) and Coyle (1996).

To simplify the model, this study applies several assumptions: (1) the supply-demand system of coal is open; (2) the influence of non-technical factors is neglected in supply-demand; (3) the economic growth target influences the system; (4) the coal demand structure is mainly formed by the mid-term development program of 35,000 MW electricity generation; (5) the coal reserves are an endogenous variable that will be affected by the exploration rate; (6) changes in the coal production rate are assumed to be affected primarily by the coal price.

2.3.2 System dynamics model structure analysis

As previously mentioned, the system dynamics of coal production in Indonesia is constructed by considering four modules, which are coal production, coal demand, carbon dioxide emissions, and the GDP. Each module is indicated by a different color and position in Figure 2-3. The coal production module (green color) is controlled by the production rate; the coal demand module (blue color) is controlled by the electricity generation and other industries demanding coal; the carbon dioxide emissions module (orange color) is controlled by the carbon dioxide emission; and the GDP module (yellow color) consists of GDP and population. All the modules were developed by considering Wang et al. (2018) with necessary modifications based on the coal production activity in Indonesia.

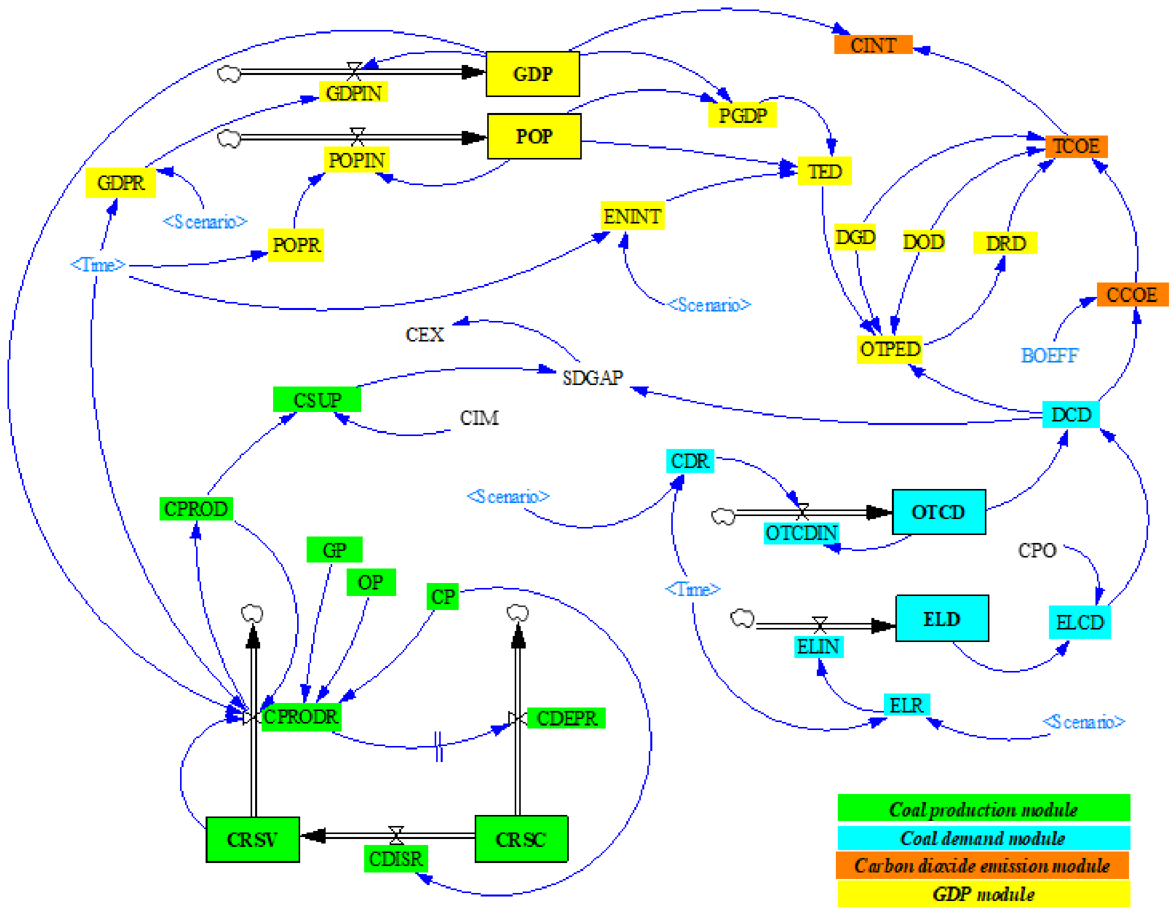


Figure 2-3: System dynamics model of Indonesia's coal production

The coal production module is constructed in a significantly different way from Wang et al. (2018), because it was designed by considering the transformation mechanism of coal resources into coal reserves, as mentioned in the Joint Ore Reserves Committee Code for the Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC, 2012) and the National Standardization Committee of Indonesia on the Guideline for Exploration Report (Badan Standardisasi Nasional, 2011). This assumption has been considered in order to tackle the disagreement on the absence of universal guidance in coal resources and reserves classification, as well as to improve the appropriateness of the model. Coal reserves is a part of the coal resources, which have a good geological confidence level and can be economically extracted to the surface. The geological confidence of a deposit can be improved by carrying out extensive exploration activity, which is affected directly by the coal price in terms of the expected profits of mining. Usually, a higher coal price will generate more investment in coal exploration activity. The transformation of coal resources into coal reserves is reflected by the discovery rate in the coal production module.

Surface mining is a predominant mining exploitation method in Indonesia, where most coal mining companies are conducting coal production activity using the open-pit mining method. This method is less expensive and easier than underground mining. Moreover, the production rate from open-pit coal mining is significantly higher than that of underground coal mining. Coal production from the open-pit mining method contributes more than 90% of Indonesia's total coal production (Ministry of Energy and Mineral Resource of the Republic of Indonesia, 2018).

To determine the amount of production or the boundary in open-pit coal mining, the break-even stripping ratio (BESR) is commonly calculated by coal mining companies (Hartman, 1987). The BESR is compared to the stripping ratio (SR), which is the ratio between the amount of overburden removal (V_{OB}) in bank cubic meters and the amount of coal extracted (M_{coal}) in tons (see Eq. (1.1)). The boundary of coal mining should be within the BESR line (SR < BESR), which will generate profits for the company. The BESR is shown in Eq. (1.2). The revenue (R) and cost of coal extraction (C_{coal}) are stated in \$/ton, while the cost of the overburden (C_{OB}) is stated in \$/BCM. The revenue from coal mining activity is more fluctuate than cost, therefore coal price will directly influence the production rate.

$$SR = V_{OB}/M_{coal} \tag{2.1}$$

$$BESR = (R - C_{coal})/C_{OB} \tag{2.2}$$

As mentioned previously, energy consumption has a unidirectional relation with economic growth. Therefore, the GDP will influence the coal production rate. By considering gas and oil prices in the model, the estimation result for future coal production can be more accurate. By taking into consideration all the factors above, the production rate is calculated as a result of several factors, which are the coal price, price of substitution, previous coal production, and GDP.

The coal demand module is also constructed differently from Wang et al. (2018). In their study, the coal demand was calculated in a portion-based way, considering the historical trend on the primary energy mix in China. They also consider coal production only for the domestic market, without considering the export market, because most of the coal production in China was utilized in the domestic market. A different condition is applied in Indonesia, where the annual coal production will be sold in both the domestic and foreign markets. Even though the amount of coal production in Indonesia is sufficient to supply both markets, only around 30% of its production was utilized in the domestic market (British Petroleum, 2019). In the future, this condition should be adjusted, considering the installation of new coal-fired power plants to support the national electrification ratio and the coal domestic market obligation policy according to the MEMR (2018), which will have an immediate impact on the future domestic market for coal, as illustrated in the coal demand module. Therefore, the coal demand module will consist of coal demand from electricity generation and coal demand from other industries.

The coal demand from other industries consists of the demand for metallurgy, pulp, cement, textile, and others. This approach will also have an impact on scenario prediction.

The carbon dioxide emission module is constructed similarly to that of Wang et al. (2018). However, with respect to the historical data from British Petroleum (2019) and a statement from MEMR (2018) as well, which shows a decreasing amount of carbon dioxide emission in 2015, a boiler efficiency has been introduced in the system dynamics model to calculate the carbon dioxide emission. The total amount of carbon dioxide emission is estimated from the utilization of coal in the domestic market, added to the amount of carbon dioxide emitted from other energy sources, as can be seen in the carbon dioxide emission module. To analyze the impact of coal utilization on the environment, the carbon dioxide emission intensity can be used as an indicator in a similar approach to that utilized in Wang et al. (2018).

The GDP module is also similarly constructed to that of Wang et al. (2018), except for the modification of the primary energy demand component. The GDP and population are estimated by considering the historical trend. The relationship between the state and flow variables in the GDP and population simply reflects the actual condition using the macroeconomic principle. These formulations were also implemented by Wang et al. (2018) and, because of the similar condition in Indonesia, these formulations are simply applied to the system dynamics model of coal production in Indonesia. However, to provide a clearer and more detailed view of the primary energy structure, the primary energy demand was composed of oil, natural gas, coal, and renewable energy.

2.3.3 Parameter setting and calibration

The system dynamics model was built utilizing data collected from 1980–2000 from various sources. The data on primary energy production and consumption was taken from British Petroleum (2019), while macroeconomic data was taken from a publication by the World Bank (2018). The relationship between all the variables is generated considering their actual interaction in the coal mining industry by using linear regression with the ordinary least squares method. The model was able to reproduce similar behavior to the actual data. The model consisted of three types of variable, as described in Table 2-2.

Table 2-2 Variables in system dynamics model of Indonesia's coal production

Types	Variables	Description	Unit
Rate	CDEPR	Annual depletion rate of coal resources due to the production activity	million ton/year
	CDISR	Annual rate of additional coal reserves from exploration activity	million ton/year
	CPRODR	Annual coal production rate	million tons/year
	ELIN	Annual change in electricity generation	TWh/year
	GDPIN	Annual change in GDP	million USD/year
	OTCDIN	Annual change of coal demand from non-power generation industry	million ton/year
	POPIN	Annual change in population	million persons/year
State	CRSC	The amount of remaining coal resources	million tons
	CRSV	The amount of remaining coal reserves	million tons
	ELD	Total electricity that will be generated	TWh
	GDP	Gross domestic product of Indonesia	million USD
	OTCD	Total amount of coal demand from non-power generation industry	million tons
	POP	Total population of Indonesia	million persons
Auxiliary	BOEFF	Boiler efficiency	%

Types	Variables	Description	Unit
	CCOE	Carbon dioxide emission from coal utilization	million tons
	CDR	Annual growth rate of coal demand from non-power generation industry	%
	CEX	Exported coal	million tons
	CIM	Imported coal	million tons
	CINT	Carbon intensity of GDP	tons/USD
	CP	Coal price	USD/ton
	CPO	The amount of coal required for each unit of power generation	tons/TWh
	CPROD	Total coal production	million tons
	CSUP	Total coal supply	million tons
	DCD	Total domestic coal demand	million tons
	DGD	Total domestic natural gas demand	mtoe
	DOD	Total domestic oil demand in the domestic market	mtoe
	DRD	Total domestic renewable energy demand	mtoe
	ELCD	Total coal demand for electricity generation	million tons
	ELR	Annual growth rate of electricity generation	%
	ENINT	Energy intensity to GDP	mtoe/USD
	GDPR	Estimated annual growth of GDP	%
	GP	Natural gas price	USD/tcf
	OP	Crude oil price	USD/barrel
	OTPED	Primary energy demand fulfilled by oil, gas, and renewable energy	million tons
	PGDP	Per capita GDP	USD/person
	POPR	Estimated annual population growth	%
	SDGAP	Difference between coal supply and domestic coal demand	million tons
	TCOE	Total carbon dioxide emission from all industries	million tons
	TED	Total energy demand	mtoe

To validate the model, it is necessary to check the consistency of each variable or parameter by using the dimensional consistency test. The energy conversion factor was utilized to convert units, such as (1) 1 million ton oil equivalent = 4.4 TWh; (2) 1 million ton oil equivalent = 1.7 million tons of coal; (3) 1 million barrels of oil = 0.14 million ton oil equivalent; (4) 1 billion cubic feet of natural gas = 0.025 million ton oil equivalent.

The formulation of the rate variables above is derived from the historical data from 1980–2000. The variables of CDEPR, ELIN, GDPIN, and POPIN were calculated by multiplying the demand at a certain period of time with the growth rate. The variable of CDEPR was calculated by using the delay function because it was equal to the amount of coal production in the previous year. The variable of CDISR was calculated by using random uniform distribution of the coefficient of coal price, while the variable of CPRODR was calculated by using the conditional clause of the coal reserves, considering the relation between the coal production and several parameters, which are coal price (CP), oil price (OP), natural gas price (GP), GDP, and coal production (CPROD) in the previous year. The numerical equations of the rate variables are expressed by Eq. (2.3)–(2.9).

$$CDEPR = DELAY1(CPRODR, 1) \quad (2.3)$$

$$CDISR = RANDOM\ UNIFORM(low.coeff, up.coeff) * CP \quad (2.4)$$
$$CPRODR = IF\ THEN\ ELSE(CRSV > 0, (0.676 * (DELAY1(CPROD, 1)) - 0.250 * CP + 1.129 * OP - 3.801 * GP + 0.177 * GDP / 1000 - 39.832), 0) \quad (2.5)$$
$$ELIN = ELD * ELR \quad (2.6)$$
$$GDPIN = GDP * GDPR \quad (2.7)$$
$$OTCDIN = OTCD * CDR \quad (2.8)$$
$$POPIN = POP * POPR \quad (2.9)$$

The variables of CINT, CPROD, CSUP, DCD, DRD, PGDP, and SDGAP were calculated as identity values, while the variables of CCOE, ELCD, OTPED, TCOE, and TED were derived from regression analysis using the ordinary least squares (OLS) technique. The variables of GD and OD have linear growth trends as observed in the historical data from 1980–2018. The numerical equations of the auxiliary variables are expressed by Eq. (2.10)–(2.23).

$$CCOE = (1.86/BOEFF) * DCD + 7.48 \quad (2.10)$$
$$CEX = SDGAP \quad (2.11)$$
$$CINT = TCOE/GDP \quad (2.12)$$
$$CPROD = CPRODR \quad (2.13)$$
$$CSUP = CPROD + CIM \quad (2.14)$$
$$DCD = ELCD + OTCD \quad (2.15)$$
$$DGD = 0.37 * Time - 702.28 \quad (2.16)$$
$$DOD = 1.02 * Time - 1981.17 \quad (2.17)$$
$$DRD = OTPED \quad (2.18)$$
$$ELCD = 1.70 * ELD * CPO \quad (2.19)$$
$$OTPED = TED - (DCD/1.7) - DGD - DOD \quad (2.20)$$
$$PGDP = GDP/POP \quad (2.21)$$
$$TCOE = CCOE + 3.07 * DOD + 2.35 * DGD + 1.91 * DRD \quad (2.22)$$
$$TED = 0.20 * (ENINT / 1000) * PGDP * POP - 3.52 \quad (2.23)$$

2.3.4 Model test

The applicability of the system structure and system behaviors was tested to confirm that the SD model can precisely simulate the actual condition. The test results indicate that the model can emulate the actual condition in terms of the relationship between coal production and market supply-demand feedback. All the key variables are covered, and all the dimensions are homogeneous in the dimensional test. The model boundary is comparatively relevant, and all of the parameters of the model have practical significance according to the statistical regression analysis. The suitability test of model behaviors also shows that a slight variation of the parameters does not lead to significant changes in the model behaviors or conclusion, thus showing that the model has good behavioral suitability.

Furthermore, the capability of the model to accurately simulate the actual condition and the reliability of all of the parameter settings were tested. In principle, whether the simulation is appropriate to the actual condition or not is a relative result of the comparison. From the results (Figure 2-4), it can be concluded that the model was able to reproduce similar behavior to the actual condition, with only a small error. The simulation results are generally considered to be reliable if the error is less than 5% (Wang et al., 2018), although a smaller value is better. In this study, the mean absolute percentage error (MAPE) is utilized to calculate the simulation error of several parameters. The error values (see Table 2-3) for the production rate, domestic coal demand, export coal, electricity demand, and total CO_2 emissions are 4.38%, 4.28%, 4.29%, 0.85%, and 3.21%, respectively. By considering the results, the model can replicate the current coal production condition in Indonesia. When considering the impact of substitution for coal, the error value is smaller. This shows that the modification of the model in the production module gives better results for the prediction of Indonesia's coal production.

Table 2-3 Error of simulation

Parameter	MAPE
Production rate	4.38%
Domestic coal demand	4.28%
Export coal	4.29%
Electricity demand	0.85%
Total CO_2 emission	3.21%

2.4 Numerical experiment

2.4.1 Scenario design

The purpose of this research is to predict the future of coal production, in order to provide an alternative to the government for coal utilization in Indonesia, where coal is the main source of energy. However, the amount of coal reserves in Indonesia is very limited. Therefore, production needs to be carried out wisely.

To analyze several scenarios and causes of fluctuations in coal production, parameters are constructed by considering both the supply and demand sides. In designing the scenario, the parameters used as the main input factors are economic growth, energy utilization, growth in electricity generation, growth in coal demand in the industrial sector, and electricity generation efficiency.

Economic growth is represented by GDP in accordance with historical data and the target set by the Government. It is one of the important aspects of the simulation process, where there is a close relationship between economic growth and energy demand in accordance with Fatai et al. (2004). GDP is an indicator of economic development related to government spending, investment, export, and import.

Energy utilization is represented by energy intensity, which is an indicator that measures how much energy benefits the economy. This indicator is the ratio of the total use of primary energy to GDP. This is used to indicate how effectively a certain economy is using its energy. When a country reduces the amount of energy it wastes, it becomes more efficient; this lowers its energy intensity.

Electricity generation efficiency is an indicator that shows the combustion efficiency in the generator. The higher the value of efficiency, the smaller the negative impact on the environment.

GDP will have an influence on coal production, which can ultimately be used to determine the coal utilization policy. Domestic coal utilization will have negative effects on the environment, which can be analyzed by the amount of CO_2 emissions. Then, the CO_2 intensity of the GDP can be used as a major indicator in analyzing the effectiveness of energy utilization. In this study, four different scenarios (Table 2-4) were designed: Business as Usual (BaU), Economic Growth Priority with Policy Regulation (PR), Economic Growth Priority (EGP), and Environmentally Oriented (EO) as follows.

Table 2-4 Scenarios and primary parameter settings

Primary Parameters	BaU Scenario	EGP Scenario	PR Scenario	EO Scenario
Economic growth *GDP growth scenario*	5.0% (Historical data)	7.0% (MF, 2014)	7.0% (MF, 2014)	7.0% (MF, 2014)
Electricity growth *Electricity growth scenario*	6.3% (Historical data)	9.1% (MEMR, 2018)	9.1% (MEMR, 2018)	9.1% (MEMR, 2018)
Energy efficiency *Boiler efficiency*	75% (Historical data)	80% (MEMR, 2018)	80% (MEMR, 2018)	80% (MEMR, 2018)
Coal demand in other industry *Demand growth scenario*	8.0% (Historical data)	15.0% (MEMR, 2018)	8.0% (Historical data)	8.0% (Historical data)
Energy utilization *Energy intensity scenario*	3.53 MJ/$ (Historical data)	3.53 MJ/$ (Historical data)	3.53 MJ/$ (Historical data)	3.02 MJ/$ (MEMR, 2018)

The BaU scenario is developed by considering the current situation of the coal mining industry in Indonesia. All the parameter values are taken from historical data for 1980–2016. The GDP growth rate is around 5.0% annually, while the energy intensity of the GDP is equal to 3.53 MJ/$. The boiler efficiency of a power plant is assumed to be equal to the last condition, which is 75%. From the demand side, the growth rate of the demand for coal in electricity generation is 6.3% annually, while it is around 8.0% per year for other industries. The prices of coal, oil, and gas are assumed to follow the estimation of the World Bank in 2018 (Table 2-5) and will be applied for all scenarios.

Table 2-5 Price assumptions for all scenarios

Year	Coal Price ($/ton)	Oil Price ($/barrel)	Gas Price ($/tcf)
2019	100.00	64.29	7.20
2020	90.00	61.61	6.72
2025	73.50	62.05	7.20
2030	60.00	62.50	7.68

The BaU scenario is designed as the baseline. The EGP scenario is developed considering the government's economic development target. Therefore, in the EGP scenario, the GDP growth rate is assumed to be 7.0% annually (Ministry of Finance, 2014). The growth of the GDP will be driven by the electricity generation, which is reflected by the higher growth rate in the industry and electricity generation. The demand for coal for electricity will grow 9.1% annually as targeted by the Ministry of Mineral and Energy Resource in the Handbook of Energy and Economic Statistics of Indonesia 2017 (MEMR, 2018). The coal demand in other industries will grow 15.0% annually, also as targeted by the MEMR (2018). However, the boiler efficiency in this scenario is assumed to be 80% based on the data from MEMR (2018). The energy intensity of the GDP in this scenario is assumed to be the same as the current condition, which is 3.53 MJ/$.

Because the EGP scenario will significantly increase the negative impact on the environment, the PR scenario has been developed by considering the conservation of coal so as to reduce the impact on the environment. Therefore, all the parameters in the PR scenario are similar to the EGP scenario, excluding the coal demand in other industries. This means that in this scenario, electricity generation is the priority for national development, with the demand for energy sources still following the MEMR target. However, other industries will be assumed to have a lower dependency on coal as an energy source by utilizing other energy sources.

The EO scenario is designed to measure the future of coal production in Indonesia by considering the environmental issue. Therefore, in this scenario, the energy intensity is assumed to be different from other scenarios. The value of the energy intensity of the GDP is derived from the average value of the energy intensity of developed countries such as the USA, Korea, and Japan. The energy intensity in a developed country is lower, showing an efficient utilization of energy to support national development. By considering this condition and setting a higher target of energy efficiency in the future, the energy intensity value will be equal to 3.02 MJ/$.

2.4.2 Model validation

To determine the significance of the introduction of oil and gas as substitutes for coal in the SD model of coal production in Indonesia, two kinds of simulations are applied. The first, as the benchmark, does not consider the impact of oil and gas prices in the SD model (simulation 1 in Figure 2-4), while the second does consider oil and gas prices (simulation 2 in Figure 2-4). From that figure, we can conclude that oil and gas prices are very important in increasing the accuracy of the prediction of coal production in Indonesia. The average error for simulation 1 is -2.88%, while it is -1.23% for simulation 2. The MAPE also shows a similar conclusion, which is 7.86% for simulation 1 and 4.38% for simulation 2. Therefore, simulation 2 simply produces better result compared to simulation 1, having much smaller error and being able to reproduce the same behavior as in reality. Based on this result, the modification in this respect from the previous research is reasonable.

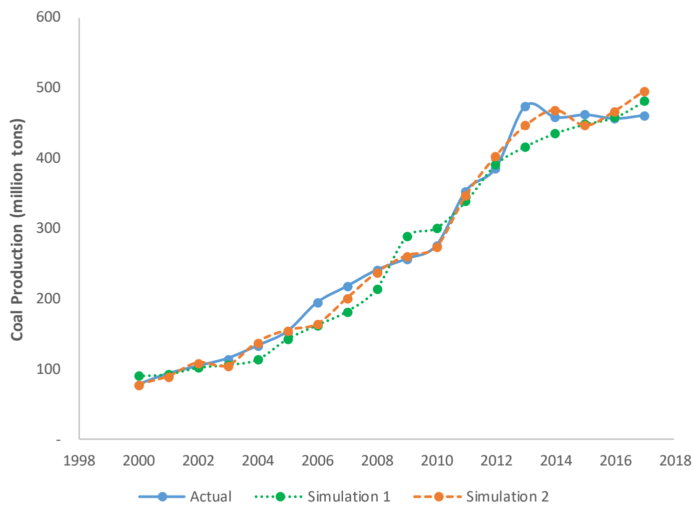


Figure 2-4: Simulation results for coal production

The prediction results in this research did not include a sensitivity analysis for the commodities price, particularly the coal price because the model was built based on the current condition of coal utilization in Indonesia. Currently, coal mining in Indonesia acts as the price taker, where the coal price was taken from the global coal market. As illustrated in the SD model, the coal price will directly affect the coal production. However, the coal demand will not be affected by the coal price because it was primarily generated by the electricity and other industry demand.

Coal production in the future is estimated to grow at a decreasing rate from the previous years (2000–2017), primarily being affected by the coal price, which fluctuates. However, the coal price in the future is not expected to increase significantly. There will be a different condition for the coal demand, which is expected to increase at a similar rate as previously. Future coal demand will be chiefly affected by the demand from the domestic market, mostly for electricity generation. A similar condition will be applied for the export market, considering the electricity generation growth in other countries (see Figure 2-4).

According to the fundamental principles of scenario analysis, the overall focus is on the influence of non-quantitative factors such as policy and the environment on coal production. Based on the abovementioned scenario settings, the changes in coal production and its affecting factors were simulated. The prediction results can be seen in Figure 2-5 for coal production and the carbon intensity of the GDP from 2018 to 2030.

2.5 Summary

To analyze the differences between scenarios and the origins of the change of coal production, the parameters are established on both the supply side and the demand side. On the one hand, the parameters of population, economy, and technology are established to determine the likely energy demand in the future. By setting the scenario of the demand module, future coal demand in Indonesia can be estimated from the demand side. On the contrary, the parameters of commodities prices, and changes of coal resources and reserves are set to predict the future trend of coal production from the supply side. On this basis, by measuring the comparison between scenarios of coal supply and demand, some recommendations are given for policymaking to regulate the coal production in Indonesia. Detail explanation on the results for coal production, coal demand, carbon dioxide emission, and coal portion to the national energy can be seen as follows.

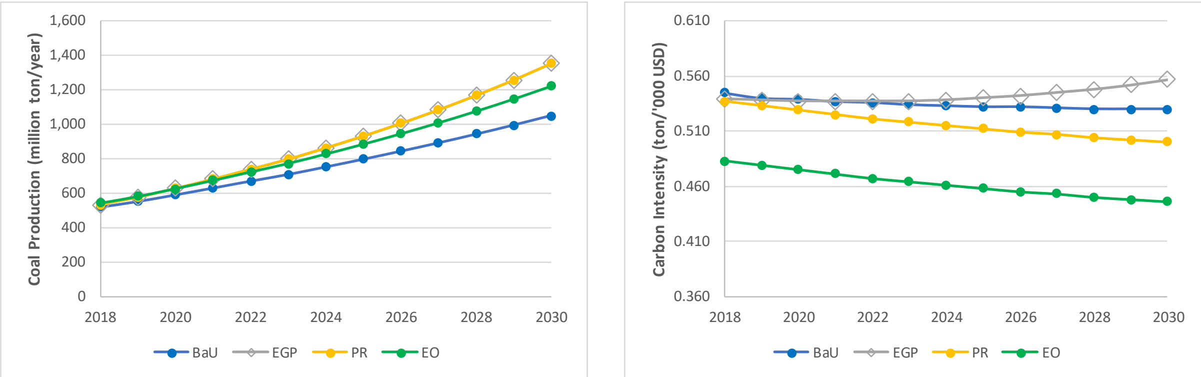


Figure 2-5: Estimation of Indonesia's (a) coal production and (b) carbon intensity of GDP in 2018–2030.

1) *Coal production*

As shown in Figure 2-5, the simulation results differ greatly because of the different parameter settings. However, the EGP and PR have similar values for coal production due to similar assumptions in the parameters. In the EGP and PR, the coal production experiences greater growth than the current trend (BaU) in order to achieve the economic growth target that was set by the government. The amount of coal production in 2030 is around 1.42 billion tons and 1.39 billion tons for EGP and PR respectively, while it is around 1.08 billion tons for BaU. Coal production in the EO scenario will reach 1.22 billion tons in 2030 as a result of GDP growth.

In general, Indonesia's coal production will continue to increase and will not reach its peak until 2030. The increase in coal production is primarily driven by the domestic demand, which will continue to increase, especially with the 35,000 MW electricity generation project. The annual coal production rate should be increased in a trend close to the latest condition if the government wants to achieve the target of economic growth (EGP, PR, and EO scenarios).

2) *Coal demand*

According to the prediction results, Indonesia's future energy demand will increase and shows a growth in industrial development. However, the growth rate varies significantly between scenarios. Total coal demand in the EGP will be the largest considering the highest target of domestic demand and economic growth, reaching 479.93 million tons in 2030. Total coal demand in the BaU, PR, and EO is smaller, at around 242.79 million tons, 275.61 million tons and 275.61 million tons respectively.

3) *Carbon dioxide emission*

Differences between scenarios appear in the carbon dioxide emission and carbon intensity of the GDP. From the value of these two indicators in 2030, EGP will be the worst alternative in environmental terms due to its sharp increase of carbon dioxide emissions (Figure 2-6) and the carbon intensity of the GDP (Figure 2-5b). This condition is generated by the significant increase of domestic utilization without being accompanied by a significant increase in the GDP. In 2030, the value of carbon intensity of the GDP for EGP is 0.557 tons of carbon/thousand USD of GDP. EO will be the best alternative for the environment, with the lowest value of this indicator, at around 0.446 tons of carbon/thousand USD of GDP.

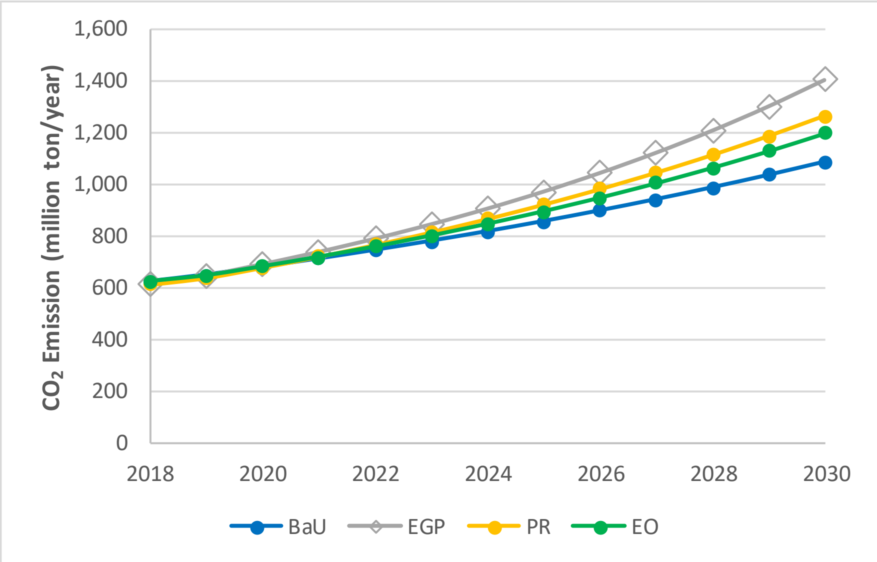


Figure 2-6: CO_2 emissions for all scenarios in 2018–2030

In detail, the order of scenarios from the worst to the best in terms of carbon dioxide emission in 2030 is EGP (1,406.61 million tons of CO_2), PR (1,262.73 million tons of CO_2), EO (1,197.67 million tons of CO_2), and BaU (1,086.14 million tons of CO_2). From this result, BaU can be assumed as the best alternative from the environmental aspect. However, considering the carbon intensity of the GDP, the EO scenario is the best alternative, with the lowest amount of the carbon intensity of the GDP (0.446 ton of CO_2/thousand USD of GDP in 2030). The second-best scenario is PR with 0.500 ton of CO_2/thousand USD of GDP in 2030.

4) Coal portion in the national energy mix

According to Figure 2-7, the predictions of Indonesia's coal production in the EGP and PR scenarios are remarkably higher than the BaU in terms of the share of coal in the national energy mix. The figure shows the amount of coal in the total primary energy demand in each year. The sizes of the pie charts in Figure 2-7 illustrate the total primary demand in each year. The total energy demand in 2030 for the BaU, EGP, PR, and EO scenarios is 455.24 mtoe, 604.94 mtoe, 555.45 mtoe, and 484.34 mtoe, respectively.

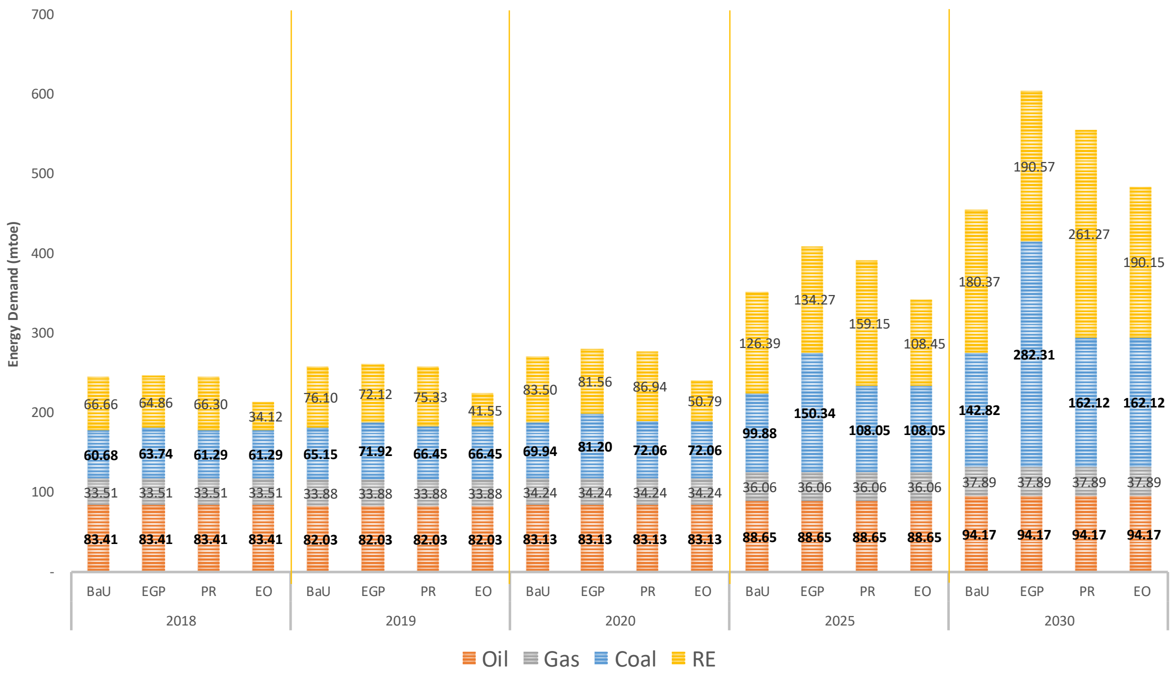


Figure 2-7: Total primary energy demand in 2018–2030

The share of coal in the national energy mix is proportional to the total primary energy demand for all scenarios. The proportion of coal in the primary energy mix will increase for all scenarios, due to the increasing demand for coal and the depletion of oil and natural gas reserves (see Figure 2-5 and Figure 2-7). The contribution of coal to the primary energy mix will increase in all scenarios, but EGP will have the most significant growth, while BaU and PR will approximately follow the current trend due to their different targets for economic growth. The EO scenario will have relatively stagnant growth in the portion of coal in the energy mix. The PR scenario also has the same economic growth target, although, because of the prioritization of domestic supply over exports, the amount of coal production is relatively sustained. The coal share for BaU, EGP, PR, and EO in 2030 is 31.4%, 46.7%, 29.2%, and 33.5%, respectively.

Based on the results explained above and with respect to the Blueprint of Primary Energy Mix (Sekretariat Panitia Teknis Sumber Energi, 2006), the future share of coal in the primary energy structure should be higher than 30% in 2025. These conditions can be fulfilled by EGP and EO scenarios. However, the total CO_2 emission from these two scenarios is larger than the BaU scenario due to the larger amount of total fossil fuels (oil, gas, and coal) consumption. There are two kinds of targets stated on the Blueprint of Primary Energy Mix: baseline and General Plan of the National Energy (RUEN) target. The baseline target constructed by assuming that all parameters will continue to grow in the future following the current trend. On the other hand, the RUEN target constructed by considering economic and environmental aspects to achieve national energy independence and security of energy. Based on these considerations, the CO_2 emission from the baseline target will be higher than RUEN target as can be seen on Table 2-6.

Table 2-6 CO_2 emission (in million tons of CO_2) comparison

No	Scenario	2025	2030
1	Baseline target	1,370.00	1,806.80
2	RUEN target	893.40	1,061.40
3	BaU	855.51	1,086.14
4	EGP	971.60	1,406.61
5	PR	920.97	1,262.73
6	EO	894.89	1,196.67

Furthermore, the CO_2 emission from all scenarios in the proposed research cannot be suppressed to be lower than the RUEN target. BaU scenario will have a lower CO_2 emission because of a higher portion of renewable energy in the primary energy mix. However, the BaU scenario failed to meet both the economic growth and energy demand criteria. The second-best alternative in terms of the environmental aspect is the EO scenario. Even though it also was not able to produce a lower amount of CO_2 emission compared to the RUEN target, the EO scenario has the lowest value of carbon intensity of the GDP and able to fulfill both economic growth and energy demand requirement.

Differences in the model construction and assumption were the main factor for the different results between the proposed research and the government's target. In the RUEN target, the government utilized an optimistic approach for the parameters such as GDP growth rate, population growth rate, energy intensity, and energy elasticity. The optimistic approach for energy intensity and energy elasticity indicators makes the output significantly different, particularly on the CO_2 emission. The government assumed the elasticity of energy in Indonesia can be lower than 1 in 2025, while the energy intensity could be reduced by 1% each year.

In modeling the primary energy mix, the government also considering energy diversification by maximizing the utilization of renewable energy resources to reduce the CO_2 emission from energy utilization. Several assumptions for the RUEN target are as follows.

- Electricity generation will be assumed to be the biggest contributor in CO_2 emission, followed by industrial and transportation sectors. Therefore, the model assumed to has a highly efficient energy conversion rate.
- Energy diversification has been considered by maximizing renewable energy resources and minimizing fossil fuel utilization.
- Clean coal technology for electricity generation has been applied in the model.
- Substituting the oil portion in the primary energy mix with natural gas optimally.
- Implementing an energy conservation program in the model, which assumed to have highly efficient fuel and equipment utilization.

System dynamics model of coal production in Indonesia has been constructed in this research. The model can be used to analyze the correlation between coal production and its factors, particularly oil and gas as the substitution, and the price of commodities. Furthermore, the model also can be utilized to predict the future of coal production, as well as the impact to the economy and environment. In summary, the results of this research can be concluded as follows.

- Coal production in Indonesia can be modeled by considering the price of substitution.
- Coal production in Indonesia will continue to increase in the future.
- The BaU scenario cannot be applied if the government wants to achieve the electricity generation target, which it has announced as an additional 35,000 MW.
- The EGP scenario can accomplish the target of economic growth but will have a greater impact on the environment in terms of CO_2 emissions. Therefore, another alternative should be considered, such as the PR or EO scenarios.
- The PR scenario can achieve the target of economic growth and address the environmental aspect. However, compared to the EO scenario, the PR scenario still generates more CO_2 emissions. Therefore, the different approach to energy intensity used in the EO scenario is introduced, which is assumed to be the same as in developed countries. By applying the higher energy intensity, the government will be able to accomplish both its economic and environmental targets. The growth of GDP in the EO scenario will rely on other sectors and investment in renewable and clean energy.
- The best alternative for Indonesia's coal policy is the EO scenario, which can meet the economic growth target while also having the lowest impact on the environment in terms of the carbon intensity of the GDP.

In the system dynamics model of Indonesia's coal production, the coal reserves are assumed to be endogenous variables that are affected by the discovery rate. This assumption is less significant for medium-term simulation (until 2030); however, by applying this assumption, we can predict how long Indonesia can secure its domestic coal supply in the long term. To ensure the security of coal supply in the long run, the government can also implement an export restrictions policy.

The current system dynamics model of coal production in Indonesia also did not consider the breakdown of energy sources other than coal in more detail. This issue will be taken into consideration in the future research on coal production. Other scenarios in the energy mix should also be carried out in the future.

3 Optimization of coal supply for coal-fired power plants in Indonesia

3.1 Introduction

Coal is classified as a non-renewable resource, and it has long been utilized to fulfill energy consumption needs. As of 2018, coal accounted for 33.18% of the total primary energy mix in Indonesia, with around 104.47 million tons of coal consumption (British Petroleum, 2020). In the domestic market, most of the coal consumed is utilized as fuel for power generation because of its amount of resource, comparatively low cost, and the limitations of renewable energy. A coal-fired power plant (CFPP) has a lower average cost compared to other types of power generator (IESR, 2019). Therefore, more than 61.2% of the electricity in Indonesia is generated by CFPPs in 2019–2028 (PT. PLN, 2019). Furthermore, at the end of 2018, the Indonesian government announced a 35,000 MW electricity project which will result in the additional installation of 20,000 MW of CFPPs. This project will have a significant impact on the increasing coal demand in the domestic market, which will see around 5% of annual growth from 2020–2024 (Ministry of Energy and Mineral Resources Republic of Indonesia, 2020).

Most of the coal reserves in Indonesia are classified as low and medium rank coal, which accounts for around 86.6% of the total reserves. The low and medium rank coal contains a relatively high level of moisture content and volatile matter, with a low heating value, so this type of coal is very suitable for direct combustion, in both CFPP and other industries. However, it has a greater impact on the environment, so coal with a higher quality is more favorable in respect to environmental concerns. According to the data from the Geological Agency of the Ministry of Energy and Mineral Resources of the Republic of Indonesia (Ministry of Energy and Mineral Resources Republic of Indonesia, 2019), Indonesia has 128.06 billion tons of coal resources and 28.46 billion tons of coal, which are distributed in several regions including Sumatra, Kalimantan, Sulawesi, and Papua Island, mostly in Kalimantan and Sumatra. Indonesian coal can be divided into four categories based on its quality, which are low (below 3,200 kcal/kg on a GAR basis), medium (3,200–4,900 kcal/kg GAR), high (4,900–6,000 kcal/kg GAR), and very high rank coal (above 6,000 kcal/kg GAR).

Electricity generation in Indonesia is conducted under the supervision and management of the state-owned electricity company, which is called PT Perusahaan Listrik Negara (Persero). Currently, the procurement system for coal as the raw material for power plants is conducted individually by each power plant unit without considering other units in other locations, with cost minimization as the main consideration. The delivery of coal from suppliers to the CFPP units is conducted using the traditional direct supply method, without considering blending different qualities of coal. Consequently, there are only a limited number of candidates that can be selected as a supplier of coal that has an exact match with the power plant's quality specification. This existing procurement system will raise problems in terms of the availability of coal reserves in Indonesia, which will directly affect the continuity and flexibility of the coal supply for CFPPs. The existing condition also tends to have a high total cost because of the higher quality of coal that is delivered, and is moreover also quite inefficient in terms of transportation because of the utilization of smaller ships. Another important issue related to the coal supply for CFPPs is the consequences for the environment. In general, CFPPs have higher CO_2 emission levels compared to other types of power plant.

CO_2 emission is one of the greatest challenges for the environment and is becoming a global concern, especially in the energy sector. The growing consumption of energy has resulted in excessive emission of CO_2. In response to the goal of the 21^{st} Conference of the United Nations Framework Convention on Climate Change (COP21), CO_2 emission should be reduced from the current condition. In 2019, the CO_2 emission in Indonesia was around 2.32 tons per capita, which was an increase of 6.92% from 2018 (World Resources Institute, 2021). Therefore, in order to achieve the CO_2 emission reduction target set by Indonesia's government, it is necessary to consider a suitable power planning model concerning the environmental impact.

As an archipelago country, Indonesia consists of many islands and has various types of coal of differing quality, which increases the complexity of coal distribution from the suppliers to the CFPPs. This study is carried out to analyze the advantages of a proposed new scheme for coal procurement in Indonesia. The new scheme will consider the integration and zonation of coal procurement for all power plant units, and it will introduce a coal-blending mechanism to deal with both the economic (total cost) and environmental (CO_2 emission) aspects. In general, the coal market in Indonesia can be categorized as a complex business when taking into consideration the activity from downstream to upstream. The complexity includes the availability of coal reserves, the coal quality, power plant requirements, coal port characteristics, ship types, and price volatility.

The introduction of a coal-blending mechanism will have several impacts on coal supply. One of the most notable impacts is on the supply route and number of suppliers. In the existing condition, the supply route of coal from the producer to the CFPPs is conducted by using direct supply. A coal-blending mechanism will offer another option for the supply route and number of suppliers, because coal from various suppliers with different quality can be blended to produce the desired coal product to be utilized by the CFPPs. This option is expected to guarantee the continuity of the coal supply, because it could accommodate multiple coal producers with various coal specifications to become suppliers for CFPPs in the long term.

This research was conducted to optimize the coal supply for CFPPs in Indonesia by considering a coal-blending mechanism, in order to minimize both total cost and CO_2 emission. Two kinds of proposal will be formulated in this research and compared to the existing condition; the first one is blending at the CFPP facility and the second one is blending at a coal-preparation plant (CPP) facility located at a third location between the suppliers and power plants. The formulation assumes that all inputs are known with certainty, such as the coal reserves, coal quality, coal demand, power-plant specifications, port characteristics, ship types, coal price, and cost. The problem is formulated as a multi-objective optimization model by using mixed-integer linear programming (MILP) and solved by the epsilon-constraint method. Moreover, in order to give a clearer view on the coal supply problem for CFPP, a bi-objective optimization to minimize both total cost and CO_2 emission will be carried out in this research.

The objective functions of the optimization are 1) the total cost of coal procurement, and 2) the total CO_2 emission. The selection of Indonesia as the research subject can represent also similar problems of coal supply optimization on a larger scale or on the international coal market. The authors hope that the results of this research can be implemented not only by the Indonesian government, but also in other countries or regions in the global commodity market. This research can be utilized to provide policy guidelines for policy makers in the coal trade, as well as guidelines for both coal mining and power generator companies. The coal mining company can use this research as a reference to find suitable buyers in order to focus more on the optimization of their coal reserves. Similarly, coal consumers, particularly power generators, can utilize this research to review their existing contracts in order to determine the best coal procurement strategy for their CFPPs. Furthermore, the government can utilize this research to analyze the impact of installing carbon capture storage (CCS) in CFPPs as an alternative for reducing CO_2 emission. CCS is a method to capture CO_2 from power stations or industrial facilities without emitting it to the atmosphere and to store it stably deep underground.

This research consists of five sections, which are the introduction, literature review, optimization model for coal supply for CFPPs, computational experiments, and conclusions. The introduction section has explained the background and purpose of the study, while information on the recent condition of coal resources, supply and demand in Indonesia will be explained in the literature review. Optimization model will be constructed based on the actual condition of coal supply and demand in Indonesia, particularly for the electricity generation. After understanding the current situation of coal supply and demand in Indonesia, computational experiments will be conducted by considering a coal-blending mechanism to optimize the coal supply for CFPPs in Indonesia. The optimization results will be analyzed by comparing several conditions. Finally, the conclusions of this study will be explained in the last part of this research.

3.2 Coal blending and transportation problems

Coal blending is not a new thing in the coal mining industry, because coal quality is a varying natural attribute. Sometimes, although located in the same coal deposit, individual coal seams can have different coal quality within a close range (Fettweis, 1977). From the coal mining company's viewpoint, coal blending can be utilized to improve certain aspects of coal quality, such as the calorific value, total moisture, ash content, or sulfur content, to enable the product to be sold to the market (Amini et al., 2019).

The possibility of coal blending in practical conditions has been studied by several researchers, such as Lineberry & Gillenwater (1987), Gupta et al. (2007), Santhosh Raaj et al. (2016), and Wang et al. (2017), who conducted a study to find the coal-blend composition that resulted in the optimal ash content for the designed gasification plant by using linear programming. Lyu et al. (1995) also used a linear programming approach to blend domestic and imported coal, considering the sulfur content as the main constraint. Xi-jin et al. (2009) introduced the utilization of genetic algorithms to solve a similar optimization for ash content. The idea of blending different sources of imported coal at the power plant location was introduced by Shih (1997), who used mixed-integer programming for Taiwan Power Company to improve previous research conducted by Lai & Chen (1996). Similar techno-economic analysis on imported coal for a coal-fired power plant was also carried out by Nawaz & Ali (2020).

More complex coal-blending optimization was carried out by Liu & Sherali (2000) and Arigoni et al. (2017), by considering more parameters, such as the coal quality and port limitations. Both research works conducted an optimization with cost minimization as the objective. Arigoni et al. (2017) expanded the optimization by not only considering coal blending, but also considering the optimal transportation method.

Classical linear programming, which was utilized in Lyu et al. (1995), Santhosh Raaj et al. (2016), and Wang et al. (2017), is not able to find a feasible solution for this proposed research because more variables and parameters need to be considered, such as optimizing the coal blending by considering all the quality parameters and the transportation method. Their research was conducted to evaluate the feasibility of blending coal in practical conditions but only considered the partial quality of the material and they were not able to optimize it simultaneously.

Shih (1997) and Arigoni et al. (2017) considered the transportation mode in the optimization model. However, they only considered two ship types, namely 50,000 tons and 80,000 tons capacity vessels, because they dealt with the imported coal market, which needs larger quantities of coal. In their research, the sources of coal had already been determined, so they focused more on optimizing the process of finding the optimal transportation. Furthermore, they only considered the partial quality of the coal. A different kind of transportation optimization in the mining industry was carried out by Gupta et al. (2018) to achieve the minimum CO_2 emission and transportation cost, as well as to achieve the maximum efficiency. Meanwhile, Akgun et al. (2020) considered a multi-modal, multi-commodity, and multi-period linear programming model for coal distribution to households.

Currently, the global market has increasing concern about the utilization of coal for electricity generation due to its higher impact on air pollution through its CO_2 emission. However, the lower cost of electricity generation and the availability of coal reserves make the use of coal attractive, particularly in the developing countries like Indonesia. The situation is different in developed countries, which have strict regulations on greenhouse gas emission. Thus the global coal trade has changed since the previous decade (Wang et al., 2019). Much research focusing on the analysis of the cost and environmental impact trade-offs of coal utilization for the industry has been carried out by scholars such as Zhijun & Kuby (1997), Yu et al. (2018), and Ning et al. (2020).

It is necessary to consider the reduction of CO_2 emission from coal utilization due to the increased concern with the environment. Concerns over the future impact of coal utilization on the environment have been discussed by Li & Nie (2017), Hodgkinson & Smith (2018), Li et al. (2018), Li et al. (2020), and He et al. (2021). Xu et al. (2017) proposed an idea for an eco-friendly paradigm for coal utilization towards an integrated energy system, while Whitehead (2001) and Gu et al. (2020) discussed clean coal technology for the utility sector. The impact of CCS technology in power plants will be further analyzed for all schemes by considering several references regarding the potential application and effectiveness of CCS in power plant in various countries. The prospects for coal-fired power plants with CCS were discussed by Hammond & Spargo (2014), Ma et al. (2018), and Wu et al. (2020), while techno-economic analyses of CCS in CFPP were carried out by Hu & Zhai (2017), Fan et al. (2018), Al Lagtah et al. (2019), and Guerras & Martín (2019).

The limitations in the previous related research on coal blending have motivated the authors to conduct this study of the Indonesian coal market. A coal-blending mechanism for CFPPs has not yet been implemented in Indonesia. Therefore, the proposed research will deal with the determination of blending at both a power plant and a CPP facility. Modification of the previous related model is necessary to accommodate different problems in coal blending, such as determining the suppliers and composition of the coal, defining the transportation mode, which consists of six alternative ship types, as well as calculating the number of ships required for coal delivery. Considering the different conditions in the optimization, mixed-integer linear programming with a multi-objective function was selected. Multi-objective optimization was carried out to give a clearer view for the implementation of the results in the coal supply for CFPP in Indonesia. By considering the total cost, comprising the cost of purchasing and transportation, PT PLN can reduce the fuel cost component for electricity generation. Furthermore, by considering the total CO_2 emission from the transportation and coal-firing, PT PLN can minimize the environmental impact of coal utilization.

Table 3-1. Research comparison.

No	Author(s)	Year	Object	Parameter[1]					Decision variable[2]			Objective[3]			
				Q	F	R	D	P	T	S	ϕ	C. Cost	F. Cost	CO_2	Oth.
1	Lyu et al.	1995	Coal	v*	-	-	-	-	v**	-	-	-	-	-	v
2	Shih	1997	Coal	v*	-	-	v	v	v**	-	-	v	-	-	-
3	Liu and Sherali	2000	Coal	v	-	-	v	-	v**	-	-	v	-	-	-
4	Xi-Jin et al.	2009	Coal	v*	-	-	v	v	v**	v	-	v	-	-	-
5	Papageorgiou et al.	2012	Coal	-	v	-	v	v	-	v	-	-	v***	-	-
6	Santosh Raaj et al.	2016	Coal	v*	-	-	-	-	v**	-	-	-	-	-	v
7	Wang et al.	2017	Coal	v*	-	-	-	-	v**	-	-	-	-	-	v
8	Arigoni et al.	2017	Coal	v	v	-	v	v	v**	v	-	-	v	-	-
9	Fomeni	2018	Tea	v*	-	v	v	-	v	-	-	v	-	-	-
10	Gupta et al.	2018	Coal	-	v	-	v	v	-	v	-	-	v	v	-
11	Akgun et al.	2020	Coal	-	v	-	v	v	-	v	-	v	v	-	-
12	**Proposed**	**-**	**Coal**	**v**	**v**	**v**	**v**	**v**	**v**	**v**	**v**	**v**	**v**	**v**	-

Note:
* quality was partially considered
** only determines the composition of blending from the sources already defined
*** only considering the variable cost of transportation
[1] **Q** = quality; **F** = freight or transportation; **R** = reserves; **D** = demand; **P** = port or facility capacity
[2] **T** = tonnage or quality of material; **S** = number of ships; **ϕ =** binary variable for ship type selection
[3] **C. Cost** = cost of purchasing coal; **F. Cost** = freight or transportation cost; **CO_2** = carbon dioxide emission; **Oth.** = Other

Some modifications from the previous related research were considered in order to develop the proposed model and improve the results, particularly in the decision variables and objective functions. Table 3-1 above shows the differences between each research study in terms of their parameters, decision variables and objectives compared to the previous related research. The integration of several additional variables and parameters is conducted, which resulted in a greater number of variables and parameters included in the calculation. A detailed explanation of the parameters, decision variables, and objective functions will be given in the following paragraphs.

Firstly, in terms of parameters, the proposed research considered integrating all the parameters necessary for the coal supply, such as the coal quality, transportation mode, available coal reserves, coal demand and requirement, and port facility. By considering all the parameters, the result of the calculation will have a higher level of accuracy, which can be more reliable to use as a reference to improve the existing condition of coal supply. The detailed explanation of the key differences can be summarized as follows:

- All the parameters of the coal quality, namely the calorific value, total moisture, ash content, and sulfur content, will be considered. In the majority of previous related research, the coal quality was only partially considered in the optimization problems. By considering all the quality parameters simultaneously, a better result is expected, such that the results of optimization can be directly implemented by the government. In the coal procurement procedure for CFPPs, the calorific value, total moisture, ash content, and sulfur content are mandatory parameters that must be fulfilled by the coal supplier. This approach is beneficial for both parties, namely the power generation and the coal mining companies.

- The transportation mode or ship type selection will also be considered in the proposed research, as in Papageorgiou et al. (2012), Arigoni et al. (2017), and Akgun et al. (2020). The difference in the proposed research is that more freight options or ship types are considered. Furthermore, the port limitation is also considered in the ship selection.
- Coal reserves will be considered in the proposed research because the purpose of the research is to choose the optimal coal from the available candidate coal suppliers for a long-term contract. Fomeni (2018) used the production rate instead of the availability of reserves, because the object (tea) was renewable. This approach was utilized to secure the long-term supply of coal for coal-fired power plants in Indonesia. By considering the amount of coal reserves for each candidate coal supplier, it is expected that this research can give a greater view on the security of the coal supply from many candidates, and not only from the smaller number of big coal mining companies in Indonesia.

The subsequent difference in the proposed research is the decision variables. By considering the coal tonnage and number of ships as the decision variables simultaneously, the proposed model will analyze the problem as a whole system for the supply chain, not only selecting the best alternative from the coal suppliers, but also considering the best transportation mode, route, and distance alternatives. The decision variables in the proposed research include the coal tonnage, number of ships, and a binary variable to choose the ship type. This modification is an extension from Xi-jin et al. (2009), Papageorgiou et al. (2012), Arigoni et al. (2017), and Fomeni (2018), who only consider the number of ships without considering the ship type. The ship type selection will also be defined from the calculation to improve the results, so that they are closer to the actual condition.

Lastly, the objective functions will consist of cost and CO_2 emission, which represent the economic and environmental aspects. The multi-objective optimization is selected to deal with the trade-offs between the economic and environmental aspects in the industry, which are often analyzed separately by other scholars.

Lyu et al. (1995), Santhosh Raaj et al. (2016) and Wang et al. (2017) conducted research in order to analyze the feasibility of blending coal in practical conditions, but did not consider cost and CO_2 emission as the objective function. In their research, they tried to minimize the fluctuation of the coal requirement to maintain uniform usage of stockpiles.

CO_2 emission is also calculated as the objective function to give more detail on the impact of coal-blending problems for the policy implications. This approach was conducted considering the increasing attention to coal mining, particularly as concerns environmental protection. Gupta et al. (2018) tried to analyze sustainable transportation in mining by integrating AHP and DEA techniques. The main objective of their research was to find the best vehicle type and the number of units to be transported considering both total cost and total CO_2 emission. A similar approach to the objective function will be considered in the proposed research to give a clearer view on coal optimization from both the economic and environmental aspects, which is necessary to respond to the world-scale issues of global warming and low carbonization. However, the optimization will be solved by using an epsilon-constraint method, differently from Gupta et al. (2018), who conducted the optimization by using a fuzzy interactive approach to find a compromise solution through a sequence of interactive steps involving updating aspiration levels and bounds on the objective values. In this proposed study, the epsilon-constraint method is used so that the Pareto solution can be obtained from the optimization to analyze the trade-off relationship between total cost and CO_2 emission.

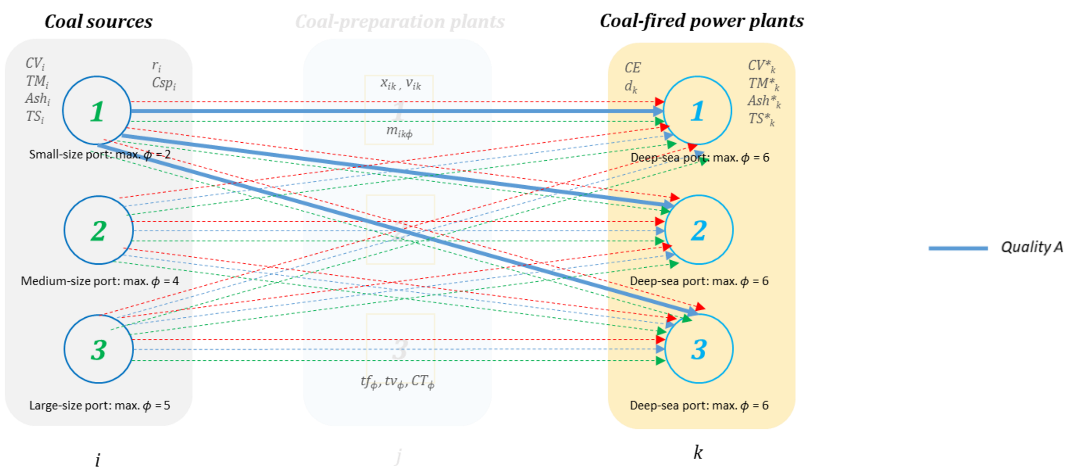
3.3 Optimization model for coal supply for coal-fired power plants

The optimization model of coal supply for CFPPs in Indonesia has been developed to minimize the coal purchasing costs and transportation costs, as well as the CO_2 emission from both transportation and coal combustion in power plants. Three schemes were developed considering the current condition of coal procurement for CFPPs as shown in Fig. 3-1, which represents the existing, CFPP-blending, and CPP-blending schemes. A detailed explanation of each scheme will be given in the following sub-section.

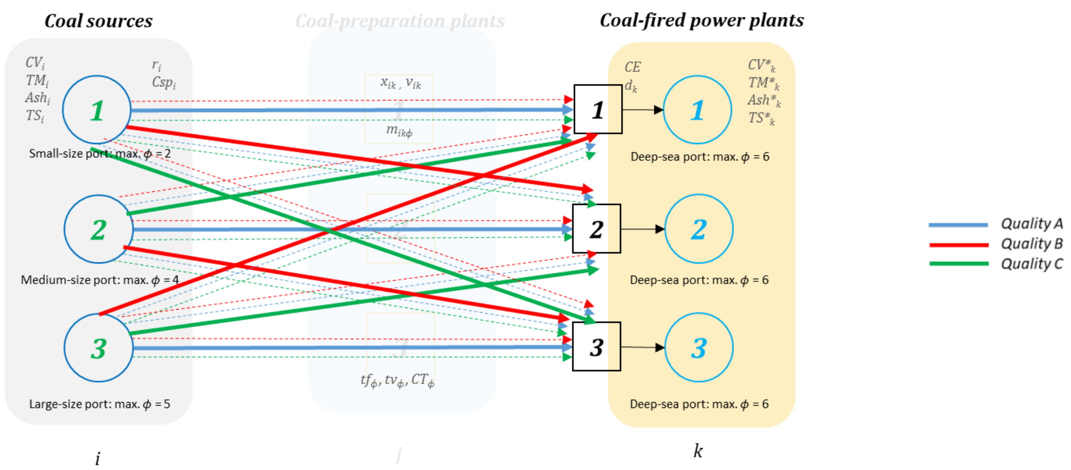
Based on the illustration in Fig. 3-1, each coal source will have different coal quality consisting of the calorific value (CV_i), total moisture (TM_i), ash content (Ash_i), and sulfur content (TS_i), and the availability of coal reserves (r_i). A similar condition has been applied for the CFPPs, which also have different coal demand (d_k) and specifications (CV^*_k, TM^*_k, Ash^*_k, and TS^*_k,). Each coal source, CPP, and CFPP has port limitations, defined as small-size, medium-size, large-size, and deep-sea port. Each port will have different allowable ship types (ϕ) depending on its port capacity. A small-size port only accommodates 6,000 ton and 10,000 ton barges (max. $\phi = 2$); a medium-size port only allows 6,000 ton, 10,000 ton and 12,000 ton barges, and 30,000 ton vessels (max. $\phi = 4$); a large-size port allows all ship types except 60,000 ton vessels (max. $\phi = 5$); while a deep-sea port is able to handle all ship types (max. $\phi = 6$). Each ship type has a different transportation cost (tf_ϕ and tv_ϕ) and CO_2 emission factor (CT_ϕ). A bigger ship, if fully loaded, will have a cheaper transportation cost and produce fewer CO_2 emissions.

The first scheme will be called the existing scheme (Fig. 3-1a). Under the existing scheme, coal suppliers will be selected without considering the coal-blending mechanism. Therefore, only certain candidate coal suppliers which have an exactly matching coal quality with the CFPP specification will be able to be selected as suppliers. Because no blending is considered, it is expected that only a few coal sources can be selected under this scheme, which will raise concerns about the future continuity of the coal supply. Therefore, coal-blending mechanisms are proposed as illustrated in Fig. 3-1b and Fig. 3-1c.

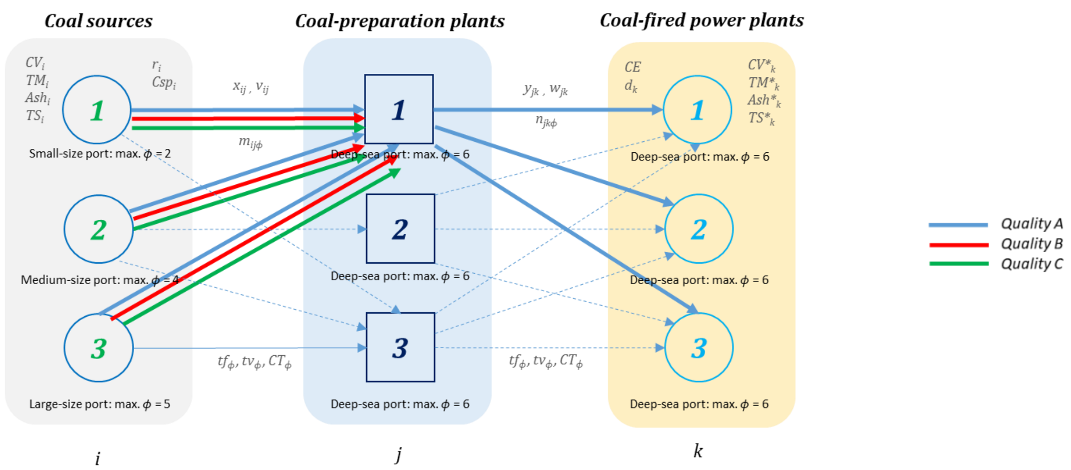
Both the CFPP-blending and CPP-blending schemes were constructed by taking into consideration the coal-blending mechanism. The only difference between the two schemes is the blending location. In the CFPP-blending scheme coal from various sources will be delivered and blended at the CFPP facilities, while in the CPP-blending scheme coal from various sources will be delivered first to the CPP before final delivery to the CFPPs, as shown in Fig. 3-1b. The selection of the CPP location was estimated based on specific criteria for site selection (Elson, 1972; Hanline, 1980).



(a)



(b)



(c)

Fig. 3-1. Supply network for (a) existing, (b) proposed CFPP-blending, and (c) proposed CPP-blending scheme.

In the CFPP-blending scheme, it is expected that the coal transportation requirement will be much greater because the blending will be conducted at each CFPP. Therefore, in order to obtain more efficient coal transportation, the CPP-blending scheme was introduced (Fig. 3-1c). It is expected that both the cost and CO_2 emission can be reduced by utilizing the CPP-blending scheme. It is considered that the coal-blending mechanism will have significant advantages compared to the existing scheme, such as ensuring the security of supply, greater flexibility in meeting power plant specifications, reducing the total cost of procurement, and reducing CO_2 emission (see Table 3-2).

Table 3-2. Comparison of each scheme.

No	Parameter	Existing	Proposed	
			CFPP-blending	**CPP-blending**
1	Coal quality	Exact match	Blended product match	Blended product match
2	Security of supply	Short-term	Long-term	Long-term
3	Flexibility	Inflexible	Flexible	Flexible
4	Cost of purchasing coal	Higher	Lower	Lower
5	Freight cost	Higher	Lower	Lower
6	Blending cost	No cost	Additional cost	Additional cost
7	CO_2 emission from freight	Higher	Lower	Lower
8	CO_2 emission from coal combustion	Lower	Higher	Higher

All the parameters in Table 3-2 were incorporated into the model in the computational experiment that will be explained in the next section. The coal quality and flexibility were taken into consideration as constraints, consisting of CV, TM, TS, and ash. The security of supply was considered by including the coal reserves and coal demand data for 15 years, in order to secure a long-term supply without changing sources, while costs, additional investments, and the CO_2 emission parameter were accommodated as the objective functions.

3.4 Numerical calculations

The model will be constructed by using several mathematical expressions as can be seen in Table 3-3.

Table 3-3. Notation.

Expression	Definition
Sets	
I	The set of coal sources, i.e. suppliers
J	The set of CPP (coal-preparation plant) locations
K	The set of CFPP (coal-fired power plant) ports
$\Phi_{i,j}$, $\Phi_{i,k}$	The set of allowable ship types to deliver coal from sources *i* to CPP *j* or CFPP *k*
$\Phi_{j,k}$	The set of allowable ship types to deliver coal from CPP *j* to CFPP *k*
Variables	
$x_{i,j}$, $x_{i,k}$	Coal amount to be delivered from supplier *i* to CPP *j* or CFPP *k* (million tons/week)
$y_{j,k}$	Coal amount to be delivered from CPP *j* to CFPP *k* (million tons/week)
$v_{i,j}$, $v_{i,k}$	Travel distance from supplier *i* to CPP *j* or CFPP *k* (nautical miles)
$w_{j,k}$	Travel distance from CPP *j* to CFPP *k* (nautical miles)
$m_{i,j,\phi}$, $m_{i,k,\phi}$	Binary variables if coal from supplier *i* to CPP *j* or CFPP *k* adopts ship type ϕ
$n_{j,k,\phi}$	Binary variables if coal from CPP *j* to CFPP *k* adopts ship type ϕ

Expression	Definition
$s_{i,j,\phi}$, $s_{i,k,\phi}$	Number of ships from supplier *i* to CPP *j* or CFPP *k* by using ship type ϕ
$h_{j,k,\phi}$	Number of ships from CPP *j* to CFPP *k* by using ship type ϕ
Parameters	
d_k	Coal demand at CFPP *k* (million tons/week)
r_i	Available coal reserve from coal supplier *i* (million tons/week)
C_{SPi}	Capacity of coal jetty/port *i* (tons)
CV_i, CV^*_k	Calorific value of coal source *i* or typical calorific value of CFPP *k* (kcal/kg)
TM_i, TM^*_k	Total moisture of coal source *i* or typical total moisture of CFPP *k* (%)
TS_i, TS^*_k	Total sulfur content of coal source *i* or typical total sulfur of CFPP *k* (%)
Ash_i, Ash^*_k	Ash content of coal source *i* or typical ash content of CFPP *k* (%)
c_i	Price of coal to be delivered from supplier *i* ($/ton)
b_j, b_k	Handling fee to blend coal in CPP *j* or CFPP *k* ($/ton)
tf_ϕ	Fixed transportation cost using ship type ϕ ($/shipment)
tv_ϕ	Variable transportation cost using ship type ϕ ($/nautical mile/shipment)
γ_ϕ	Capacity of ship type ϕ (tons)
u_{Bj}	Maximum number of coal sources that can be blended in CPP *j*
z_{Pk}	Maximum number of sources from CPP that can be delivered to CFPP *k*
P_k	CFPP *k* capacity (MW)
CF_k	Conversion factor of CFPP *k* (kcal/MWh)
t	Working hours of CFPP in a week (hours/week)
E_k	CFPP's boiler efficiency *k* (dimensionless)
CE	Carbon dioxide emission constant for coal firing (tons of CO_2 /MWh . ton of coal/kcal)
IC	Intercept for carbon dioxide emission regression formula (tons of CO_2 /MWh)
CT_ϕ	Carbon dioxide emission constant for transporting coal using ship type ϕ (tons of CO_2/nautical mile/shipment)
cc_k	Unit operating cost of carbon capture in CFPP *k* ($/ton)
EC_k	Released carbon dioxide constant in CFPP *k* (dimensionless)

The optimization is conducted to minimize the total cost and CO_2 emission from coal utilization for CFPPs, which have a contradictory relationship. Usually, coal with lower quality will be selected to minimize the total cost, which has a greater impact on the environment, and vice versa. Low rank coal has a low calorific value (*CV*) and high total moisture (*TM*), and will release more CO_2 from the combustion in the CFPP. However, low rank coal has a lower price which is more favorable in terms of cost. Apart from the coal quality, to produce the same amount of energy, more coal tonnage is needed for the low rank coal, which also has the effect of a greater amount of CO_2 emission. Although there are no trade-offs between the cost and CO_2 emission in transportation, each source will utilize a different ship type depending on its facility and location. The ship type that will be used is not related to the coal quality. For example, a source that has a high rank coal is not guaranteed to have the ability to choose the biggest ship with the lowest transportation cost and CO_2 emission. Therefore, the transportation selection will be considered in the model formulation because it affects the total cost and CO_2 emission. From these examples, the economic and environmental aspects of the coal supply problem are interesting to analyze considering the interaction between both aspects, so a trade-off analysis will also be conducted in the proposed research. To compare the existing and proposed schemes that have been constructed, optimization will be conducted by considering two objective functions and constraints for 1) the existing scheme, 2) the proposed CFPP-blending scheme, and 3) the proposed CPP-blending scheme, as follows.

3.4.1 Objective functions

3.4.1.1 Existing scheme

$$minimize\ Z_1 = \sum_{i\epsilon I}\sum_{k\in K} c_i x_{i,k} + \sum_{i\epsilon I}\sum_{k\in K}\sum_{\phi\in\Phi_{i,k}} (tf_\phi + tv_\phi v_{i,k}) s_{i,k,\phi} + \sum_{i\epsilon I}\sum_{k\in K} cc_k x_{i,k} \quad (3.1)$$

$$minimize\ Z_2 = \sum_{i\epsilon I}\sum_{k\in K}\sum_{\phi\in\Phi_{i,k}} CT_\phi v_{i,k} s_{i,k,\phi} + \sum_{i\epsilon I}\sum_{k\in K} \frac{(CV_i\ CE + IC) E_k CV_k^* EC_k x_{i,k}}{CF_k} \quad (3.2)$$

The first objective in Eq. (3.1) sums the cost of purchasing coal (first term in the equation), the cost of transportation from the coal sources to the CFPPs (second term in the equation), and the carbon capture cost (third term in the equation) if the CCS facility is installed. Under the initial condition, a CCS facility is not installed yet at the CFPPs, so the value of cc_k is 0. The second objective in Eq. (3.2) sums the CO_2 emission from transportation (first term in the equation) and coal-firing (second term in the equation). The CO_2 emission constant (*CE*) and the intercept (*IC*) for the CO_2 emission from coal combustion were derived by using the regression method from Winschel (1990). Under the initial condition, all CO_2 emission from coal-firing in the CFPP will be released to the air, so the value of EC_k is equal to 1. The amount of coal demand (d_k) for each CFPP was estimated by using the formulation given in Eq. (3.3).

$$d_k = \frac{P_k CF_k t}{E_k CV_k^*} \quad (3.3)$$

3.4.1.2 Proposed CFPP-blending scheme

$$minimize\ Z_1' = Z_1 + \sum_{i\epsilon I}\sum_{k\in K} b_k x_{i,k} \quad (3.4)$$

$$minimize\ Z_2' = Z_2 \quad (3.5)$$

The objective functions for the CFPP-blending scheme are similar to the existing scheme, and consist of cost minimization as shown in Eq. (3.4) and CO_2 emission minimization as shown in Eq. (3.5). The only difference from the existing scheme is that there is an additional blending cost in the CFPP-blending scheme as shown in the second term of Eq. (3.4), as the result from coal-blending activity at the CFPP location.

3.4.1.3 Proposed CPP-blending scheme

$$minimize\ Z_1'' = \sum_{i\epsilon I}\sum_{j\in J} c_i x_{i,j} + \sum_{i\epsilon I}\sum_{j\in J} b_j x_{i,j} + \sum_{i\epsilon I}\sum_{j\in J}\sum_{\phi\in\Phi_{i,j}} (tf_\phi + tv_\phi v_{i,j}) s_{i,j,\phi}$$
$$+ \sum_{j\epsilon J}\sum_{k\in K}\sum_{\phi\in\Phi_{j,k}} (tf_\phi + tv_\phi w_{j,k}) h_{j,k,\phi} + \sum_{j\epsilon J}\sum_{k\in K} cc_k y_{j,k} \quad (3.6)$$

$$minimize\ Z_2'' = \sum_{i\epsilon I}\sum_{j\in J}\sum_{\phi\in\Phi_{i,j}} CT_\phi v_{i,j} s_{i,j,\phi} + \sum_{j\epsilon J}\sum_{k\in K}\sum_{\phi\in\Phi_{j,k}} CT_\phi w_{j,k} h_{j,k,\phi}$$
$$+ \sum_{j\epsilon J}\sum_{k\in K} \frac{(CV_k^*\ CE + IC) E_k CV_k^* EC_k y_{j,k}}{CF_k} \quad (3.7)$$

The objective functions for the CPP-blending scheme are significantly different from both the existing and the CFPP-blending schemes, although they also consist of cost minimization and CO_2 emission minimization as expressed in Eq. (3.6) and (3.7), respectively. The different location of the blending facilities (CPPs), which are located between the coal sources and CFPPs, is expressed by the additional variables related to the CPP *j*. The transportation differs from both the existing and the CFPP-blending schemes because the coal is transported to the

CPP before final delivery to the CFPPs. The total cost as shown in Eq. (3.6) consists of the coal purchasing cost from sources i (first term in the equation), the blending cost at CPP j (second term in the equation), the transportation cost from sources i to the CPP j (third term in the equation), the transportation cost from the CPP j to the CFPP k (fourth term in the equation), and the carbon capture storage cost at the CFPP k (fifth term in the equation). Meanwhile, the CO_2 emission as shown in Eq. (3.7) consists of the CO_2 emission from transportation from sources i to the CPP j (first term in the equation), transportation from CPP j to the CFPP k (second term in the equation), and coal-firing at the CFPP k (third term in the equation).

3.4.2 Constraints

3.4.2.1 Existing scheme

Coal reserves

$$\sum_{k\epsilon K} x_{i,k} \leq r_i \ , \qquad \forall i \in I \tag{3.8}$$

Coal demand

$$\sum_{i\epsilon I} x_{i,k} \geq d_k \ , \quad \forall k \in K \tag{3.9}$$

Coal quality

$$\mathrm{CV}_i x_{i,k} \geq CV_k^* x_{i,k} \ , \quad \forall \mathrm{i} \in I, k \in K \tag{3.10}$$

$$TM_i x_{i,k} \leq TM_k^* x_{i,k} \ , \quad \forall \mathrm{i} \in I, k \in K \tag{3.11}$$

$$Ash_i x_{i,k} \leq Ash_k^* x_{i,k} \ , \quad \forall \mathrm{i} \in I, k \in K \tag{3.12}$$

$$TS_i x_{i,k} \leq TS_k^* x_{i,k} \ , \quad \forall \mathrm{i} \in I, k \in K \tag{3.13}$$

Number of sources

$$\sum_{i\in I} \sum_{\phi\in\Phi_{i,k}} m_{i,k,\phi} \leq z_{P_k} \ , \qquad \forall k \in K \tag{3.14}$$

Ship type selection

$$\sum_{\phi\in\Phi_{i,k}} m_{i,k,\phi} \leq 1, \ \forall i \in I \,, k \in K \tag{3.15}$$

$$x_{i,k} \leq \sum_{\phi\in\Phi_{i,k}} \gamma_\phi s_{i,k,\phi} \ , \ \forall i \in I \,, k \in K \tag{3.16}$$

$$s_{i,k,\phi} \leq M \, m_{i,k,\phi} M \ , \ \forall i \in I \,, k \in K, \, \phi \in \Phi_{i,k} \tag{3.17}$$

Port capacity and active route

$$\sum_{k\epsilon K} x_{i,k} \leq C_{SP_i} \ , \quad \forall i \in I \tag{3.18}$$

$$x_{i,k} \leq M \sum_{\phi\in\Phi_{i,k}} m_{i,k,\phi} \ , \ \forall i \in I \,; \forall k \in K \tag{3.19}$$

Number of ships

$$s_{i,k,\phi} + M\big(1 - m_{i,k,\phi}\big) \geq 0.25 \ , \ \forall i \in I \,, k \in K, \, \phi \in \Phi_{i,k} \tag{3.20}$$

Eq. (3.8) shows that the total coal delivered from coal source i to the CFPP k must remain at or below the amount of available coal reserves for source i, while the constraint in Eq. (3.9) shows that the sum of coal delivered to the destination k should meet the minimum requirement, that is d_k.

The constraints in Eq. (3.10)–(3.13) ensure that the coal quality requirements, which consist of the calorific value, total moisture, ash content, and sulfur content for each CFPP k, should not be violated for each coal mining company or sources i, while Eq. (3.14) ensures that demand node k cannot receive coal from more than the maximum number of sources.

Eq. (3.15) ensures that only one ship type is selected for each source i and destination k. The amount of coal from each source i for CFPP k should be less than or equal to the capacity of the selected ship type as expressed in Eq. (3.16). The number of ships is calculated only for an active route by using the binary value of the ship type multiplied by high number M, as can be seen in Eq. (3.17).

Eq. (3.18) is a constraint to ensure that the sums of coal delivered do not violate the maximum capacity of each port i, while Eq. (3.19) is used to examine the active route for coal delivered from source i to CFPP k. Finally, Eq. (3.20) is a constraint to ensure that the number of ships used to deliver coal from sources i to CFPP k is more than or equal to 1 in 4 weeks or a month.

3.4.2.2 Proposed CFPP-blending scheme

Coal reserves

see Eq. (3.8)

Coal demand

see Eq. (3.9)

Coal quality

$$\sum_{i \in I} CV_i x_{i,k} \geq CV_k^* \sum_{i \in I} x_{i,k}, \quad k \in K \tag{3.21}$$

$$\sum_{i \in I} TM_i x_{i,k} \leq TM_k^* \sum_{i \in I} x_{i,k}, \quad k \in K \tag{3.22}$$

$$\sum_{i \in I} Ash_i x_{i,k} \leq Ash_k^* \sum_{i \in I} x_{i,k}, \quad k \in K \tag{3.23}$$

$$\sum_{i \in I} TS_i x_{i,k} \leq TS_k^* \sum_{i \in I} x_{i,k}, \quad k \in K \tag{3.24}$$

Number of sources

see Eq. (3.14)

Ship type selection

see Eq. (3.15), (3.16), and (3.17)

Port capacity and active route

see Eq. (3.18) and (3.19)

Number of ships

see Eq. (3.20)

The constraints related to the availability of coal reserves and demand are the same as the existing scheme, as can be seen in Eq. (3.8)–(3.9) respectively, while Eq. (3.21)–(3.24) are constraints related to the CFPP requirements, which differ from the existing scheme because of the introduction of coal blending. These equations ensure that the coal quality requirements, which consist of the calorific value, total moisture, ash content, and sulfur content for CFPP k, are met by the blended coal products from various sources i, which is different from the existing scheme (in the existing scheme, each coal mining company should have individual suitable coal quality as demanded by the CFPP).

The constraint related to the maximum number of allowable sources is also the same as the existing scheme, as can be seen in Eq. (3.14). The ship type and route selection are the same as the existing scheme, therefore there is no modification for these constraints, which can be seen in Eq. (3.15) –(3.17).

Similarly, both constraints related to the port capacity and active route are constructed in the same way as in the existing scheme, and are shown in Eq. (3.18)–(3.19). Lastly, the formulation of the minimum number of ships to deliver coal in a month is constructed in exactly the same way as the existing scheme, as shown in Eq. (3.20).

3.4.2.3 Proposed CPP-blending scheme

Coal reserves

$$\sum_{j\in J} x_{i,j} \le r_i \ , \qquad \forall i \in I \tag{3.25}$$

Coal demand

$$\sum_{i\in I} x_{i,j} \ge \sum_{k\in K} y_{j,k} \ , \quad \forall j \in J \tag{3.26}$$

$$\sum_{j\in J} y_{j,k} \ge d_k \ , \qquad \forall k \in K \tag{3.27}$$

Coal quality

$$\sum_{i\in I} CV_i x_{i,j} + M\left(1 - \sum_{\phi\in\Phi_{j,k}} n_{j,k,\phi}\right) \ge CV_k^* \sum_{i\in I} x_{i,j} \ , \quad \forall j \in J, k \in K \tag{3.28}$$

$$\sum_{i\in I} TM_i x_{i,j} - M\left(1 - \sum_{\phi\in\Phi_{j,k}} n_{j,k,\phi}\right) \le TM_k^* \sum_{i\in I} x_{i,j} \ , \quad \forall j \in J, k \in K \tag{3.29}$$

$$\sum_{i\in I} Ash_i x_{i,j} - M\left(1 - \sum_{\phi\in\Phi_{j,k}} n_{j,k,\phi}\right) \le Ash_k^* \sum_{i\in I} x_{i,j} \ , \quad \forall j \in J, k \in K \tag{3.30}$$

$$\sum_{i\in I} TS_i x_{i,j} - M\left(1 - \sum_{\phi\in\Phi_{j,k}} n_{j,k,\phi}\right) \le TS_k^* \sum_{i\in I} x_{i,j} \ , \quad \forall j \in J, k \in K \tag{3.31}$$

Number of sources

$$\sum_{i\in I} \sum_{\phi\in\Phi_{i,j}} m_{i,j,\phi} \le u_{B_j} \ , \qquad \forall j \in J \tag{3.32}$$

$$\sum_{j\in J} \sum_{\phi\in\Phi_{j,k}} n_{j,k,\phi} \le z_{P_k} \ , \qquad \forall k \in K \tag{3.33}$$

Ship type selection

$$\sum_{\phi\in\Phi_{i,j}} m_{i,j,\phi} \le 1, \ \forall i \in I, j \in J \tag{3.34}$$

$$\sum_{\phi\in\Phi_{j,k}} n_{j,k,\phi} \le 1, \ \forall j \in J, k \in K \tag{3.35}$$

$$x_{i,j} \le \sum_{\phi\in\Phi_{i,j}} \gamma_\phi s_{i,j,\phi} \ , \ \forall i \in I, j \in J \tag{3.36}$$

$$y_{j,k} \le \sum_{\phi\in\Phi_{j,k}} \gamma_\phi h_{j,k,\phi} \ , \ \forall j \in J, k \in K \tag{3.37}$$

$$s_{i,j,\phi} \le M\, m_{i,j,\phi} \ , \ \forall i \in I, j \in J, \phi \in \Phi_{i,j} \tag{3.38}$$

$$h_{j,k,\phi} \le M\, n_{j,k,\phi} \ , \ \forall j \in J, k \in K, \phi \in \Phi_{j,k} \tag{3.39}$$

Port capacity and active route

$$\sum_{j\in J} x_{i,j} \leq C_{SP_i} \ , \quad \forall i \in I \tag{3.40}$$

$$x_{i,j} \leq M \sum_{\phi \in \Phi_{i,j}} m_{i,j,\phi} \ , \ \forall i \in I \, ; \forall j \in J \tag{3.41}$$

$$y_{j,k} \leq M \sum_{\phi \in \Phi_{j,k}} n_{j,k,\phi} \ , \ \forall j \in J \, ; \forall k \in K \tag{3.42}$$

Number of ships

$$s_{i,j,\phi} + M\left(1 - m_{i,j,\phi}\right) \geq 0.25 \ , \ \forall i \in I \, , j \in J, \ \phi \in \Phi_{i,j} \tag{3.43}$$

$$h_{j,k,\phi} + M\left(1 - n_{j,k,\phi}\right) \geq 0.25 \ , \ \forall j \in J \, , k \in K, \ \phi \in \Phi_{j,k} \tag{3.44}$$

The constraint in Eq. (3.25) shows that the sum of coal delivered from coal source i to the CPP j must remain at or below the amount of available coal reserves for source i, while the constraints in Eq. (3.26) and Eq. (3.27) show that the sum of coal delivered to the CPP j and CFPP k should meet the minimum requirements, which are y_{jk} and d_k, respectively.

Eq. (3.28)–(3.31) ensure that the coal quality requirements, which consist of the calorific value, total moisture, ash content, and sulfur content for CFPP k, are met. The symbol M represents a large value. These equations ensure that the blended products from various sources i do not violate the CFPP's requirements. In order to avoid non-linear problems for the quality of coal in CPP j, the coal quality of the final blended products consisting of CV_j, TM_j, Ash_j, and TS_j is calculated by using the quality of coal required by the CFPP k, which are CV^*_k, TM^*_k, Ash^*_k, and TS^*_k. These constraints are significantly different from the other schemes, because of the location of the blending facility (CPP).

Eq. (3.32) and (3.33) ensure that demand node j and k cannot receive coal from more than the maximum number of sources, similarly to the other schemes. Because of the introduction of the CPP as a blending facility located between the coal sources and CFPPs, additional constraints are constructed for the CPP-blending scheme. Eq. (3.34) and (3.35) ensure that only one ship type is selected for each source i and CPP j, as well as for each CPP j and destination k. The amount of coal from each source i for CPP j and from each CPP j for CFPP k should be less than or equal to the capacity of the selected ship type as expressed in Eq. (3.36) and (3.37). The number of ships is calculated only for the active route by using the binary value of the ship type multiplied by high number M as shown in Eq. (3.38) and (3.39).

Eq. (3.40) is a constraint to ensure that the sums of coal delivered do not violate the maximum capacity of each port i, while Eq. (3.41) and (3.42) are used to examine the active route for coal delivered both from source i to CPP j and from CPP j to CFPP k.

Finally, Eq. (3.43)–(3.44) are constraints to ensure that the number of ships used to deliver coal both from sources i to CPP j and from CPP j to CFPP k should be more than or equal to 1 in 4 weeks or a month, which is similar to the formulation in the existing scheme.

As previously explained, the problem has been formulated as a bi-objective optimization model by using the MILP and solved by using the epsilon-constraint method. The output has been calculated manually by changing the ε as an upper bound in the software to obtain the Pareto solution set. We conduct the calculation by using the following procedure: 1) minimize Z_1 (total cost) with Z_2 (total CO_2 emission) as an additional constraint, 2) obtain the ε for Z_2 as the upper bound from the minimization results of Z_1, 3) minimize Z_1 by changing the ε or upper bound value of Z_2, and 4) minimize Z_2 with Z_1 as an additional constraint using the same procedure as in 1) – 3) to obtain the Pareto solution set. The problem size and computation time for each scheme are shown in Table 3-4. The computation time is not only positively correlated with the problem size, but also affected by the number of iterations considering the objective bounds and gap in the computation. The variability of computation times for each scheme occurred due to different value of ε for each calculation that changed manually in the computation. In general, smaller ε will result on faster computation time, while bigger ε will result on slower computation time due to the greater range of possible solution.

Table 3-4. Problem size and computation time.

No	Measures	Existing	CFPP-Blending	CPP-Blending
1	Number of variables			
	a. Continuous	224	4802	1554
	b. Binary	189	4116	1064
2	Time (s)			
	a. Minimum	0.41	0.89	0.20
	b. Maximum	4.82	11897	16957
	c. Average	2.60	2228	3848

Generally, it can be concluded that transportation will be more efficient by applying the CPP-blending scheme, which is reflected by the bigger size of ship type selected and the smaller number of ships for transporting the coal. In determining the coal supply optimization for coal-fired power plants, all the results are compared as shown in Table 3-5–Table 3-8. The results of the optimization are compared in Fig. 3-2 and Fig. 3-3 for the initial condition and the environmental consciousness policy, respectively.

The proposed schemes have better performance due to their different formulations compared to the existing scheme, especially because of the introduction of the blending mechanism. By blending various coals, it will be possible to obtain an alternative for reducing the total cost or suppressing the CO_2 emission. For example, the proposed schemes are able to reduce the total cost under the same level of CO_2 emission. At the same level of 0.46 million tons of CO_2 emission/week, the total cost can be reduced to 27.85 million USD/week and 24.34 million USD/week for the CPP-blending scheme and CFPP-blending scheme, respectively compared to the existing scheme (30.54 million USD/week) in the baseline scenario. The main factor for this total cost reduction is because of the greater number of sources that can be selected in the proposed schemes, which resulted in the selection of lower coal quality and more efficient transportation. The analysis will be discussed in more detail in the following subsections.

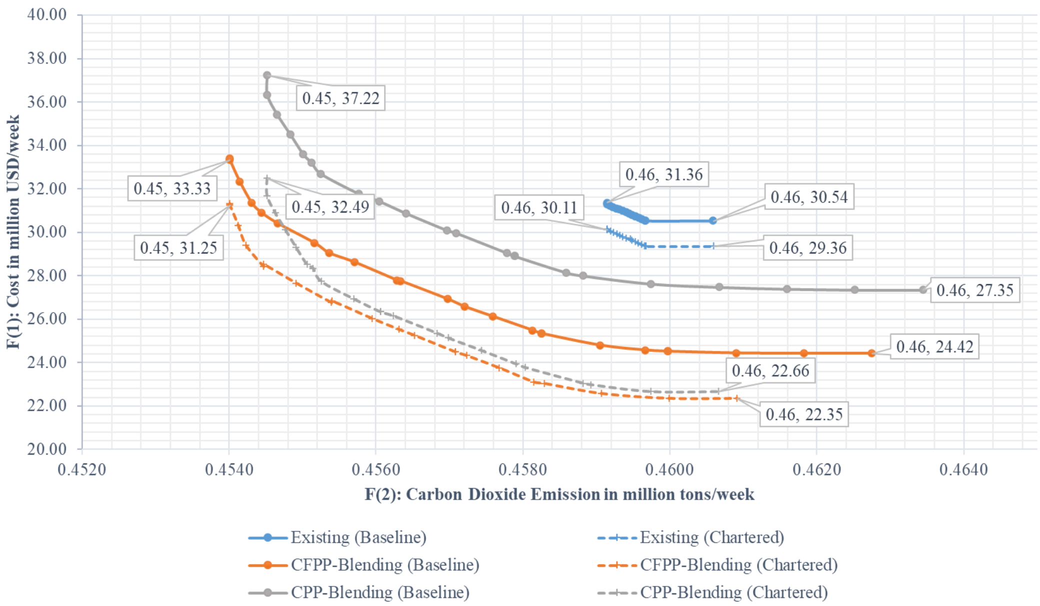


Fig. 3-2. Optimization results.

3.4.3 Baseline scenario

As previously mentioned, the model formulation was initially constructed by considering a freight cost consisting of fixed and variable transportation costs. In the baseline scenario, it is assumed that the transportation will be carried out by the power company; therefore, there will be an ownership cost that acts as the fixed transportation cost.

In the baseline scenario, the CFPP-blending scheme has the best performance because its Pareto front is superior to the other scheme. Furthermore, based on the Pareto front shown in Fig. 3-2, the CFPP-blending and CPP-blending schemes can be utilized for optimizing the coal supply for CFPPs in Indonesia. This condition is due to the different formulations in the proposed CFPP-blending and CPP-blending schemes compared to the existing scheme, particularly because of the introduction of the blending mechanism. In the existing scheme, only 7 candidate coal suppliers from the total of 98 coal sources are able to fulfill the CFPPs' requirement, considering their coal quality.

Table 3-5 and Table 3-6 show the calculation results for the baseline condition, which considers fixed and variable transportation costs. In this baseline condition, the existing scheme is only able to produce a narrow range of optimization results (30.54–31.30 million USD/week with 0.4591–0.4597 million tons of CO_2/week) due to the limited number of coal sources that have an exact quality match with the CFPPs' requirement.

Table 3-5. Comparison results for baseline scenario (cost minimization priority).

Parameter	Unit	Existing	Proposed			
			CFPP-blending		CPP-blending	
		Value	Value	RD*	Value	RD*
Total Coal Purchasing Cost	million USD/week	25.47	19.08	*-25.10%*	19.05	*-25.19%*
Total Blending Cost	million USD/week	-	1.30	*-*	1.30	*-*
Total Fixed Transportation Cost	million USD/week	2.74	2.72	*-0.52%*	5.52	*101.62%*
Total Variable Transportation Cost	million USD/week	2.33	1.32	*-43.51%*	1.48	*-36.30%*

TOTAL COST	million USD/week	30.54	24.42	*-20.03%*	27.36	*-10.40%*
CO_2 Emission from Transportation	million tons/week	0.006	0.004	*-26.69%*	0.005	*-16.50%*
CO_2 Emission from Coal Firing	million tons/week	0.454	0.458	*0.81%*	0.458	*0.82%*
TOTAL CO_2 EMISSION	**million tons/week**	**0.4597**	**0.4618**	***0.47%***	**0.4625**	***0.61%***

** **RD:** relative difference from the existing scheme*

Table 3-6. Comparison results for baseline scenario (CO_2 emission minimization priority).

Parameter	Unit	Existing	Proposed			
			CFPP-blending		CPP-blending	
		Value	Value	RD*	Value	RD*
Total Coal Purchasing Cost	million USD/week	26.21	28.32	*8.06%*	28.34	*8.11%*
Total Blending Cost	million USD/week	-	1.30	-	1.30	-
Total Fixed Transportation Cost	million USD/week	2.75	2.76	*0.27%*	5.62	*104.05%*
Total Variable Transportation Cost	million USD/week	2.33	0.94	*-59.74%*	1.21	*-48.18%*
TOTAL COST	**million USD/week**	**31.30**	**33.33**	***6.49%***	**36.47**	***16.52%***
CO_2 Emission from Transportation	million tons/week	0.006	0.002	*-56.47%*	0.003	*-43.66%*
CO_2 Emission from Coal Firing	million tons/week	0.453	0.452	*-0.43%*	0.452	*-0.42%*
TOTAL CO_2 EMISSION	**million tons/week**	**0.4591**	**0.4540**	***-1.12%***	**0.4548**	***-0.95%***

** **RD:** relative difference from the existing scheme*

Inflexibility in the existing scheme is influenced by the limited number of coal sources. Only 7 sources (i = 65, 66, 67, 72, 88, 89, and 90) are selected from the optimization, with aggregate coal quality ranging from 4,888.59–4,973.58 kcal/kg of CV; 27.25–28.17% of TM; 0.13–0.16% of TS; and 2.23–2.50% of ash content. This condition occurred because there was a strong correlation of the coal quality parameters with the output. The range of the aggregate coal quality is very narrow, because it was derived from only 7 sources. Both the CFPP-blending and CPP-blending schemes are able to produce more flexible and better results compared to the existing scheme, particularly because of the lower cost of purchasing coal, which contributes more than 75% of the total cost. The coal price has a positive correlation with the coal rank, which means that lower rank coal is cheaper. The optimization results for the CFPP-blending scheme are obtained from 12 coal sources (i = 4, 10, 13, 29, 30, 58, 59, 60, 74, 76, 79, and 93) with coal quality ranging from 4,242.13–5,287.17 kcal/kg of CV; 20.98–32.00% of TM; 0.40% of TS; and 4.77–6.00% of ash content, the minimum quality of which is lower than the existing scheme. The optimization results for the CPP-blending scheme are obtained from 13 coal sources (i = 4, 10, 13, 21, 25, 29, 30, 58, 59, 60, 74, 76, and 79) with coal quality ranging from 4,226.09–5,287.17 kcal/kg of CV; 20.98–32.00% of TM; 0.40% of TS; and 4.77–6.00% of ash content, which also has a lower minimum quality compared to the existing scheme.

The inflexibility in the existing scheme will result in more restricted options to reduce the cost and CO_2 emission from both coal purchasing and transportation. The purchasing cost in the existing scheme is higher because of the higher aggregate coal quality, while the transportation cost is higher because of inefficient transportation. The total CO_2 emission in the existing scheme is worse because the transportation also contributes to the CO_2 emission. The total distance and number of ships in each week in the existing scheme are 8,828.76 nautical miles and 18.66 ships, respectively. The proposed schemes can significantly reduce the total distance and number of ships in each week. For the CFPP-blending scheme, the total distance is 5,481.47 nautical miles with 15.74 ships, while in the CPP-blending scheme, the total distance is 5,551.34 nautical miles with 25.77 ships.

Considering the results, the coal-blending mechanism can improve the current condition of coal procurement from both the economic and environmental aspects. The highest portion of the total cost is the coal purchasing cost, which can be minimized by utilizing a lower coal rank. The existing scheme is not able to produce lower quality compared to the product of blending in both proposed schemes. From the transportation aspect, the cost and CO_2 emission from the transportation can be reduced in both proposed schemes because of the number and reserves of the candidate coal suppliers, as well as the location of the selected coal suppliers. The total transportation distance in the existing scheme is farther than the proposed schemes, and larger ships are selected in both proposed schemes, as is reflected by the smaller number of ships.

3.4.4 Chartered ship scenario

The chartered ship scenario was constructed after taking into consideration the actual condition in the coal supply for coal-fired power plants in Indonesia, in which the freight cost was carried by a third party instead of by PT PLN. In the baseline condition, the barge or vessel is assumed to be owned by PT PLN, which will have the effect of a double count of the fixed transportation cost. Therefore, the chartered ship scenario was performed assuming that there is no fixed cost component for the transportation cost ($tf_{\phi} = 0$) because it will be integrated into the variable cost component reflected by the chartered cost (tc_{ϕ}) in USD/nautical mile/shipment units.

Table 3-7 and Table 3-8 show the optimization results for the chartered ship condition, which is considered because there are some limitations in the baseline condition, particularly with the double handling of transportation for the CPP-blending scheme. Therefore, in the chartered ship condition the fixed transportation cost will be integrated into the variable transportation cost as a charter fee instead of the ownership cost. In the chartered ship condition, the existing scheme is also only able to produce a narrow range of optimization results (29.36–30.11 million USD/week with 0.4591–0.4597 million tons of CO_2/week).

Table 3-7. Comparison results for chartered ship (cost minimization priority*).*

Parameter	Unit	Existing	Proposed			
			CFPP-blending		CPP-blending	
		Value	Value	RD*	Value	RD*
Total Coal Purchasing Cost	million USD/week	25.47	19.84	*-22.11%*	20.27	*-20.42%*
Total Blending Cost	million USD/week	-	1.30	-	1.30	-
Total Fixed Transportation Cost	million USD/week	-	-	-	-	-
Total Variable Transportation Cost	million USD/week	3.89	1.21	*-68.79%*	1.09	*-71.90%*
TOTAL COST	**million USD/week**	**29.36**	**22.35**	***-23.86%***	**22.66**	***-22.81%***
CO_2 Emission from Transportation	million tons/week	0.006	0.002	*-64.26%*	0.002	*-70.16%*
CO_2 Emission from Coal Firing	million tons/week	0.454	0.458	*0.87%*	0.458	*0.89%*
TOTAL CO_2 EMISSION	**million tons/week**	**0.4597**	**0.4600**	***0.07%***	**0.4597**	***0.01%***

**** RD:** relative difference from the existing scheme*

Table 3-8. Comparison results for chartered ship (CO_2 emission minimization priority).

Parameter	Unit	Existing	Proposed			
			CFPP-blending		CPP-blending	
		Value	Value	RD*	Value	RD*
Total Coal Purchasing Cost	million USD/week	26.21	28.32	*8.06%*	28.31	*8.00%*
Total Blending Cost	million USD/week	-	1.30	-	1.30	-
Total Fixed Transportation Cost	million USD/week	-	-	-	-	-
Total Variable Transportation Cost	million USD/week	3.89	1.62	*-58.43%*	2.08	*-46.47%*
TOTAL COST	**million USD/week**	**30.11**	**31.23**	***3.79%***	**31.70**	***5.28%***
CO_2 Emission from Transportation	million tons/week	0.006	0.002	*-57.47%*	0.003	*-47.70%*
CO_2 Emission from Coal Firing	million tons/week	0.453	0.452	*-0.43%*	0.452	*-0.42%*
TOTAL CO_2 EMISSION	**million tons/week**	**0.4591**	**0.4540**	***-1.12%***	**0.4545**	***-1.01%***

** **RD:** relative difference from the existing scheme*

The results obtained in the chartered ship scenario were similar to the baseline scenario, with the CFPP-blending scheme being superior to the other scheme. However, the Pareto front of the CFPP-blending scheme becomes less superior compared to the CPP-blending scheme, which means that the chartered ship scenario can improve the performance of the CPP-blending scheme. This is because, in the baseline scenario, the transportation cost of the CPP-blending scheme will be twice as high as the other scheme because of the two stages of transportation, to the CPP facility and then to the CFPP. Furthermore, if we take a further look at the Pareto solution shown in **Fig. 3-2**, the CPP-blending scheme in the chartered ship scenario is better at reducing the total cost and CO_2 emission.

3.4.5 Environmental consciousness scenario

The environmental consciousness scenario was constructed in order to give another perspective for the future of the coal supply for CFPPs in Indonesia related to this global issue, which is very important to reduce CO_2 emission. To suppress the CO_2 emission from the utilization of CFPPs in generating power, carbon capture storage (CCS) technology can be installed. The installation of CCS will result in additional investment and operating costs. In this research, the investment cost of CCS is neglected because the utilization of CCS is still in the development stage in most countries of the world. However, the operating cost of CCS is incorporated in the numerical calculation based on the estimation by Al Lagtah et al. (2019). Based on their research, the additional operating cost of capturing CO_2 (cc_k) is around USD 16.01/ton of coal, while the amount of CO_2 that will be captured by the CCS is around 40.4% (EC_k = 59.6%). These modifications are considered in the objective functions, for both the total cost and total CO_2 emission.

Based on Fig. 3-3, the installation of CCS at the CFPPs will result in the reduction of CO_2 emission. However, implementing cleaner technology such as CCS at the power plant will raise the total cost as a consequence. Compared to the initial condition (**Fig. 3-2**), the installation of CCS can reduce CO_2 emission by around 39.40–40.30% for all schemes but will increase the total cost by around 33.25–42.14%.

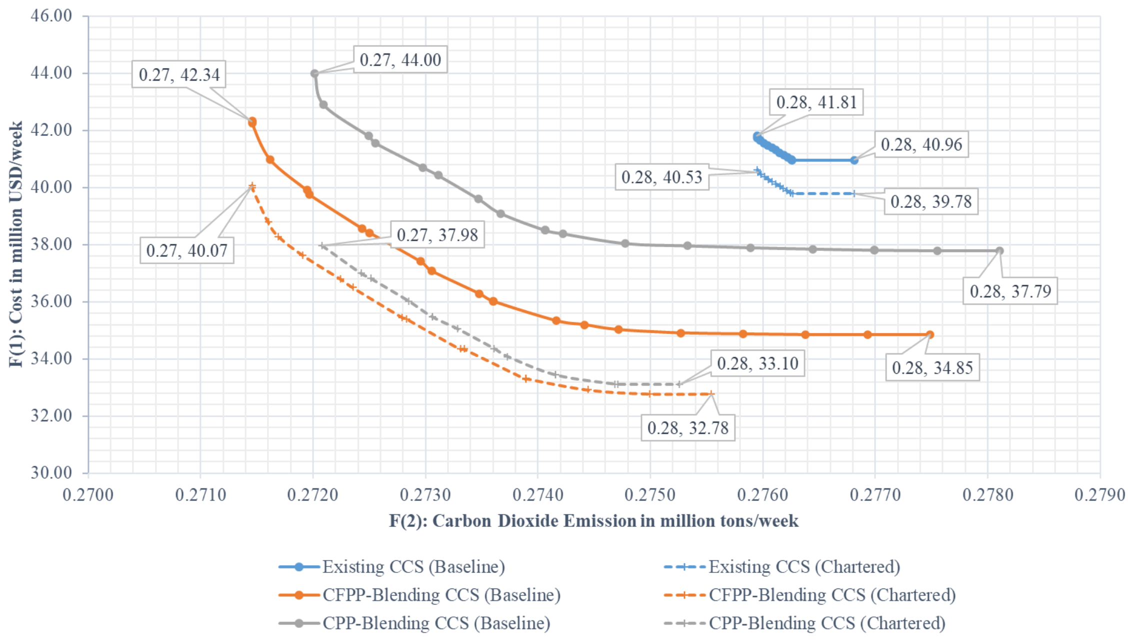


Fig. 3-3. Optimization results with CCS.

3.4.6 Trade-offs

Comparing all the schemes in each scenario (**Fig. 3-2** and Fig. 3-3), the CFPP-blending scheme is the best alternative in each condition. Furthermore, by considering the percentage difference matrix as shown in Table 3-9, under the baseline scenario, the CFPP-blending scheme was able to reduce 1.11% of total CO_2 emission and significantly reduce 20.22% of the total cost compared to the existing scheme. The CFPP-blending scheme was also able to reduce 0.50% of the total CO_2 emission and reduce 11.09% of the total cost compared to the CPP-blending scheme.

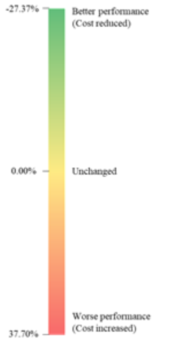
The significant difference in the total cost and slight difference in the total CO_2 emission compared with the existing scheme were derived from both the cost of purchasing coal and the cost of transportation. The cost of purchasing coal in the existing scheme is significantly higher compared to the CFPP-blending and CPP-blending schemes due to the higher quality of the coal required in the existing scheme. Furthermore, the limited options for coal sources in the existing scheme also result in higher transportation costs, due to the smaller ships that have to be used and the greater number of ships for coal delivery. Blending the coal will make it possible to reduce the cost of purchasing the coal because it is possible to mix low, medium, high, and very high rank coal. The transportation cost and CO_2 emission from transportation can also be reduced, because larger and fewer ships can be used under the blending scheme.

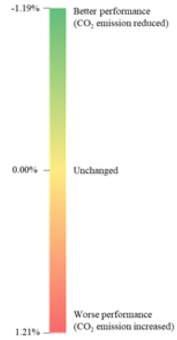
Under the chartered ship condition (Table 3-9), the CFPP-blending scheme was also able to reduce 1.19% of total CO_2 emission and significantly reduce 27.37% of the total cost compared to the existing scheme. The performance of the CPP-blending scheme was significantly increased under the chartered ship scenario, as illustrated in Table 3-9. The CO_2 emission in the CPP-blending scheme was only 0.14% worse than the CFPP-blending scheme, from 0.50% difference in the baseline scenario, while the total cost is only 1.46% worse compared to the 12.48% difference initially. The improvement was affected significantly by the integration of the transportation cost into the variable costs. Based on the average difference in Table 3-9, the alternatives can be sorted from the best to the worst as follows.

- CFPP-blending scheme (chartered ship scenario)
- CPP- blending scheme (chartered ship scenario)
- CFPP-blending scheme (baseline scenario)
- CPP-blending scheme (baseline scenario)
- Existing scheme (chartered ship scenario)
- Existing scheme (baseline scenario)

Table 3-9. Difference in all schemes under the baseline scenario.

ΔCost (%) *			1		2		3	
			B	C	B	C	B	C
			w/o CCS	w/o CCS	w/o CCS	w/o CCS	w/o CCS	w/o CCS
1	B	w/o CCS	#N/A	3.97	25.34	37.70	11.44	35.71
	C	w/o CCS	-3.81	#N/A	20.56	32.44	7.19	30.54
2	B	w/o CCS	-20.22	-17.05	#N/A	9.86	-11.09	8.27
	C	w/o CCS	-27.37	-24.49	-8.97	#N/A	-19.07	-1.44
3	B	w/o CCS	-10.26	-6.70	12.48	23.56	#N/A	21.78
	C	w/o CCS	-26.31	-23.39	-7.64	1.46	-17.89	#N/A
ΔCO_2 Emission (%)			1		2		3	
			B	C	B	C	B	C
			w/o CCS	w/o CCS	w/o CCS	w/o CCS	w/o CCS	w/o CCS
1	B	w/o CCS	#N/A	#N/A	1.12	1.21	1.15	1.07
	C	w/o CCS	#N/A	#N/A	0.97	1.15	0.43	1.00
2	B	w/o CCS	-1.11	-0.96	#N/A	0.15	-0.50	0.01
	C	w/o CCS	-1.19	-1.14	-0.15	#N/A	-0.65	-0.14
3	B	w/o CCS	-1.14	-0.43	0.50	0.65	#N/A	0.51
	C	w/o CCS	-1.06	-0.99	-0.01	0.14	-0.50	#N/A





*** Notes:**
1 = Existing scheme; **2** = CFPP-blending scheme; **3** = CPP-blending scheme
B = Baseline scenario; **C** = Chartered ship scenario
#N/A = comparison not available, no overlay between each scheme

$$\Delta Cost\ (row\ r\ to\ column\ c) = \frac{\sum_i^n \left(cost_{r_{a_i,b_j}} - cost_{c_{a_i,b_j}}\right)/cost_{c_{a_i,b_j}}}{n};\ i = 1,2,\ldots,n;\ b = CO_{2r_{a_i,b_j}} = CO_{2c_{a_i,b_j}}; n = 15$$

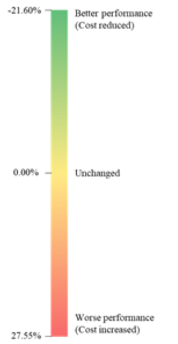
$$\Delta CO_2\ Emission\ (row\ r\ to\ column\ c) = \frac{\sum_j^n \left(CO_{2r_{a_i,b_j}} - CO_{2c_{a_i,b_j}}\right)/CO_{2c_{a_i,b_j}}}{n};\ j = 1,2,\ldots,n;\ a = cost_{r_{a_i,b_j}} = cost_{c_{a_i,b_j}}; n = 14$$

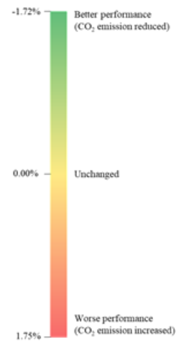
$$a_1 = \max(\min CO_{2_r}\ or\ \min CO_{2_c}) = 0.4592;\ a_n = \min(\max CO_{2_r}\ or\ \max CO_{2_c}) = 0.4606$$
$$b_1 = \max(\min cost_r\ or\ \min cost_c) = 29.3579;\ b_n = \min(\max cost_r\ or\ \max cost_c) = 30.1050$$

By considering the cleaner CCS technology, CO_2 emission can be suppressed in all schemes, as shown in Table 3-10. All schemes can produce better results if CCS technology is implemented, with the existing scheme able to reduce up to 39.90% of CO_2 emission, the CFPP-blending scheme up to 40.30%, and the CPP-blending scheme around 40.14%. A brief comparison of the percentage difference of all the schemes under the environmental consciousness scenario can be seen in detail in Table 3-10. The order of alternatives from the best to the worst is the same as the initial condition, in which the CFPP-blending scheme in the chartered ship scenario is the best alternative, while the existing scheme in the baseline scenario is the worst option.

Table 3-10. Difference in all schemes under the environmental consciousness scenario.

ΔCost (%)			1		2		3	
			B	C	B	C	B	C
			with CCS	with CCS	with CCS	with CCS	with CCS	with CCS
1	B	with CCS	#N/A	2.95	18.55	27.55	10.36	#N/A
	C	with CCS	-2.86	#N/A	15.15	23.90	6.01	#N/A
2	B	with CCS	-15.64	-13.16	#N/A	7.02	-7.88	5.35
	C	with CCS	-21.60	-19.29	-6.55	#N/A	-13.86	-1.60
3	B	with CCS	-9.39	-5.67	8.56	16.10	#N/A	14.28
	C	with CCS	#N/A	#N/A	-5.07	1.63	-12.49	#N/A
ΔCO_2 Emission (%)			**1**		**2**		**3**	
			B	C	B	C	B	C
			with CCS	with CCS	with CCS	with CCS	with CCS	with CCS
1	B	with CCS	#N/A	#N/A	1.71	#N/A	1.75	#N/A
	C	with CCS	#N/A	#N/A	1.57	1.75	1.05	#N/A
2	B	with CCS	-1.68	-1.55	#N/A	0.26	-0.70	0.22
	C	with CCS	#N/A	-1.72	-0.26	#N/A	-1.18	-0.12
3	B	with CCS	-1.72	-1.04	0.71	1.20	#N/A	1.50
	C	with CCS	#N/A	#N/A	-0.22	0.12	-1.47	#N/A





*** Notes:**
1 = Existing scheme; **2** = CFPP-blending scheme; **3** = CPP-blending scheme
B = Baseline scenario; **C** = Chartered ship scenario
#N/A = comparison not available, no overlay between each scheme

$$\Delta Cost\ (row\ r\ to\ column\ c) = \frac{\sum_i^n \left(cost_{r_{a_i,b_j}} - cost_{c_{a_i,b_j}}\right)/cost_{c_{a_i,b_j}}}{n};\ i = 1, 2, \ldots, n;\ b = CO_{2_{r_{a_i,b_j}}} = CO_{2_{c_{a_i,b_j}}} n = 13$$

$$\Delta CO_2\ Emission\ (row\ r\ to\ column\ c) = \frac{\sum_j^n \left(CO_{2_{r_{a_i,b_j}}} - CO_{2_{c_{a_i,b_j}}}\right)/CO_{2_{c_{a_i,b_j}}}}{n};\ j = 1, 2, \ldots, n;\ a = cost_{r_{a_i,b_j}} = cost_{c_{a_i,b_j}}; n = 14$$

$$a_1 = \max\left(\min CO_{2_r}\ or\ \min CO_{2_c}\right) = 0.2721;\ a_n = \min\left(\max CO_{2_r}\ or\ \max CO_{2_c}\right) = 0.2753$$

$$b_1 = \max(\min cost_r\ or\ \min cost_c) = 39.7847;\ b_n = \min(\max cost_r\ or\ \max cost_c) = 41.8099$$

3.5 Summary

This study aims to find an optimized solution for the coal supply for CFPPs in Indonesia by considering the coal-blending mechanism. By applying the proposed CFPP-blending and CPP-blending schemes, the total cost and CO_2 emission can be reduced. The CFPP-blending scheme produces the best result compared to the other schemes. Slight differences between the CFPP-blending scheme and CPP-blending scheme in the chartered ship condition are mainly influenced by the same limitations with respect to the port capacity and ship type, so the largest ship type will be selected in both schemes.

The proposed CFPP-blending and CPP-blending schemes also ensure the continuity of coal supply for 15 years for all coal-fired power plants in the north-western region of Java. These proposed schemes will make it easier for the government and PT PLN to conduct coal procurement, because they will allow long-term contracts to be made with the chosen coal suppliers. Furthermore, the blending consideration in the CFPP-blending and CPP-blending schemes can improve the flexibility of supply by giving more options for suppliers. In the current condition, different contract periods have been applied for short-term contracts (less than 1 year) and long-term contracts (1–5 years).

The utilization of real data in this research means that it can be used as a reference for the government and PT PLN in order to optimize the coal supply for CFPPs in the north-western region of Java. If the proposed option is implemented, reductions of more than 10.01–24.00% of the total cost and 0.67–1.11% of CO_2 emission can be achieved from the current condition. Furthermore, if a carbon tax policy is implemented in the future, the multi-objective optimization constructed in this research can be utilized to analyze the impact of regulation. The characteristics of the coal supply in Indonesia, in which the transportation is by both barges and larger vessels, can make this research applicable also for the global coal market or also for other commodities that have similar characteristics in terms of the quality parameters. Moreover, the proposed research is also applicable for other kinds of transportation optimization problems that include more than one alternative of transportation type.

Finally, this research shows economic benefits, a reduction of the environmental impact in terms of CO_2 emission, and a lower risk to the continuity of supply by applying a coal- blending mechanism for the coal supply in Indonesia. However, the current results show that blending at CFPPs will have more benefit than blending at CPPs. Therefore, overcoming this shortcoming should be addressed by introducing additional factors in future research, such as the mass-heating value, installation of cleaner technology, etc.

4 Optimization of coal supply with economic, environmental, and social aspects consideration in Indonesia

4.1 Introduction

Coal is one of non-renewable resource available in Indonesia to fulfill the domestic energy demand, and it is relatively abundant, compared to the other energy resources. Coal mining industry can be considered as the prime mover for regional development which occupying an important role at the beginning of the resource supply chain. As of 2018, coal accounted for 33.18% of the total primary energy mix in Indonesia, with around 104.47 million tons of coal consumption (British Petroleum, 2020). In the domestic market, most of the coal consumption in Indonesia is utilized as a fuel or raw material for the electricity generation. As of 2021, coal-fired power plant (CFPP) is contributing more than 60% of total electricity generation. Furthermore, since 2018, the Indonesian government announced the 35,000 MW electricity project which resulted in an additional installment of 20,000 MW CFPPs. This project will have a significant impact on the increasing coal demand in the domestic market, which will see around 5% of annual growth from 2020– 2024 (Ministry of Energy and Mineral Resources Republic of Indonesia, 2020). Moreover, Baskoro et al. (2021) provides a forecasted Indonesia's coal production in Indonesia from 2018 – 2030 which shows a growth in both domestic coal and primary energy demand in order to support the national economic development.

Sustainability has become a necessity for industry, including coal mining. It has attracting interest for many scholars, which tend to concern the economic, environmental, and social impacts in supply chain management (SCM). Sustainability issue in coal mining industry is an interesting topic, which deal with a non-renewable resource. Indonesian coal can be divided into four categories based on its quality, which are low (below 3,200 kcal/kg on a GAR basis), medium (3,200–4,900 kcal/kg GAR), high (4,900–6,000 kcal/kg GAR), and very high rank coal (above 6,000 kcal/kg GAR). Most of the coal reserves in Indonesia are classified as low and medium rank coal, which accounts for around 86.6% of the total reserves. The low and medium rank coal contains a relatively high level of moisture content and volatile matter, with a low heating value, so this type of coal is very suitable for direct combustion, in both CFPP and other industries.

As an archipelago country, Indonesia consists of many islands, which will increase the complexity of coal distribution from the suppliers to the CFPPs. This study is carried out as an extension from the previous research from (Baskoro et al., 2019) to analyze the advantages of a new scheme on coal procurement in Indonesia by considering economic, environment, and social aspects. The new scheme will consider the integration and zonation of coal procurement for all power plant units. In this proposed study, environmental and social aspect will be considered to improve the previous research which only considering economic aspect. In general, the coal market in Indonesia can be categorized as a complex business. The complexity in the coal trade in Indonesia include:

1. Coal supply specifications: coal is a heterogeneous substance which has different coal quality, including varying calorific value, total moisture, ash content, and sulfur content.
2. Power plant requirements: each CFPPs has its specifications, defined by government and PLN considering its location and capacity.

3. Coal price: different coal with different specifications will have different coal prices.
4. Coal port capacities: each coal port has a finite capacity, and draft restrictions depend on the bathymetry condition that may prevent the bigger size of barge or vessel entering the port.
5. Coal blending facility capacity: each coal blending facility has its capacity.
6. Coal availability: only coals with its specifications and availabilities can be delivered from a coal port considering the amount of its reserve.
7. Shipment types and rates: a variety of different types of bulk carriers are used in Indonesia. The rates vary differently by ship capacity and distance traveled.
8. Price volatility: coal price and transportation cost vary significantly over time.

There are several research related to the coal supply optimization considering the economic and environmental aspect. However, study on coal mining contribution to the social development is not quite well analyzed. This proposed research will deal with the economic, environmental, and social aspects. The economic aspect will be considered by using the total cost of coal procurement which consist of coal purchasing, coal transportation, coal blending, and carbon capture cost. While the environmental aspect will be consisted of the CO_2 emission from both coal firing and transportation. The social impact will be analyzed through the utilization of Human Development Index (HDI) based on the publication of (United Nations Development Programme, 2020b), as well as the corporate social responsibility (CSR) cost spent by coal mining company to the local community.

The optimization model will be similarly constructed as (Shafiee et al., 2021) and considering the review paper from (Messmann et al., 2020), with the main modification focusing on the social impact. The social impact from coal supply will be modeled following similar approach from (Ericsson & Löf, 2019) and (International Council on Mining & Metals, 2020), which constructed by using HDI data. In developing the model, several assumptions will be applied such as an assumption for the transportation cost that will be simplified by using variable transportation cost, while carbon capture storage (CCS) technology will be assumed to be installed at the CFPP to reduce the environmental impact from the coal-firing. The multi objective optimization model will be solved by using epsilon-constraint method. The proposed research considers the blending mechanism in coal supply for coal fired power plant and focuses on the most important factors for obtaining the optimal solution in terms of efficiency (total cost and ship selection), and sustainability (environmental and social impacts). Hopefully, the outcomes of the proposed research can provide a valuable insight for researcher and stakeholders in coal mining and electricity generation industry.

The main contribution of this proposed study are as follows: a) developing multi objective optimization model for sustainable coal supply chain network; b) optimizing coal supply through coal blending and ship selection procedure; and c) analyzing coal contribution to the social development. This research will be consisted of five sections, which are the introduction, numerical formulation, numerical calculation, results and discussion, and conclusions. This introduction section explains the background and purpose of the study. It will be followed by the literature reviews on recent condition of coal production and consumption in Indonesia. After understanding the current situation of coal mining in Indonesia, the explanation of model construction will be provided in the next section. The model was constructed by considering constraint and condition on the coal supply-demand. The last two sections are the analysis of the results and the conclusion.

4.2 Coal mining and regional development

Most of related research were conducted by only considering economic and environmental aspects. Social impact from the industry or activities are rarely addressed in related research (Table 4-1). Social impact is considered as one of important aspect in SDGs. Social impact also cannot be neglected in coal mining industry, which its activity is highly affecting the society. Rathore & Sarmah (2020) have been considered the economic, environmental, and social aspects in municipal solid waste conversion into biogas. However, they did not solve the optimization problem using multi-objective approach. All factors were incorporated into an objective function, which is total cost. Economic aspect was represented by functioning cost, transportation cost, and hiring cost (operating cost). Environmental aspect was represented by environmental cost and penalty. Social aspect was represented by social cost.

Shafiee et al. (2021) have also been considered the economic, environmental, and social aspects in dairy products. Economic aspect was represented by production cost, transportation cost, environmental cost, and social cost. Environmental aspect was represented by CO_2 emission. Social aspect was represented by the number of job creation (number of workers).

By considering closely related research, some modifications will be conducted. Some additional constraints will be included. Coal quality, which includes CV, TM, TS, and ash content. Coal reserves, which express the limited availability of the resource (coal classified as a non-renewable resource). The objective functions will be similarly constructed as in Shafiee et al. (2021). Economic aspect will be represented by purchasing cost, transportation cost, and CSR cost. Environmental aspect will be represented by CO_2 emission from transportation and coal firing. Social aspect will be represented by the HDI in the region/area of industry. Therefore, one of the main different of the proposed research is the consideration of blending/mixing different type of coal (various coal quality) and consideration of transportation selection which not considered in related research, particularly in Shafiee et al. (2021).

Table 4-1 Research comparison

Author(s)	Year	Object	Method	Parameter[1]					Decision variable[2]				Objective[3]		
				Q	F	R	D	C	P	T	W	ϕ	Eco.	Env.	Soc.
Oh et al.	2001	H_2 Plant	NSGA	-	-	-	v	v	v	-	-	-	v	v	-
Gupta et al.	2018	Coal	Fuzzy	-	v	-	v	v	-	v	-	-	v	v	-
Rathore and Sarmah	2020	Solid Waste	MINLP	-	v	v	v	v	v	v	-	-	v**	v**	v**
Varas et al.	2020	Wine	MILP	-	v	-	v	v	v	-	-	-	v*	-	-
Shafiee et al.	2021	Dairy	Robust	-	v	-	v	v	v	-	v	-	v	v	v
Wei et al.	2021	Thermal-Solar-Wind Power	LP	-	-	-	v	v	v	-	-	-	v	-	v
Proposed	**2021**	**Coal**	**MILP**	**v**	**v**	**v**	**v**	**v**	**v**	**v**	**-**	**v**	**v**	**v**	**v**

Note:
* Objective functions consist of minimize total cost and maximize product quality which both represent economic aspect
** All factors were incorporated into one objective function, which is total costs
[1] **Q** = quality; **F** = freight or transportation; **R** = reserves; **D** = demand; **C** = facility capacity
[2] **P** = amount of product; **T** = number of selected transportations; **W** = workers or social index; **ϕ =** binary variable for ship type selection
[3] **Eco.** = economy; **Env.** = environmental; **Soc.** = social

The method/approach will be like the related research (MILP and epsilon-constraint method). The decision variable will include transportation selection other than the amount of product. The utilization of HDI can be used to analyze the social development in certain area/region, which can be considered by the stakeholders in order to optimize the social benefits of coal mining industry. The blending problems also can be used by the decision makers in order to select suppliers.

HDI data for each region has been collected from the Central Bureau of Statistics of Indonesia (2017 – 2020). CSR cost for each coal mining company will be estimated by using data from the annual report and best practice from the company. The correlation between HDI and CSR cost associated to the coal mining will be empirically analyzed by using regression method. HDI will be also analyzed associated with coal production fraction. Some references on coal mining and sustainability by using HDI or other social indicators are available, such as from Ariza et al. (2020), Mateus & Martins (2020), and Cole & Broadhurst (2020).

Ariza et al. (2020) uses two municipalities, which are coal mining host municipalities and oil host municipalities in their research to analyze the performance of social indicators of activity. The panel data estimation methodology is used in their research. The results show that mining-energy municipalities had better performance in social indicators than in other non-mining municipalities. Education, child mortality, homicides, and fiscal performance data were utilized. Similar panel data estimation will be utilized in the proposed research in order to analyze the correlation between coal mining with social development in an area/region in Indonesia.

Development of mineral-based value chain concept was used by Mateus & Martins (2020). They state that the mineral-based value chain emerges as solution to sustainable development from a country which has high mineral dependency. The concept from Mateus & Martins (2020) will be used in the proposed research to analyze further for policy implication. They do the delineation of mining host communities and selecting and analyzing the indicator and data based on the delineation. Based on their research, mining or coal mining can improve the socio-economic indicator by comparing the results data in mining host communities with whole nation of South Africa.

Cole & Broadhurst (2020) more focus in socio-economic factor without considering the environmental aspects. Similar action will be conducted in the proposed study by collecting the HDI in the area around the coal mining company.

It will be beneficial for the government in controlling and optimizing CSR programs/cost of coal mining company, therefore coal mining company can increase the social benefit to the local communities. Coal mining company can utilize the results from proposed research as strategy for selling its coal resources as well as for arranging CSR programs that suitable for the region (education, health, or wealth). Power generation company can select the best alternative of coal mining sources considering the total cost, CO_2 emission, and social benefit. The utilization of HDI can give more benefit than using number of workers, because it can be used to measure 3 socio-economic indicators (education, health, and wealth/income in the area around the coal mines). Moreover, by using HDI, 3 dimensions of SDGs which are household income (SDG #1), health (SDG #3), and education (SDG #4) can be analyzed.

4.3 Optimization model for coal supply for coal-fired power plants and sustainable development

For CFPPs in Indonesia, the optimization model minimizes total cost and total CO_2 emission, as well as maximizes social benefits by considering the network flow on coal supply-demand in the domestic market for CFPP. The model has supply and demand capacities, arc costs, and arc capacities. The sets, parameters, and variables can be seen in Table 3.

Table 4-2 Notation

Expression	Definition
Sets	
I	The set of coal sources, i.e. suppliers
K	The set of CFPP ports
$\Phi_{i,k}$	The set of allowable ship types to deliver coal from sources *i* to CFPP *k*
Variables	
$x_{i,k}$	Coal amount to be delivered from supplier *i* to CFPP *k* (million tons/week)
$v_{i,k}$	Travel distance from supplier *i* to CFPP *k* (nautical miles)
$m_{i,k,\phi}$	Binary variables if coal from supplier *i* to CFPP *k* adopts ship type ϕ
$s_{i,k,\phi}$	Number of ships from supplier *i* to CFPP *k* by using ship type ϕ
Parameters	
d_k	Coal demand at CFPP *k* (million tons/week)
r_i	Available coal reserve from coal supplier *i* (million tons/week)
C_{SPi}	Capacity of coal jetty/port *i* (tons)
CV_i, CV^*_k	Calorific value of coal source *i* or typical calorific value of CFPP *k* (kcal/kg)
TM_i, TM^*_k	Total moisture of coal source *i* or typical total moisture of CFPP *k* (%)
TS_i, TS^*_k	Total sulfur content of coal source *i* or typical total sulfur of CFPP *k* (%)
Ash_i, Ash^*_k	Ash content of coal source *i* or typical ash content of CFPP *k* (%)
c_i	Price of coal to be delivered from supplier *i* ($/ton)
b_k	Handling fee to blend coal in CFPP *k* ($/ton)
tf_ϕ	Fixed transportation cost using ship type ϕ ($/shipment)
tv_ϕ	Variable transportation cost using ship type ϕ ($/nautical mile/shipment)
γ_ϕ	Capacity of ship type ϕ (tons)
zp_k	Maximum number of sources that can be delivered to CFPP *k*
P_k	CFPP *k* capacity (MW)
CF_k	Conversion factor of CFPP *k* (kcal/MWh)
t	Working hours of CFPP in a week (hours/week)
E_k	CFPP's boiler efficiency *k* (dimensionless)
α	Conversion parameter for CSR expenses to the social index per $
cs_i	Unit corporate social responsibility cost spent by source *i* ($/ton)
HDI_i	HDI in 2020 for source *i* regency (%)
$IHDIH_i$	Relative difference index of health level at source *i* regency using 2019 and 2020 data (%)
$IHDIE_i$	Relative difference index of education level at source *i* regency using 2019 and 2020 data (%)
$IHDII_i$	Relative difference index of income level at source *i* regency using 2019 and 2020 data (%)
CE	Carbon dioxide emission constant for coal firing (tons of CO_2 /MWh . ton of coal/kcal)
IC	Intercept for carbon dioxide emission regression formula (tons of CO_2 /MWh)
CT_ϕ	Carbon dioxide emission constant for transporting coal using ship type ϕ (tons of CO_2/nautical mile/shipment)
cc_k	Unit operating cost of carbon capture in CFPP *k* ($/ton)
EC_k	Released carbon dioxide constant in CFPP *k* (dimensionless)

The numerical formulation will be constructed by using several mathematical expressions. There are a set of coal sources as coal suppliers' candidate *i* that will be used as main source for a set of coal-fired power plants *j*. Coal that will be selected as supplier is delivered by using allowable ship type ϕ by using binary variable $m_{i,k,\phi}$ and the number of ship in each week will be notated by $s_{i,k,\phi}$. The amount of coal to be delivered from supplier *i* to CFPP *k* will be notated by $x_{i,k}$ in million tons/week to fulfill the coal demand at CFPP *k* (d_k) in million tons/week.

Available coal reserve in million tons/week (r_i) from coal supplier *i,* capacity of coal jetty/port *i* (C_{SPi}) in tons, calorific value of coal source *i* in kcal/kg (CV_i), total moisture of coal source *i* in % (TM_i), total sulfur content of coal source *i* in % (TS_i), and ash content of coal source *i* in % (Ash_i) will be considered as the main constraints in coal blending.

The objective functions will be considering the price of coal to be delivered from supplier *i* in \$/ton (c_i), blending cost at facility in \$/ton (b_k), variable transportation cost using ship type ϕ in \$/shipment (tv_ϕ), capacity of ship type ϕ in tons (γ_ϕ). The consideration of environmental aspect through the installation of CCS technology at the CFPP will respect to the CFPP *k* capacity in MW (P_k), conversion factor of CFPP *k* in kcal/MWh (CF_k), working hours of CFPP in a week (t), CFPP's boiler efficiency *k* (E_k), CO_2 emission constant for coal firing in tons of CO_2/MWh . ton of coal/kcal (CE), intercept for CO_2 emission regression formula in tons of CO_2/MWh (IC), CO_2 emission constant for transporting coal using ship type ϕ in tons of CO_2/nautical mile/shipment (CT_ϕ), unit operating cost of carbon capture in CFPP *k* in \$/ton (cc_k), and released CO_2 constant in CFPP *k* (EC_k).

The last objective function which consider the socio-economic impact will respect to the relative difference index of health level in source *i* regency using 2019 and 2020 data ($IHDIH_i$), relative difference index of education level in source *i* regency using 2019 and 2020 data ($IHDIE_i$), relative difference index of income level in source *i* regency using 2019 and 2020 data ($IHDII_i$), HDI in 2020 for source *i* regency (HDI_i), unit corporate social responsibility cost spent by source *i* in \$/ton (cs_i), and conversion parameter for CSR expenses to the social index per \$ (α).

4.3.1 Objectives

$$minimize \sum_{i\epsilon I}\sum_{k\in K} c_i x_{i,k} + \sum_{i\epsilon I}\sum_{k\in K} b_k x_{i,k} + \sum_{i\epsilon I}\sum_{k\in K}\sum_{\phi\in\Phi_{i,k}} (tf_\phi + tv_\phi v_{i,k}) s_{i,k,\phi} + \sum_{i\epsilon I}\sum_{k\in K} cc_k x_{i,k} \quad (4.1)$$

$$minimize \sum_{i\epsilon I}\sum_{k\in K}\sum_{\phi\in\Phi_{i,k}} CT_\phi v_{i,k} s_{i,k,\phi} + \sum_{i\epsilon I}\sum_{k\in K} \frac{(CV_i\ CE + IC) E_k CV_k^* EC_k x_{i,k}}{CF_k} \quad (4.2)$$

$$maximize \sum_{i\epsilon I}\sum_{k\epsilon K} \left\{ \{IHDIH_i + IHDIE_i + IHDII_i + 3(1 - HDI_i)\} x_{i,k}/TD + cs_i \alpha x_{i,k} \right\} \quad (4.3)$$

The first objective in Eq. (4.1) sums the cost of purchasing coal, the cost of transportation from the coal sources to the CFPPs, and the carbon capture cost if installed. The second objective in Eq. (4.2) sums the CO_2 emission from transportation and coal-firing. The CO_2 emission constant (CE) and the intercept (IC) for the CO_2 emission from coal combustion were derived by using the regression method from (Winschel, 1990). The social impact in Eq. (*4.3*) was constructed based on publication from (International Council on Mining & Metals, 2020) and (Ericsson & Löf, 2019) considering the HDI and CSR cost. The amount of coal demand (d_k) for each CFPP was estimated by using the formulation given in Eq. (4.4).

$$d_k = \frac{P_k CF_k t}{E_k CV_k^*} \quad (4.4)$$

The social index in the Eq. (4.3) was developed in order to analyze the socio-economic impact of an activity, particularly coal mining, to the development of the region where coal mining is located. The idea for considering socio-economic impact is derived from (Shafiee et al., 2021), which quantify the social impact in dairy industry through the job creation from the number of workers. However, the fact that the same job can have different social benefits in different regions is often neglected. Therefore, to give more emphasis on the social impact analysis focusing on the set of indicators and aggregation, HDI was utilized. The HDI was created to emphasize that people and their capabilities should be the ultimate criteria for assessing the development of a country, not economic growth alone. The HDI is a summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and have a decent standard of living. The HDI is the geometric mean of normalized indices for each of the three dimensions (United Nations Development Programme, 2020a).

Furthermore, in the publication from (International Council on Mining & Metals, 2020) and (Ericsson & Löf, 2019) were obtained that HDI and CSR cost can be used to analyze the contribution of coal mining sector to the economy. Based on these findings, the Eq. (4.3) was constructed by considering the idea of prioritizing the development of fast-growing region by utilizing the new index from the relative difference in 2019 to 2020 of health, education, and income level ($IHDIH_i$, $IHDIE_i$, and $IHDII_i$), prioritization of underdeveloped region by the utilization of low value of aggregate HDI in 2020 ($1 - HDI_i$), and the impact of CSR that spent by the coal mining company (cs_i). The value of socio-economic index in the Eq. (*4.3*) will be ranging from 0 – 100 as similar to the HDI.

4.3.2 Constraints

Several constraints were constructed in the numerical formulation to find the solution for the optimization problems in coal blending for CFPP, such as coal reserves, coal quality, maximum number of ships, and ship type selection as can be seen in Eq. (4.5) – (4.17).

$$\sum_{k \in K} x_{i,k} \le r_i \,, \quad \forall i \in I \tag{4.5}$$

$$\sum_{i \in I} x_{i,k} \ge d_k \,, \quad \forall k \in K \tag{4.6}$$

$$\sum_{i \in I} CV_i x_{i,k} \ge CV_k^* \sum_{i \in I} x_{i,k} \,, \quad k \in K \tag{4.7}$$

$$\sum_{i \in I} TM_i x_{i,k} \le TM_k^* \sum_{i \in I} x_{i,k} \,, \quad k \in K \tag{4.8}$$

$$\sum_{i \in I} Ash_i x_{i,k} \le Ash_k^* \sum_{i \in I} x_{i,k} \,, \quad k \in K \tag{4.9}$$

$$\sum_{i \in I} TS_i x_{i,k} \le TS_k^* \sum_{i \in I} x_{i,k} \,, \quad k \in K \tag{4.10}$$

$$\sum_{i \in I} \sum_{\phi \in \Phi_{i,k}} m_{i,k,\phi} \le z_{P_k} \,, \quad \forall k \in K \tag{4.11}$$

$$\sum_{\phi \in \Phi_{i,k}} m_{i,k,\phi} \le 1, \quad \forall i \in I \,, k \in K \tag{4.12}$$

$$x_{i,k} \le \sum_{\phi \in \Phi_{i,k}} \gamma_\phi s_{i,k,\phi} \,, \quad \forall i \in I \,, k \in K \tag{4.13}$$

$$s_{i,k,\phi} \le M \, m_{i,k,\phi} \,, \quad \forall i \in I \,, k \in K, \, \phi \in \Phi_{i,k} \tag{4.14}$$

$$\sum_{k\epsilon K} x_{i,k} \leq C_{SP_i}\ , \quad \forall i \in I \tag{4.15}$$

$$x_{i,k} \leq M \sum_{\phi \in \Phi_{i,k}} m_{i,k,\phi}\ , \ \forall i \in I\ ; \forall k \in K \tag{4.16}$$

$$s_{i,k,\phi} + M\left(1 - m_{i,k,\phi}\right) \geq 0.25\ , \ \forall i \in I\ , k \in K,\ \phi \in \Phi_{i,k} \tag{4.17}$$

Constraint in Eq. (4.5) shows that the sum of coal that will be delivered from coal source i to the coal blending facility must remain at or below the amount of available reserve for source i.

Constraint in Eq. (4.6) shows that the sum of coal that will be delivered to CFPP k should meet the minimum requirement, that is, d_k.

Constraints in Eq. (4.7) – (4.10) ensure that coal quality requirement which consists of calorific value CV_k^*, total moisture TM_k^*, ash content Ash_k^*, and sulfur content TS_k^* for CFPP k are met. The symbol M represents a large value.

Constraint in Eq. (4.11) shows that the number of suppliers that can deliver coal to each unit of CFPP k should no more than maximum allowable number of suppliers z_{pk}.

Constraints in Eq. (4.12) – (4.16) ensure the optimal selection of transportation mode for deliver coal sources i to CFPP k, and ensure that the port capacity of coal source i is not violated by the amount of coal that will be delivered from coal source i.

Constraint in Eq. (4.17) reflects to the number of ships that will be used to transport coal from source i to CFPP k, which minimum 1 ship/month or 0.25 ship/week.

4.4 Numerical calculations

The proposed idea is able to produce better results compares to the ordinary optimization, because it can be obtained a Pareto solution set for each objective function, which are total cost, CO_2 emission, and socio-economic impact. There will be sets of solution that can be used for the decision making in coal supply for CFPP, instead of single solution which optimized each objective function partially. The results of optimization can be seen in Figure 4-1.

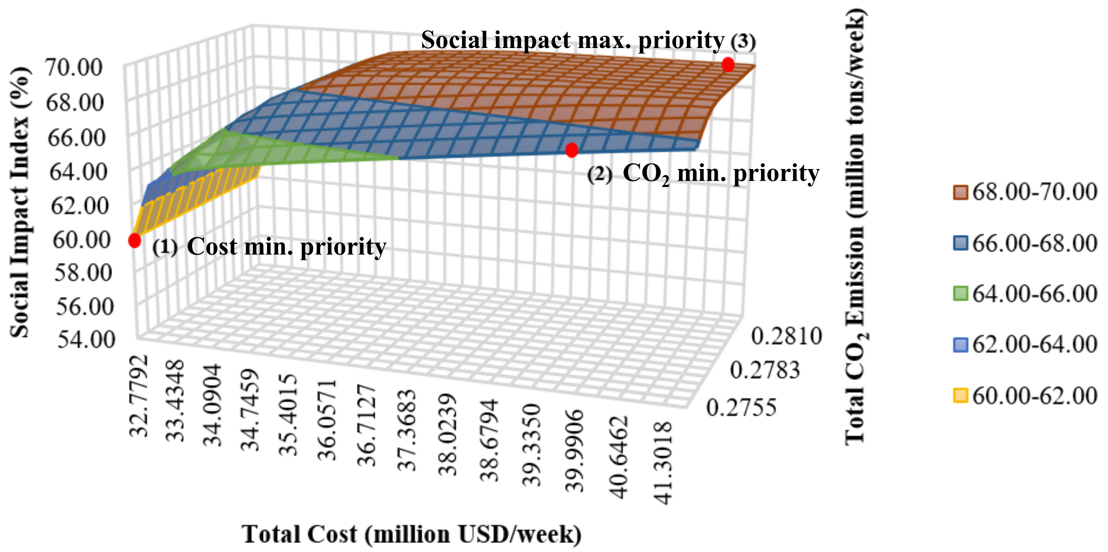


Figure 4-1: Optimization results

From the Figure 4-1 above, it can be seen the correlation between each objective function. The total cost and CO_2 emission has a negative correlation, which reflect the actual condition in the industry. Both the total cost and socio-economic impact as well as the socio-economic impact and CO_2 emission, has a positive correlation. The positive correlation between the total cost and socio-economic impact also reflecting the actual condition, which the higher cost will be assumed to be able to improve the regional development, both for the direct and indirect benefits. Research from (Rybski et al., 2013) showing a positive correlation between the HDI and CO_2 emission in several country, which also reflected by the optimization results.

The value of socio-economic indicator is ranging from 60.0189–69.2912, which means that the proposed idea is able to produce several alternatives of coal supply that has a high value of socio-economic benefits to the local community (~70). UNDP has classified the social development into 4 categories, which are a) low (HDI < 60), b) moderate (HDI between 60–70), c) high (HDI between 70–80), and d) very high (HDI ≥ 80). Considering the value of HDI from the coal suppliers' candidates that has minimum value of 66.79, the proposed research can obtain an optimized social benefit that can be utilized both for the government and electricity company to improve the existing condition for coal supply, because it has several alternatives to reduce cost, CO_2 emission, as well as improve the regional development based on the model.

In the cost minimization which pointed out by (1) in the Figure 4-1, the total cost, CO_2 emission, and social index is USD 32.78 million/week, 0.275 million tons/week, and 60.0020% respectively. While in the CO_2 emission minimization which pointed out by (2) in the Figure 4-1, the result for each parameter is USD 39.99 million/week (+22.00%), 0.272 million tons/week (-1.27%), and 60.92% (+1.54%). In the social index maximization, which pointed out by (3) in the Figure 4-1, the result for each parameter is USD 41.63 million/week (+27.00%), 0.283 million tons/week (+2.73%), and 60.92% (+15.48%). The value inside parentheses showing the relative different to the cost minimization solution.

In terms of flexibility of supply, the number of suppliers for each optimization prioritization are 10, 7, and 9 for the total cost, CO_2 emission, and social index, respectively. This can be concluded that to consider the sustainability issue in coal supply optimization, coal blending can be utilized for increasing the flexibility, because it can have a greater number of coal suppliers. However, both the CO_2 emission and social index prioritization have less flexible option for the sources compare to the cost prioritization. From the viewpoint of the government and national power company (PT. PLN), the results can be utilized as alternative to deal with both environmental and social aspect, that often neglected in the business framework for coal supply. The formulation of multiple objective optimizations will give possibility to the government and PT. PLN to decide the best supplier for long-term period considering the sustainability issues.

The total cost and CO_2 emission has a negative correlation, which reflect the actual condition in the industry which in order to reduce CO_2 emission, an additional cost should be provided by the business actor. Both total cost and social benefits have a positive correlation, which in accordance with the hypothesis that regional development can be improved by spending an investment related to the social programs. The higher the investment (until certain amount of money) will have direct impact on the higher development of the region. The total CO_2 and social benefits also have a positive correlation, which in accordance with the hypothesis from Rybski et al. (2013) as well as shown in the Figure 4-2 that processed from UNDP (for the HDI) and The World Bank (for the CO_2 emission per capita) data. The Figure 3 shows that country with a higher HDI value, will also has a greater value of CO_2 emission.

In Figure 4-2, the correlation between the HDI and CO_2 emission from the optimization results can be compared to the global data regression. It shows that the Pareto solution set from optimization results of coal supply for CFPP in Indonesia is having better performance because it is below the regression line from the global data. Moreover, the HDI or social benefits can be increased with slightly increase in CO_2 emission. As discussed previously, total cost and social benefits has a positive correlation, therefore the higher cost will directly affecting on higher HDI value as can be seen on the Pareto solution sets of the optimization results. Compared to the national data of Indonesia, it shows that the optimization results is performing better in terms of the CO_2 emission, however the performance of HDI is worse than Indonesia. The worse performance of HDI in the optimization results is because in the coal supply model it is focus on coal mining, which mostly located in the remote area.

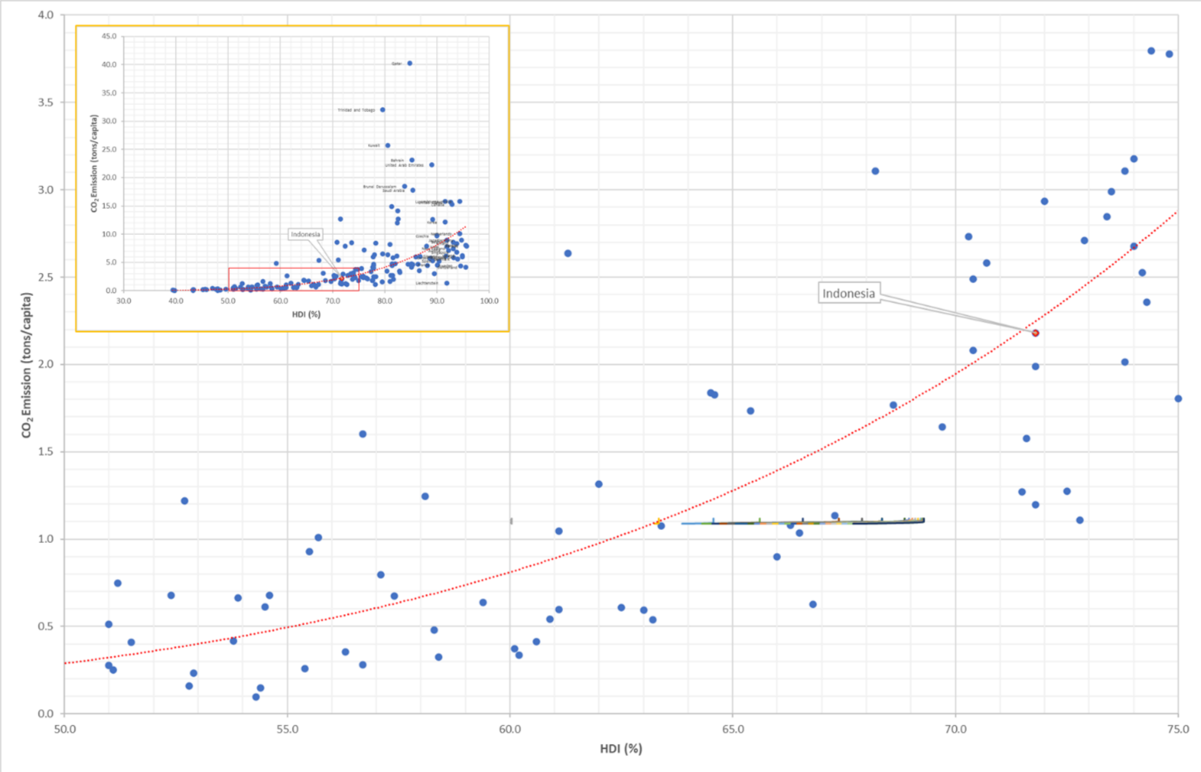


Figure 4-2 Correlation of HDI and CO_2 emission from the optimization results compared to the global data

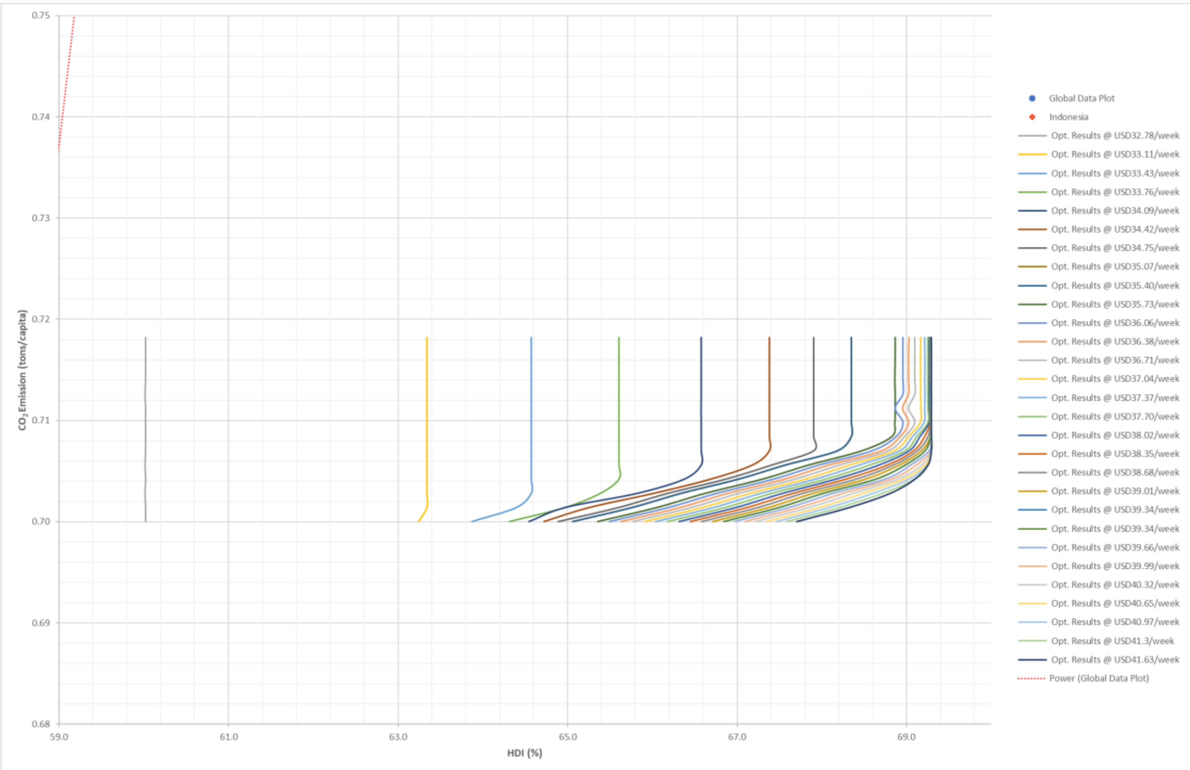


Figure 4-3 CO_2 emission and HDI from the optimization result

4.5 Summary

This study aims to find an optimal solution for the coal supply for CFPP in Indonesia by considering the coal-blending mechanism. By applying the proposed idea, the total cost and CO_2 emission can be reduced, while the social indicator index can be increased.

The proposed research also ensures the continuity of coal supply for 15 years for all CFPPs in the north-western region of Java. This proposed idea will make it easier for the government and PT PLN to conduct coal procurement, because they will be allowed to make a long-term contract with the chosen coal suppliers with various coal quality. Furthermore, the blending consideration can improve the flexibility of supply by giving more options for suppliers. In the current condition, different contract periods have been applied for short-term contracts (less than 1 year) and long-term contracts (1–5 years).

The utilization of real data means that this research can be used as a reference for the stakeholders to optimize the coal supply for CFPPs. If the proposed idea is implemented, reductions of around 27.00% of cost and 1.27% of CO_2 emission, as well as improvement of around 15.48% of the social indicator index can be achieved from the current condition. The characteristics of the coal supply in Indonesia, in which the transportation is conducted by both barges and larger vessels, can make this research also applicable for the global coal market. Finally, this research shows economic, environmental, and social benefits, and a lower risk to the continuity of supply of coal in Indonesia.

There are still some limitations in this proposed research, such as lower social index value obtained from the optimization compared to the national data. Therefore, we would like to consider other aspects in the future research in order to improve the optimization results, such as using additional social indicator and construct several scenarios.

5 Conclusions

In this part, two kinds of explanation will be provided. The first one is the conclusions of the proposed study, and the other is the plan for extending the current research.

5.1 Conclusions

Considering the key questions on the research objectives and based on the results, we can conclude that:

- The future coal production and its factor in Indonesia are analyzed by using system dynamics model
    a. Coal production in Indonesia will still increase to fulfill domestic demand
    b. Coal will remain the major contributor in the national primary energy mix
    c. The best alternative for Indonesia's coal policy is the EO scenario, which can satisfy both economic and environmental aspects
- In order to optimize the domestic coal demand, coal supply for CFPPs is formulated as a multi-objective optimization by using a MILP and solved by using epsilon-constraint method
    a. The objective functions are total cost and total CO_2 emission
    b. Proposed blending schemes are able to decrease total cost and CO_2 emission
    c. Total CO_2 emission can be reduced significantly by introducing CCS facility
- As an extension from the previous research, social aspect is considered in the optimization
    a. Social benefits from coal utilization can be improved by considering HDI and CSR cost
    b. Optimization should be prioritizing fast growing and high developing region

However, the proposed study still has some weaknesses, such as neglecting the mass heating value relationship for coal and investment cost for CCS installation. Therefore, this proposed study will be extended in the future in order to improve the performance of current study as well as to solve future problem related to coal utilization.

5.2 Future research plan

To continuously contribute more to coal utilization topic as well as considering the current trend, particularly in terms of environmental issue as global concern, future research should be carried out. Several ideas for future research that will be conducted consisting of:

- Coal supply considering blending and mass heating value relationship
- Domestic coal price regulation scenario
- Optimization towards clean coal utilization
- Optimization towards zero emission
- Integrated power systems model
- Optimization of integrated power systems

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