Master's Thesis of City Planning

Analysis Of Indonesia's Long-Term Electricity Plan Toward a Net-Zero Society

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Abstract

The electrical industry in Indonesia is the largest source of greenhouse gas emissions in the energy sector. As a result, the electrical sector makes a significant contribution to decarbonization. This study aims to provide insight in term of finding the least-cost and optimum electricity plan for Indonesia until 2050 as well as analyze the best way to reduce the greenhouse gas emission. This study has four scenario, Reference Scenario (REF), and three alternatives' scenarios (GPS, APS, and ZEPS) that consider government plan in term of decarbonization, new technology development such as CCS and capacity storage, least-cost optimization as well as supply and demand balance. LEAP software will be used by using year 2020 data as the base year to 2050 as a target year. Besides, LEAP will be integrated with NEMO so that it can provides more accurate way to analyze the pathway to reach zero emissions in the electricity. This study shows that coal will be the main source to generate the electricity in Indonesia based on REF and GPS. However, with the higher penetration in renewable energy, the coal dependency can be cut down. Besides, in term of emission, ZEPS shows no emission produced in year 2050.

Keyword: electricity plan, renewable energy, emission, least-cost, LEAP, Indonesia

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List of Abbreviation

AFOLU	: The Agriculture, Forestry and Other Land Use
ASEAN	: the Association of Southeast Asian Nations
ESDM	: Ministry of Energy and Mineral Resources
EU	: European Union
GHG	: Green-house Gas
IPCC	: Intergovernmental Panel on Climate Change
IPPs	: Independent Power Producers
KEN	: National Energy Policy
LEAP	: The Low Emissions Analysis Platform
LUCF	: Land Use Change of Forestry
NDCs	: Nationally determined contributions
NEMO	: the Next Energy Modeling System for Optimization
RPJMN	: Medium-Term National Development Plan
RUEN	: National Energy General Plan
RUKN	: The National Electricity Master Plan
RUPTL	: Electricity Supply Business Plan

Chapter 1. Introduction

1.1 Background

The global climate crisis is a major challenge. The world is currently taking urgent effort to address this issue, which is regarded as the most serious threat to modern humans (United Nation, 2021). Many nations are now pledging net-zero carbon targets, which are a promising strategy to decrease carbon emissions in accordance with the 2015 Paris Agreement. By doing so, carbon emissions must be reduced to as close to zero as possible while also limiting global temperature rise to 1.5 degrees Celsius in many areas.

So far, there are 135 countries that has pledged the net zero carbon based on Net Zero Tracker and Georgieva (2021). As many as 66 of them have signed a formal pledge in support of this move. Fourteen of the 66 nations, including the EU, Japan, South Korea, and Canada, have written the aim into their national laws, while the remaining 51 are writing the plan into associated policies. Unfortunately, in comparison to the number of nations having written laws, the majority of countries do not yet have a written plan and are currently debating their commitment to this plan.

Nonetheless, when it comes to the time range for achieving the goal, most nations are aiming for 2050. Finland has declared 2035 as its target year (Finland's Ministry of Finance, 2022), followed by Iceland and Austria in 2040, and Germany in 2045. (Jennen, Rathi, & Rogers, 2021). Meanwhile, the Indonesian government has stated its commitment to engage with the net zero objective, with the year 2060 as the maximum recommended year target (IESR, 2021). Unlike China, which has set 2060 as the year to achieve carbon neutrality, Indonesia has yet to develop a formal strategy to meet this objective. This situation pushed this country to the bottom of the list of carbon-neutral countries.

Commitment, planning, and action are required for Indonesia to meet the target. But what is possible? Globally, the energy sector plays an essential role in reducing carbon emissions because it contributes the most to global GHG emissions. According to the IPCC (2007) report, energy accounted for little more than a quarter of total emissions in 2004. Meanwhile, the second largest is forestry (17%), then followed by agriculture (15%). In the newest report by IPCC (2022), energy sector makes up as the highest proportion (33%) of the global emissions in which 23% of that comes from electricity and heat. When these two reports are compared, it is clear that energy is one of the primary sources of world emissions.

In comparison to developed countries, Indonesia has lower emissions. However, Indonesia is a part of the ASEAN region, which is one of the most vulnerable to climate change (Ding & Beh, 2022). Furthermore, the rate of increase in emissions in ASEAN countries is faster than before. In the case of Indonesia, AFOLU accounts for 50% of emissions, while energy accounts for 32%. Even while Indonesia's AFOLU sector has a greater potential to cut carbon emissions, the energy sector is equally essential since the average annual rise in emissions in the energy sector (4.5%) is considerably faster than the 2.7% rise in land-based emissions (Wijaya, et al., 2017). As a result, without proper planning, the emissions from the energy sector may exceed those from the land-based sector.

Same goes as global emission status, one of the core sectors that play significant part to reach net zero emission in energy sector is electricity and heat. Besides, electricity sector also important for the society welfare and country's economic growth. Because of that, it is fundamental to map-out electricity plan to provide reliable, reasonable, affordable price while addressing the climate change issue at the same time.

The ambition to reduce emissions in the electrical industry is not a new agenda for Indonesia, but it remains a significant challenge. The government has established many regulations, including Indonesia's Medium-Term National Development Plan (RPJMN), which sets a target of 16 percent renewable energy mix by 2019. Unfortunately, Indonesia was unable to meet the aim.

The difficulty that has hampered Indonesia's efforts to decarbonize the electrical industry is the dominance of coal in power plant capacity. Coal accounts for up to half of the total, followed by gas (29%) and fuel (7 percent). Meanwhile, the percentage of renewable energy in the power plant is just 14%. Despite the Indonesian government's plans to increase the percentage of renewable energy, growth in renewable energy has remained sluggish since 2011.

In terms of politics, the slow pace of renewable energy production occurs for a variety of reasons. First, there is regulation change and policy uncertainty in meeting the renewable energy objective. This issue has slowed the rise of renewable energy since a systemic transition to more efficient energy requires effective and stable governance. Secondly, Indonesia's government favors on lowest cost energy such as coal for managing its renewable energy mix target due to the abundance availability. Using fossil fuels will both directly contribute to and be threatened by climate change since they release emissions. Because of these challenges, Indonesia will struggle to attain net zero emissions. Even still, based on current NDCs status, Indonesia is a country that is still a long way from meeting the 1.5-degree Celsius Paris Agreement.

IESR (2021) predicts that Indonesia has tremendous renewable energy potential which is around 7,879.4 GW (scenario 1) and 6,811.3 GW (scenario 2). For this reason, it is vital for Indonesia to shift into cleaner energy especially when the country wishes to achieve net zero carbon. As future Indonesia's electricity demand is also predicted to be increased, Indonesia has to anticipate with the provision of power plants. Moreover, with the urgency to meet net-zero agenda, it can be a good momentum for the nation to start to move toward environmentally friendly energy that emit less pollution. Thus, analyzing its current status and long-term plan is needed to build a good policy to achieve the target.

The most effective way makes an effective policy is policy appraisal which based on accurate data. In this case, long-term electricity outlook and CO_2 mitigation is important to be analyzed. Various methods from statistical to machine learning have been applied for analyzing the electricity sector. However, LEAP model is better solution since it provides more benefit especially when the time series data is not complete. LEAP model gives a suitable modeling platform in giving estimation accuracy based on the scenario that is built in the model. Besides, the new version of LEAP provides more accurate detail in depicting energy model.

So far, several studies in Indonesia including Ministry of Energy and Mineral Resources (ESDM) have used the energy model to predict energy outlook in Indonesia. However, most of the research are based on previous economic growth and have not included the COVID-19 situation as well as how to reach net zero emissions. Since the COVID-19 has affected current energy demand, it is fundamental to include the situation in the assumptions.

In order to build an effective policy, long-term electricity outlook and CO_2 mitigation is important to be analyzed. Various methods from statistical to machine learning have been applied for electricity forecast. However, LEAP model is better solution since it provides more benefit especially when the time series data is not complete. LEAP model gives a suitable modeling platform in giving estimation accuracy based on the scenario that is built in the model. Besides, the new version of LEAP provides more accurate detail in depicting energy model.

Some studies in Indonesia also have used LEAP for energy plan and electricity plan. For instance, Handayani, Krozera, & Filatova (2017) and Handayani, Krozera, & Filatova (2019). However, most of the study only focus on Java-Bali power plant. Besides, the studies also do not include the limitation and constraint on CO_2 emissions. However, the newest research in term of net zero emissions pathway has been conducted by Handayani et al., (2022) regarding ASEAN electricity plan to reach net zero emissions. Even though this study has integrated the newest software which is NEMO, however this research is not focus on Indonesia as a sample and not really consider the demand side of electricity sector in building the scenario.

Based on these situations, this study will fill the gaps of the previous studies. Firstly, this study will integrate LEAP model with NEMO since it can give faster analysis for LEAP model compare to before. Besides, NEMO also can give optimization in electricity sector since it provides feature on emission constraint as well. To supplement previous studies in Indonesia, this study suggests various scenarios based on three alternative scenarios as well as business as usual to achieve clean energy and zero emissions. This research also includes new potential technologies for capacity development in Indonesia's future plans. Furthermore, by utilizing LEAP and NEMO, this study will provide more accurate data on the electrical industry and government targets for achieving zero CO_2 emissions.

1.2 Research Objectives

The objective of this research is to analyze the long-term electricity plan of Indonesia based on several scenarios which consider impact of government plan and policy related to renewable energy, technology capacity expansion for providing alternative solution and recommendation to shape future electricity plans. Besides, this research also tries to fill the gaps of previous research in term of zero emissions pathway of electricity in Indonesia by using LEAP and NEMO.

Chapter 2. Study Background and Literature Review

2.1. Study Background

2.1.1 Indonesia NDCs Status

Indonesia's GHG emissions were recorded in 2005 as 1.8 $GtCO_2e$. This amount has risen by 0.4 $GtCO_2e$ since 2000. (Ministry of Environment and Forestry, 2021). In 2012, Indonesia's emissions also experienced an increased and reaches 1.453 $GtCO_2e$. This number comes mainly from Land Use Change of Forestry (LUCF) (47.8%) and energy (34.9%). In 2016, it is recorded that the number of emissions keep increasing where LUCF including peat fires contributes to 43.59% and energy 36.91% of the emissions respectively. Over a four-year period (2012-2016), the increase rate of GHG emissions from energy is faster even than LUCF. It is expected that South-east Asian countries, including Indonesia, would face a rapid increase in emissions due to population rise, increased urbanization, and industrialization.

In term of NDCs, the current government has pledged to reduce the emission as much as 29% under unconditional reduction target and conditional reduction target up to 41% of the business-as-usual scenario by 2030 (Ministry of Environment and Forestry, 2021). Judging from the emission level, it is predicted that energy has higher emission increase rate compare to FOLU. Projected emission level and emission reduction from each sector in Indonesia is presented in the

Table 1. The year 2010 is the base year for the analysis, CM1 is the unconditional reduction while CM2 is conditional reduction. Based on the results, it can be seen that emission from the energy sector in 2030 will be higher than FOLU. If Indonesia keep depend on its BAU, annual growth rate of emission from energy will be 6.7% (United Nations Framework Convention on Climate Change, 2021), this rate is even the highest among all sectors. Climate Action Tracker (2020) mentioned that even with the newest update of the country's NDCs, Indonesia did not increase its climate ambition and to achieve net zero emission by 2060 will be a very hard goal for this country.

Table 1. Projected Emission Level and Reduction from Each Sector

Sector	GHG Emission Level 2010* (MTon CO_2e)	GHG Emission Level 2030			GHG Emission Reduction				Annual Average Growth BAU (2010-2030)	Average Growth 2000-2012
		MTon CO_2e			MTon CO_2e		% of Total BaU			
		BaU	CM1	CM2	CM1	CM2	CM1	CM2		
1. Energy*	453.2	1,669	1,355	1,223	314	446	11%	15.5%	6.7%	4.50%
2. Waste	88	296	285	256	11	40	0.38%	1.4%	6.3%	4.00%
3. IPPU	36	70	67	66	3	3.25	0.10%	0.11%	3.4%	0.10%
4. Agriculture**	111	120	110	116	9	4	0.32%	0.13%	0.4%	1.30%
5. Forestry and Other Land Uses (FOLU)***	647	714	217	22	497	692	17.2%	24.1%	0.5%	2.70%
TOTAL	**1,334**	**2,869**	**2,034**	**1,683**	**834**	**1,185**	**29%**	**41%**	**3.9%**	**3.20%**

Notes: **CM1**= Counter Measure 1 (*unconditional mitigation scenario*)
CM2= Counter Measure 2 (*conditional mitigation scenario*)

*) Including fugitive.
**) Only include rice cultivation and livestock.
***) Including emission from estate crops plantation.

Source: Republic of Indonesia (2016)

Based on United Nations Framework Convention on Climate Change (2021), there are several things that Indonesia has to do to achieve the target. Firstly, forestry sector will be the main sector to reduce the emissions, meanwhile energy will be the second important sector that can give the significant transition by raising renewable energy, increasing energy efficiency, and reducing the usage of coal. Even though the rate of energy is higher than forestry, in term of reducing the emission, forestry has ability for carbon sinking. Because of this, forestry is the main sector for emission reduction and energy will be the second one.

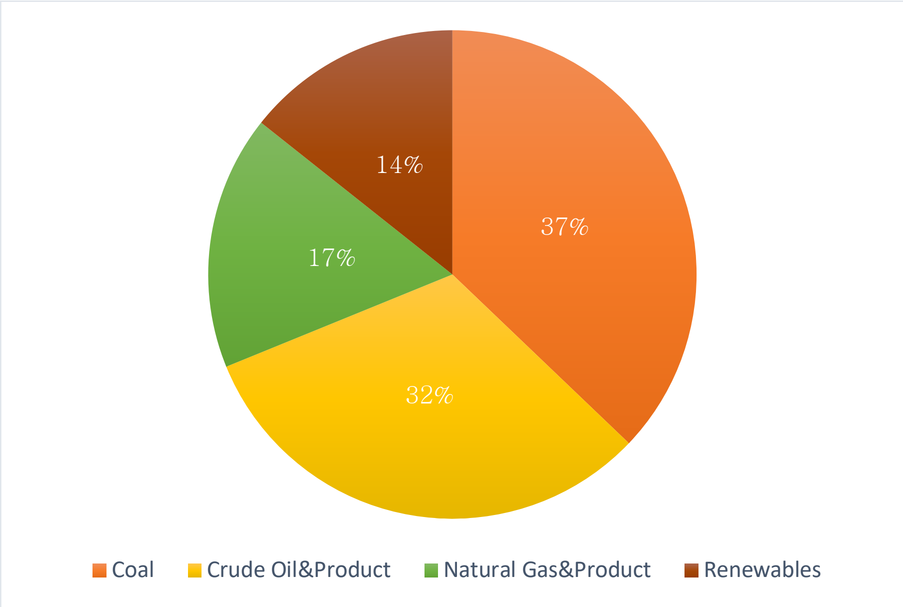
Even so, the energy plays important role in reducing the emissions. It is because most of greenhouse gases are the results of many human activities where mostly related to fossil fuel. For this reason, emission reduction from the energy is fundamental to be reduced, especially the rate of emission for energy can be faster than the forestry with the increase of population.

2.1.2 Indonesia's Energy Status

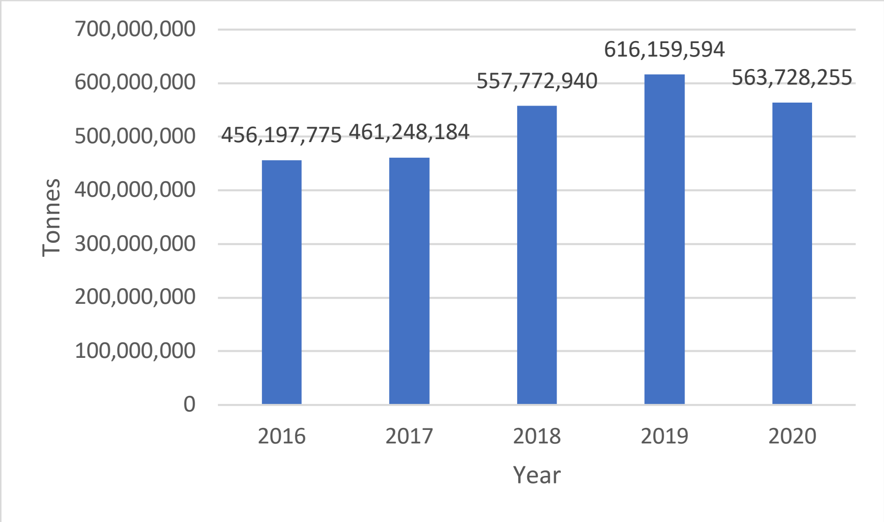
Indonesia is the 4th largest population in the world and considered as a developing country. For that reason, sufficient energy has to be supplied to maintain the economy. Handbook of Energy & Economic Statistics of Indonesia (2020) stated that the primary energy supply mix in this country is dominated by coal. In term of primary energy supply (Figure 1), coal accounted as much as 37.14 percent following by oil as the second largest with 31.69 percent. Natural gas is on the top three energy usage which contributed 16.83 percent of energy mix. The new renewable energy share is still considered low compared to other energy sources (14.32%). Even though the renewable energy proportion is the lowest, the number has slightly increased from 9.2 percent in 2019.

As the country which has abundant natural energy resources, coal is still the main energy supply for this country. Since the year

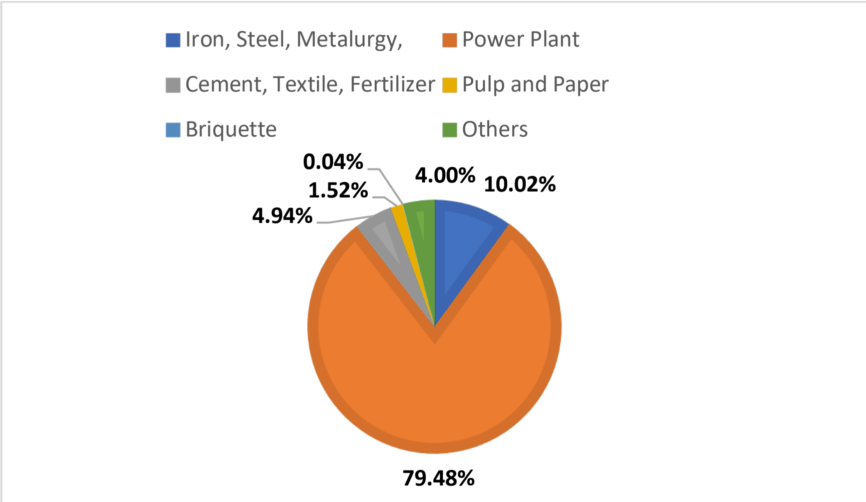
2016, the coal production keeps increasing every year until the year 2019. However, during covid-19 pandemic, coal production has decreased by 8.5% in 2020. On the other hand, coal domestic sales (Figure 3) shows that power plant sector is the main user of the coal (75.48%). Iron, steel, and metallurgy sector consumed around 10% in 2020 while others sector only used less than 5%. This indicates that coal sector is highly related with the power plant industry.



Source: Indonesia Ministry of Energy and Mineral Resources (2020)
Figure 1. Primary Energy Supply by Sources in 2020



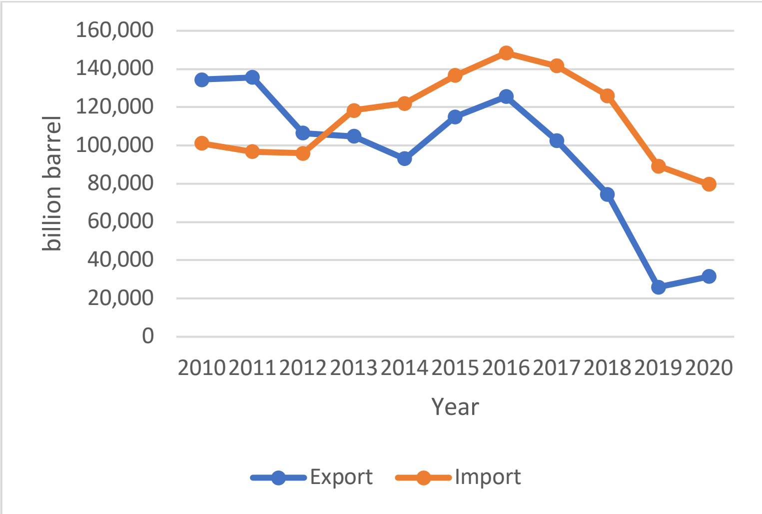
Source: Indonesia Ministry of Energy and Mineral Resources (2020)
Figure 2. Coal Production (Tonnes/year)



Source: Indonesia Ministry of Energy and Mineral Resources (2020)
Figure 3. Domestic Coal Sales in 2020 (percent)

Regarding the oil energy, the oil sector of Indonesia has contributed in the international industry. Indonesia joined and became a member of OPEC for the first time in 1962, but suspended in 2008 due to Indonesia's declining oil production. Indonesia joined again OPEC in 2015, but for the second time, Indonesia decided to pull out of OPEC in 2016. Indonesia had enjoyed its greatest day as an oil-exporting country, with abundant oil production and low domestic consumption.

As shown in the Figure 4, in the time between 2012 and 2013, Indonesia turns to be importer of oil which started with the increase of oil import and the decrease of oil export. Until the year 2020, this situation keeps persisting even though the number of export and import shows declines.



Source: Indonesia Ministry of Energy and Mineral Resources (2020)
Figure 4 Oil Import and Export

On the other hand, total oil reserve in Indonesia keeps showing the decrease, especially it falls sharply from 2018 (7.51 billion barrel) to 2019 (3.77 billion barrel). Even though in 2020 the total oil reserve rises back slightly, the number of oil reserve jump sharply compare to a decade before. Indonesia cannot continue to depend on oil imports to fulfill domestic energy consumption, because it can expand the government expenditure. Besides, oil-based energy also creates emission.

Table 2. Oil Reserves (Billion Barrel)

Year	Reserve		
	Proven	Potential	Total
2016	3.31	3.94	7.25
2017	3.17	4.36	7.53
2018	3.15	4.36	7.51
2019	2.48	1.29	3.77
2020	2.44	1.73	4.17

As for gas, Indonesia is considered as world's top LNG exporters in 2019. PwC (2020) stated that the rank of Indonesia global gas production is 12th in the world (Figure 5). The gas production in 2020 is 67.5 billion cubic metres (equivalent to 2.4 trillion cubic feet (Tcf)). Meanwhile, its proven reserves, Indonesia is in the 21st position in the world and marks as the 3rd in the Asia-Pacific region with total proven reserves as much as 50.5 Tcf. However, this amount has down almost 50% from 100.4 Tfc in 2019.

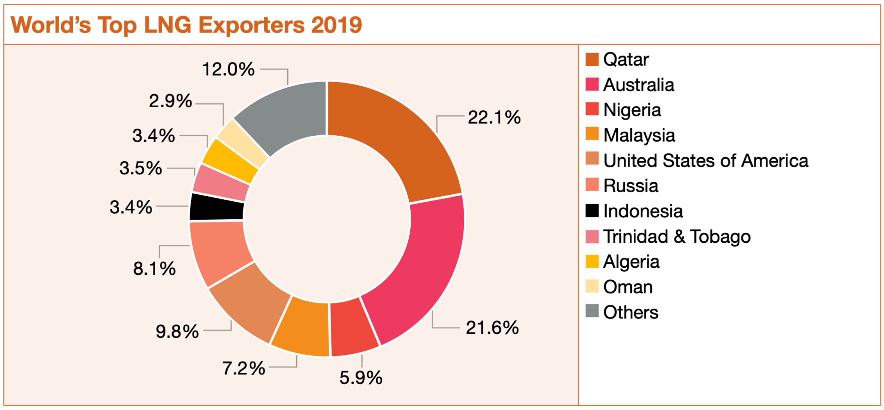


Figure 5. Global LNG Exporters in 2019

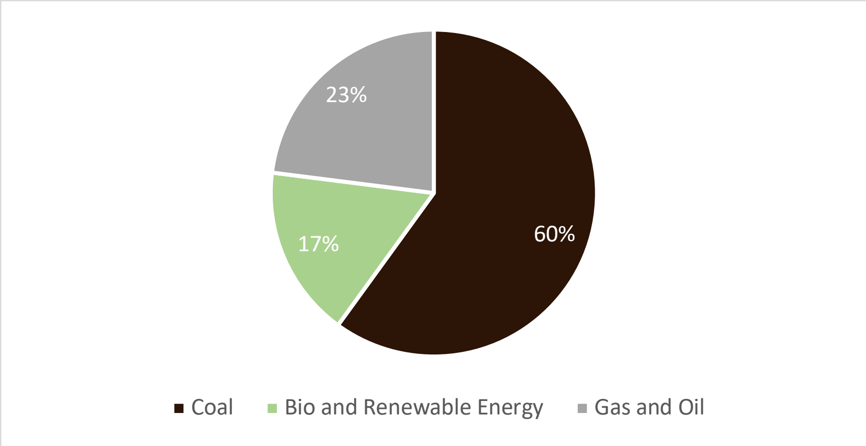
Indonesia will experience downward trend in natural gas production with 3% of decline rate per year (Wayan Ngarayana, Sutanto & Murakami, 2021). For that reason, Indonesia is also predicted to be gas importer starting from 2028. This condition is slightly better than petroleum due to smaller consumption. Even so, Indonesia has to anticipate the scarcity in natural gas as well as other fossil-based energy by increasing its energy mix diversity as soon as possible to minimize fossil energy dependency. Therefore, renewable energy penetration is needed considering tremendous renewable energy potential in Indonesia (DEN, 2019). The detail of renewable energy potential is presented in Table 3.

Table 3. Renewable Energy Potential

Renewable Energy Type	Potential (GW)
Hydro	94.3
Geothermal	28.5
Bioenergy	32.6
Solar	207.8
Wind	60.6

2.1.3 Indonesia Electricity Sector

Power plant capacity of Indonesia's electricity sector in 2020 (Figure 6) reaches 71 GW. Coal shares 60% of the capacity while gas and oil are less than quarter (23%). In term of renewable energy, it is recorded that bio and renewable energy contributes to 17% of the shares. This capacity is mostly contributed by Java-Bali-Nusa Tenggara power plant (44.8 GW) following by Sumatra as the second biggest installed capacity of this country (14.7 GW) while the rest of it comes from Kalimantan, Sulawesi and Maluku-Papua.



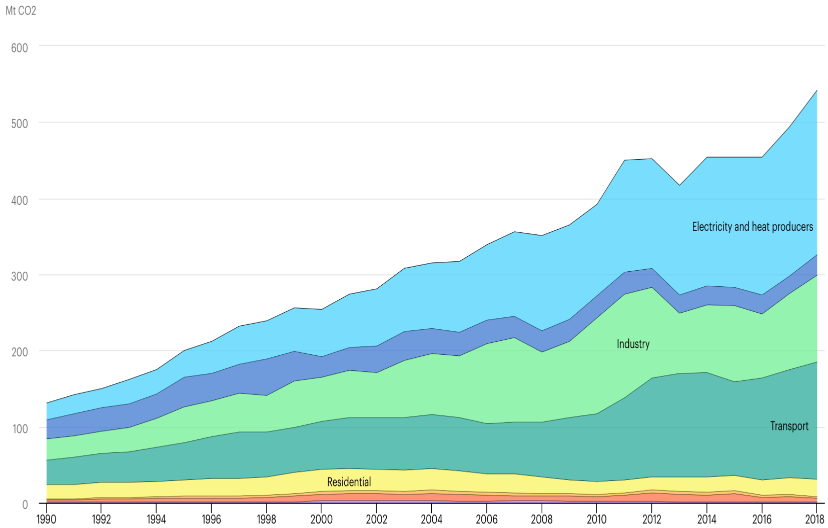
Source: Ministry of Energy and Mineral Resource (2020)
Figure 6. Power Plant Capacity in Indonesia in 2020

In term of electricity consumption, the electricity consumption in 2020 is lower than 2019, except in the residential sector (Table 4). Total electricity consumption in 2019 is 262,026 GW and goes down to 264,536 GW in 2020 due to Covid-19. The biggest electricity consumption in Indonesia usually comes from residential. In 2020, total electricity consumption in this sector is 117,695 GW. Industry is recorded as the second highest (88,390 GWh) following by commercial and transportation with 58,159 GWh and 292 GWh, respectively.

Table 4. Indonesia's Electricity Consumption in 2019 and 2020

Sector	Electricity Consumption (GWh)	
	2019	2020
Industry	94,281	88,390
Residential	103,833	117,695
Commercial	63,611	58,159
Transportation	301	292
Total	**262,026**	**264,536**

In term of Indonesia's emission in energy sector, electricity and heat sector is contributed as the highest CO_2 emitters in Ind onesia in 2018 with total emission 216.0 Mt CO_2 (Figure 2). This number keep increasing since 1990. Even, in 2018, the total emission from this sector raised rapidly from 2017. This indicates the emission in electricity sector gives significant impact to the total emission in this country.



Source: IEA (2020)
Figure 7. Total Emission per sector

Based on the Indonesia's current energy status, in term of primary energy supply mix, coal still dominates the supply mix. Besides that, in power generation capacity, coal is still accounted as the biggest capacity. The emissions from electricity sector also shows how important shifting energy to the renewable. Therefore, analyzing electricity sector's long-term plan and CO_2 mitigation is important.

2.1.4 Electricity Sector Related Policy

In order to reach NDCs target, Indonesia has several related policies in term of energy planning as well as electricity. Most of the policies explains about the renewable energy target and planning for long-term electricity plan which mostly should be reached in 2025 and 2050. These following sections are the electricity sector related policy and plan:

a) National Energy Policy (KEN)

KEN is the policy in which explains energy related policy in Indonesia. This policy is based on Indonesia's President Regulation No. 5/2006 regarding renewable energy development. In this policy there are several targets for optimization of energy mix in 2025 such as: the use of oil should be less than 20%; the usage of gas can be more than 30%; the usage of coal can be more than 33%; biofuel percentage more than 5%; geothermal percentage more than 5%; while more than 5% of energy mix should come from other renewable sources such as biomass, nuclear, micro hydro, solar PV and wind; lastly, liquefied coal accounts for more than 2%.

In the KEN, the target of renewable energy target is at least 23% by 2025. This target can be achieved by cutting the oil usage by quarter of the mix. Besides, this policy also aims energy efficiency target by decreasing 1% of energy consumption (DEN,2020).

b) Electricity Supply Business Plan (RUPTL 2019-2028)

The National Electricity Supply Business Plan (RUPTL) is policy that is based on Ministry of Energy and Mineral Resources (ESDM)

Decision No. 39 K/20/MEM/2019) sets out a business plan of the state-owned National Electricity Company (Perusahaan Listrik Negara) (PLN). The RUPTL provides data for energy sector such as energy mix, renewable energy sources.

This plan maps out the proportion of renewable energy target in 2028 such as the proportion of hydro/mini-hydro power plants (9.7GW), followed by geothermal power plants (4.6 GW) Also, it is predicted that 3.2 GW rooftop solar photovoltaic will be used.

Based on this plan state-owned electricity corporation will deliver 16,243 MW electricity. Other powerplant will be managed by IPPs and will be distributed 33,666 MW. In regard to the energy mix, by 2028, coal is projected to account for half of the percentage (54%) of Indonesia's electricity production, renewables 23%, gas 22% and fuel the balance. In summary, the RUPTL provides forecast relating to the growth of electricity demand, energy mix, infrastructure and the number of electricity that will be distributed by Independent Power Producers (IPPs).

c) National Energy General Plan (RUEN)

RUEN is the plan which is built upon the Law No. 30 Year 2007 on Energy and Presidential Regulation No.22/2017. In the RUEN, it is written that renewable energy mix shares on the total primary energy will be at least 23% in 2025 and 31% in 2050. This target is applied for all energy sector.

d) The National Electricity Master Plan (RUKN)

The RUKN states that the renewable energy targets that is written in KEN (23% renewable energy target) can be fulfilled by 2025.

This plan explains about roadmap and determination of energy supply and demand projection. In this plan, two economic growth assumptions are used to calculated the supply-demand projection which are 6.7% and 5.2%. Therefore, there are two scenarios of the supply-demand projections based on this economic growth. The numbers of economic growths are referred to the Ministry of National Development Planning data.

2.2. Literature Review

2.2.1 Energy Model

Energy model is not a new thing in the energy policy analysis. It has been existed since 1960 and started to develop more before the oil crisis in 1973 (Rath-Nagel & VOSS, 1981). Energy model is important in analyzing system and structure of the energy. Inappropriacy in building energy model can create inaccuracy in making policy and decision. Chang, et al., 2021 explained that the role of energy system model in understanding the energy transition is crucial and every tool has their own function in modeling the energy.

In structuring energy model, there are several categories and approaches and each of category has different purpose and outcome. Neshat , Amin-Naseri, & Danesh (2014) research about energy model method and characteristic and explained van Beek (1999) approach regarding the energy model group based on the purposes. The research stated that van Beeck (1999) grouping the energy model into three categories that is explained as follows:

1. Prediction/forecasting

   This model method using historical data to predict the trend. This method is suitable for analyzing the long term impact of actions.

2. Exploring

   This method is contructed for exploring the future by comparing certain scenarios with current government policy as a reference. The assumption in this method could not refer to the past behavior.

3. Back-casting

   This approach consider the uncertainty and what happens in current condition to predict the future. This approach can be used to design step to achieve the desired goals.

Meanwhile other researchers make different approaches in energy model which is called modeling paradigm. There is two distinction of the energy modeling approaches which are top-down and bottom-up (van Beek, 1999; Jacobsen, 1998). Top-down modelling is an approach that refers to macroecomics principle and general equilibrium effects. Meanwhile bottom up is based on technical approaches and more focus on technological development. Unlike van Beek (1999), Jacobsen (1998) added one more approaches which is integration between top-down and bottom-up approach.

Most of the cases, planner and policy makers refer to two differences approach in making the modeling. Governments, academicians, and researchers mosly apply top-down and bottom-up energy modeling than the three group of energy modeling. For top-down approach, it is mostly used to see the worst case scenario while bottom-up approach is more optimistic scenario since technology development and possibility of technology development are taken into account. However, whatever the approach, it can be used with many tools and softwares. This study will use LEAP software for the analysis since it can depict the future energy outlook based on several assumptions and scenario which will create the optimum option with the least cost.

2.2.2 Previous Studies

With regards to long-term electricity plan, there are several research already by using LEAP. However, there is lack of research regarding the role of technology capacity in the electricity plan as well as research which solely focus on CO_2 mitigation. LEAP software works based on the assumptions and scenarios that are built in the study. Due to this reason, every study can be different depends on the research scenarios. In addition, there is a new software which is NEMO that can integrate together with LEAP that can focus more on CO_2 mitigation. Since this software was launched in 2020, not many research using this new feature. For this reason, this research will fill the gaps the previous studies.

The electricity sector is the most important sector in the energy since it is closely related to society's welfare. This sector also have potential to reduce energy sector's GHG emissions since it contributes as the biggest emitters in this sector. Based on these basis, provision of electricity is important to be analyzed. Since this study plan to use LEAP model, this section explains the previous studies related to the application of LEAP model in energy and electricity sector.

Kumar (2016) assesses the renewable energy security and carbon mitigation in Southeast Asia by using LEAP model. This research focuses on Indonesia and Thailand by using the maximum potential of renewable energy. This study uses 2010 data as baseline year and include the nuclear energy even though it is not presence in both countries. The study concludes that the electricity in 2050 should be based on renewable energy by considering the full exploitation of renewable energy potential. Besides, CO_2 emission in Indonesia and Thailand can be cut around 81% and 88% respectively.

Since this study was conducted in 2016, this study only considers several technologies in the energy mix without considering new technology. Besides, this study only focuses on the supply side without considering different demand sides. CO_2 emissions in this study can only decrease around 81% for Indonesia case. Based on these results, research regarding zero emissions target is still needed.

Another research in Indonesia was done by Handayani, Krozera, & Filatova (2017). This study analyzes the barriers between electrification and climate change mitigation in Java-Bali power plant. This research uses four scenario which is business as usual, increase in natural gas usage to reduce the coal, renewable energy expansion, and least-cost energy. In the year 2019, Handayani, Krozera, & Filatova publishes another paper related to analysis of long term scenario of Java and Bali power plant. In here, the research stress on different technological learning which is low, medium, and high. The study finds that with the increase of the technological learning phase, the cost to achieve renewable energy target will be lower. Another finding is the renewable energy enhancement in Java-Bali power plant can reduce CO_2 emissions by 38.9 million ton and concludes that emission reduction target can be achieved.

Both of these studies only focus on Java-Bali transmission and not for the whole Indonesia's power sector. Besides, these two studies focus on how to reduce emissions and reach NDCs targets in electricity sector through the electricity mix only. In addition to that, most of these studies only based on the optimalization of energy plan by focusing on technology development to reduce the emissions. Therefore, these two studies still lack of analysis in term on different new additional technology such as carbon capture storage and capacity technology in the electricity mix as well as net zero emissions analysis.

However, there are several research regarding renewable energy transition to achieve zero emissions target. For example, Hong., et al. (2019) analysed the long-term energy scenario for South Korea. This study uses top-down approach with LEAP model which focus on supply and demand side. The study analysed BaU and three alternatives' scenarios which concludes that the alternative scenarios show a more successful transition for South Korea than the BaU scenario. Furthermore, the Visionary Transition Scenario (VTS) which aims 100% of renewable energy target is able to cut 90.9% of emission compare to the baseline. Same goes as other studies, this study lack of analysis in term on different new additional technology such as carbon capture storage and capacity technology in the electricity mix to achieve net zero emissions.

The most recent studies by Handayani et al., (2022) regarding ASEAN electricity plan to reach net zero emissions is able to fill the gap of all the research mentioned above. Firstly, this study includes the role of several technologies such as energy storage and carbon capture storage to reach more than the NDCs target in ASEAN. Secondly, this research uses NEMO and also LEAP to analyze the study. Even though this study also analyzes Indonesia, it is focus more on ASEAN and not analyze Indonesia deeper. Also, this study only focuses on supply side without considering the demand side.

Based on all the studies, this study will try to fill the gap that all the research that are mentioned lack of. This study will focus on whole Indonesia power plant system. In term of methodology, this study will focus more on the pathway of net zero emissions in supply and demand side. Besides, several technologies such as carbon capture storage and energy storage will be added to the study for maximizing future possibilities technology in Indonesia electricity sector. Lastly, in term of software, NEMO and LEAP will be used together to depict more accurate way to analyze net zero pathway.

Chapter 3. Methodology and Data

3.1 Modeling Analysis

This research uses Long-range Energy Alternatives Planning system (LEAP) which is a software for energy policy analysis. LEAP is widely used for energy policy and climate change mitigation assessment. This software is developed by Stockholm Environment Institute. LEAP model is chosen in this study since it can be used as a simulation tool to investigate future long term electricity plan. Due to this research purpose that focus more on the electricity sector, specifically electricity outlook, LEAP is selected because of its ability to work as scenario-based modeling tool that can be used to track electricity production in all sectors. Therefore, LEAP software is suitable to analyze Indonesia's power sector and renewables energy integration in the electricity sector.

In general, LEAP suggest the energy alternatives by considering both accounting and the least cost option. For this reason, LEAP can provide different possibilities based on the scenarios. Based on Heaps (2002), the objective formula for least-cost energy alternative is written as follows:

$$\min,\ v_{obj} = \sum_{c,a,g,t} \left(C_{a,g,t}^{fuel} + C_{a,g,t}^{fixed O\&M} + C_{a,g,t}^{var\ O\&M} + C_{a,g,t}^{inv}\right) \quad (1)$$

Whereas $C_{a,g,t}^{fuel}$ is feedstock fuel costs for generation technology (g) in area (a) at time (t); $C_{a,g,t}^{fixed\ O\&M}$ is fixed operation and management cost for generation technology (g) in area (a) at time (t); $C_{a,g,t}^{var\ O\&M}$ is variable operation and management cost for generation technology (g) in area (a) at time (t); and $\mathbf{C^{inv}_{a,g,t}}$ is investment cost in the new generation technology (g) in area (a) at time (t);

This program divides the modeling analysis into three sections: electricity demand, transformation, and electricity supply analysis. The calculation of each analysis is based on the general LEAP formula which is written in Wijaya & Limmeechokchai (2009). Electricity demand is obtained from the total activity level and energy intensity at each given technology branch and calculated for the current year or the baseline year that will be used in the analysis and for each future year. Energy demand equation is explained in the Equation 2.

$$D_{b,s,t} = TA_{b,s,t} \times EI_{b,s,t} \qquad (2)$$

According to the formula above, D is electricity demand, TA is total activity, EI is energy intensity, b is the branch, s is scenario and t is year (from the baseline year to the end year of simulation). The yearly average of final electricity consumption (EC) per unit activity is defined as energy intensity (Equation 3)

$$EI = \frac{\text{EC}}{\text{Activity level}} \qquad (3)$$

The total activity level that is used in the LEAP model is the product of the activity levels in all hierarchy of the branches (Equation 4):

$$TA_{b,s,t} = A_{b',s,t} \times A_{b'',s,t} \times A_{b''',s,t} \cdots \qquad (4)$$

Where, A_b is the activity level in a particular branch b, b' is the parent of branch b, b'' is the grandparent, etc.

Secondly, in the transformation analysis, there are two important aspects which are the planning reserve margin and the plan of renewable energy shares. The planning reserve margin is used to give supplementary endogenous capacity. Based on the LEAP model, the supplementary capacity will be used to adjust the planning reserve margin. In this case, reserve margin is calculated based on formula as follows:

$$PRM = 100(MC - PL)/\,PL \qquad (5)$$

Where, PRM represents the planning reserve margin (%), MC represents the module capacity in MW and PL is the peakload in MW. Module capacity is defined as the sum of all processes in the module:

$$MC = \text{Sum}\,(\text{Capacity} \times \text{Capacity Value}) \qquad (6)$$

Peak system power is computed by functioning the overall energy requirements and the system load factor.

$$PR = \frac{ER}{LF \times 8760} \qquad (7)$$

Whereas, PR is peak requirement in MW, ER is energy requirement in MWh, and LF is the load factor.

The LEAP is developed using the most up-to-date global warming potential (GWP) variables proposed by the IPCC (Intergovernmental Panel on Climate Change) Tier-1 in terms of emissions. This formula is used to calculate the emission:

$$\text{Emissions}_{t,y,p} = EC_{t,y} \times EF_{t,y,p} \qquad (8)$$

Based on Formula 8, t means type of technology (fuel), y is year, and p is pollutant. The LEAP contains data on the GWPs as well as the most common gases in non-energy sector

3.2 Scenario Formulation

The major goal of this research is to determine the optimum pathway for the electricity power to minimize emissions. The simulated scenarios in these studies are based on the country's technological capabilities, as well as the government's plans and strategies for achieving the NDCs target in the electrical sector. The data for this research ranges from 2020 to 2050. In this study, four scenarios are developed: a reference scenario (REF) which is a reference scenario in this study and three alternative scenarios which consist of Government's Pathway Scenario (GPS), Accelerated Pathway Scenario (APS), and Zero Emissions Pathway Scenario (ZEPS).

Reference Scenario (REF) is the scenario which is based on the current condition of Indonesia's power sector. This scenario is added into the study as a comparison for others alternative scenarios which consider the technology aspects, costs, and emissions. Therefore, this scenario is named as a Reference Scenario (REF). There are several assumptions for this scenario such as:

- The technology is confined to traditional sources that were already employed before the base year, primarily coal-fired power plants and natural gas power plant.
- Increased renewable capacity in Indonesia is limited to the technologies already in use.
- No limits apply to the use of domestic fossil fuels.
- There is no defined objective for renewable energy expansion.

The demand side of this study using 7% of electricity demand growth that is stated by Ministry of Energy and Mineral Resources (2020). In the supply side, this scenario represents current condition of Indonesia’s power sector without taking into consideration future renewable energy targets. As a consequence, this scenario depicts the continuity of Indonesia's present power technology without any newer technology introduced for energy transitional purposes. This scenario can be used as a starting point for developing new policies and plans.

Government Pathway Scenario (GPS) is a scenario which refers to Indonesia renewable energy target that is written in several policies and target such as KEN, RUPTL, and RUEN. This scenario is named as a stated pathway since it has specific target for renewable energy compare to the reference scenario. Characteristics of this scenario includes:

- This scenario has renewable energy target as much as 23% by 2025 and 31% by 2050. In the electricity sector, there is no exact target of renewable energy mix. For that reason, the percentage of renewable energy in this scenario is based on overall energy target and assumes to be the same for the electricity sector. The renewable energy target acts as a constraint in this scenario. In other words, capacity expansion is planned to meet the renewable energy objective.

- Prospective capacity expansion technologies comprise fossil-based energy such as: natural gas combined cycle (NGCC), ultra-supercritical coal (USC coal) natural gas open cycle (NGOC); and renewable energy that comprises of hydropower and mini hydro, wind, geothermal, biomass, nuclear, and solar PV.
- LEAP is computed by least-cost optimization.

The proportion of renewable energy objective in this scenario represents Indonesia's attempt to fulfill the NDCs target and electricity plan. The technologies included in this scenario are built based on Indonesia's power plan technologies stated in RUPTL. The demand projection in this scenario is similar with REF.

Accelerated pathway scenario (APS) is the scenario which has higher renewable energy target compare to the GPS. This scenario is named as accelerated pathway since another source of energy will be use to accelerate the low emission target. This simulation refers to Indonesia's government plan to reduce the emission by maximum 2060. However, same as other scenarios, this study will set the year 2050 instead of 2060 as the target year to achieve the goal. The demand growth rate in this study is based on efficiency effort from Indonesia's government (6.5%). APS includes several characteristics such as:

- Same goes as GPS, renewable energy works as a constraint in this scenario and the renewable energy target by 2025 is 23%.

- However, the target of capacity expansion in this scenario in 2050 is higher than GPS which is 85% of renewable energy. The proportion of renewable energy target in this scenario is based on deep carbonization based on IRENA (2018) which stated that 85% renewable energy target is needed to achieve deep carbonization. Besides, this number is also based on government plan to reach net zero emissions.
- Several technologies are added for future capacity additions, including fossil-based source such as natural gas combined cycle (NGCC), natural gas open cycle (NGOC), ultra-supercritical coal (USC coal), diesel; renewable based energy such as hydro and mini hydro, wind, geothermal, biomass, solar PV, nuclear; and capacity storage such as battery and hydro pumped storage (HPS).
- LEAP works by choosing the technology based on least-cost optimization.

Zero Emissions Pathway Scenario (ZEPS) is the scenario which consider more than renewable energy target usage to reach the zero emission in electricity sector. This scenario is only a pathway to reach zero emissions target, but different with net zero emissions which require more strict effort. For this reason, this scenario is named as zero emissions pathway scenario

In this scenario the demand side growth rate is based on more ambitious target from Indonesia's government which is 6%. Meaning there is 1% demand growth reduction as efficiency effort. In supply side, several technologies such as carbon capture storage and battery will be inputted as possible future capacity expansion. In this simulation, the power sector targeting the zero emission by 2050.

Several characteristics are set as follows:

- Renewable energy target as much as 23% by 2030
- Emission should reach zero by 2050
- Renewable energy is set based on each technical potential
- Future capacity technology consists of ultra-supercritical coal (USC coal), natural gas combined cycle (NGCC), natural gas open cycle (NGOC), diesel, hydro and mini hydro, geothermal, wind, biomass, solar PV, and nuclear. Besides, CCS technology in coal (CCS), natural gas (NGCCS) and bio-energy (NGCCS) are employed to see the possibilities of these technology to help to reduce the emissions. In addition, capacity storage such as hydro pumped storage (HPS), and Li-ion battery are also added.

3.3 Indonesia's LEAP model framework and Data Input

To use the LEAP model, the current account or current condition should be set first before adding the scenario on the software. The current condition will be the parameters in this study. The parameters consist of electricity demand, technical aspect, economic aspect, and several constraints (Figure 8).

The electricity demand comprises of projected demand from the previous studies and demand load curve. Technical aspect parameters are consisting of the aspects that are related with transformation of the electricity in the LEAP model. Other parameter is economic parameter that is related to the cost starting from the initial of the powerplant planning until its management and operational.

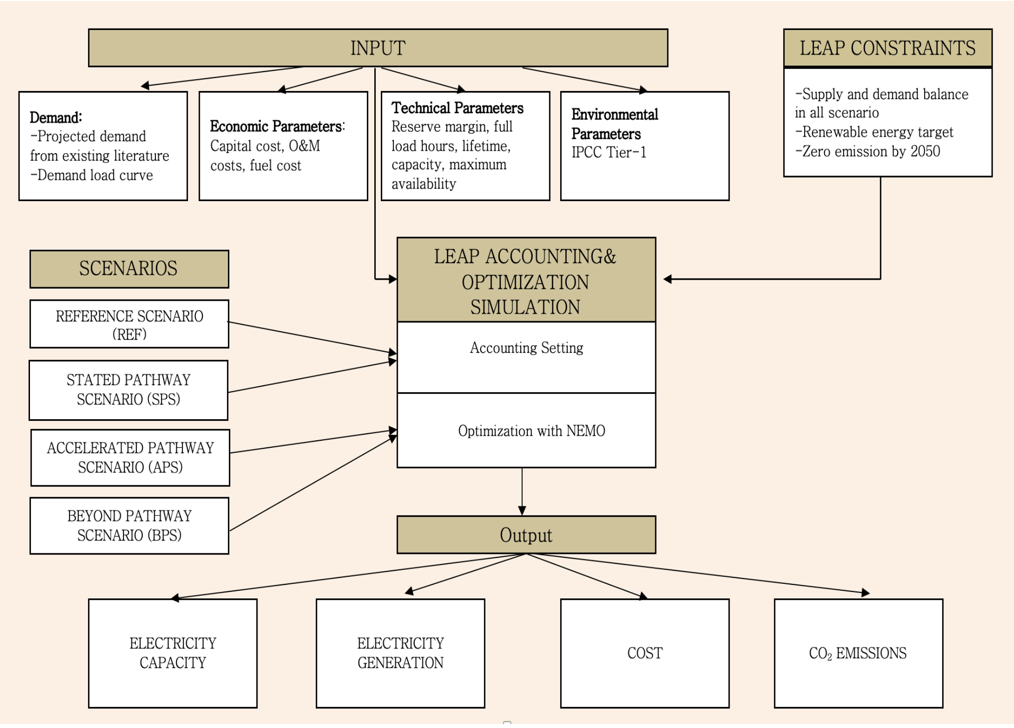


Figure 8. LEAP Model Framework for the Analysis

In this study, the powerplant is analyzed for every transmission and treating the country as whole electricity system. The data is collected from various sources such as Indonesia's electricity outlook, Indonesia's statistic handbook, and other studies. Since this study hope to depict the real condition of Indonesia, the research relies more on the actual data rather than LEAP default data. The Table 4. Contains the input data for this research.

Table 5. Basic Data for LEAP model Current Account

Current Account Data	Value	Source
Annual Demand Growth	4.9%	PLN (2020)
Load Curve		PLN (2020)
Existing Capacity and Retirement	Varies based on technology	ASEAN Country Statistic, and ASEAN Energy Outlook
Environmental Parameter[1]	Varies based on technology	IPCC tier-1 emission factor
Losses in Transmission and Distribution	9.15%	PLN (2020)
Planning Reserve Margin[2]	35%	National Electricity Plan 2019-2038
Discount Rate	12%	National Electricity Plan 2019-2038

1. Refer to Table 6
2. For the whole study period, the load shape (load curve) of Indonesia's power demand is anticipated to be identical each year.

In term of electricity demand, the data was obtained from demand growth projection from the existing studies. Demand for the future electricity is obtained by considering the anticipated growth. Meanwhile, total electricity demand is calculated by summing the electricity demand with the electricity loses during transformation and distribution.

Population growth is added into assumption since it can influence the energy demand. Besides, it is also related to the economic growth and closely affecting the energy demand volume and composition. In this modeling, population growth that is used in this study is 0.8% per year which refers to recent data that have been updated by the Central Bureau of Statistics (Appendix 1)

Besides population growth, GDP is also added into LEAP model assumption. Based on previous study, the real GDP growth in 2018 was 5.17%. It slightly decreased to 5.02% in 2019 (Central Bank of Indonesia, 2019). “Due to the COVID-19 pandemic, the growth was dropped to 2.1% in 2020 and in the year of 2021, the economy is expected to rise back to 4.3%” (Economic Research Institute for ASEAN and East Asia (ERIA), 2021). Indonesia's National Development Agency (BAPPENAS) publication data predict that Indonesia GDP will be around 5.6% until the year 2045. However, this study research will not refer to BAPPENAS data since the GDP growth based on BAPPENAS is not include the recent economic recession due to COVID-19. Therefore, the study assume that the GDP will grow by an average 4.8% per year from 2017 to 2050 due to COVID 19 effect (Table 12 and Table 13).

For the electricity supply simulation, four scenarios are added based on several assumptions and parameters. In term of base scenario, the research is set without considering the least-cost optimization so that it can fulfill the need of the future electricity demand. In contrast, the least-cost capacity expansion setting is used for alternatives scenarios to provide the best energy sources option for future electricity plan.

Emission factor of CO_2 in this research refers to IPCC tier-1 (Directorate General of Electricity, 2018). Based on IPCC (2006) there are three tiers that are provided regarding the emission factor. Tier 1 is the basic one and does not require complex data. Besides Tier-1 is the method for carbon dioxide emission. Therefore, tier-1 is used in this study. Emission factor of CO_2 is presented in the Table 6.

Table 6. Emission Factor of CO_2 based on Fuel's Type (Directorate General of Electricity, 2018)

No	Type of Fuels	Kg GHG/TJ CO_2
1	Gas Oil (HSD/ADO)	74,100
2	Natural Gas	56,100
3	Coal (lignite)	101,000

In term of technology, this study consider several technology that can be potential source for electricity expansion in Indonesia. The technology consist of Ultra Super Critical Coal (USC Coal), Natural Gas Combined Cycle (NGCC), Natural Gas Open Cycle (NGOC), diesel, geothermal, hydro, mini-hydro, biomass, wind, solar photovoltaic (Solar PV), nuclear, coal with CCS, natural gas combined cycle with CCS (NGCCS), bioenergy with CCS (BECCS), Li-ion battey, and hydro pumped storage (HPS) the details of the technology is presented in the Table 7.

Table 7. Indonesia's Power Sector Energy Sources List

Technology	Lifetime (years)	Efficiency (%)	Capacity Credit (%)*	Max Availability (%)
Ultra-supercritical Coal	30	42	100	80
Natural Gas Combined Cycle	30	56	100	85
Natural Gas Open Cycle	30	33	100	92
Diesel	30	45	100	95
Hydro	80	100	51	41
Mini Hydro	50	100	58	76
Hydro Pump Storage	50	80	25	90
Geothermal	40	15	100	80
Solar PV	25	100	27	22
Wind	27	100	35	28
Biomass	20	31	100	80
Nuclear	40	33	100	85
Coal CCS	30	34	100	80
Natural Gas CCS	30	48	100	80
Bio-energy CCS	20	30	100	90
Li-ion Battery	20	94	22	17

Based on Table 7, the efficiency of power plant means the percentage of a power plant's total energy content that is transformed into electricity. Capacity credit in the LEAP model means the percentage of a power plant's installed capacity that can be relied on at any particular time.

Table 8. Cost of Each Technology

Technology	Capital Cost (USD/MW)	Fixed O/M Cost (USD/MW)	Variable O/M Cost (USD/MW)	Fuel Cost (USD)
Ultra-supercritical Coal	1,520-1,900	56.6	0.11	2-4 per MMBTU
Natural Gas Combined Cycle	690-1200	23.5	2.3	7-11.7 per MMBTU
Natural Gas Open Cycle	770-1,100	23.2	1	7-11.7 per MMBTU
Diesel	800	8	6.4	0.6 per Liter
Hydro	1,450-2,080	37.7	0.65	-
Mini Hydro	2,400-2,700	53	0.5	-
Hydro Pump Storage	860	8	1.3	-
Geothermal	2,497-4,000	50	0.25	-
Solar PV	1,190-2,000	14.4	0	-
Wind	1,500-2,550	60	0	-
Biomass	2,000-2,300	47.6	3	1.3-3.5 per MMBTU
Nuclear	6,000	164	8.6	9.3 per MWh
Coal CCS	3,470	98.4	3.21	2-4 per MMBTU
Natural Gas CCS	1,840	32.5	3.5	7-11.7 per MMBTU
Bio-energy CCS	5,453	64	8	1.3-3.5 per MMBTU
Li-ion Battery	2,002	7.6	2.3	-

This study wishes to analyze the low emission possible for the electricity sector. For that reason, NEMO is used to analyze the low cost and low emission scenarios for Indonesia's electricity sector. NEMO is the extension of the LEAP model that is made in 2019 by Stockholm Environment Institute. Integrating NEMO with LEAP model can give more accurate results in depicting electricity outlook. Besides, NEMO gives feature to select several areas to the analysis which is suitable for a country that is consist of several islands and fragmented power-plant like in Indonesia.

Furthermore, NEMO is designed considering more robust planning to the climate change for energy modeling. Nemo can be used together with multiple solvers such as GLPK, Cbc, Cplex. In this study, Cplex optimizer is used to work with NEMO.

Chapter 4. Results and Discussions

4.1 Results

This section provided LEAP simulation's results per scenario in the following orders: power plant's capacity expansion, total electricity generation, cost, and CO_2 emissions.

4.1.1 Reference Scenario (REF)

In the REF, total power capacity in the base year is 71GW and increase to 258GW by the end of the simulation (2050). As depict in the Figure 10, based on the capacity, coal will expand and contribute as the biggest capacity. Meanwhile, hydropower would be contributed as the main source of renewable energy in this scenario starting from the year 2035 from 12.66GW to 24.51GW in 2050. Besides hydropower, other renewable energy sources such as geothermal also plays contribution in term of capacity in this scenario in the end of the plan with 9.80 GW.

The total electricity generation in the REF increases from 275.80TWh in the base year (2020) to 1,109.30TWh in 2050 as illustrated in Figure 11. This means the electricity generation in the end of the simulation is around 4 times higher than the base year. In term of the type, coal would be the main source to generate the electricity which supplies as much as 640.50TWh in 2050 and natural gas. In the year of the simulation geothermal, biomass, and hydropower contributes as the biggest sources of renewable energy.

In term of renewable energy to generate the electricity, in the end of the period, renewable energy proportion will reach 21.7%. This proportion mainly contributes by hydropower as much as 105.00 TWh and solar PV as much as 52.50 TWh.

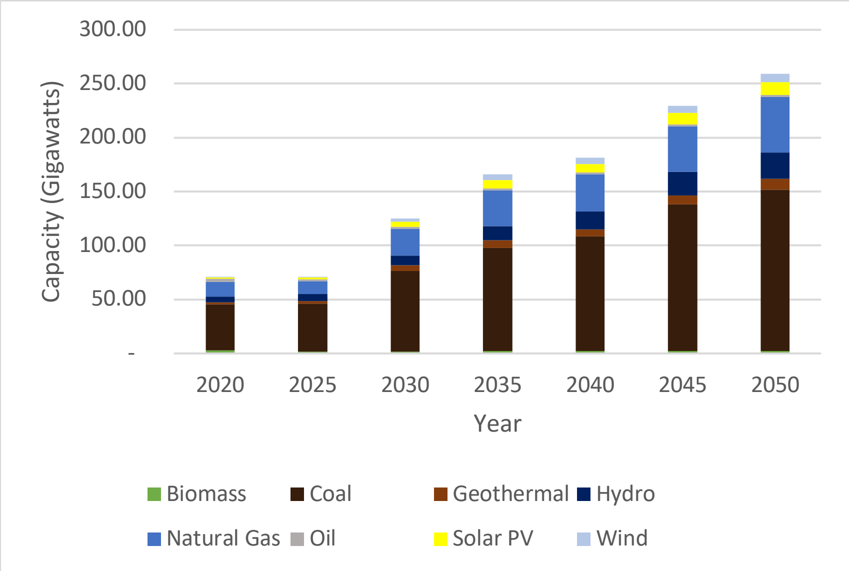


Figure 9. Capacity Results of REF

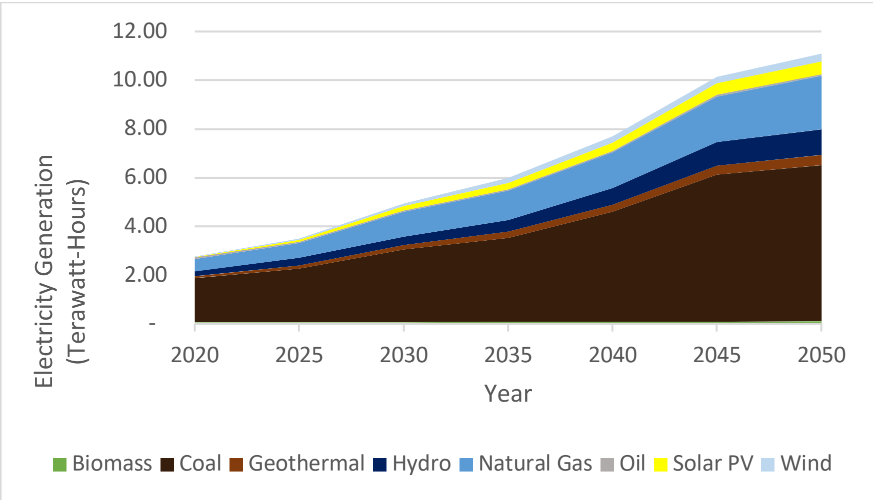


Figure 10. Electricity Generation Results of REF

In this scenario, the total cost of capacity expansion would increase gradually along the year of the simulation as shown in the Figure 12. In the end of the period, the production cost will reach 118 billion USD from 10 billion USD in the base year. The total of emission in this scenario would increase from the beginning of simulation scenario from 190.80 million metric tonnes CO2 to 571.50 million metric tonnes CO2 in 2050. The annual of emission is illustrated in the Figure 13.

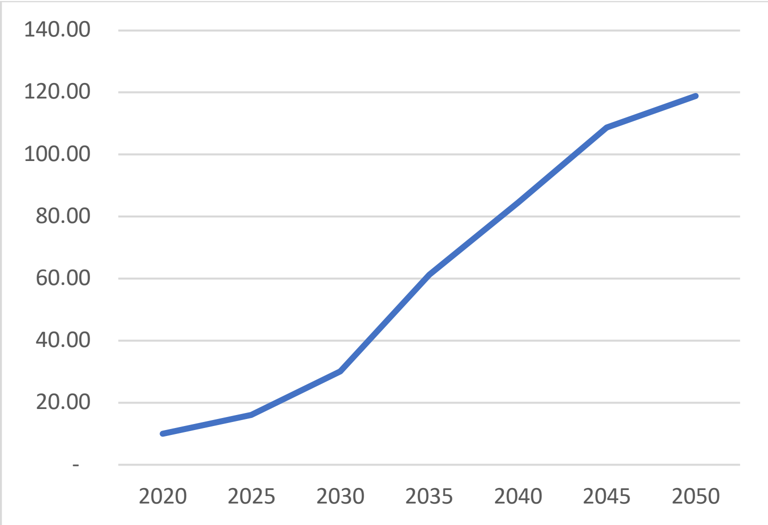


Figure 11. Cost of Production of REF

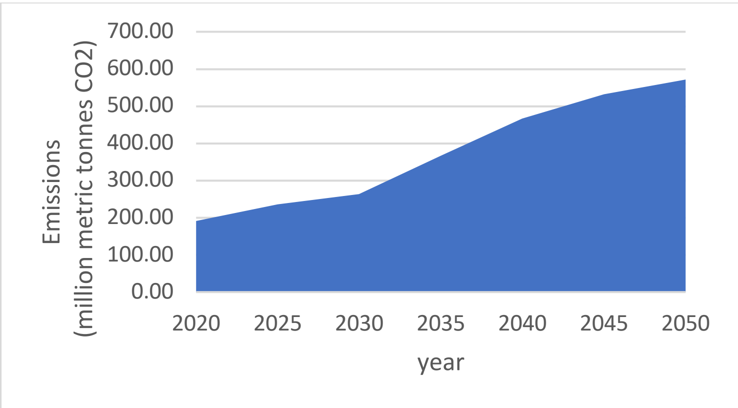


Figure 12. Emissions of REF

4.1.2 Government Pathway Scenario (GPS)

The overall capacity expansion of power generation in GPS reaches 289.89 GW, rising from 71 GW in 2020. According to Figure 14, coal remains the primary energy source for capacity expansion in this scenario. In comparison to the base year, the coal expands four times at the end of the simulation (168 GW). Hydropower is the most significant renewable energy source, contributing for 31.27 GW, slightly more than natural gas. Other renewable energy sources, such as solar PV, wind, biomass, and geothermal, will contribute to the expansion of power generation in 2050, despite the fact that each of these power plant's capacity are significantly below hydropower.

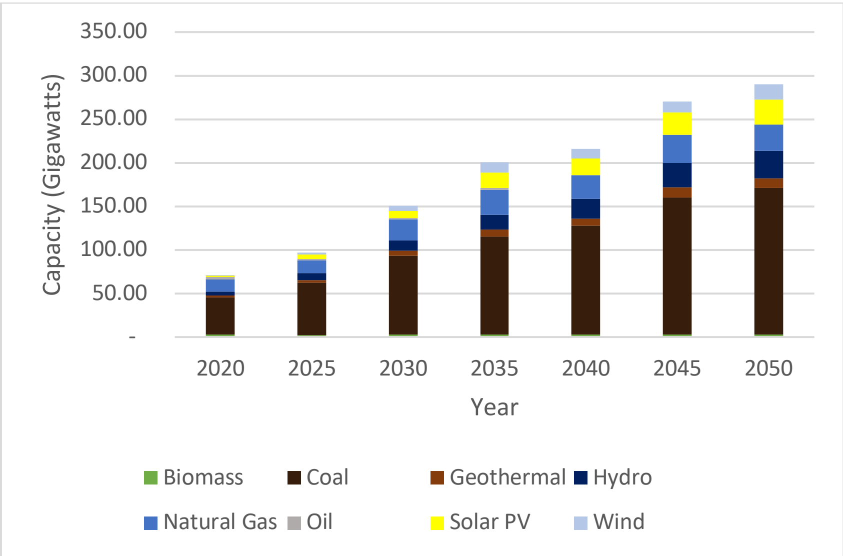


Figure 13. Capacity Results of GPS

In terms of energy generation (Figure 15), coal is still the major source. In the base year of the simulation, overall power generation is 275.80 TWh, with renewable energy accounting for 13% of that total.

The entire amount of electricity generated in 2050 will be 1,136.17 TWh. Coal generates 181 TWh at the start of the simulation and continues to increase to 1660.50 TWh at the end of the year simulation.

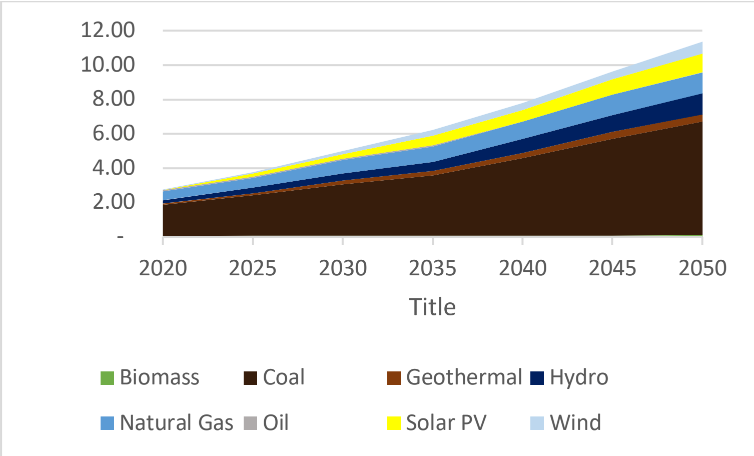


Figure 14. Electricity Generation of GPS

The initial cost for GPS scenario would increase along the year of the simulation. The initial cost for capacity expansion is 10 billion U.S. Dollars and reaches 102.42 billion U.S. Dollars in the end of the simulation (Figure 16). In term of emission, with 31% of renewable energy target in the end of the simulation, this scenario emission is 400.92 million Metric Tonnes CO_2 Equivalent.

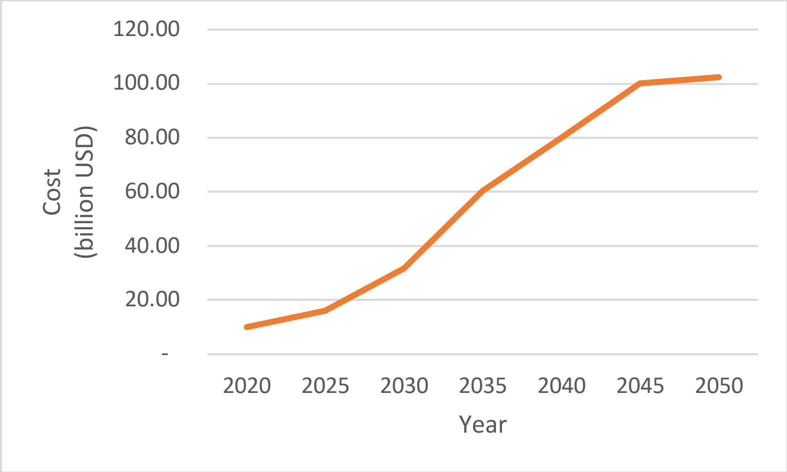


Figure 15. Cost of Production of GPS

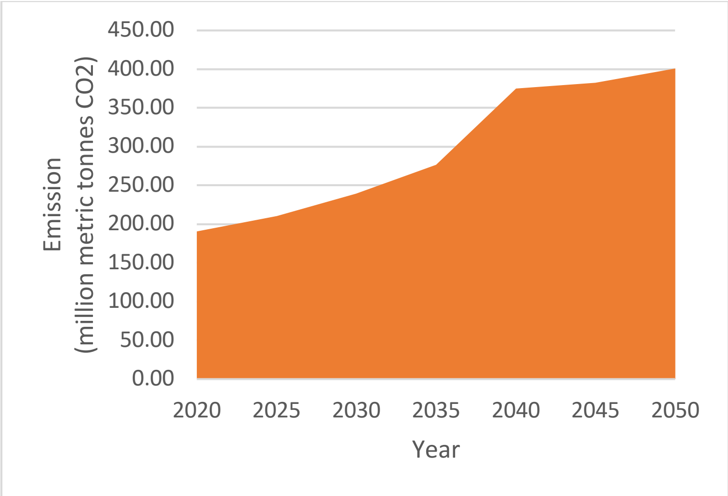


Figure 16. Emissions of GPS

4.1.3 Accelerated Pathway Scenario (APS)

Figure 18 depicts the APS capacity. In the base year, total power capacity is 71 GW. The largest capacity comes from coal, which accounts for 61 % capacity. Natural gas is the second largest source of capacity after coal (19.95 GW). Coal capacity continues to grow, reaching a peak of 113.14 GW in 2030. The simulation results in a coal capacity of 73.18 GW. Solar PV experiences the greatest growth in terms of renewable energy, reaching 229.62 GW and making up the biggest percentage of total capacity. Aside from solar PV, hydropower grows dramatically from the baseline year, reaching 73.28 GW in 2050. Battery and hydro PS technology also appear as capacity sources in this scenario, with 12.60 GW and 10.00 GW, respectively.

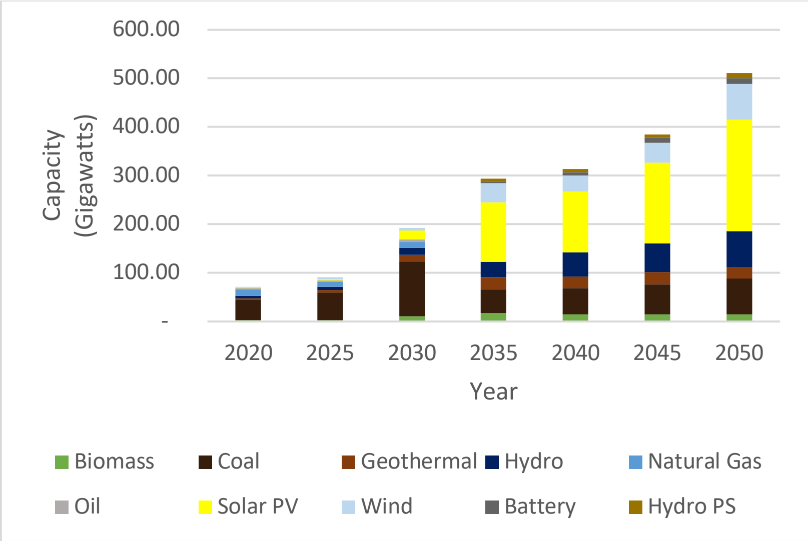


Figure 17. Capacity Results of APS

Figure 19 represents the overall electricity generation in the base year in this scenario. Because this scenario aims for 85% renewable energy by 2050, coal's contribution to power generation during this year will be 188.50 TWh, or 15% of total electricity generation. At the end of the plan, total electricity generation is 1,256.67 TWh, with solar PV accounting for nearly half of the total. To minimize reliance on coal, hydropower has expanded sharply compared to the baseline year, reaching 188.50 TWh. Furthermore, wind contributes 15% of the electricity generation in this scenario (188.50 TWh).

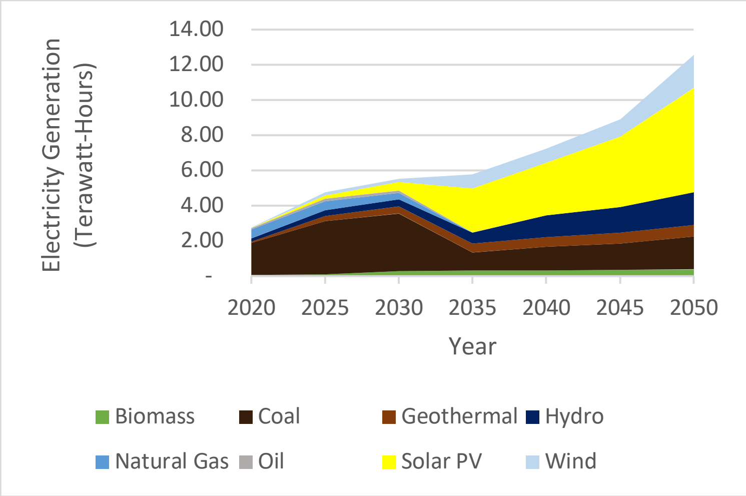


Figure 18. Electricity Generation Results of GPS

Figure 20 illustrates the cost of production of APS. The cost of capacity expansion in the simulation keep increasing along the year of simulation. Even though least-cost is set in the LEAP setting, it requires more investments to expand the capacity of renewable energy to reach the target. As a result, the cost in this scenario continues to rise from the first year until the end of the period. The total investment required to meet the 85 percent renewable energy target by 2050 is 121.50 billion USD.

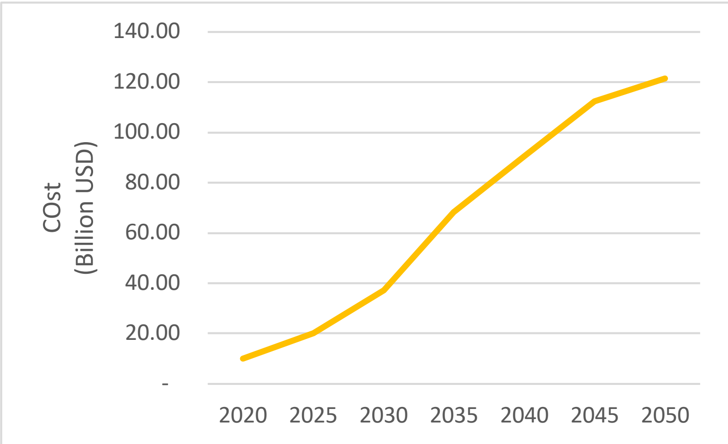


Figure 19. Cost of Production of APS

In regards to the emissions, figure 21 represents the emissions in APS. At the beginning of the planning period, the total CO_2 emissions is 190.80 mi llion Metric Tonnes CO_2 Equivalent. This number is keep increasing and reached the peak in 2030 (210.40 million metric tonnes CO_2 Equivalent). At the end of the period, with the expansion of 85% renewable energy, the total emissions reach 100.87 million Metric Tonnes CO_2 Equivalent.

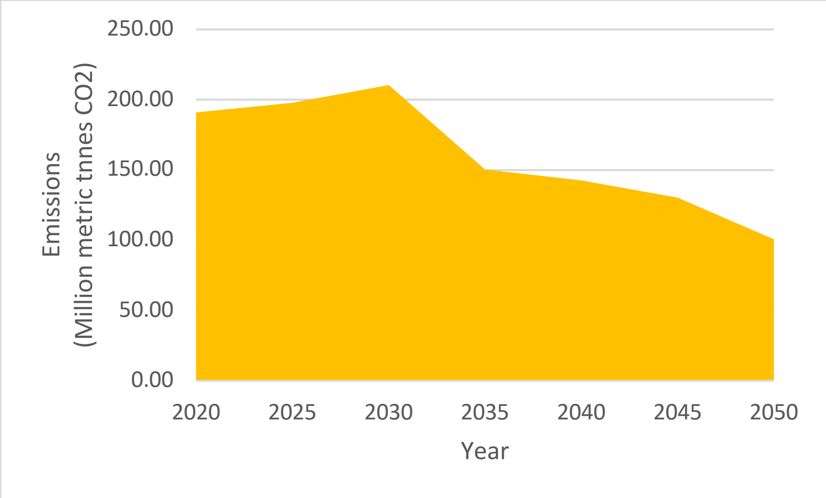


Figure 20. Emissions of APS

4.1.4 Zero Emission Pathway Scenario (ZEPS)

In the optimization plan, this scenario specified a target of zero emissions at the end of the simulation by increasing renewable energy penetration to 23% by 2025 and 100% by 2050. Figure 22 depicts the result of capacity expansion for ZEPS. In the end of the scenario, the result of total capacity expansion is 575.38 GW. There are 7 types of power plants in the end of the year target from 11 different types of power plants that are installed for the analysis. Solar PV has the most capacity during this time frame, accounting for half of total capacity (319.35 GW). Aside from solar PV, wind and hydropower have the second highest capacity, with potential expansion of up to 120.00 GW each. The presence of battery and hydro PS capacity, which contribute 13.50 GW and 11.28 GW, respectively, is an intriguing feature in this scenario.

In comparison to the baseline year, electricity capacity continues to grow in order to reach the target. Coal contributes the most capacity at the start of the plan and continues to increase until it reaches a peak in 2035 (162.47 GW). However, coal will plummet to 118.07.00 GW in 2040 and continue to fall until it hits zero in 2050. Aside from coal, natural gas is the second largest capacity at the start of the plan and will stay so until 2030. Natural gas capacity will have reached zero by 2035.

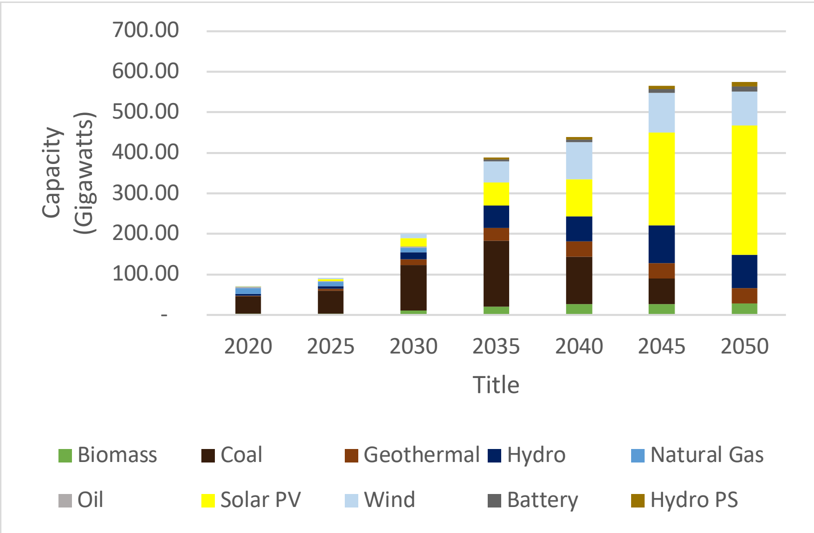


Figure 21. Capacity Results of ZEPS

Figure 23 displays the ZEPS electricity generating result. Total power generation in this scenario rises from 275.80 TWh in the base year to 1,143.56 TWh at the end of the simulation year. Solar PV will be the primary source of electricity generation, producing 686.14 TWh. Aside from solar PV, other renewable energy sources contribute to electricity generation, particularly wind and hydropower, which produce equal amounts of electricity.

The coal-based power plant generates electricity as much as 181.00 TWh in the beginning of the simulation. This number keep increase until 2030. In 2040, the coal generates 40% lower than 2035 and keeps declining until it reaches zero in 2050. In this scenario, the natural gas power plants generating the electricity only until 2030.

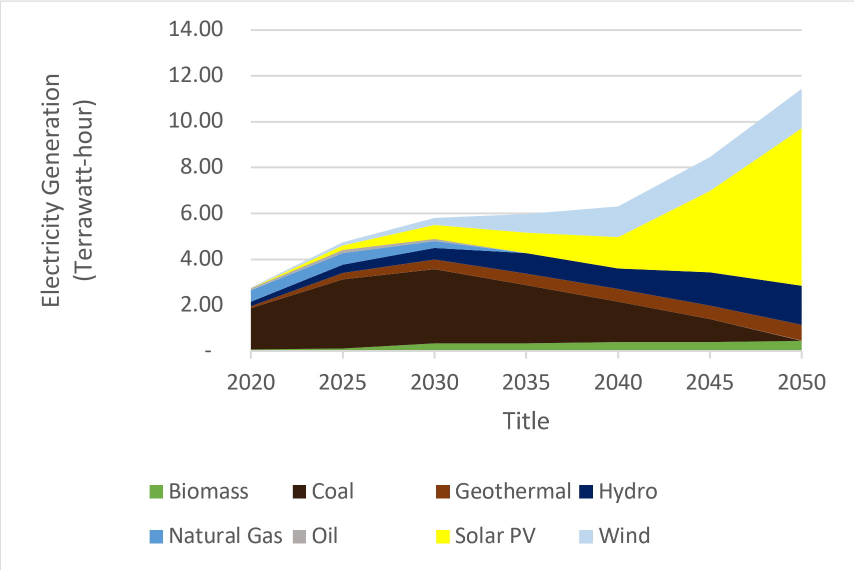


Figure 22. Electricity Generation of ZEPS

In the beginning of the plan, the cost is 10.00 billion USD. The total cost of capacity expansion increases following with the increase in the demand projection. The total cumulative of capacity expansion in this scenario is 130.40 billion USD in 2050. The cost keeps increasing since the installed renewable energy penetration is also expanding. Therefore, although the LEAP software has been set to least-cost feature, to meet the renewable energy target and electricity demand, the investment cost is more costly. The detail of the cost for this scenario is presented in Figure 24.

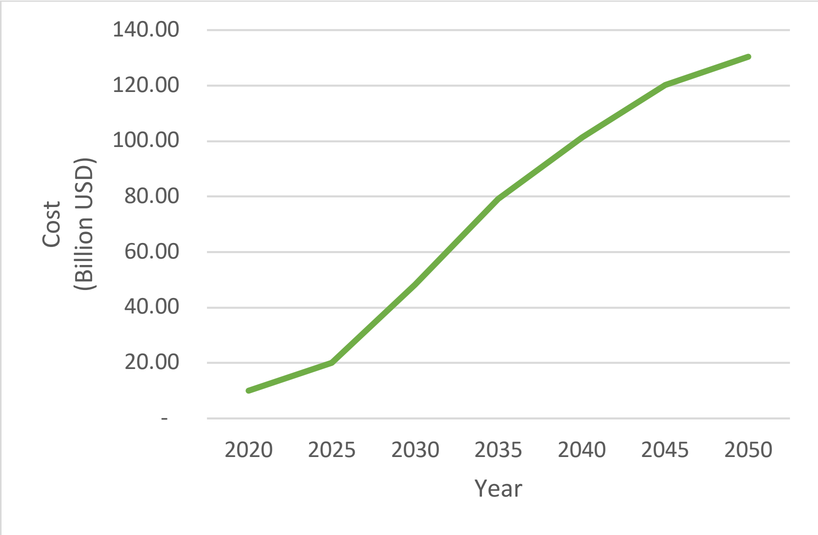


Figure 23. Cost of Production of ZEPS

By the end of the planning period of this scenario, the total CO_2 emissions released would reach zero. At the beginning of the plan, the total CO_2 emissions is 190.80 million metric tonnes and keep increasing until it peaks at 210.40 million metric tonnes in 2030. This emission is caused by the expansion of the coal until this year. As seen in Figure 25, emissions continue to fall from 2040 until finally reach zero at the end of the plan.

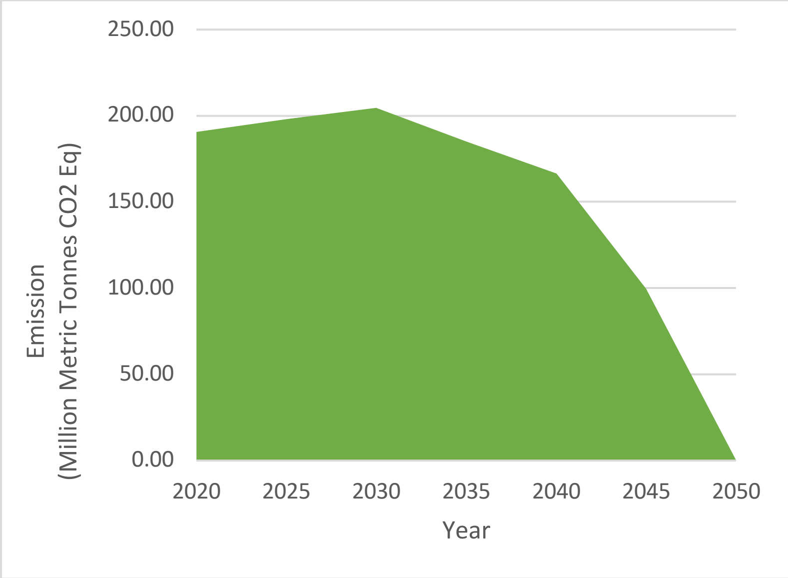


Figure 24. Emissions of ZEPS

4.2 Discussion

4.2.1 Electricity Capacity Expansion

Figure 26 represents the capacity results for the base years 2020 and 2050. According to the Indonesian power system, total capacity increase in REF would reach 258.96 GW in 2050. This capacity is approximately four times greater than the capacity in 2020, which is just around 71.04 GW. The power capacity would be made up of eight different types of power generation by the end of the planning scenario.

Coal is the primary capacity, accounting for 57.73 % capacity in 2050. When compared to the start of the plan, coal capacity has nearly quadrupled. This is because coal reserves have a higher potential and availability than other energy sources. Natural gas has the second highest capacity, with 51.47 GW at the end of the planned period. In terms of renewable energy, hydropower has the largest share, which is about five times greater than in the base year. Other renewable energy sources, such as solar PV, are also expanding in this scenario.

The results of the LEAP simulation for the GPS scenario with a 23% renewable energy target in 2025 and a 31% renewable energy target in 2050 demonstrate that the capacity in 2050 is not significantly different than REF. At the end of the planning period, the total capacity expansion is 289.89 GW. Hydropower accounts for the majority of the renewable energy capacity, which spans from 4.83 to 31.27 GW. Furthermore, solar PV capacity has expanded significantly, reaching 28.19 GW at the end of the study. The LEAP software, which considers the least-cost setting, also selects biomass and geothermal. However, because of the availability of energy sources, hydropower plays a larger role in reaching the renewable energy objective for this scenario.

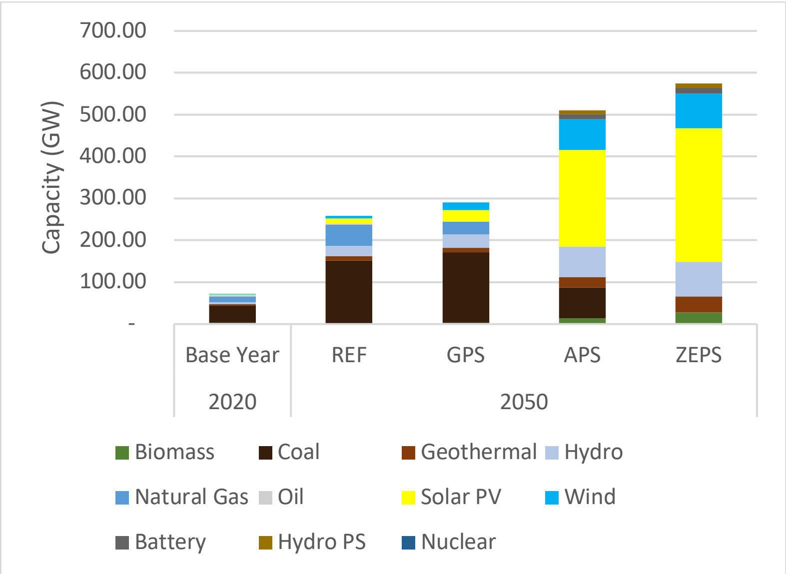


Figure 25. Capacity Comparison

Compare to REF, 31% renewable energy target by 2050 could not decrease coal power source in term of capacity. Based on LEAP results, this scenario is still considered coal power plant as the highest capacity for this scenario. Even though the percentage of renewable energy has increased, coal is still dominant source for electricity capacity.

In the APS, total power capacity is higher than REF and STS scenario which reaches 511.16 GW in 2050. Compare to the base year, the total capacity of the power plant is 7 times higher. The main source of the power plant comes from renewable energy. In this scenario, the coal proportion experiences 50% reduction compare to REF and GPS.

Coal power plants have the most capacity in the base year. Furthermore, another fossil energy, such as natural gas, contributes to Indonesia's power plant as the second main capacity. In the end, solar PV expands much more than REF and GPS and reaches 229.62 GW. In other words, solar PV in APS is 94% higher than in REF and 87% higher than in GPS. As a result, solar PV supplies the most electrical capacity in APS. When compared to REF and GPS, solar PV capacity expands because renewable energy penetration is higher. Furthermore, wind and hydropower capacity are larger than REF and GPS.

Interesting finding in this scenario is the presence of the capacity storage. In here, hydro pumped storage and battery contribute to achieve renewable energy target. Hydro PS capacity in the end of the plan is 12.60 GW while battery capacity is 10.00 GW. However, compare to all energy source, solar PV is the most promising source to meet the renewable energy target judging from its capacity in this scenario.

In the ZEPS which target zero emission by 2050, the electricity generation capacity shows the highest result among the scenarios (575.38 GW in 2050). Since the emission should reach zero by 2050, there is absence of the fossil fuel power plant in this year-end capacity's scenario. Similar like APS, solar PV shares as the majority of the power plant capacity which reach 319.35 GW. This number is higher than the capacity of solar PV in APS. In addition to solar PV, wind and hydropower also contribute to the power plant capacity in this scenario with 82.59 GW, respectively. In ZEPS, biomass and geothermal power plant capacity are not much different compare to other scenarios. Even though in term of price these energy sources are cheaper, but the availabilities are much lower compare to other scenarios. For this reason, biomass and geothermal are not really expanding.

In ZEPS, the LEAP selects energy sources based on the lowest cost option. According to the LEAP results, there will be more capacity storage for power plant capacity in 2050 than there will be for nuclear power. Based on this result, Indonesia's government plant should consider investing more in capacity storage than nuclear power plants to reach the zero-emission target, as nuclear energy is more expensive.

Besides, ZEPS also set other type of possible capacity such as carbon capture storage. However, based on LEAP results, all of the CCUS technology are not selected in this study. Since, this scenario applies least-cost optimization as well as zero emission target, based on LEAP results any CCS are not effective to achieve the target in term of price and capability to reduce the emissions.

4.2.2 Electricity Generation Mix

In terms of power generation mix, coal accounts for 65.63 percent of total energy generation in 2020. If Indonesia just relies on business as usual, the proportion of coal will not decrease significantly by the end of 2050. As seen in Table 9, the coal portion is not declining significantly by the end of the study. Even with a 31% renewable energy target in the GPS scenario, only 7.5 % of coal will be phased out. Based on this finding, Indonesia should prepare to increased renewable energy penetration to minimize its reliance on coal.

Other than coal, other fossil energy is also used to generate the electricity. Natural gas contributes 18.49 % of electrical generation in the base year, while oil contributes 2.47 %. Natural gas generates 19.88 % of total electricity in REF by the end of the scenario period. The contribution of natural gas to electrical generation in the GPS is 9% lower than in the REF. Meanwhile in APS and BPS, natural gas reach zero in 2050.

In term of renewable energy trends in the electricity generation mix, REF and GPS have almost similar trends. The differences only lie in the percentage of the mix since GPS sets renewable energy target compare to REF. To meet the renewable target, there is a slightly more increased in renewable energy mix in GPS compare to REF. Solar PV generates the biggest electricity and makes this power plant shares the biggest proportion in the electricity generation mix. Similar results are also experienced in the APS and ZEPS. In these two scenarios which aims for higher renewable energy target show that solar PV produces the biggest electricity. This means, based on LEAP model, to meet renewable energy target solar PV is the most promising source to generate the electricity. This is happened due to the abundant source of solar PV in Indonesia as well as cost efficient compare to other sources.

Hydropower and also wind are also promising source of electricity generation. With the higher target of renewable energy target, these two sources can generate bigger electricity. However, compare to solar PV, these two sources have lower ability to generate the electricity. Therefore, these two sources can only be complementary source to meet renewable energy target.

Table 9. Electricity Generation Mix Summary

Branch	2020	2050			
	Base Year	REF	GPS	APS	ZEPS
Biomass	2.54%	0.95%	1.01%	3.00%	4.00%
Coal	65.63%	57.74%	58.13%	15.00%	0.00%
Geothermal	2.90%	3.79%	3.73%	5.00%	6.00%
Hydro	6.89%	9.47%	10.79%	15.00%	15.00%
Natural Gas	18.49%	19.88%	10.57%	0.00%	0.00%
Oil	2.47%	0.61%	0.00%	0.00%	0.00%
Solar PV	0.36%	4.73%	9.73%	47.00%	60.00%
Wind	0.73%	2.84%	6.04%	15.00%	15.00%

4.2.3 Technological Aspect and Learning Rate of Energy

Technology is fundamental aspect for the future electricity sector. Depend on the technology, the country can find alternative solution to reduce the emission as well as shift to cleaner energy. In this study, APS employs various technology for electricity capacity expansion. Compare to REF and GPS, APS adds the storage capacity such as battery and HPS as possible technologies for the capacity expansion. Besides, the presence of nuclear target in this scenario makes APS distinctive than REF and GPS.

Based on the APS capacity expansion, battery and HPS are chosen as potential future capacity expansion by LEAP starting from 2035. These two capacity technologies are expanding until the end of the plan. Capacity storage is getting more popular these days since wind and solar energy are being deployed. Based on the type of the storage, Li-ion battery has ability in energy storage due to its high power and energy density (Sarker, Murbach, Schwartz & Ortega-Vazquez, 2017). Besides, cost per unit energy is relatively low so that it can be source of grid level energy storage system. Meanwhile, HPS also can be used to store the energy, but in term of capacity, HPS can be more cost efficient for large-scale energy storage compare to battery (Blakers, Stocks, Lu & Cheng, 2021).

In Indonesia, HPS has higher potential. For this reason, the capacity expansion of HPS is higher than battery. Even so, the battery plays crucial role due to the limitation of HPS storage. Based on Sarker, Murbach, Schwartz & Ortega-Vazquez (2017), battery is mostly beneficial for smaller storage such as home and electric vehicle. For power sector, HPS is better since the storage is more long-term than battery. In term of cost, currently, HPS is cheaper than battery. Based on Chen et al., (2020) the grid-level energy storage can help in balancing the power generation and utilization especially when wind and solar energy proportion is more than half. Therefore, it can be promising source of capacity storage for Indonesia's future power sector.

Beside APS, ZEPS also set some storage technology as well as capacity expansion with using CCS/CCUS. As mentioned in the previous sub-chapter, none of CCS technology are chosen for the capacity expansion. Since the LEAP consider least-cost option in this scenario, CCS is not selected due to the price. Besides, the effectiveness of CCS to reduce GHG emissions is still questionable.

In Europe, the deployment of CCS faces some challenges in term of the cost as well as technological aspect (Holz et al., 2021). Gielen et al., (2019) mentioned that CCS is more beneficial for industry such as iron, cement, paper and steel industry due to its challenge to reduce the emissions. Meanwhile, for power sector, CCS is not really a feasible option considering current price data. Since LEAP only consider the current price with several assumption without considering the possible technology in the future, CCS is still considered expensive compare to other low carbon energy in short term. Based on this study with current data, emission reduction can be done by renewable energy deployment.

Besides the employment of the new technology to reduce the emissions and possibility as capacity expansion, other renewable energy potential is also important to be discussed. As shown in every scenario, there is always expansion in hydropower and solar PV. Based on the LEAP results, these two energies can be the most potential source for future Indonesia power especially for solar PV which experiences the biggest expansion compare to all energy sources. The highest capacity expansion in the solar PV results also similar with the research conducted by Handayani et al., (2022) about ASEAN electricity plan. According to this research, solar PV in ASEAN country has the biggest technological learning. After utilizing alternative renewable potentials, solar PV became the sole feasible choice. Beside its fast-learning rate, solar PV potential is also high in Indonesia. Because of that, solar PV's capacity expands bigger than hydropower's as well as other renewable energy.

4.2.4 Costs

The total expenses of capacity expansion for each scenario are shown in Figure 27. Total costs in here consists of capital cost, fixed operation and maintenance (O&M) cost, variable O&M cost, and feedstock fuel cost. The total costs accounted for 118.90; 102.42; 121.50; and 130.40 billion USD, respectively, under REF, GPS, APS, and ZEPS. ZEPS has the highest cost among all scenarios. Meanwhile, GPS demonstrates the lowest cost of capacity expansion. When compared to the cost results of APS and ZEPS, these two scenarios are more expensive than GPS. It could imply that battery and capacity storage are more expensive than renewable energy alone.

In addition to that, nuclear energy is not selected in any scenarios. It is because compare to renewable energy sources, capital cost of nuclear power in Indonesia is really expensive. Nuclear power will be beneficial and cost-efficient if the country does not have to build from the beginning since the initial cost to establish nuclear power plant is more expensive than extending the operational cost. Based on IEA (2019), nuclear power has significant role as a low-carbon energy for advanced economies country like the EU, Korea, and Japan, especially for reducing the energy import dependency. However, for a country like Indonesia which has some renewable energy potential, nuclear power is less appealing. Therefore, it would be better if Indonesia's government focus more on renewable energy expansion such as solar and wind compare to nuclear energy.

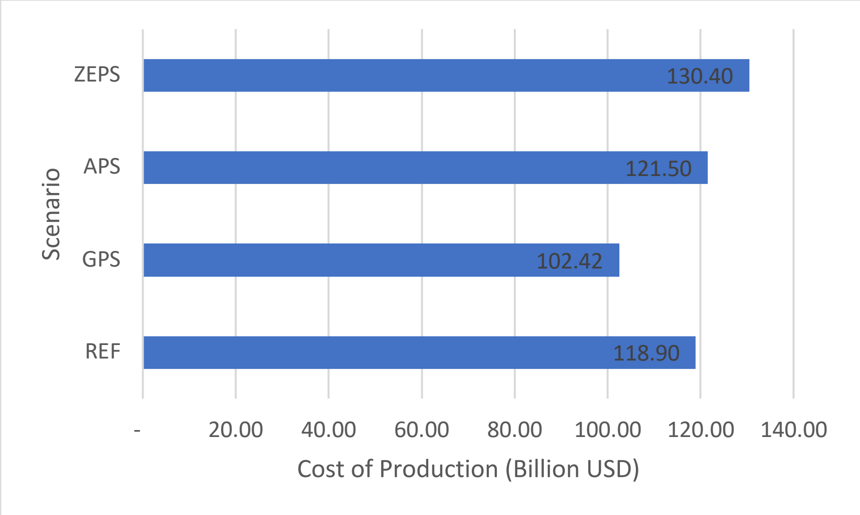


Figure 26. Cumulative Cost of Production Comparison

4.2.5 GHG Emissions

Figure 28 illustrates the emissions comparison in all scenarios. In 2020, GHG emissions is 190.80 million metric tonnes CO_2eq where 65% of the electricity comes from from coal and natural gas as the second largest electricity source. Based on REF, the emission increases gradually until it reaches 571.50 million million metric tonnes CO_2eq in 2050. It is because the electricity generation is getting higher and coal power plant is the biggest source as the electricity source.

With the target to use 31% renewable energy in 2050 as used in the GPS, the GHG emission is only reduced around 170 million metric tonnes CO_2eq compare to the REF. In the other hand, under APS, the emission can be reduced around 47.13% compare to REF. Meanwhile, under ZEPS, the net zero emission target can be achieved in 2050. The details of emission reduction compare to the base year is presented in the Table 10.

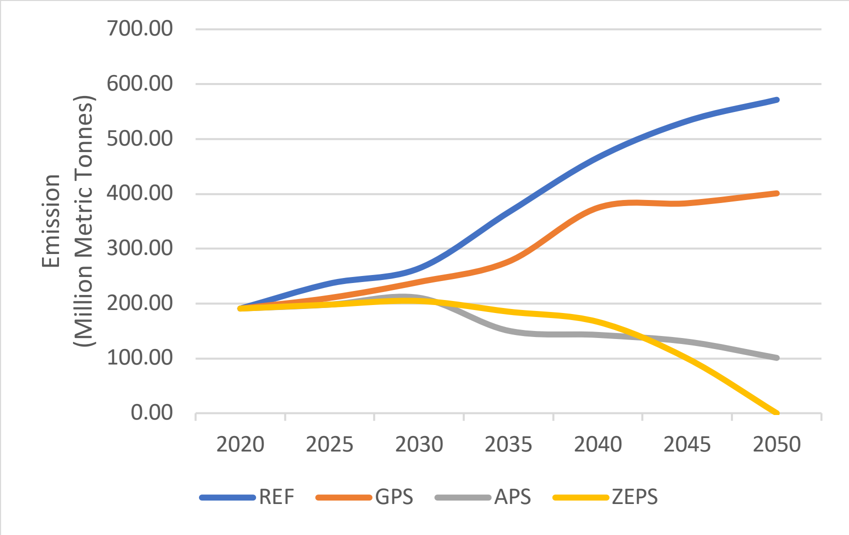


Figure 27. GHG Emission in All Scenarios

Table 10. Carbon dioxide Emission and Emission Reduction Compare to Base Year

Scenario	2025	2030	2035	2040	2045	2050
REF	236.43	264.20	366.30	466.20	532.80	571.50
	+23.92%	+38.47%	+91.98%	+144.34%	+179.25%	+199.53%
GPS	210.23	239.25	276.39	374.62	382.80	400.92
	+10.18%	+25.39%	+44.86%	+96.34%	+100.63%	+110.13%
APS	198.00	210.40	150.34	142.70	130.37	100.87
	+3.77%	+10.27%	-21.21%	-25.21%	-31.67%	-47.13%
ZEPS	198.00	204.60	185.15	166.50	99.80	0.00
	+3.77%	+7.23%	-2.96%	-12.74%	-47.69%	-100.00%

As seen in Table 10, in APS, the GHG emissions keep rising until it reaches the peak in 2030. From 2035, the emission is gradually decreasing until it reaches 100.87 million metric tonnes CO_2eq in the end of the plan. In ZEPS scenario, the increase of the emission is much lower than other scenarios. In 2025, the emission only increases as much as 3.77%. Then, it rises as much as 7.23% and goes down in

2035. Compare to the base year, the emission in 2045 experiences 47.69% reduction and reaches zero in 2050

Chapter 5

Conclusion

5.1 Conclusion

This study suggests three different scenarios for the Indonesian electrical sector to achieve zero emissions and compares them to the REF. Each scenario is built on a set of assumptions that take into account both the supply and demand sides. This research evaluates the electrical mix, electricity generation, emissions, and cost of capacity growth from 2020 to 2050 for each scenario.

Based on this study, there are several key features that can be highlighted from the long-term electricity plan of Indonesia. Firstly, this study shows that based on the base year data, Indonesia relies a lot on coal. It is because coal availability is abundant and in term of price coal is cheaper than other energy sources. Even so, with ZEPS, Indonesia can use 100% from renewable energy while 85% renewable energy can be achieved by APS. In contrary coal will still be the main source to generate the electricity under REF and GPS.

Next, in term of capacity, in REF the capacity in 2050 reaches Coal accounts as the biggest capacity in this scenario under REF and GPS. Meanwhile solar PV plays important role as capacity expansion under APS and ZEPS. More interesting result is the presence of storage technology (battery and hydropower storage) as capacity source in this scenario. ZEPS shows the highest capacity among all where most of the capacity is supported by solar PV, hydropower, and wind. However, CCUS technologies are not selected in the capacity expansion in the ZEPS. Based on this scenario, the presence of CCUS technology could not contribute to the capacity expansion to reach net zero emissions.

In regard to the cost of production, ZEPS shows the highest cost. Meanwhile GPS shows the lowest cost among all scenarios. These amounts show renewable energy is predicted to be cheaper. However, based on APS and ZEPS results, capacity storage is still expensive for Indonesia electricity plan. None of CCUS and nuclear are selected on APS and ZEPS due to the price. In this case, to reach net zero emissions in Indonesia, depending on renewable energy penetration is better than adding the nuclear power into the energy mix.

Lastly, in term of emission, this study shows that with sufficient effort on both the supply and demand sides of the electricity sector, Indonesia can achieve its zero-emission target by 2050. At the beginning of the study, hydropower played a big role as an electricity source, but by 2030, solar PV will be more competitive. Furthermore, capacity storage can contribute in the expansion of renewable energy to meet electricity demand in 2050. As a result of this finding, Indonesia should boost the adoption of capacity storage and solar PV technologies due to its high learning rate.

5.2 Recommendation

This study aims to analyze the long-term electricity plan based on the possible technology, government policies, NDCs target, and environmental parameters as well as illustrates the least-cost option for Indonesia's future electricity plan to reach net zero emission. In addition to that, this study also expects to provide alternative electricity planning scenario to achieve net zero emissions through supply and demand balance. Based on these objectives, there are several recommendations based on analysis results:

Firstly, even though three alternatives' scenarios are designed by setting the least-cost option, it is found that the adding renewable energy penetration into the energy mix need high investment cost. It is because the technology related to clean and renewable energy is not as mature as conventional fossil energy. Therefore, the technology still needs more research and development for future development. Since LEAP software does not include the anticipation of future technological development, the results of the LEAP are still based on the current price and current technology condition. For example, CCUS technology are not feasible in Indonesia right now due to the high initial cost and lower effectiveness to reduce the GHG emissions compare to other alternative sources. Another example is solar PV which show as the most viable source in Indonesia. It is because the learning rate of solar PV is good and the technology of this energy is already mature in Indonesia

Next, Indonesia's government has to commit more to achieve NDCs target in order to reach zero emissions. If the government still depend on business as usual, the emissions in electricity sector in 2050 will never go down and even will likely to increase due to dependency on coal. Furthermore, even with 31% of renewable energy target, the emission target from the electricity in 2050 could not be achieved. Since electricity sector is one of the important sectors to reduce emission in energy sector, it is fundamental to plan the long-term electricity plan well.

Lastly, it is wise for the government to focus more on adding storage capacity and renewable energy penetration compare to adding nuclear to reach net zero emissions target. It is because the cost to use renewable energy source is cheaper than adding nuclear to the energy mix. Even though in other countries such as Germany and South Korea nuclear is important for clean energy transition, but for several reasons these two countries consider to phase out nuclear energy in the future. Therefore, considering safety and cost of nuclear energy, renewable energy penetration is better for electricity plan.

5.3 Limitations and Suggestion for Future Research

This study tries to analyze long-term electricity plan in Indonesia by using LEAP and NEMO. Moreover, this study tries to fill the gap the lack of previous research, especially in term of electricity plan in Indonesia. Even so, after conducting this study, there are several aspects that is important to be analyze more such as:

1. Transmission and distribution constraints are not incorporated in this study due to model limitations. As a result, this study assumes that all electrical transmissions are linked together. To depict more accurate electricity plan, it would be better if transmission and distribution constraint can be analyzed as well.
2. This study does not calculate cost of each technology expansion. This study only calculates cost of production. Therefore, there is no result in term of which technology is the most affordable or more expensive in this study.
3. Even though this study analyzes different scenario of demand side, but the demand projection is calculated for the whole sectors. It would be nice if there are some assumptions are

inputted for demand analysis in each sector since every sector can give different impact on renewable energy transition.

4. This study does not include effect of different learning rate of each technology. It would be nice if there is analysis of this to the data especially for the expensive technology such as CCS.

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APPENDICES

APPENDIX I. LEAP BASIC DATA CALCULATION

Table 11. Population Growth Assumption

Year	Population Growth
2015-2020	1.07
2020-2025	0.94
2025-2030	0.81
2030-2035	0.68
2035-2040	0.54
2040-2045	0.41

Table 12. GDP Growth Assumption

Year	2017-2020	2020-2030	2030-2040	2040-2050	2017-2050
GDP Growth %	3.8	5.3	4.9	4.5	4.8

Source: Malik (2021)

Table 13. GDP Data (billions of 2010 USD)

	2017	2020	2030	2040	2050
GDP	1,090	1,220	2,038	3,304	5,131

Source: Malik (2021)

APPENDIX II. LEAP BASIC DATA (2)

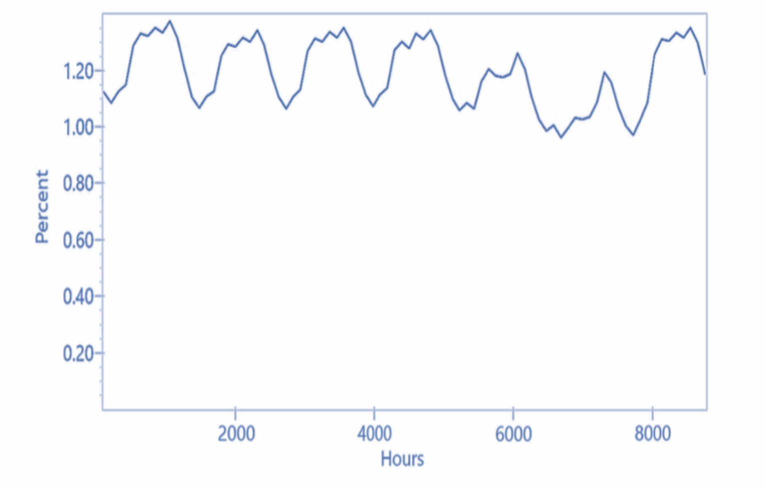


Figure 28. Load Curve

Table 14. Installed Capacity Data

Branch	2016	2017	2018	2019
Coal	23.84	25.69	26.41	29.40
Natural Gas	15.81	14.65	15.16	17.44
Oil	7.22	8.16	7.92	6.50
Hydro	4.40	4.86	4.94	4.98
Solar PV	0.01	0.02	0.03	0.06
Wind	0.00	0.00	0.07	0.13
Biomass	0.04	0.15	0.17	0.17
Geothermal	1.37	2.10	1.72	2.44
Total	**52.69**	**55.63**	**56.42**	**61.13**

APPENDIX III. CAPACITY EXPANSION (GW)

Energy Source	2020	2050			
	Base Year	REF	GPS	APS	ZEPS
Biomass	2.67	2.45	2.93	14.66	27.53
Coal	42.40	149.52	168.52	73.28	-
Geothermal	2.34	9.80	10.82	24.43	38.54
Hydro	4.83	24.51	31.27	73.28	82.59
Natural Gas	13.95	51.47	30.63	-	-
Oil	2.85	1.59	-	-	-
Solar PV	1.00	12.26	28.19	229.62	319.35
Wind	1.00	7.35	17.52	73.28	82.59
Battery	-	-	-	12.60	13.50
Hydro PS	-	-	-	10.00	11.28
Nuclear	-	-	-	-	-
Total	**71.04**	**258.96**	**289.89**	**511.16**	**575.38**

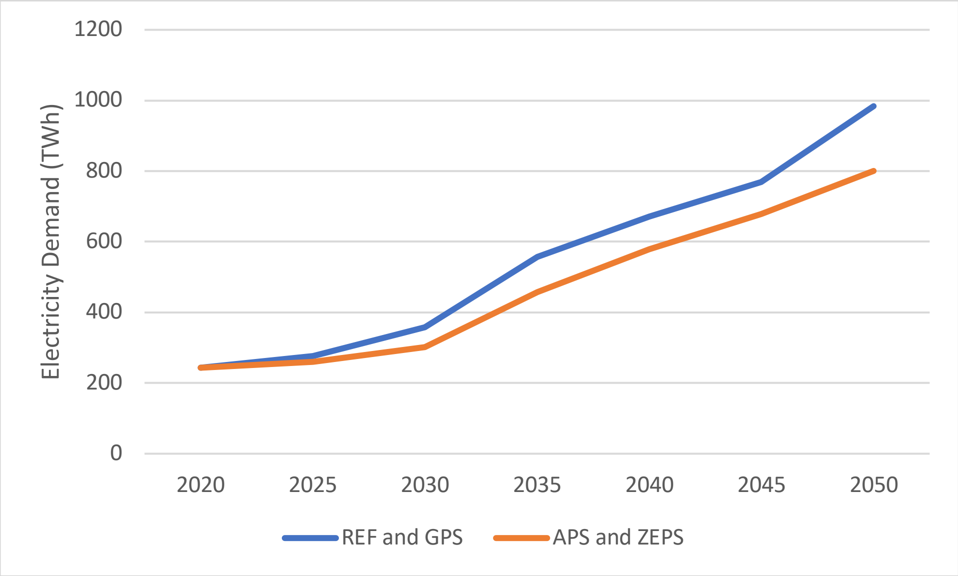
APPENDIX IV. ELECTRICITY GENERATION (TWh)

Branch	2020 Base Year	2050			
		REF	GPS	APS	ZEPS
Biomass	7.00	10.50	11.50	37.70	45.74
Coal	181.00	640.50	660.50	188.50	-
Geothermal	8.00	42.00	42.40	62.83	68.61
Hydro	19.00	105.00	122.56	188.50	171.53
Natural Gas	51.00	220.50	120.06	-	-
Oil	6.80	6.80	-	-	-
Solar PV	1.00	52.50	110.50	590.63	686.14
Wind	2.00	31.50	68.65	188.50	171.53
Total	**275.80**	**1,109.30**	**1,136.17**	**1,256.67**	**1,143.56**

APPENDIX V. COST OF PRODUCTION (Billion USD)

Scenario	2020	2025	2030	2035	2040	2045	2050
REF	10.00	16.00	30.00	61.34	84.56	108.70	118.90
GPS	10.00	16.00	31.56	60.23	80.00	100.23	102.42
APS	10.00	20.00	37.30	68.30	90.45	112.50	121.50
ZEPS	10.00	20.00	48.20	79.02	101.20	120.20	130.40

APPENDIX V. DEMAND COMPARISONS



Abstract in Korean

인도네시아의 전력 산업은 에너지 부문에서 국가 전체 온실 가스 배출량에서 가장 큰 비중을 차지한다. 따라서, 전기 부문에서의 정책을 통해 인도네시아 전체의 탈탄소화에 상당한 기여를 할 수 있다. 이 연구는 2050년까지 인도네시아가 비용을 최소화하고 최적의 전력 수급 계획을 찾는 것뿐만 아니라 온실가스 배출을 효과적으로 줄일 수 있는 방법을 분석하는 것을 목표로 하고 있다. 이 연구에는 기준 시나리오 (REF) 와 더불어 탈탄소화, 탄소포집·저장·활용 및 용량 스토리지와 같은 신기술 개발, 최저 비용 최적화 및 수요 균형 측면에서 정부 계획을 고려하는 세 가지 대안 시나리오(GPS, APS, ZEPS) 총 네 가지 시나리오를 보여준다. LEAP 소프트웨어를 통해 기준연도인 2020년부터 목표연도인 2050년까지 분석한다. 또한, LEAP는 NEMO와 통합되어 전력에서 배출량이 0에 도달하는 경로를 보다 정확하게 분석할 수 있다. 연구 결과를 통해 REF와 GPS시나리오에서는 석탄이 인도네시아에서 전기를 생산하는 주요 공급원이 될 것이라는 것을 보여준다. 그러나 재생 에너지 보급률이 높아짐에 따라 석탄 의존도를 줄일 수 있는 것 또한 시사점으로 도출할 수 있다. 마지막으로, 배출량 측면에서 ZEPS시나리오는 2050년에 배출량이 전혀 없다는 것을 보여준다.

키워드 : 전력 계획, 재생 에너지, 배출, 최소 비용, LEAP, 인도네시아
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