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Energy Transition Planning in Achieving the Net Zero Emission 2060 Target in the Provincial Electricity Sector North Sumatra

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Abstract
This research discusses the energy transition towards the Net Zero Emissions (NZE) 2060 target in the electricity sector of North Sumatra Province. The challenges faced include dependence on fossil fuels, high greenhouse gas emissions, and limited renewable energy capacity. The study aims to model energy transition scenarios, evaluate the optimal renewable energy mix, and determine emission reduction strategies in the electricity sector using LEAP-NEMO software. This study uses a forecasting-based simulation modeling method with a mathematical approach through LEAP software and NEMO optimization framework. Three scenarios were analyzed, namely Business As Usual (BAU), Net Zero Emissions Carbon Capture Storage (NZE CCS), and Net Zero Emissions Full Renewable Energy (NZE FRE).
The simulation results show that the NZE FRE scenario is able to achieve a 100% renewable energy mix by 2060, outperforming the BAU (42.1%) and NZE CCS (70.8%) scenarios. Solar, biomass, hydro, and geothermal energy are the main sources of energy, with solar energy as the largest contributor. Greenhouse gas emissions are reduced by up to 265.9 million tons of CO2 (70.5%) compared to the BAU scenario. These findings provide policy recommendations that support the implementation of renewable energy, reduction of greenhouse gas emissions, and fiscal policies that internalize environmental costs. The study also highlights the importance of investing in clean energy technologies to realize a sustainable electricity system in Indonesia.

1 Introduction

The generation of electrical energy using fossil fuels has a serious impact on the sustainability of non-renewable resources as well as increasing greenhouse gas emissions which have a significant impact on global temperature rise. Based on the Ember Climate report, global emissions produced by power plants increased to 12,431 million tons of CO2 (mt CO2) in 2022 with Indonesia ranking ninth in the country with the highest CO2 emitters.2 largest in the world with total GHG emissions of 192.7 mt CO2 and it is projected that the value of GHG emissions will continue to increase until 2030 (Ember C, 2024). In an effort to limit the rate of global temperature rise and reduce the adverse effects of climate change, in 2015 the *Paris Agreement* was agreed which requires countries to contribute and strive to reduce emissions to the maximum. The agreement was supported by 195 countries present at the time, including Indonesia, which had also ratified the *Paris Agreement* in 2016.

North Sumatra Province with a population of 15.47 million people or 5.51% of the total national population (Dukcapil.Kemendagri.Go.Id, 2022) occupies the fourth position in the largest population in Indonesia. In 2023, the province recorded economic growth of 5.01% (Central, G. 2024), ranking among the highest middle levels in Indonesia. North Sumatra is also the sixth province with the largest distribution of electrical energy, reaching 12,059 GWh in 2022 (Ministry,E. 2023). Based on the IEA report, greenhouse gas emissions in Indonesia are influenced by variables of population growth, energy consumption, and economic rate (International, E. 2022). Some of these variables make North Sumatra one of the provinces that plays a key role in decarbonization efforts towards the net-zero emission target by 2060 in Indonesia.

The energy transition towards a greener electricity system has been a global concern, with a focus on shifting from a centralized model to a decentralized model that utilizes renewable energy sources. According to research by Christophe Defeuilley (2019), public policy and institutional change have an important role in shaping the future of the electricity sector. These factors are recognized as the main drivers of electricity system change, along with increasing public support, decreasing technology costs, and innovations in energy storage (Defeuilley, 2019).

Many studies have simulated energy transition planning in the electricity sector from fossil fuel sources to clean and renewable energy, such as a study conducted by Handayani et al. (2023) in Cambodia, Laos, and Myanmar which shows the potential for the application of renewable energy supported by energy storage technology to achieve net zero emission targets. The study uses *the Low Emissions Analysis Platform* (LEAP) as software to simulate a 100% renewable energy integration scenario in the electricity sectors of the three countries, which has proven feasible and sustainable despite requiring a large cost investment (Handayani, K. 2023). Meanwhile, on a regional scale in the province of North Sumatra, the research of Sri Ulina et al. (2022) shows significant potential in hydro, wind, and biomass energy, which is expected to make an important contribution to the decarbonization of the electricity system at the regional level until 2028 (Ulina, S. et al. 2022).

Another study conducted by V. Wambui et al. (2022) in Kenya highlighted the benefits of renewable energy development accompanied by the internalization factor of environmental externalities. The results of this study show that the development of renewable energy sources with energy storage can reduce CO_2 emissions, improve the reliability of the electric power system and provide great benefits in terms of cost-effectiveness, especially when environmental externalities are taken into account in the form of emission taxes (Wambui, V. et all. 2022). On the other hand, research by Zhongrui Ren et al. (2024) in China uses LEAP software combined with NEMO (*Next Energy Modelling System for Optimization*) to simulate a scenario of high renewable energy penetration and gradually increasing carbon prices, as well as a subsidy scenario for the renewable energy sector. The results show that the combination of carbon pricing and subsidy policies in the renewable energy sector plays an important role in achieving *net zero emissions* by 2050 (Ren, Z. 2024).

Another study by Ahmed Hassan et al. (2023) explored the scenario of the renewable energy mix in Egypt in the 2020-2050 range and concluded that optimizing the increase in the portion of renewable energy in the national energy mix can significantly reduce greenhouse gas emissions and reduce energy production costs in the long term Sayed, AHA. 2023: Handayani, F, et al. (2020) conducted a study using LEAP software combined with WEAP to simulate climate change mitigation efforts and long-term electricity system planning in the Java-Bali system by considering the impact of climate change on the demand and supply of electrical energy (Sonjaya, A. et all. 2023) .

Research on the energy transition at another regional level, namely on the Sumatra electricity system by Abeth Novria Sanjaya et al. (2023) which mapped and harnessed the renewable energy potential in Sumatra Island for 2020-2050 using *LEAP software* highlighted that without significant intervention, CO_2 emissions in the region could almost double by 2028 (Handayani, K. et all. 2022). Meanwhile, another study by Handayani, Anugrah, et al. (2022) on the ASEAN electricity system stated that *the net-zero emission target* can be achieved with the optimal use of renewable energy, especially PV technology which will contribute 61% to the energy capacity mix by 2050, although this scenario requires greater costs than other scenarios.

Although the literature on energy transition models continues to grow, there is still a significant gap in understanding the socio-economic and political challenges that hinder the implementation of the energy transition at the provincial level. Previous studies have mostly focused on the technical and economic aspects of the energy system without adequately considering institutional, policy, and social dynamics. Research by Christophe Defeuilley (2019) highlights that public policy and institutional change are critical in shaping the future of the electricity sector, emphasizing that the energy transition requires more than just technological advancement and cost reduction.

In addition, regional studies such as those conducted by Handayani et al. (2023) in Southeast Asia and Sri Ulina et al. (2022) in North Sumatra highlight the technical feasibility of renewable energy integration but ignore the complex policy environment and stakeholder dynamics. Similarly, international examples from Kenya, China, and Egypt provide valuable insights into renewable energy implementation strategies but are less relevant to Indonesia's decentralized energy governance structure.

Based on the background of the problems raised and several previous research studies, North Sumatra Province with a projection of electrical energy consumption that will continue to increase in the future and has great potential in the development of renewable energy sources, has a strategic role in the clean energy transition efforts to achieve net *zero emissions* targeting Indonesia by 2060. This study aims to plan and analyze the energy transition in the electricity sector of North Sumatra province, identify renewable energy mixes that can meet electrical energy needs, and determine the best emission reduction scenario to achieve the *net-zero emission target* by 2060.

2 Materials and Methods

This study uses an energy modeling method with forecasting-based simulation calculations with a mathematical approach using analytical programming (LEAP-NEMO model framework). *LEAP software* with the NEMO optimization framework is used as a modeling tool to estimate and evaluate energy transition scenarios in the electricity sector of North Sumatra Province. Below are some sub-discussions about the research methods conducted in this study.

A. Electricity System Modeling Design Methods

The modeling uses the LEAP-NEMO framework which is designed by having several modules for the simulation process. The modules used include: an electricity demand projection module that aims to model how energy needs will evolve in the future, a power supply projection module that aims to model the electricity supply to meet a given demand, a cost module, and an emissions projection module that is used to calculate and compare GHG emissions generated from the electricity system in various scenarios.

The next process in designing system modeling is to compile three scenarios used in the modeling simulation process. These three scenarios are designed based on reference to regulations, policies and recommendations related to the energy transition in the electricity sector to achieve NZE 2060 in Indonesia. The first scenario is the *Business as Usual* (BAU) scenario which assumes the continuation of portfolio flows based on the Electricity Supply Business Plan 2021-2030 [15] and the Regional Energy General Plan [16] in the current electricity sector without significant intervention with a target of implementing renewable energy of 23% by 2025 and at least 31% by 2050 [17]. In the BAU scenario, the addition of coal-fired power plants and natural gas coal-fired power plants is unlimited and competes with all available generation technologies. In addition, the BAU scenario also serves as a comparative reference when assessing the implications of the other two scenarios.

The second scenario is the Net Zero Emissions Carbon *Capture Storage* (NZE CCS) scenario based on a progressive renewable energy utilization policy of at least 70% by 2060 [18] whose implementation is limited by the potential resources available & technical potential. The CCS NZE scenario also applies *carbon capture* technology to coal, natural gas, and biomass power plants starting in 2035 which is also supported by the application of *biomass cofiring* starting in 2025 in coal-fired power plants to reduce greenhouse gas emissions. To optimize the results of electrical energy generation from renewable energy, this scenario also utilizes *energy storage technologies*, including *hydro pump storage* (HPS) and *battery energy storage systems* (BESS).

Meanwhile, in the last scenario, namely the Net Zero Emission *Full Renewable Energy* (NZE FRE) scenario which simulates the integration of 100% of existing renewable energy potential into the electricity system of North Sumatra province. This scenario does not use carbon capture technology in the simulation process, the application of renewable energy is limited by the potential of available resources and their technical potential as well as the development of the utilization of *energy storage technology* which includes *hydro pump* storage (HPS) and *battery energy storage systems* (BESS).

B. Modeling Simulation Method with LEAP-NEMO

This research uses LEAP software or stands for *Low Emissions Analysis Platform.* LEAP is a software developed by the Stockholm Environment Institute (SEI) that is widely used for energy policy analysis and climate change mitigation evaluation. The modeling simulation with the hybrid model paradigm in this study combines top-down and bottom-up approaches in the process of analysis and forecasting of electricity system development. In the early stages, macroeconomic data, electricity sales activity, and load curves are used to estimate the final demand for electrical energy through a top-down approach, which can provide a big picture of energy demand based on macroeconomic indicators and historical data on electricity consumption.

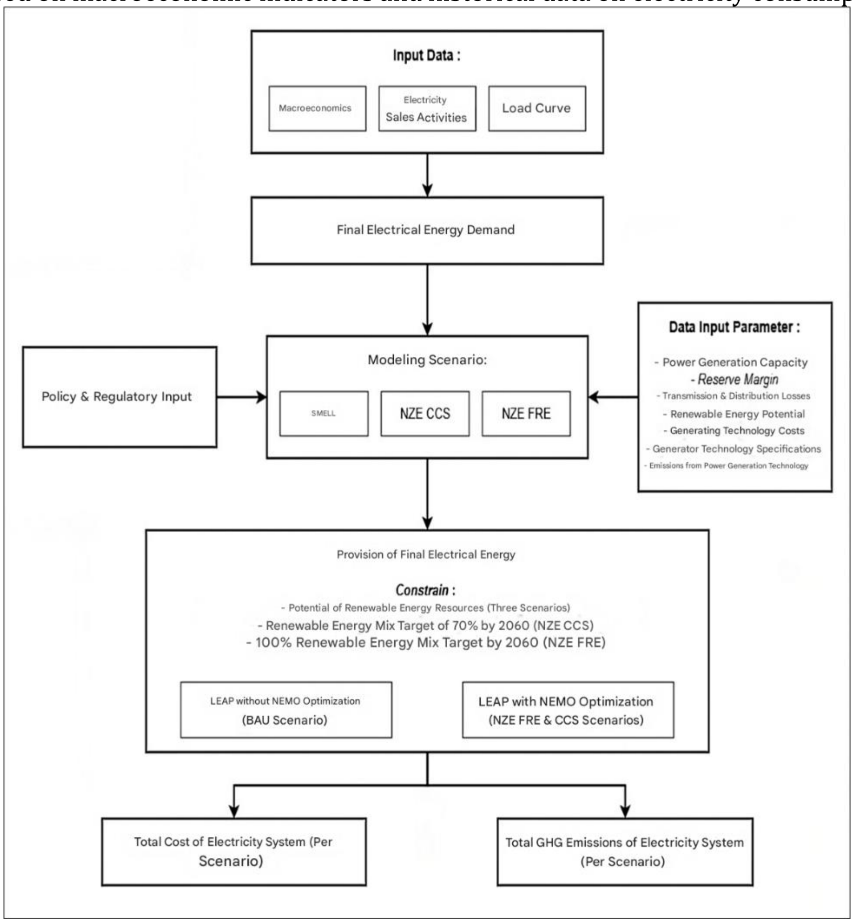

Figure 1. LEAP-NEMO Modeling Simulation Framework

This simulation framework includes policy and regulatory inputs in each modeling scenario. Parameters such as the technical specifications of the power plant, reserve margins, transmission and distribution losses, renewable energy potential, and others are used as databases for the simulation of the final electrical energy supply. A bottom-up approach is applied to simulate specific policies and technologies in the provisioning module towards basic energy consumption.

The process of providing electrical energy in each scenario must meet several limitations. The simulation was carried out under two conditions: without NEMO optimization for the BAU scenario and with NEMO optimization for the NZE CCS and NZE FRE scenarios. In a scenario without optimization, LEAP adds new electricity capacity to meet annual needs and regulates electricity distribution based on priority in accordance with policies and regulations. Meanwhile, in a scenario with NEMO optimization, LEAP manages the expansion of generation technology capacity, capacity addition time, and electricity distribution to achieve the lowest cost of electrical system expansion. The simulation results show electrical energy generation, energy mix per scenario, and expansion of plant technology capacity from 2023 to 2060. The final stage of this hybrid model provides an output in the form of total system cost, external cost of GHG emissions, and total GHG emissions for each scenario.

C. Simulation Data

Electrical energy demand modeling carried out on the LEAP software estimates the electrical energy demand calculated based on the multiplication between the value of electrical energy intensity and the total electrical energy consumption activity. Total electrical energy activity can be reflected in the accumulation of the number of electricity customers or the accumulation of economic activity levels (GDP). Meanwhile, energy intensity is the ratio of energy consumption value per electricity customer or per value of economic activity (GDP). In this study, the ratio of growth in the number of customers, economic growth, growth in electrical energy consumption, and energy intensity growth value were used to simulate *forecasting* in the modeling year period (2023 – 2060) using growth trends based on historical data over the last 10 years (2013 – 2022), in this case this study follows the same projected growth of electrical energy demand as in the RUPTL 2021-2030. Table 1 below is a tabulation of the simulated data of electrical energy demand used in this study.

Table 1. Tabulation of Electrical Energy Demand Simulation Data

Data Caption	Data Value
Customer Growth Projections	4,00 %
Business Growth Rate Projection *as Usual*	4,72 %
Energy Intensity (*Base Year*)	0.00298 GWh/ Customer
Energy Intensity Growth Projections	0,70 %
Energy Elasticity	1,00 %
Projected Electrification Ratio (2023-2060)	100 %

Furthermore, Table 2 below is data on the potential of renewable energy sources in North Sumatra Province. The potential of this renewable energy will be one of the limitations used in the transformation process of electric energy plants.

Table 2. Potential Renewable Energy Resources [16][20]

Resource Type	Potential (MW)
Biomass	3.939
Biogas	116
Municipal Solid Waste (MSW)	31
Water	5.012
Sun	11.852
Wind	356
Geothermal	2.026
Total Resource Potential	23.332

Table 3 below is data on the existing generation capacity that has been operating in the province of North Sumatra in 2022. This data is the input value in the capacity of 2022 or the base year of the LEAP software.

Table 3. Existing Power Plant Capacity 2022 [4]

Types of Generators	Capacity (MW)
PLTU	1.350
PLTG	1.057,96
PLTD	135,96
Hydropower Plant	1.002,45
PLTM	154,53
PLTP	504,15
PLTB	0

Solar Power Plant	0,45
PLTSa	0
PLTBm	145,57
PLTBg	21,51
Total Capacity	4.372,58

Some technical parameter data is required as input data in the LEAP software. There are 16 types of technologies used in this study, but the use and utilization of these types of technologies will differ according to the characteristics of each scenario, such as the absence of *Battery Energy Storage System* (BESS) technology in *the Business As Usual* scenario because the scenario is a simulation and not an optimization scenario in *the software* JUMP. Table 4 below shows the data on the technical parameters of the power plant technology used in this study.

Table 4. Technical Parameter Data of Power Plant Technology [21][22][23]

Types of Technology	*Lifetime* (Years)	*Process Efficiency* (%)	*Maximum Availability* (%)	*Capacity Credits (%)*
Coal	30	42	73	100
Natural gas	25	56	85	100
Diesel	25	45	95	100
Biomass	25	31	81	100
Biogas	25	32	85	100
MSW	25	28	90	100
Hydro	50	100	41	52
Mini Hydro	50	100	76	58
HPS	60	80	80	25
Solar PV	30	100	22	22
Wind	30	100	35	35
Geothermal	30	15	80	100
BESS	25	30	17	22
CCS Coal	30	34	80	100
NG CCS	25	48	80	100
BECCS	25	30	90	100

The projected cost of expanding the electricity system in this study has several cost variables that play a role in influencing power generation technology until 2050. Costs considered include *capital costs* , *fixed o&m costs* , *variable o&m costs,* and *fuel costs* . Table 5 below is the cost parameters of power generation technology.

Table 5. Power Plant Technology Cost Parameters [21][22][23]

Kind Technology	*Capital Cost* (Million USD/MW)		*Fixed O&M Costs* (USD/MW)	*Variable O&M Cost* (USD/MWh)	*Fuel Cost* (USD/MWh)
	2023	2050			
Coal	1,73	1,63	56,6	1,25	9,53
Natural gas	1,08	0,95	23,5	2,6	23,90
Diesel	0,91	0,89	8	7,3	41,50
Biomass	2,28	1,82	47,6	3,4	8,34
Biogas	2,45	1,84	14,85	0,13	30,71
MSW	5,97	4,94	243,7	27,5	5,88

Hydro	2,2	1,96	37,7	0,74	0
Mini Hydro	2,5	2,23	53	0,57	0
HPS	1,2	1,2	8	0,94	0
Solar PV	1,2	0,6	14,4	0	0
Wind	1,65	0,95	60	0	0
Geothermal	4,4	3,96	50	0,27	0
BESS	1,33	0,64	7,6	2,3	0
CCS Coal	3,46	2,77	98,4	4,2	9,53
NG CCS	1,84	1,72	32,5	4,36	23,90
BECCS	5,45	5,09	64	8	8,34

The cost of capital is projected to decline by 2050, as seen in the table. This is influenced by the *learning rate factor* of each technology, where the more research and development is obtained in energy technology, the lower the investment cost will be incurred [21].

In the projection of the electrical energy supply system module, this study also pays attention to other variables such as margin *reserve data* planning and also electrical energy loss projection data in the transmission and distribution system in North Sumatra province. Table 6 below is a tabulation of data requirements.

Table 6. *Planning Reserve* Margins and *Transmission Losses* – Distribution [15][4][24]

Input Parameters	Data
Planning Reserve Margins	35 %
Transmission Loss *Projections - Distribution*	8,3 – 6,1 %

The Planning Reserve Margin in the LEAP software is used to determine how much additional capacity (as a percentage) is required above the peak load to maintain system security. Meanwhile, in the transmission and distribution loss data, the value will decrease until 2038 with a percentage value of 6.1%.

3 Results and Discussion

A. Projected Results from Electrical Energy Demand

Based on the input process of several simulation data in the LEAP software, the results of the projection of electrical energy needs in North Sumatra province are obtained as shown in Figure 2 below.

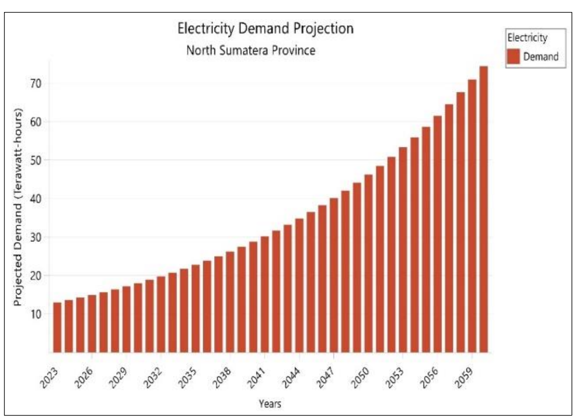

Figure 1. Projected Electrical Energy Needs in North Sumatra Province

In 2023 the demand for electrical energy will reach 13.0 TWh. Projected demand for electrical energy will continue to increase, until it reaches 18.0 TWh in 2030 and the growth trend will continue in the next 10 years, where in 2040 the value will reach 28.8 TWh or there will be an increase of 10.8 TWh over a period of 10 years. Furthermore, in the middle of this century, namely in 2050, the demand for electrical energy is expected to soar to 46.2 TWh. In the last period of the study, namely 2060, the demand for electrical energy in the province of North Sumatra will reach 74.4 TWh, an increase of more than five times when compared to the first year of the research period. So that the total accumulated electrical energy needs of North Sumatra province during the projected energy transition planning period (2023 - 2060) will be 1,341.2 TWh.

B. Projected Results from Electrical Energy Supply

1) BAU Scenario Projection

Based on the simulation results, electrical energy production in North Sumatra province until 2060 will still be dominated by the energy mix produced from fossil fuels, namely coal and natural gas. It is recorded that in 2025 energy production from coal-fired power plants will reach 4.5 TWh, and will increase to 4.6 TWh in 2030, 6.8 TWh in 2040, then this energy production is projected to continue to increase consistently until it reaches 23.3 TWh in 2060.

Energy produced by natural gas power plants also recorded a consistent increase. In 2025 the energy produced is expected to reach 3.3 TWh, and in 2040 it is projected to reach 5.1 TWh which will also continue to increase to 22.0 TWh by 2060. Furthermore, the energy generated in other fossil fuel power plants, namely diesel plants, will reach 0.4 TWh in 2025 which is projected to continue to decline until it reaches 0 TWh in 2050. This diesel power plant is widely used in isolated electricity systems on the island of Nias.

In addition to the energy produced from fossil fuel power plants, renewable energy power plants will also be one of the resources that will be utilized. In this scenario, the energy from renewable energy power plants will be dominated by hydro, geothermal and biomass power plants. In 2060 hydropower plants are projected to generate 12.4 TWh of electrical energy, while geothermal power plants are 7.8 TWh and biomass power plants are projected to contribute 5.5 TWh by 2060. Figure 3 below shows the projected results of electric energy generation in the BAU scenario until 2060.

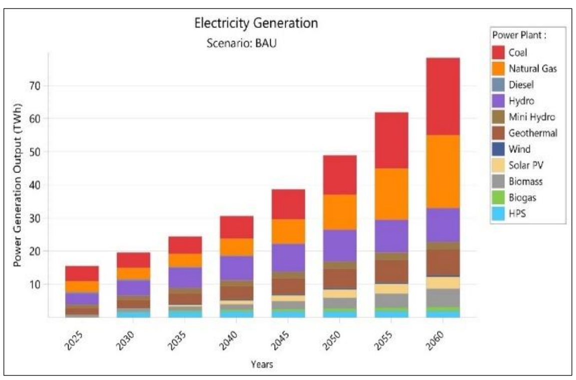

Figure 2. BAU Scenario of Electrical Energy Generation

2) CCS NZE Scenario Projection

Based on the IEA Report, as an effort towards a clean energy transition in Indonesia, carbon capture and storage (CCS) technology can be one way to reduce the impact of emissions produced on the power generation sector [5]. Figure 4 below shows the projected results of an electrical energy generation in this scenario.

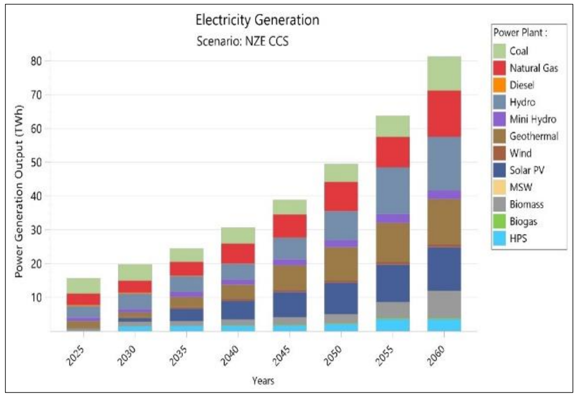

Figure 3. CCS NZE Scenario of Electric Power Plant

In the projection of electric energy generation, coal and natural gas power plants will remain in use until 2060, with the integration of CCS technology. By 2025, electricity production from coal-fired power plants is expected to reach 4.5 TWh, increase to 4.8 TWh in 2030, then drop to 4.0 TWh in 2035 due to the high cost of CCS integration and to make room for renewable energy plants to grow. By 2060, the production of electrical energy from coal-fired power plants is projected to reach 10.0 TWh, lower than the BAU scenario. Natural gas plants will produce 3.3 TWh by 2025, declining by 2035 for reasons similar to coal. However, after 2035, natural gas production will increase and surpass coal due to lower total costs. The generation of electrical energy from natural gas fuels will reach 13.7 TWh by 2060, which is also lower than the BAU scenario.

In renewable energy-fueled power plants, electrical energy production will be dominated by hydropower, geothermal, and solar power plants. Hydropower will continue to increase production value until it reaches 18.5 TWh in 2060. Geothermal power plants will also increase to reach a production value of 13.3 TWh and then followed by solar power plants whose electrical energy production value reaches 12.9 TWh. This scenario succeeded in simulating the renewable energy mix target which reached 70.8% in the last year of research. The NZE CCS scenario integrates 4.8 GW of battery storage technology (BESS) by 2060.

3) FRE NZE Scenario Projection

The NZE FRE scenario projects that the renewable energy mix in the electricity system of North Sumatra province will be 100% by 2060 by utilizing all the potential renewable energy resources available. Figure 5 below is a projection of the NZE FRE scenario.

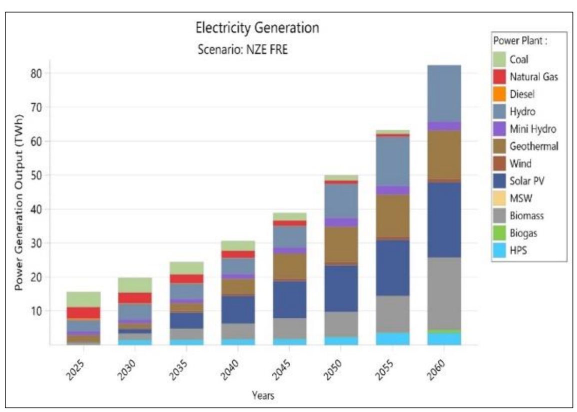

Figure 4. NZE FRE Electrical Energy Generation Scenario

Coal-fired power plants are projected to produce 4.5 TWh of energy by 2025, but their production will gradually decline to reach 0 TWh by 2060 as the process of phasing out and replacing capacity with renewable energy is carried out. A similar decline also occurred in natural gas plants, which are expected to produce 3.3 TWh in 2025 and will decline to 2.1 TWh in 2040, until reaching 0 TWh in 2060. Meanwhile, diesel power plants will be phased out in 2050, so production will also drop to 0 TWh that year. In this NZE FRE scenario, battery energy storage system (BESS) technology is integrated, as in the NZE CCS scenario, to support the stability, reliability, and balance of fluctuating renewable energy supply and demand [25]. This NZE FRE scenario requires a battery storage technology (BESS) capacity of 5.1 GW by 2060.

Hydropower is projected to produce 4.4 TWh in 2025 and continue to increase to 19.2 TWh in 2060. Energy from solar power plants will start from 0.1 TWh in 2025 and grow significantly to reach 22.2 TWh by 2060. Energy generation from biomass is expected to reach 0.5 TWh by 2025 and gradually increase to 21.2 TWh by 2060, while geothermal will also make a major contribution, with a projection of reaching 14.2 TWh by 2060. In addition to hydropower, solar, biomass, and geothermal that play a major role in the energy transition, several other energy sources also contribute, including wind, biogas, hydro pump storage (HPS), and municipal solid waste (MSW). In 2060, the generation of electrical energy from wind will reach 1.1 TWh, energy from biogas is projected to reach 0.9 TWh, a small amount due to the limited potential of biogas in North Sumatra Province. HPS technology is integrated with hydropower, adding 3.5 TWh by 2060, and MSW will contribute 0.1 TWh by 2060.

C. Projected Emissions of Electrical Systems

Projected electricity system emissions are needed as an indicator to measure the impact of greenhouse gas emissions from several scenarios in this study because of the influence of the expansion of the electricity system to meet the needs of electrical energy, as well as the extent to which the implications will have an impact on the environment in the next few years. Figure 6 below is the result of the projected greenhouse gas emissions from the three scenarios.

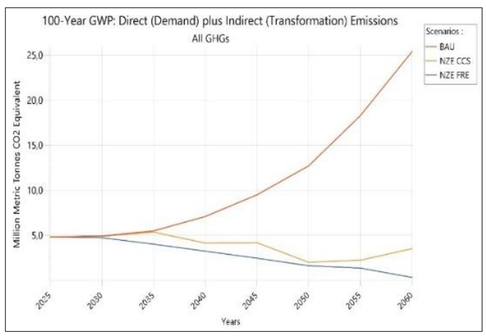

Figure 5. Third Scenario of Projected Greenhouse Gas Emissions

The BAU scenario will be the scenario with the largest carbon emission rate during the study period. The projected CO2 emissions in absolute value of this scenario will continue to grow from 4.9 Million Tons of CO2 in 2030, increasing to 25.4 Million Tons of CO2 by 2060. In the CCS NZE scenario, the projected value of CO2 imposition in absolute value is 4.9 Mton CO2 in 2030 and is projected to continue to decline to 3.5 Mton CO2 by 2060. Furthermore, in the NZE CCS scenario, the application of carbon capture technology is projected to reduce the impact of GHG emissions on fossil fuel plants by 40% starting by 2036, this reduction projection refers to several real-life case projects that have been carried out in several countries [26]. By 2050, assuming an increase in the rate of learning carbon capture technology, the carbon capture value is expected to reach 80% in accordance with the ideal conditions study conducted by the IPCC [27].

Meanwhile, in the FRE NZE scenario, the projected reduction in GHG emissions has a very significant reduction value when compared to the other two scenarios. In this scenario, the projected GHG emissions in absolute terms will decrease from 4.7 Mton CO2 in 2030 to 0.3 Mton CO2 in 2060 in line with the very aggressive penetration of renewable energy and accompanied by a decrease in fossil fuel generation capacity that will be phased out by 2060. Table 7 below shows the total greenhouse gas emissions of the three scenarios in cumulative values.

Table 7. Projections of Total Emissions from Three Scenarios in Cumulative Value

Scenario Type	Total Emissions (MtonCO2)	Emission Reduction Compared to BAU	
		Mton CO2	Percentage Reduction (%)
SMELL	377,4	-	-
NZE CCS	146,1	231,3	61 %

NZE FRE	111,5	265,9	70,5 %

D. Projected Results of Electricity System Costs

Figure 7 below is the result of the projected total cost of expanding the construction of the electrical system in cumulative values with a discount rate of 12% during the research period [22][23].

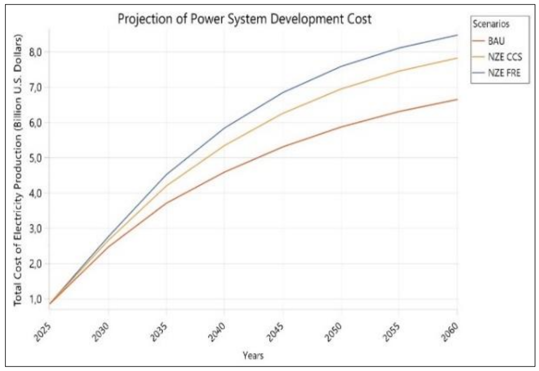

Figure 6. Total Cost Projection of Electrical System

The BAU scenario will be the scenario with the lowest projected total cost when compared to the other two scenarios. The BAU scenario will require a total cumulative cost of 6.7 billion US dollars for the expansion of the electricity system during the 2023-2060 period. The CCS NZE scenario is the second most expensive scenario, due to the lack of competitive costs of carbon capture technologies integrated into fossil fuel power plants. It should be noted that the NZE CCS scenario requires a total cumulative cost of 7.8 billion US dollars over the 2023-2060 period. Meanwhile, the NZE FRE scenario is the scenario with the most expensive projected cost, the total cost needed during the 2023-2060 period is 8.5 billion US dollars.

Furthermore, in the context of energy transition planning, efforts are also needed to identify external costs generated by the use of fossil energy, such as health impacts due to air pollution and environmental damage. These external costs are often not reflected in the projected total cost of energy transition planning [9]. Figure 8 below is the projected external costs generated in all three scenarios.

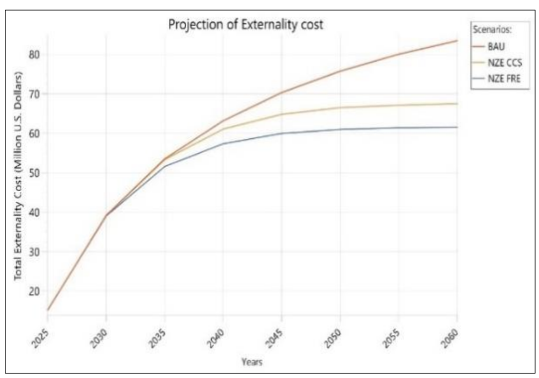

Figure 8. External Cost Projections on the Electricity System

This study uses a carbon tax rate of Rp 30,000 per ton of CO_2 equivalent based on reference to Law 7/2021 on Harmonization of Tax Regulations [28] and Presidential Decree 98/2021 on the Implementation of Carbon Economic Value [29] Based on the results of projections, the BAU scenario is projected to have a total cumulative external cost of 83.5 million US dollars during the 2023-2060 period. In the NZE CCS scenario, the total cumulative external costs would be lower, at US$67.6 million. Meanwhile, in the FRE NZE scenario, the cumulative total external cost over the 2023-2060 period is $61.4 million and will be the scenario with the lowest total external cost when compared to the other two scenarios.

4 Conclusion

This study provides recommendations for the NZE FRE scenario as the best scenario for energy transition planning as a climate change mitigation effort to achieve the NZE 2060 target. This scenario has been shown to reduce GHG emissions by 70.5% over the study period when compared to the projected GHG emissions of the BAU scenario, as well as the projected GHG emissions of almost zero by 2060. Although the total cumulative cost of developing an electrical system in the FRE NZE scenario is the largest among the other two scenarios, the projected external costs of this scenario are the lowest. In addition, environmental sustainability and climate change aspects due to GHG emissions that will be borne in the future are one of the biggest reasons for choosing the NZE FRE scenario to be the best. Further research could include the influence of future climate change variables that could affect all components of the electrical system, such as how rising temperatures and weather may affect electrical energy needs and the efficiency of power generation technology.

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