Pathways to clean energy transition in Indonesia's electricity sector with OSeMOSYS modelling (Open-Source Energy Modelling System)

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Research Article

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Abstract

Responding to the Paris agreement and climate change mitigation, Indonesia aims to reach Net Zero by 2060 or sooner. Due to Indonesia's dependence on coal and growing consumption, alternative sources of clean energy are imperative for meeting its rising energy needs and reducing energy-related greenhouse gas emissions to achieve the energy transition. This project aims to examine Indonesia's challenges, opportunities and potential to achieve low carbon ambition in the energy sector and identify alternative pathways for the energy transition in Indonesia. Cost-effective scenarios are developed by the Open Source Energy Modelling System (OSeMOSYS), providing comprehensive data analysis. OSeMOSYS is a least-cost model that enables long-term energy system modelling and its related intensive analysis. Indonesia energy data and OSeMOSYS input are obtained from an Indonesia starter data kit. In this study, a comparison of electricity generation, technology, investment, and carbon dioxide emissions is made between business-as-usual scenarios and model scenarios. The results show that NZ50 scenario is more cost-effective than others in meeting Indonesia's future energy demand at the lowest implementation cost. Although NZ50 and NZ60 are possible ways to reach carbon neutrality, NZ50 emits fewer CO2 emissions at a similar cost to NZ60. This paper's insights emphasise that large-scale renewable energy deployment and coal retirement are critical pathways to reaching carbon neutrality and achieving the energy mix transition.

Introduction

Globally, human activities associated with energy consumption constitute one of the largest sources of greenhouse gas emissions. IRENA (2018) stated that the energy transition aims to reduce energy-related CO2 emissions and limit climate change by transitioning the energy sector from CO2 emitters to zero-carbon technologies.

In Indonesia, the energy sector is the second contributor to CO2 emissions (Ministry of Energy and Mineral Resources (MEMR), 2021). Indonesia relies heavily on coal as the country is one of the world's largest coal producers and consumers. The Indonesian coal market plays a prominent role globally, particularly as a regional supplier. Over a quarter of the country's total CO2 emissions were generated by coal-fired power plants (CFPPs), accounting for 79% of the country's power sector's CO2 emissions in 2019 (Cui et al., 2022). MEMR (2021) estimates that the most dominant technologies out of install capacity were steam power plants (coal, oil, gas and co-firing) at around 37 GW or 51%, followed by combined cycle (17%) and hydro (9.1%). MEMR (2021) also mentioned that about 62% of the net electricity generation was from CFPPs in 2020. In addition, Indonesia's primary energy consumption increased by 16% between 2010 and 2020 (MEMR, 2021). IRENA (2017) also estimated that Indonesia's energy consumption will increase another 80% by 2030, making it critical for the country to meet its future energy needs and transition to renewable energy.

On the other hand, renewable sources in Indonesia are underutilised, which is detrimental to energy development and CO2 emissions reduction. Overall, Indonesia has an abundance of potential renewable energy. MEMR (2021) estimated the potential for 443.2 GW of renewable energy within the next decade, but only 10.5 GW has been deployed. Solar potential capacity is around 208 GW, while only 0.2 GW of solar energy has been installed (MEMR, 2021). Besides, there is an opportunity for the energy transition in Indonesia, as it is now becoming more economically viable. Cui et al. (2022) pointed out that coal power is losing its economic competitiveness, as renewable energy is rapidly falling in price in Indonesia.

Indonesia has shown substantial commitment to aligning with the Paris Agreement and achieving Net Zero through research, policies and Nationally Determined Contributions (NDCs). Suharsono and Lontoh (2022) stated that Indonesia signed the Global Coal to Clean Power Transition declaration at the 26th Conference of the Parties (COP26). To accommodate the transition toward net-zero emissions, the MEMR is considering accelerating coal plant retirements (Suharsono and Lontoh, 2022). Indonesia's government and state electricity company, Perusahaan Listrik Negara (PLN), pledged to stop building new CFPPs and launch a coal retirement programme by 2030. Yeap (2021) reported that PLN has committed to stop building coal plants in 2023 after being able to complete 35 gigawatts of projects. As part of this commitment, PLN will deploy only renewable energy in the future, with the aim of becoming carbon neutral by 2050.

One of Indonesia's significant challenges is the inconsistencies and discrepancies in current electricity sector policies and regulations. The Asian Development Bank (2021b) highlighted that several of Indonesia's energy policy plans rely on unrealistic data input assumptions and provide contradictory and impossible goals, making clean energy less desirable (ADB, 2021b). Besides, there is a lack of consistent and incentivising policy that encourages the development of renewable energy projects. A lack of policies and unbalanced risk-allocated contracts make Indonesian renewable energy projects the most expensive region (ADB, 2021b).

Energy planning modelling has provided insights into energy access, resource use and sustainable development, which help support energy planning. In the energy transition context, energy models are crucial to planning long-term investments and sustainable development (Cannone et al., 2022). Models serve as a tool for decision-making and a method for analysing the impact of future technologies on the energy system (Gaur et al. 2019). Recently, there have been efforts to increase the role of society in energy planning and to strengthen the science–policy interface. The role of energy systems models has become more relevant as stringent climate policy, security and economic development concerns become more prevalent (Pfenninger, Hawkes and Keirstead, 2014).

The Open Source Energy Modelling System (OSeMOSYS) energy model is one of the least-cost, long-term energy system models (ESM), which can facilitate cost and emission implications analysis (Howells et al., 2011). It can help build optimum pathways to achieve the energy transition, which could potentially support Indonesia's future energy strategies and policies. The OSeMOSYS offers insights into how the electricity supply system evolves under different scenarios to generate national energy investment outlooks and policymaking, (Allington et al., 2022). Besides, this energy modelling can be improved and built on top of previous research and models to mitigate the contradictions and overcome the constraints.

This paper offers an extensive analysis and comparison of six scenarios categorized according to their electricity production and installed capacity, costs, and carbon dioxide emissions. The scenarios are based on Indonesia's target and policy, aiming to identify the most effective scenario and policy such as Coal phase-out and Net Zero. Electricity is the only sector of energy that is being discussed in this project. The study starts with Indonesia's energy context, opportunities, challenges, and current policy. This is followed by the material and methods used. Then, the result section presents the modelling outcomes, along with discussion and policy implications. Finally, conclusions are drawn and opportunities for future work are described.

Background

Long-Term Energy Modelling is one of the accepted methods that Indonesia's government and several non-governmental organisations. Other efforts have been made to use long-term energy modelling to understand energy transition pathways in response to the Paris Agreement. In 2021, updated Indonesia's NDCs reported the new NDC pathways to a low-carbon and climate-resilient future and set new energy goals to reduce emissions. This includes a national baseline scenario (business as usual) and mitigation scenarios. In the mitigation plan, renewable energy will make up 31% of the energy supply by 2050, while oil, gas, and coal supply will be reduced to 20%, 24%, and 25%, respectively. (MEF, 2021).

The government of Indonesia and PLN issued the National Electricity Supply Business Plan (RUPTL) 2021–2030 (Suharsono and Lontoh, 2022). Over the next ten years, several plans have been outlined and modelled for Indonesia's future power development. The RUPTL presents two energy-mix scenarios: an optimal scenario that adopts the least-cost principle and a low-carbon scenario that incorporates more renewables. RUPLT 2021–2030 investigated Net Zero can be achieved by 2060 with an increase of the total share of new renewable energy (NRE) in the energy mix to 24.8% by 2030 (Suharsono and Lontoh, 2022). In response to the Net-zero announcement, MEMR and PLN also released the report entitled Intelligent Strategies Power and Utility Sector to Achieve Indonesia's Carbon Neutral by 2050 (Suharsono and Lontoh, 2022). It modelled the net-zero pathway in 2045, 2050 and 2060 scenarios. The findings show that the goal can be achieved by implementing a coal phaseout in 2026 and increasing renewable energy by one-third in the energy sector before 2040.

The Minister for Environment and Forestry (MEF) and the British Embassy partnership, Mentari, published an update on coal phaseout modelling, using PLEXOS (The Energy Analytics and Decision Platform for all Systems) to estimate feasibility, investment and emissions in three coal phaseout scenarios until 2040, varying the target retirement year between 2046, 2056 and 2066 (Mentari, 2022). Mentari (2022) stated that the assumptions comprise no new coal power construction, increasing a minimum renewable share and introducing a carbon tax ($2/t$CO_2$). Based on the results, gas will replace coal as the primary energy source, followed by solar and hydropower. Similarly, Institute for Essential Services Reform (IESR) and the University of Maryland have conducted another study, *Financing Indonesia's coal phase-out: A just and accelerated retirement pathway to net-zero*, to develop a feasible plan for retiring Indonesia's CFPPs (Cui et al., 2022). In this study, the scenarios are developed using the Global Change Analysis Model (GCAM5). Cui et al. (2022) stated that the clean energy transition scenario showed that there will be 18 plants retiring by 2030, 39 plants retiring between 2031 to 2040, and 15 plants continuing to operate beyond 2040 at a low utilisation level before retiring before 2045 with international help.

Material And Methods

This section focuses on the methodology for developing long-term scenarios for the energy sector in Indonesia. A scenario is predicted by OSeMOSYS software, providing an in-depth analysis of technology insights, electricity capacity, costs and CO_2 emissions. An Indonesia starter data kit (Allington et al., 2021b) was used as primary data to develop OSeMOSYS modelling results.

OSeMOSYS and reference energy system

This study used the OSeMOSYS model, which is a bottom-up model. The OSeMOSYS is a least-cost model chosen for its ability to create pathways over extended periods up to 2070 (Howells et al., 2011). The OSeMOSYS model is also accessible through the clicSAND for OSeMOSYS spreadsheet-based interface (Moksnes et al., 2015). OSeMOSYS and its clicSAND interface offer the advantage of allowing a wide range of scenarios to be developed for free, which will be essential for future policymaking. It represents the electricity supply system with importing and extracting technologies, converting technologies, power plants, transmission and distribution network systems, and final energy demands based on the various fuels available (Allington et al., 2021b). This model provides a complete one-step analysis of the country's energy system. Its results can be incorporated into national energy system models and analysis to inform further insights into energy investment outlooks, policy plans and the evolution of power systems (Howells et al., 2011).

A fundamental element of an energy modelling framework is the Reference Energy System (RES), representing whole energy systems, including commodities and technologies, from primary energy resources to final energy demand (Fig. 1). Allington et al. (2021a) identified that a RES represents all existing and potential new technologies used in energy supply chains in a simplified graphical form. Additionally, the model incorporates the final energy requirements according to sector and exogenously supplied fuels.

Starter data kit

According to Allington et al. (2021b), the data were obtained through public databases, websites, the PLEXOS dataset and existing modelling studies. Using the starter data kit, the data set was gathered and designed to serve as a basis for creating models and scenario analyses. Indonesia's Starter Data Kit aims to reduce the data barrier for developing a simple zero-order energy system model for Indonesia. It can be incorporated as input data into the OSeMOSYS model (Allington et al., 2021b). Allington et al. (2021b) stated that a starter data kit consists of existing electricity supply systems, technical data for electricity generation technologies, power transmission and distribution, refineries, fuel prices, emission factors, renewable and fossil fuel reserves, and electricity demand projections.

Model assumptions

The principal model assumptions in this study were based on the 'Starter Data kit' (Allington et al., 2021b). Key assumptions used in model development are divided into four categories; Supply-Side Assumptions, Demand-Side Assumptions, Time Representation and Discount Rate.

Allington et al. (2021b) provided various power generation technology options. However, Indonesia's nuclear power plant has been excluded from this project due to its high costs According to Allington et al. (2021b), variable renewables are constrained to ensure the system operates under high renewable shares and meets the maximum share of total demand, as in Table 1.

Table 1
Renewable technologies permit demand

Technologies	Permitted electricity demand
Offshore Wind	10% of the demand
Utility-Scale PV, Decentralised PV, Utility-Scale PV With Storage and Onshore Wind	15% of the demand
Onshore Wind with Storage	25% of the demand
Biomass	30% of the demand

The demand-side technologies in the starter data kit were split by sector based on the proportions of demand in cooking and heating. However, transport demand is not considered in this study. Initially, the InputActivityRatio (the rate at which fuel is consumed) and CapacityToActivityUnit (converting technical data into activity it can generate) should be set to 1. Similarly, OutputActivityRatios (the rate of fuel provided) are 1.1 and 1.3, respectively. The OSeMOSYS model uses petajoules as the default unit of measurement, so the capacity-to-activity ratio is used for converting technology units from GW to PJ (Moksnes et al., 2015). In this project, the capacity-to-activity ratio was changed to 31.536.

The result was modelled from 2020 and 2070 with 8-time slices as it represents hourly energy demand throughout one calendar year. According to Allington et al. (2021b), each model year is divided into four seasons, each with two 12-hour dayparts. The first part of the day starts at 6:00 and ends at 18:00. The second part of the day starts at 18:00 and ends at 6:00. Season one runs from December to February, season two runs from March to May, season three runs from June to August, and season four runs from September to November. Additionally, the selected discount rate in this project is 10%.

Scenarios

These six scenarios are developed to determine Indonesia's energy section's alternative pathways. The scenarios were based on current Indonesian commitment, NDCs, current policies, and an optimal scenario, developed with CCG and the ETC. A reference scenario is the BAU scenario. Then, other alternative scenarios are explored which are mainly based on Indonesia's policy and renewable opportunities. It includes coal dependence reduction, renewables deployment and Net Zero. Table 2 shows the name, description and assumptions of each model scenario.

Table 2
Scenario description and assumptions

Scenario	Description	Assumptions
Business as usual, BAU	The scenario is based on the first NDCs in 2016 (MEF, 2021) and is referred to as a baseline scenario.	CFPPs are the primary electricity source. Renewable power plants, including geothermal, hydropower, solar PV, wind turbine, biomass and biofuel, are prohibited from investing in new facilities.
Least Cost, LC	Cost-optimal solutions are determined automatically and generated by OSeMOSYS.	Energy efficiency and demand-side fuel (stoves, heating technologies) face gradual investment constraints, which limit annual investment to 5% of capacity without demand-side investment constraints by 2050.
Coal phaseout 2045, CP45	Bissett et al. (2021) stated that PLN plans to initiate coal retirement plans by 2030 and stop building new coal-fired plants after 2023. Cui et al. (2022) stated that Indonesia could phase out coal in 2045 with international help.	No new CFPPs will be built after 2023. Coal activities will decrease steadily until there is no coal activity after 2045. Various renewables are restricted to meet the maximum share of total demand. Future energy demands will be met with alternative technologies, especially renewables, instead of coal.
Coal phaseout 2056, CP56	Bissett et al. (2021) stated that PLN plans to initiate coal retirement plans by 2030 and stop building new coal-fired plants after 2023. According to RUPTL 2021–2030, Indonesia wants to phase out coal and gradually reduce coal activities by constraining imported coal and CFPPs by 2056 (Bissett et al., 2021).	No new CFPPs will be built after 2023. Coal activities will decrease steadily until there is no coal activity after 2056. Various renewables are restricted to meet the maximum share of total demand. Future energy demands will be met with alternative technologies, especially renewables, instead of coal.
Net zero 2050, NZ50	The optimal scenario, according to RUPTL 2021–2030 target (Christian Breyer *et al.*,2021)	CO2 emissions are constrained by gradually reducing carbon-emitting technologies from 2021 to 2050 to reach carbon neutrality in 2050. Solar investment and capacity are constrained to gradually meet total demand.
Net zero 2060, NZ60	According to RUPTL 2021–2030, the government aims to reach net zero by 2060 or sooner (Bissett et al., 2021).	CO2 emissions are constrained by gradually reducing carbon-emitting technologies from 2021 to 2060 to reach carbon neutrality in 2060. Solar investment and capacity are constrained to gradually meet total demand.

Results, Discussion And Policy Recommendation

This project explores six scenarios, BAU, LC, CP45, CP56, NZ50 and NZ60, with individual constraints and targets. A comparison was made between the outcomes of the different scenarios and BAU. Each scenario is evaluated based on three criteria: electricity production and installed capacity, total system costs, and CO2 emissions. Next, an explanation of policy recommendations based on modelling results follows.

Power generation and installed capacity

Figure 2 and 3 illustrate the electricity production and annual installed capacity by scenarios. BAU is a business-as-usual scenario which is the national baseline scenario in NDCs and this study. This scenario focuses only on fossil-based technologies without any renewables. So, a large portion of the electricity generated in BAU and LC scenarios comes from coal, with a maximum of 5,600 PJ in 2070 (Fig. 2). Similarly, in Fig. 3, CFPPs capacity is predicted to be the highest-used technology in BAU and LC scenarios accounting for 247 GW and 180 GW respectively. In the BAU scenario, the largest share of investments is coal, while clean power plants account for a small portion. In contrast, there is a significant proportion of renewables in the LC scenario, including solar (163 GW), wind (144 GW) and solar with storage (93 GW) (Fig. 3).

On the other hand, clean electricity production is predominant in the CP45, CP56, NZ50 and NZ60 scenarios as shown in Fig. 2. Solar and solar with storage are expected to be the most widely used technology in both CP scenarios, while NZ scenarios rely on solar and onshore wind power plants. Although there is an 11-year gap between CP45 and CP56 scenarios, they have similar installed capacity and supply generations. As a result of retiring coal plants, they rely heavily on renewable energy, especially biomass. Biomass power plants are a primary power generation in CP45 and CP56 scenarios, with a total generation of 52,716.89 and 47,740.50 PJ, respectively (Fig. 2). However, the proportion of natural gas increased after coal was retired, decreasing the share of renewable energy in both scenarios (Fig. 4). Additionally, gas-fired power plants are becoming more popular because they are more abundant, cheaper, and easier to access than renewable energy sources. According to Fig. 3, natural gas increases to meet the rising demand, which can go up to 86 GW in the CP45 and 67 GW in the CP56 scenario by the end of their period.

According to the results, renewable technologies account for a similar share of electricity production and installed capacity in both the NZ50 and NZ60 scenarios, forecasted to grow from around 80% in 2030 to 100% in 2070 in NZ50 and NZ60 scenarios (Fig. 4). Solar power plays a vital role in both scenarios for supplying electricity and with regards to installed capacity, making they have higher power generation and capacity. The NZ50 scenario invests in solar and onshore wind energy, with a small proportion of coal, natural, CCGT gas and SCGT gas remaining until 2050 (Figs. 2 and 3). By 2050, NZ50 will have 100% renewable energy in its energy mix. Similarly, solar PV (utility) and onshore wind dominate its energy mix in the NZ60 scenario, but coal, natural gas, CCGT gas and SCGT gas capacity will remain a small portion until 2060.

Costs

Figure 5 compares the discounted costs of six scenarios in a million USD from 2020 to 2070, separating the total costs into three categories: capital, fixed and variable costs. This paper used a 10% discount rate, which is a typical value, to set a benchmark for considering risks in a future investment (Allington et al., 2021b). The electricity generation in BAU scenarios heavily relies on coal. There are a few clean energy sources, while the CFPP investment is eight times higher than the investment in geothermal power plants. So, BAU has the highest variable cost relative to the other scenarios due to fuels from the high fossil-based activity and new investments. However, BAU also uses fewer new technologies, resulting in lower fixed and capital costs. The LC scenario is developed to find the cheapest pathway to meet future demand. With a cost of only 4,300 billion USD, this represents the lowest energy expenditure for Indonesia to meet its energy needs. In this scenario, renewable energy has more room to grow, even though it costs 1,700 billion USD less than BAU (Fig. 5). Thus, deploying renewable power plants can reduce the investment needed in the energy sector.

Comparatively, the cost of CP45 and CP56 scenarios does not differ according to their share of renewables. However, the coal phase-out scenarios still have higher variable costs than NZ scenarios in the long term, due to the presence of other CO2-emitting technologies such as the oil and gas sectors. According to the results, renewables and solar power play a significant role in NZ50 and NZ60 scenarios for supplying electricity and investing in installed capacity (Fig. 5). Consequently, fixed and variable costs differ according to the selected power plants in these scenarios. However, the total price does not differ significantly.

The modelling findings indicate that all scenarios can provide electricity to Indonesia's energy sector, but not all pathways are effective in terms of costs, environmental impact and implementation period. When NZ scenarios are implemented with the same initial budget as BAU, they will have a substantial advantage in long-term savings due to lower fuel variable costs.

Annual Carbon Dioxide Emissions

Undoubtedly, the BAU scenario will emit more CO2 than any other scenario over the modelling period (Fig. 6). Consequently, it is expected to increase significantly. BAU consists only of fossil-based technologies that release much more carbon dioxide into the atmosphere. This scenario generates some renewable energy, but the capacity is too small to impact the energy mix significantly. In this study, the BAU scenario is chiefly considered a reference scenario, as it will not achieve an energy transition. In Figs. 6 and 7, the CO2 emissions in the LC scenario are less than in the BAU scenario but do not achieve carbon neutrality. Similarly, the leading electricity generators also come from CO2-emitting technologies. Although the model estimates that renewable energy will account for 70% of 2070, it saves only 30% of carbon emissions (Fig. 8). Therefore, the LC scenario is not considered the best option for the energy transition,

Both CP45 and CP56 produce similar outcomes because they have the same constraints; the only difference is the target year to achieve the coal phaseout ultimately. However, the delay in the coal phaseout has resulted in CP56 emitting nearly 3,000 MtCO2 more than CP45, making cumulative carbon dioxide emissions of CP56 slightly higher than CP45 (Fig. 6). Biomass and solar production are both used in the production of electricity in CP45 and CP56. Despite the absence of new CFPPs and no coal activity after the targeted year, a small proportion of other fossil-based power generations still contribute carbon dioxide to the atmosphere. Compared to the BAU scenario (Fig. 8), CP45 and CP56 can reduce CO2 emissions by 70% and 65%, respectively. However, neither scenario results in zero carbon. In Indonesia's energy mix, the coal phaseout scenario can reduce CO2 emissions significantly but not enough to create a complete energy transition.

Alternatively, achieving the energy transition through net-zero scenarios is possible. This project focuses on achieving Net Zero by 2050 and 2060. The result illustrates that NZ50 releases the least carbon dioxide with only around 10,100 MtCO2 or 86% carbon savings compared to the BAU as renewable technologies dominate the energy mix (Fig. 8). In the same way, the NZ60 scenario emits CO2 of only around 17,000 MtCO2, which is a 76% reduction over the BAU, second only to the NZ50 scenario (Fig. 8). There is a significant difference between NZ60 and NZ50 in CO2 emissions, although NZ60 has almost the same share of renewable shares as NZ50. One of the possible reasons is that a ten-year gap between 2050 and 2060 allows fossil-based power plants in the NZ60 scenario to generate an extra 2,500 MtCO2 in the intervening years (Fig. 7).

Long-term energy modelling comparison

This section compares scenarios based on current policy and existing energy models with optimal scenarios. BAU and NZ60 scenarios refer to the first NDCs in 2016 and Indonesia's commitment, while CP56 corresponds to PLN's announcement in 2021. In comparison, LC is the most economical way to meet future energy demand, while CP45 and NZ50 scenarios are optimal goals to achieve.

The updated NDCs include a goal of using 31% renewable energy, as well as a minimum 25% reduction in coal, oil and gas usage by 2050. (MEF, 2021). In contrast, this study suggests that Indonesia has a much higher potential to expand at least 47% renewable capacity growth in LC and at most 100% in NZ50 by 2050. One possible reason is that NDCs scenarios may focus on enhancing energy efficiency, introducing renewable energy to electricity, and using alternative fuels for transportation rather than CO2-emitting technologies.

The RUPTL 2021–2030 is another energy strategy plan aiming to accelerate investment in clean energy in Indonesia to achieve Net-Zero emissions by 2060. Suharsono and Lontoh (2022) mention that the RUPTL 2021–2030 aimed to scale up the total share of NRE in the energy mix to 24.8% before 2030 to achieve the target. However, the modelled outcomes of this study illustrated that the proportion of clean energy capacity in 2030 of the CP45, CP56, NZ50 and NZ60 scenarios are higher than the (RUPTL) 2021–2030 prediction, accounting for 73%, 66%, 87% and 87%, respectively.

To achieve the PLN's coal retirement target, Yeap (2021) reported that the energy mix requires about 5,400 PJ of renewable-generated electricity by 2050. Even though the PLN’s coal phaseout scenario cannot result in zero carbon emissions, new renewable energy installations are essential for the country to step closer to its national targets. According to the coal phaseout results, clean energy in the CP45 scenario can produce an average of 3,510 PJ, while the CP56 can generate 3046 PJ by 2050. The predicted number is lower than PLN's prediction. Another study on a coal phaseout scenario – *Financing Indonesia's coal phase-out*, a report published by IESR – showed that the accelerated coal phaseout scenario is feasible by 2045 with international help (Cui et al., 2022). Also, this study corresponds and confirms that CP45 is feasible by gradually reducing all coal activities, resulting in saving 70% of CO2 emissions compared with the BAU scenario.

In general, the modelling results align with the other models. However, the numbers may differ depending on the model, the calculation, and the data set used in the model.

Policy recommendation

This study could serve as a guide for policymakers. NZ50 represents Indonesia's most cost-effective pathway to the energy transition, considering electricity production, investment and carbon dioxide emissions. Although CO2 emissions in Indonesia can also be significantly reduced in CP45 and CP56, merely phasing out coal activities cannot lead to zero carbon emissions. The level of carbon dioxide in CP45 and CP56 scenarios cannot fall to zero due to the existence of other fossil-based power plants and the rise of natural gas. Therefore, the only pathways that can reach carbon neutrality are NZ50 and NZ60. Although NZ50 has similar costs to NZ60, NZ50 has fewer CO2 emissions than NZ60.

A vital component of the energy transition is reducing CO2 emissions from energy-related sources to limit climate change. Accordingly, neither reducing carbon emissions only from coal technologies nor deploying new renewables is sufficient to achieve the Net-zero goal; both these actions need to be taken simultaneously. Thus, Indonesia's power sector will only achieve energy transition through NZ50 and NZ60 scenarios. By 2050, the goal of becoming carbon neutral would save more funds and reduce CO2 emissions more effectively than any other scenario. According to NZ50, Indonesia must adopt and deploy 87% renewable energy before 2030 and meet 100% renewables in 2070. While deploying more renewable energy, the government needs to quickly phase out CFPPs and other CO2-emitting technologies in the next few years to achieve the transition to a carbon-free energy system and reach Net Zero by 2060 or sooner.

Conclusions And Future Work

This study shows reasonable pathways to reach energy transition in Indonesia. based on OSeMOSYS modelling. All presented scenarios are possible to meet Indonesia's future energy demand at their lowest implementing cost; however, some scenarios are more cost-effective than others in terms of costs, environmental impact and implementation period. Although CO2 emissions in Indonesia can also be significantly reduced in CP45 and CP56, it is evident from previous research and this study that a coal phase-out by 2045 cannot be achieved without international support (Cui et al., 2022). CP45 reduces CO2 emissions significantly and costs less than NZ50, but may not be feasible for Indonesia, since coal is still heavily used in their energy mix. So, the only appropriate pathways that can reach carbon neutrality are NZ50 and NZ60. NZ50 has a lower CO2 footprint than NZ60 despite having almost exactly the same cost. Therefore, it can be concluded that NZ50 is the most cost-effective pathway to energy transition in Indonesia, considering readiness, feasibility and environmental benefits.

The paper emphasises that phasing out carbon-emitting technologies and new renewable energy (NRE) is imperative to the energy transition's success. Indonesia has an excellent opportunity to reduce its energy sector's climate impact through superior renewable technologies and the phaseout of fossil-based technologies. According to the NZ50 model, increasing solar PV capacity is essential to meet future energy demands, which will become more feasible and worthwhile as solar prices decline. As shown in NZ50, phasing out all fossil-based activities and increasing NRE deployment can dramatically reduce climate change-causing CO2 emissions, and it will finally be possible to transition to carbon neutrality in the energy sector.

Future work

This project presents a holistic energy analysis of Indonesia's energy section, but there are some limitations in scenario development and model application. The assumptions and results are based on a future-oriented analysis, which makes them uncertain. Inconsistent data and unpredictable events, such as natural disasters, make it impossible to predict the exact outcome in advance. So, it would be beneficial to conduct a further in-depth detailed analysis of the cost, flexibility implications and alternative technologies. The assumptions and results in this project are based on a modelled analysis, so in-depth cost analyses are advised to develop the results regarding financial implications. In addition, further flexibility and sensitivity analysis can be performed to improve the results. Better estimations will allow policymakers to make better decisions and update plans for future policies and investments.

It would be worthwhile to investigate a broader range of optional clean technologies and scenarios to create better alternative scenarios. For example, Carbon Capture and Storage (CCS) applications must be considered in the energy transition to provide the most accurate scenarios and results, as such technologies will be crucial to carbon neutrality and decarbonisation planning. However, CCS is not included in this study due to limitations in OSeMOSYS. The CCS application is still under investigation to provide the most accurate scenarios and results.

Declarations

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Figures

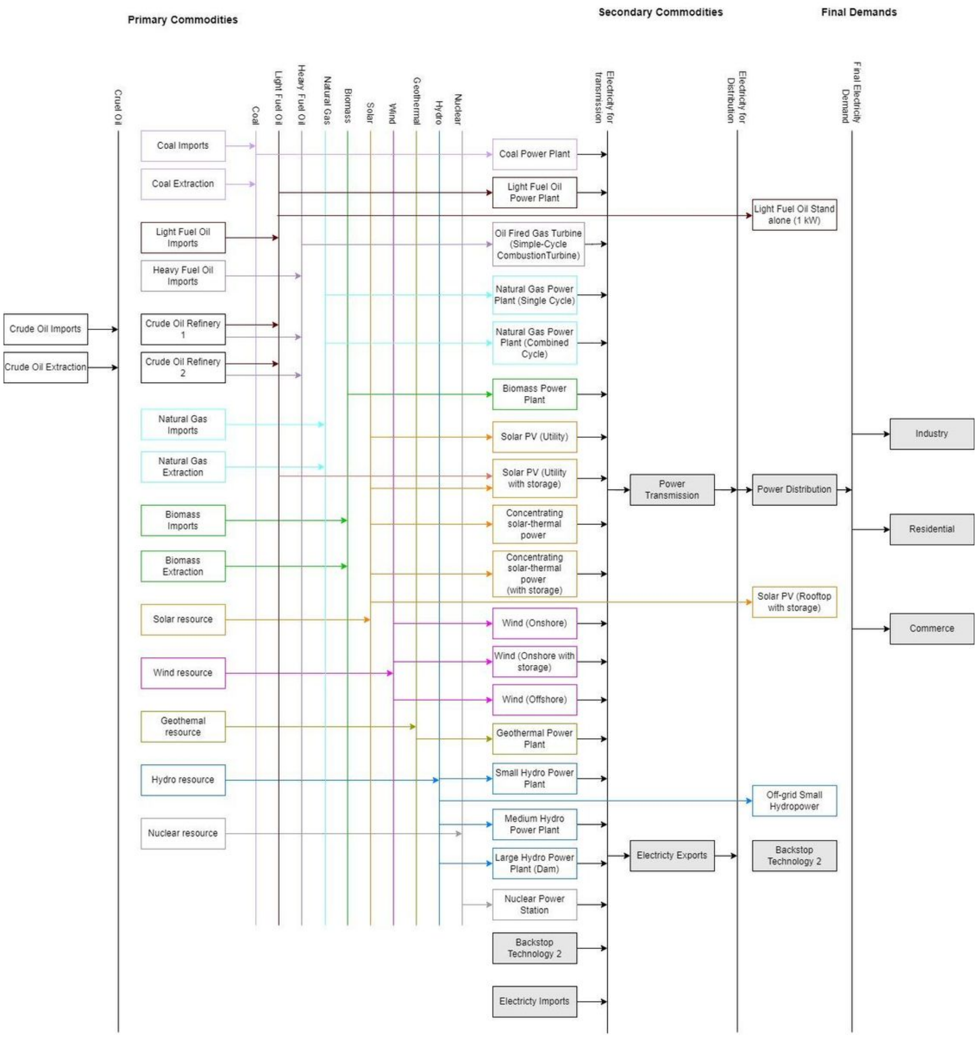

Figure 1

Full Reference Energy System (RES)

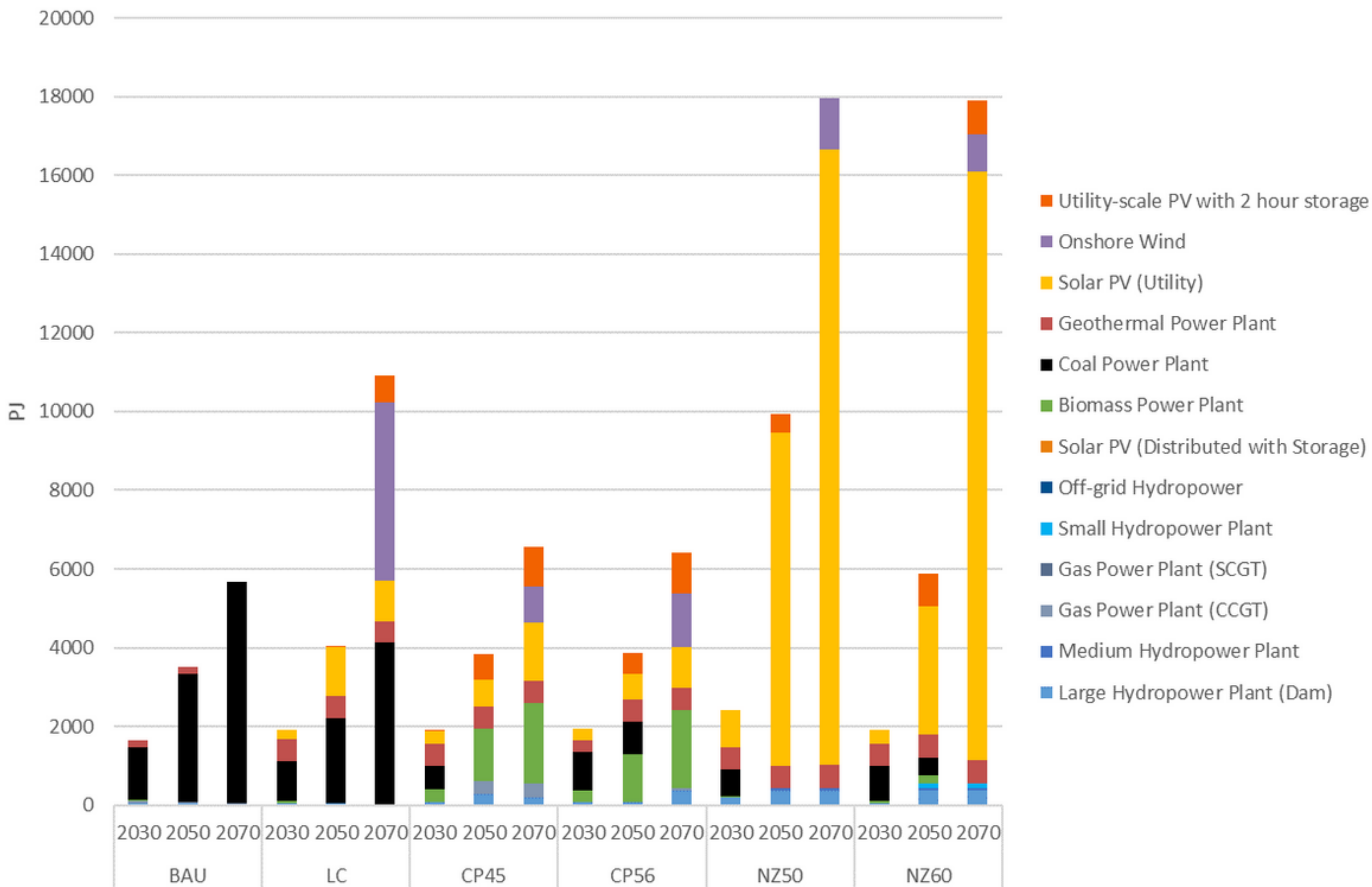

Figure 2

Electricity generation in different scenarios between 2020 to 2070

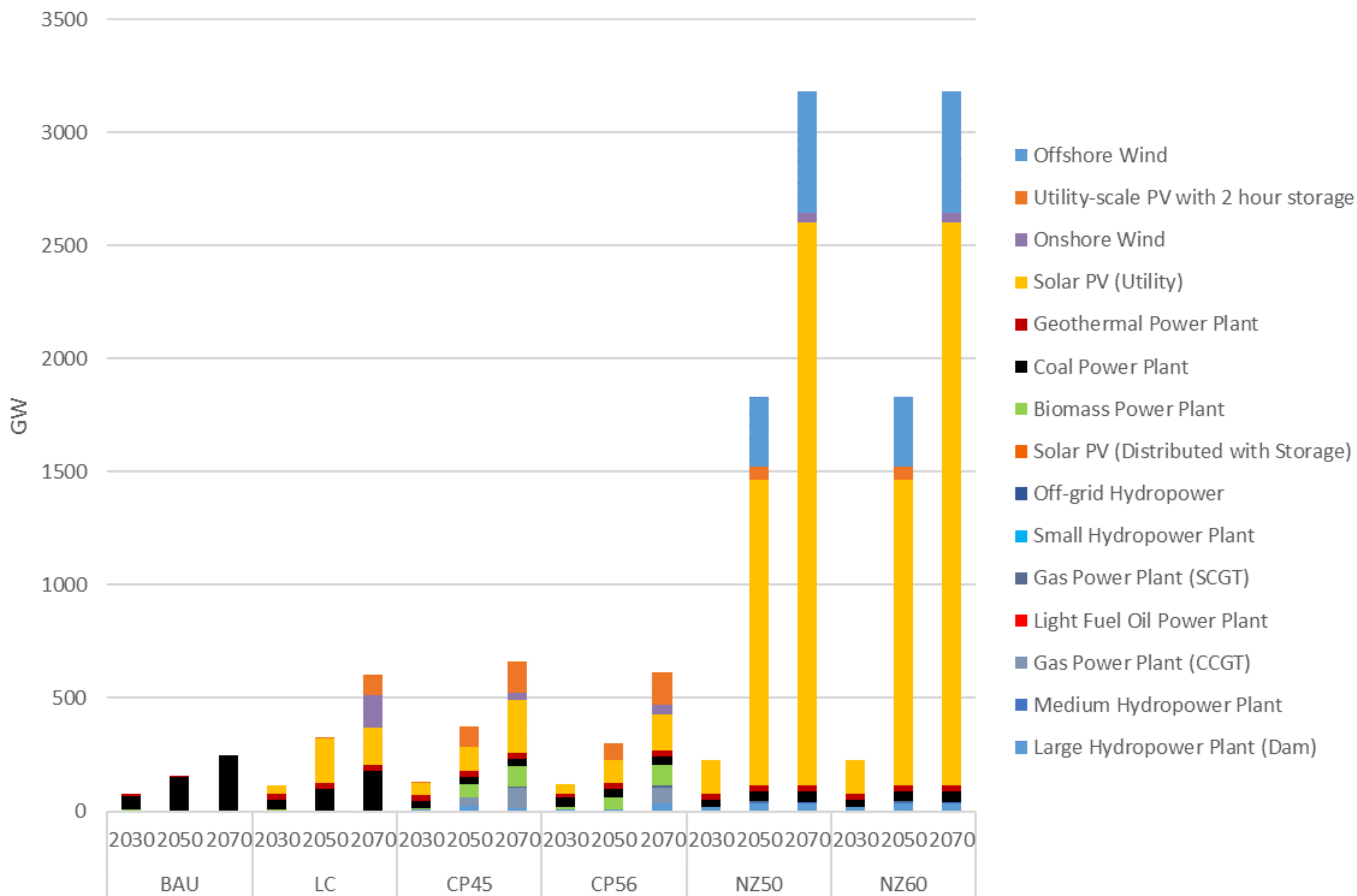

Figure 3

Installed capacity in different scenarios between 2020 to 2070

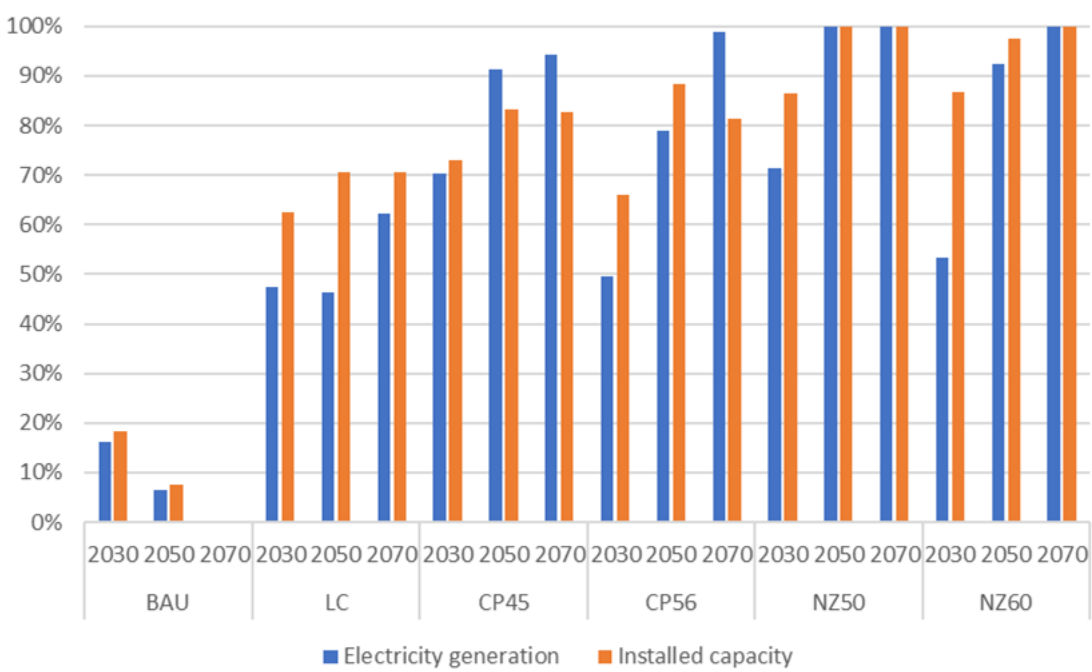

Figure 4

Electricity generation and Installed capacity in different scenarios between 2020 to 2070

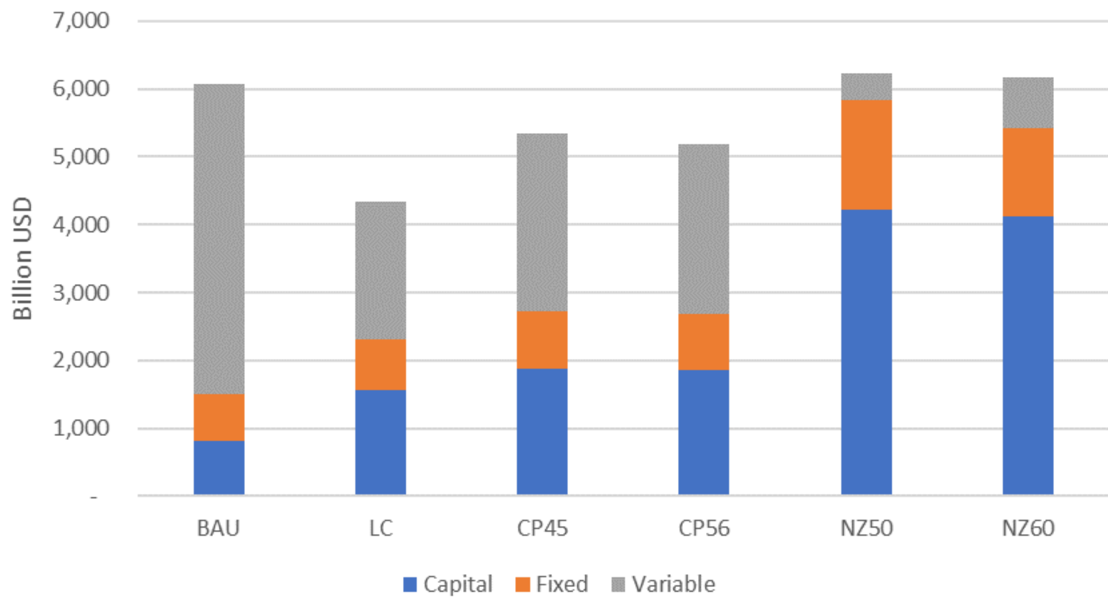

Figure 5

Total Discounted Cost by Categories

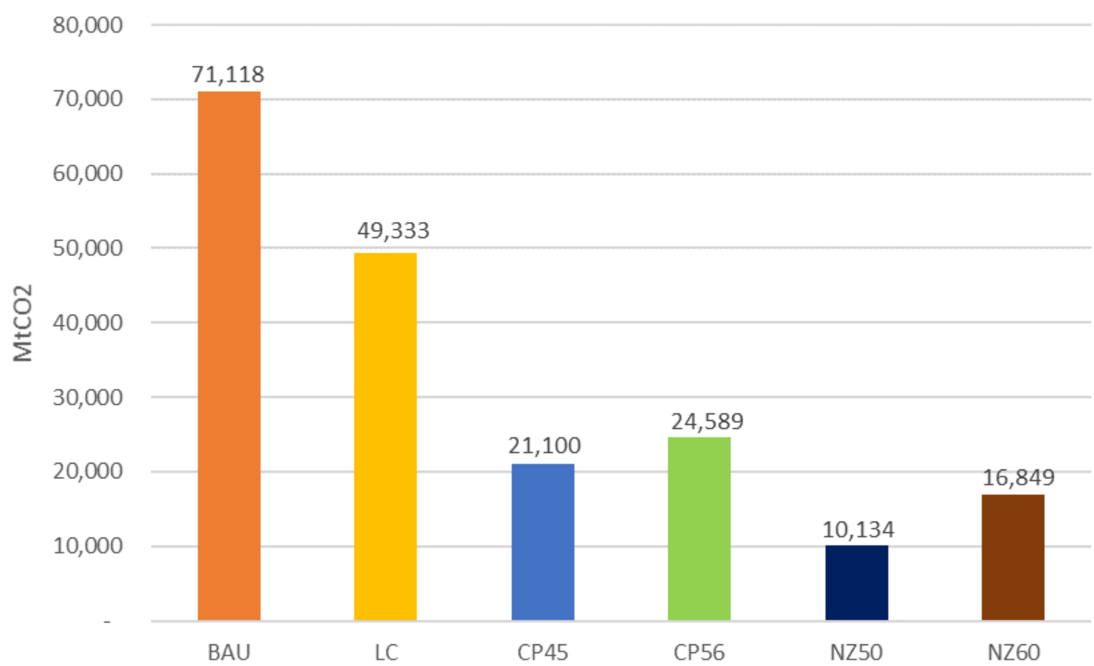

Figure 6

Annual CO2 Emissions

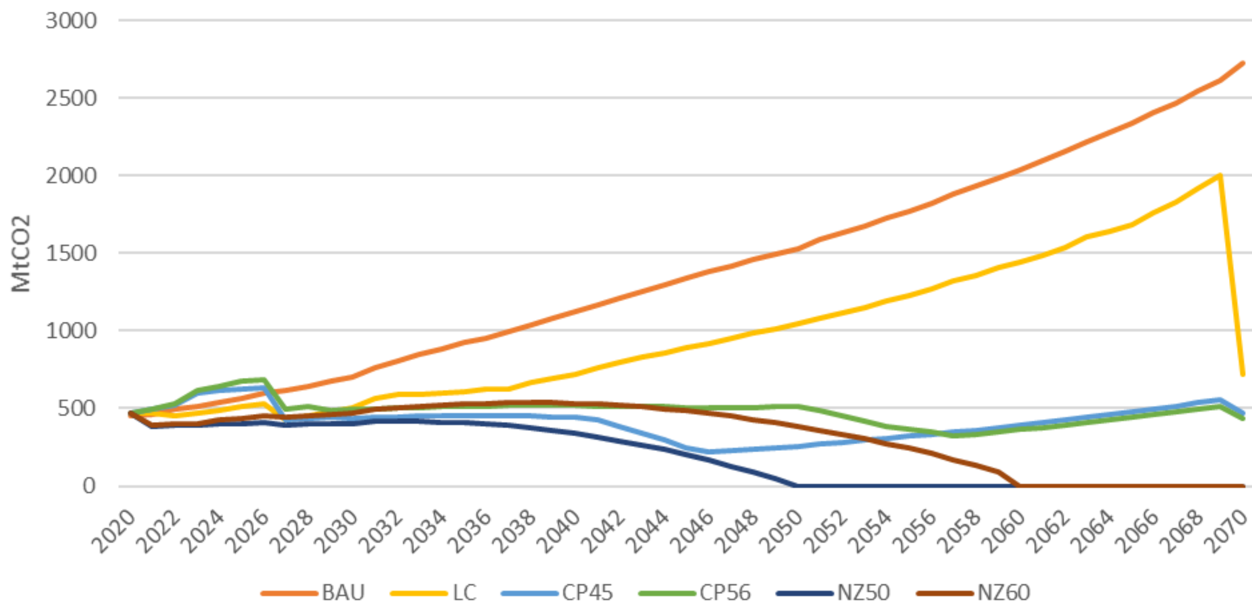

Figure 7

Annual CO2 Emissions

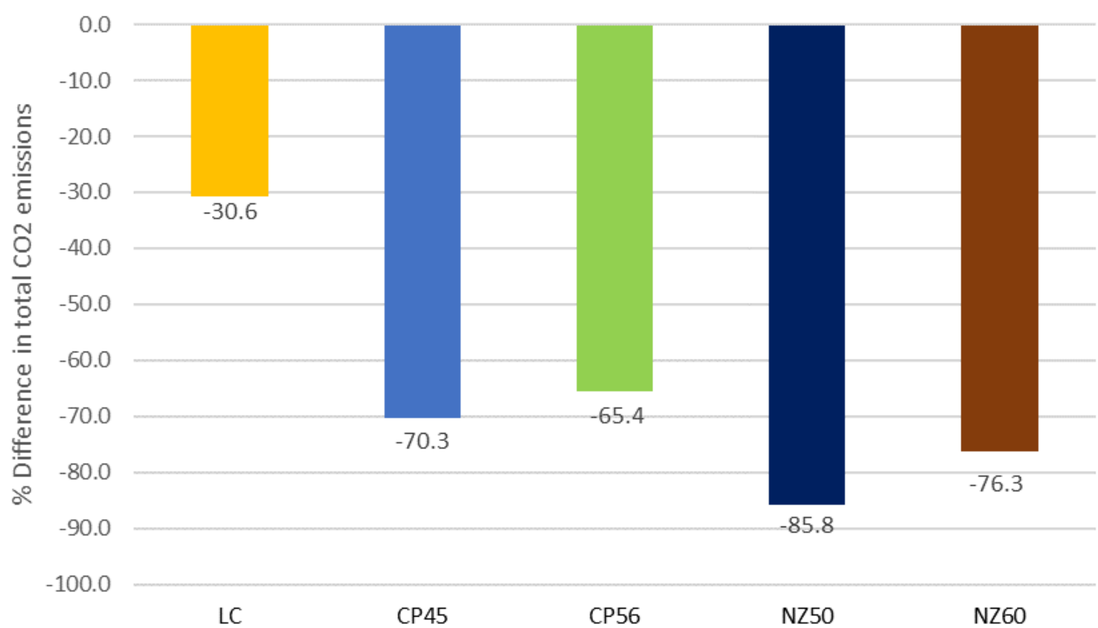

Figure 8

Total CO2 Emissions Saving Compared to BAU