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Deep decarbonization of Indonesia's energy system

A pathway to zero emissions by 2050

Imprint

Deep decarbonization of Indonesia's energy system: A pathway to zero emissions by 2050

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Foreword

The year of 2020 was a special year for climate and environment. Global carbon emissions fell 7% due to the pandemic. Countries around the world have pledged for carbon and climate neutrality by mid-century. Major economic powers such as the United States, the European Union, China, Japan, South Korea as well as developing countries such as Chile, Brazil, and South Africa have indicated the goal in their NDC updates.

The race for carbon neutrality has started to both achieve the Paris Agreement and reap the benefits of greening the economies. The average temperature has already risen 1.1 degrees above pre-industrial levels. To keep the average temperature "well below 1.5 degrees," as required by the Paris Agreement, global greenhouse gas emissions must decrease significantly and immediately.

Will Indonesia – the largest nation in Southeast Asia – be the first country in the region to declare carbon neutrality by mid-century? If so, how can Indonesia build a society that does not rely on coal and oil?

Due to its size and growing energy demand, Indonesia is of key relevance for Southeast Asia, one of the fastest growing regions in the world. At the same time, Indonesia is already today – and will be even more so in the future – highly affected by the negative impacts of climate change.

IESR, Agora Energiewende, and Lappeenranta-Lahti University of Technology (LUT) analyzed several pathways for Indonesia to reduce its GHG emissions. This study is the first of its kind for Indonesia, which makes it quite revolutionary. Can Indonesia entirely rely on renewables to supply its energy? What if the whole country – from Sabang to Merauke – were interconnected?

Looking 30 years ahead, the study describes a vision of zero emissions in the Indonesian energy sector by 2050. Though based on existing technology and the best available assumptions, this vision is not meant as the only feasible scenario or roadmap. Rather, it shows the magnitude of the transformation needed in Indonesia to reach the targets. We hope that the proposals outlined provide orientation in the ongoing debate and serve as an impetus for creative and energetic change.

May 2021

Fabby Tumiwa
Executive Director IESR

Key Messages

1

Achieving zero carbon emissions in the Indonesian energy system by 2050 is technically and economically feasible. Local renewable resources, particularly solar PV, are sufficient to meet energy demand in the country.

Our Best Policy Scenario (BPS) shows that deep decarbonization of Indonesian energy system by 2050 is technically and economically feasible, by using 100% renewable energy. In the primary energy mix, renewables' share grows rapidly to around 80% by 2040, until it finally reaches 100% by 2050. In electricity generation, around 50% electricity is produced from renewable sources by 2030 before reaching 100% by 2045.

Among the three scenarios, the BPS has the least annual cumulative system costs by 2050, despite its high share of renewables, while the Current Policy Scenario (CPS) has higher annual system costs from 2035 onwards. This low cost is driven by technological developments and the decreasing cost of capital.

The combination of increasingly competitive solar PV, batteries, low-cost electrolyzers, and huge solar potential throughout the archipelago will make solar PV the primary source of electricity generation in Indonesia by 2050 with generation share at around 88%, followed by hydropower at 6%, geothermal at 5%, and other renewables at 1%. This 88% solar PV share is equal to 1,492 GW of solar PV installed capacity with a total land requirement of 2.5% (excluding forest and water) of the country, a relatively small land requirement compared to biofuel plantations at 6.4%.

2

The major GHG emission reduction will be based on heavy utilization of electricity in different sectors, massive renewables deployment and declining fossil fuels infrastructures.

To reduce GHG emissions, not only the power sector needs to transform, but also the transport sector and the industrial heating sector. Replacing internal combustion engine (ICE) vehicles and fossil-fueled industrial heating with new technologies, such as electric vehicles and heat pumps, that run on electricity will help shift the emission source from fuels to electricity. As long as carbon is reduced on the power system (replacing fossil fueled power plants with renewables), every single electrical device will get cleaner throughout its lifetime.

3 A secure and reliable future energy system based on renewables is possible by using large amounts of storage and electrolyzers to balance supply and demand, along with energy carriers for transportation and industry.

Our model shows that the future energy system will be dominated by high shares of variable renewable energy, first and foremost solar photovoltaic (solar PV). Integrating strongly increasing shares of variable renewable energy in the system will require very substantial investments in the transmission and distribution grid and in energy storage technologies to account for daily and seasonal variations of solar PV supply. These include modern batteries and pumped hydro energy storage, the use of electricity for electrolysis to produce synthetic fuels and hydrogen, which will both serve as additional energy storage, energy suppliers, and feedstock for other sectors, such as transportation and industry.

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4 Electrification will be key for individual mobility, and biofuels will continue to play an important role in the transport sector.

In the transportation sector, electric vehicles will make up 90% of vehicles in the road passenger transport sector by 2050. Biofuels will still play a role in sub-sectors that are much harder to electrify, in particular maritime shipping and aviation. Direct electrification of the transport sector will result in higher efficiency. With large adoption of electric vehicles, the carbon emissions from the transport sector will largely depend on the decarbonization of the power sector that supplies electricity for these vehicles. Where higher energy density is needed, e.g. in freight transport, aviation or high temperature industrial heating, biofuels or new energy carriers such as hydrogen will be utilized.

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5 Energy system transformation is an opportunity to modernize energy systems while driving economic growth. To make it happen, a good investment climate is needed.

The energy system transformation will require an estimation of USD 20-25 billion investment per year from now through 2030, much higher than the average investment in the Indonesian renewable energy sector at less than USD 2 billion per year. Through 2030-2040, the country will need an annual investment of USD 60 billion to ramp up the decarbonization efforts. Investments are well spread and channeled for different clean energy technologies. Investment in solar PV (including rooftop solar PV) will become the highest at around USD 2-7 billion per year for the next ten years. The solar PV investment will need to increase to USD 20-25 billion per year between 2030 and 2040, around a third of total investment needed in that period. With solar PV becoming the backbone of the energy system from 2030 onwards, investment in batteries will be crucial and reach as high as USD 13-16 billion per annum from 2030 to 2040.

The Indonesian government must improve the investment climate in the country rapidly and comprehensively considering that renewables investments only reached USD 1.17 billion in 2019. A supportive policy and regulatory framework can attract more private investors to invest in renewable energy, energy efficiency, and low-carbon transportation projects in the country. Alignment and consistency between medium and long-term targets are also essential. Policies and regulation will need to dissuade existing preferences for carbon-intensive energy production, instead setting incentives for investments in renewables.

6 Call for moratorium on new coal-fired power plants as soon as possible.

Around 38 GW of coal-fired power plants had been installed by the first semester of 2020. The state-owned power utility plans to increase coal capacity to 57 GW by 2028, putting coal at 55% of total power generation that year. According to our analysis, however, coal's share in total power generation will have to steeply decrease to 12% in 2035 before reaching virtually zero by 2045/2050. Even existing coal fired power plants will lose their competitiveness within 15 years from now due to the competitiveness of renewables. Therefore, any additions to coal capacity will run into the risk of being a stranded investment. A coal moratorium as soon as possible is therefore necessary to protect investments and free up capital to invest in renewables instead.

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7 The archipelago country needs to be more integrated, particularly from 2030 onwards.

Located at the equator, Indonesia is rich in solar energy. While solar potential is evenly spread across the archipelago, energy demand is not. The island of Java currently accounts for around 80% of energy demand in the country. Assuming the island will remain the main energy consumer in the country, it will need to import 4.6% of its demand by 2030, 45.5% by 2040 and 82.1% by 2050 under our Best Policy scenario. The integration is also needed to allow the power, transport, and industry sector coupling.

The imports will come from neighboring islands such as Sumatra, Kalimantan, and Nusa Tenggara. To make this plan happen, grid integration is needed. Submarine connections between Java and Sumatra could be the first interconnection developed before connecting Java with other islands. Building power grids will take time, so the government should start planning and subsequently constructing a modern and capable grid infrastructure between and within all major islands straight away.

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8 Deep decarbonization will bring massive opportunities to Indonesia's economy

Rich in renewable energy, Indonesia is well-endowed to transition to a 100% renewable energy system. Deep decarbonization is not only key in reducing carbon emissions but also in rejuvenating Indonesian economy post pandemic. Projects of renewable energy, energy efficiency, and clean transport are shovel ready projects that will not only create jobs immediately but also bring long-term positive impacts on the environment and communities. At minimum, Indonesia will see more than 800,000 new jobs by 2030 and more than 3.2 million new jobs by 2050 if the country follows through the deep decarbonization pathway.

Other important co-benefits of decarbonization are the avoided costs of climate damages, increased energy efficiency, better air quality, avoided deaths and healthcare costs, more resilient energy systems, increased water availability and food security, healthy ecosystems and rich biodiversity, avoided costs of stranded assets, lower energy expenditure and subsidies, universal access to energy through the use of local, renewable energy resources, and new economic opportunities in rural areas.

Introduction: Status quo, scenarios and methodologies for assessing Indonesia's energy future

The global wave of climate pledges

The year of 2020 has become a special year, not only due to the COVID-19 pandemic, but also for the climate and environment. Global carbon emissions contracted by 7% due to the pandemic, mainly driven by the fall in global energy demand. While oil and coal consumption dropped, renewables were less affected by the pandemic. Installed renewable energy reached almost 200 gigawatts (GW) globally, with or without government support (IEA, 2020; IEEFA, 2021). Energy transitions are underway and inevitable, even amid the pandemic.

Political transformations are also happening at a high level with more political actors committed to climate actions. The increased political will translates into more commitments from countries around the world to reach carbon and climate neutrality by mid-century. Major economic powers like the US, European Union, China, Japan and Korea, as well as emerging countries like Chile, Brazil and South Africa have pledged to make its economy carbon neutral mostly by 2050 (excluding China that targets to become carbon neutral by 2060).

We are now locked in a race to achieve climate neutrality. The average temperature has already risen 1.1 degrees above pre-industrial levels. To keep the average temperature "well below 2 degrees," as required by the Paris Agreement, global greenhouse gas emissions must decrease significantly. Renewables play a major role in that process.

Indonesia is currently amongst the top 10 greenhouse gas (GHG) emitters and still projected to increase its emissions. Will Indonesia be the first country in Southeast Asia to declare carbon neutrality? If so, how can Indonesia build a society that does not rely on coal and oil?

Current status of Indonesia's energy system

Indonesia aims to reduce its greenhouse gas (GHG) emissions by 29% (or 41% with international support) compared to the Business as Usual (BAU) scenario by 2030. As one of the sectors contributing to GHG emissions, the energy sector is also the second largest emitter in Indonesia, contributing around 40% of total emissions between 2010 to 2018. Emissions from the energy sector are predicted to increase to 58% by 2030, as indicated under the BAU scenario in Indonesia's Nationally Determined Contribution (NDC), mainly driven by the increase in the final energy consumption. The projection is in line with the trend in emission intensity where GHG emissions per final energy consumption has not seen a significant improvement in the last decade.

Indonesian GHG Emission, 2010-2018 and BAU 2030 based on NDC, & GHG Emission per Final Energy Consumption, 2010-2018

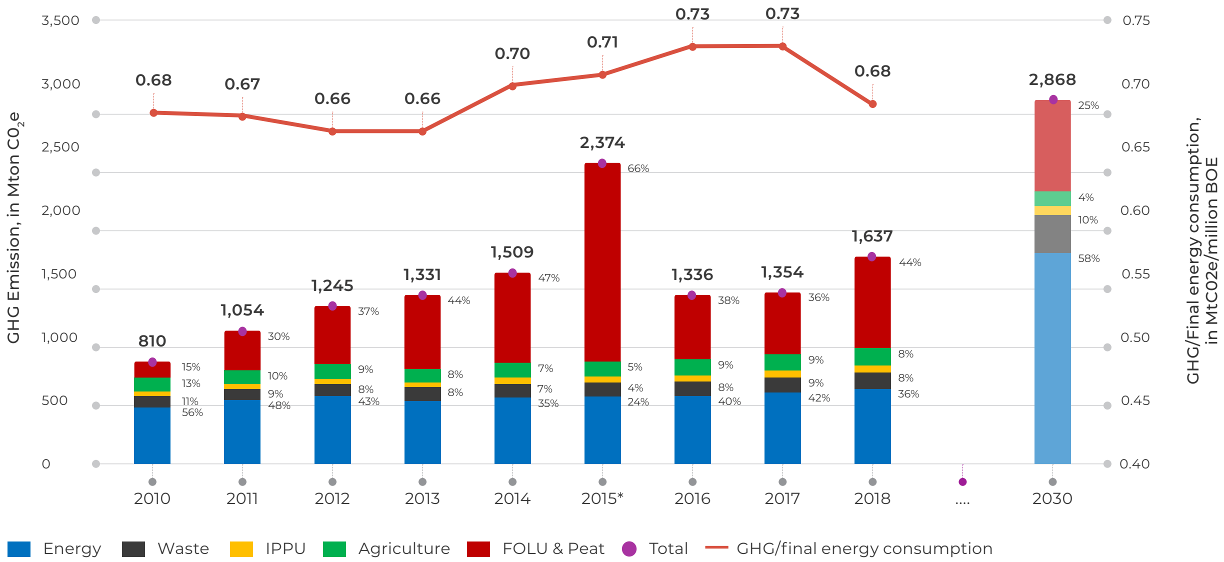


Figure 1: Indonesian GHG emissions, historic and 2030 target in NDC.
Source: (Kementerian Lingkungan Hidup dan Kehutanan (KLHK), 2020) for GHG and Handbook of Energy and Economic Statistics of Indonesia 2019 for Final Energy Consumption

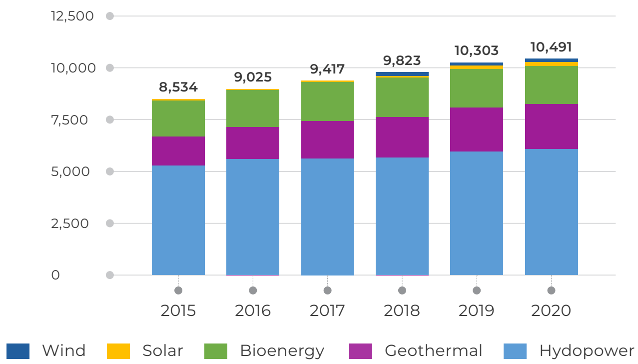
*The significant emissions increase in 2015 was mainly due to massive forest fires that year

To lower emissions from energy, Indonesia needs to transition from fossil fuels to renewable energy. Despite being rich in renewable energy, Indonesia had only installed 10,491 GW of renewable capacity by December 2020, a mere 188 MW increase over 2019. Hydropower and geothermal energy contributed the most to Indonesia's total renewable installed capacity(on-grid and off-grid), leaving other types of renewable energy underdeveloped.

In terms of power generation, renewable energy only accounted for around 15% in the first semester of 2020 (on-grid only). On average, renewable energy only made up about 12.2% of total electricity generation in the last five years (2015 to 2019). In terms of primary energy, renewable energy was even less significant at around 9% in 2019, making achieving the target of 23% renewable primary energy by 2025 more challenging.

Installed renewables capacity, 2015-2020

Installed capacity, MW



Renewables share in electricity generation, 2015-2020

Share (%)

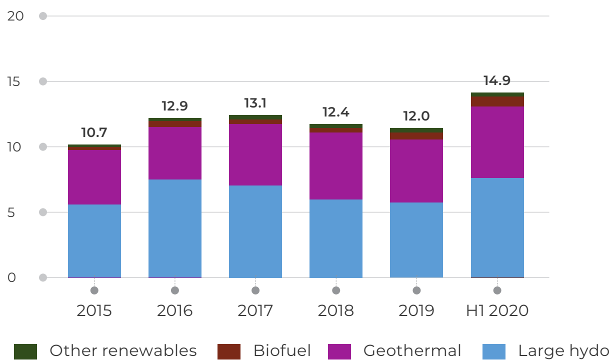


Figure 2: Renewable energy capacity and generation 2015-2020

In contrast, coal has played and will continue to play a significant role in Indonesia's energy system if no meaningful changes are made to foster decarbonization of the system. Between 2005 and 2019, Indonesia added 25 GW of coal-fired power plants, a 260% increase in 14 years. The massive expansion of coal infrastructure aimed at meeting increased energy demand driven by economic growth. Coal additions, however, do not necessarily translate into universal access to electricity; the additions are concentrated on Java. The island has been oversupplied, while other parts of the country still experience an electricity crisis.

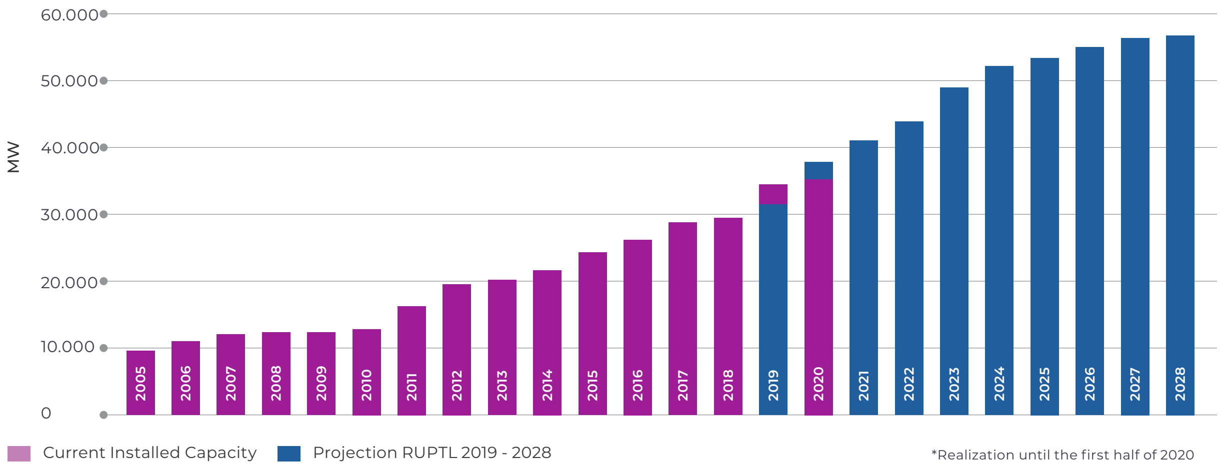


Figure 3: Installed capacity of coal fired power plants

Nevertheless, the government carries on with its plan to increase coal capacity to 57 GW by 2028 despite estimates (Gray et al., 2018) showing that new solar PV will become cheaper than new coal plants by 2021 and cheaper than existing coal plants by 2028. While the risk of stranded assets is apparent, the Indonesian government currently has no plan for a coal moratorium. In fact, the National Energy Plan (RUEN) aims to keep coal significant at 30% in 2025 and 25% in 2050. Coal interests are so strong that the government also intends to develop the coal downstream industry in the country in its effort to drive up the Indonesian coal demand amidst the risk of declining coal exports due to global energy transitions (Arinaldo, 2020).

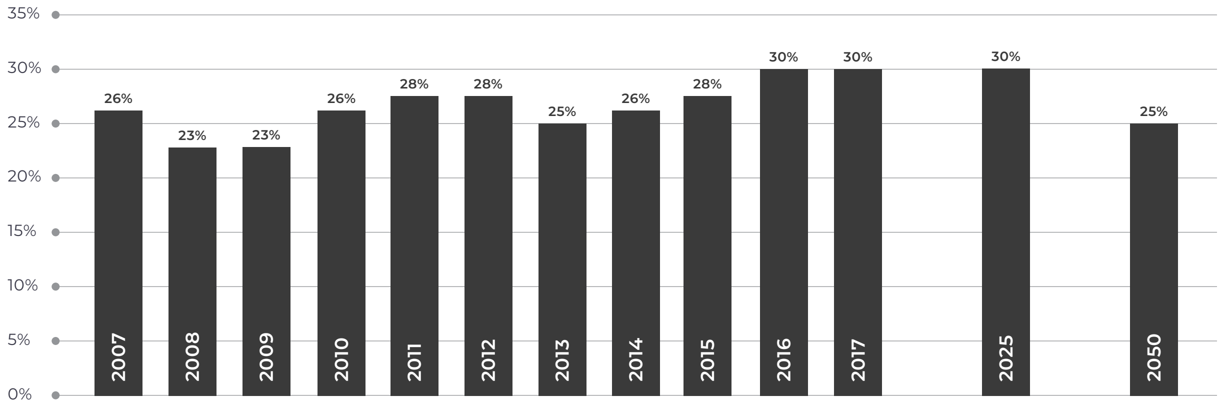


Figure 4: Coal shares in the primary energy mix. *2025 and 2050 shares are RUEN targets

Scenarios, assumptions, and methodologies

Our study analyzed energy transition from its present state, which is heavily based on fossil fuels (mainly coal for power and oil for transport) towards deep decarbonization for the energy system across the power, heat and transport sectors[1] of Indonesia by 2050. This research presents a unique technology-rich, multi-regional and cost-optimal analysis with a high spatial (8 regions) and temporal (hourly) resolution energy transition pathway in 5-year time intervals from 2020 to 2050 (see Box 1).

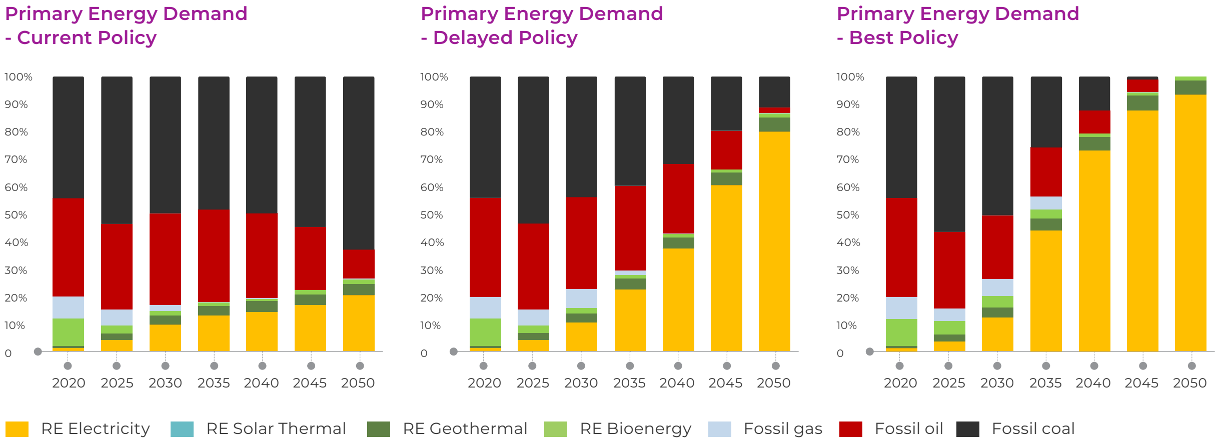


Figure 5: Primary energy demand of the CPS, DPS and BPS

The study also considered growth in the energy, industry, and economy and maintained a similar level for all scenarios. Electricity consumption is expected to increase from over 1 MWh/capita in 2020 to 8.5 MWh/capita by 2050. In addition to reflecting global technological development, the study also explored CO_2 pricing options.

Further information on model boundaries can be seen in the *Radical transformation pathway towards sustainable electricity via evolutionary steps* (Bogdanov et al., 2019).

The Indonesia energy system transition is modelled for 3 distinctive scenarios:

Current Policy

Fossil-based system

50% generation capacity from coal

60% Biofuel and 40% fossil fuel for transport in 2050

Up to 8% solar PV prosumer adoption

Delayed introduction of GHG emission cost

Delayed Policy

Renewable-based system

New coal capacity is allowed, reaching total of 57 GW coal capacity

63% Biofuel, 8% fossil fuel, and 29% of Fiscer-Tropsch in 2050

Up to 15% solar PV prosumer adopton

Delayed introduction of GHG emission cost

Best Policy

Renewable-based system

No new coal capacity

54% Biofuel and 46% Fischer-Tropsch fuel for transport in 2050

Up to 20% solar PV prosumer adoption

Early introduction of GHG emission cost

[1] To see the difference between power, heat, and transport sectors in our model, please refer to Appendix E

The Best Policy Scenario assumes a green growth narrative, where the economy will continue to grow and based on sustainable sources of energy. All scenarios take into account general assumptions on population growth of 1% per annum and electricity demand growth of 4.5% per annum. Amongst the three scenarios, only the Best Policy Scenario (BPS) reaches zero emissions in 2050. The Delayed Policy Scenario (DPS) projected a slower decline in emissions, with 125 Mton CO_{2eq} emissions remaining in 2050. On the other hand, emission in the Current Policy Scenario (CPS) grew and doubled in the next 30 years, completely not in line with the Paris Agreement commitment.

Reaching near zero emissions in 2050 requires a shift from fossil-based energy system to renewable based energy system. Renewable energy growth is observable in all scenarios due to its cost competitiveness and environmental benefits. The shift to renewable energy sources became more prominent in 2030 and became the major source of energy from 2040 onwards.

In the Current Policy Scenario where 50% of power generation comes from coal (and reaching 185 GW) in 2050, the emissions from the energy system double to around 950 Mton CO_{2eq}. Not only is the pathway not in line with the Paris Agreement, but there are also risks of stranded assets for the newly built coal power plants. When looking at the profitability of the newly installed coal power plants, the utilization of coal power plants falls to below 6000 full load hours from 2030 onwards due to competitiveness of solar PV systems.

In the Delayed Policy Scenario, the utilization of coal is gradually declining and replaced by solar PV that accounts for 80% of power generation in 2050. The emissions decline to 125 Mton CO_{2eq}, failing to meet the 1.5°C pathway. Utilization of coal-fired power plants will significantly fall from an economically attractive level of well above 6,000 full-load hours to only around 2,000 in 2050.

Meanwhile, in the Best Policy Scenario, Indonesia is using 100% renewable energy in 2050 and successfully decarbonizing its energy system in line with the 1.5°C Paris Agreement target. No fossil-based generation is observed in the system, securing zero emissions from the energy sector. Coal generation, particularly, is kicked out of the energy system due to low competitiveness in comparison to electricity produced from solar PV and batteries.

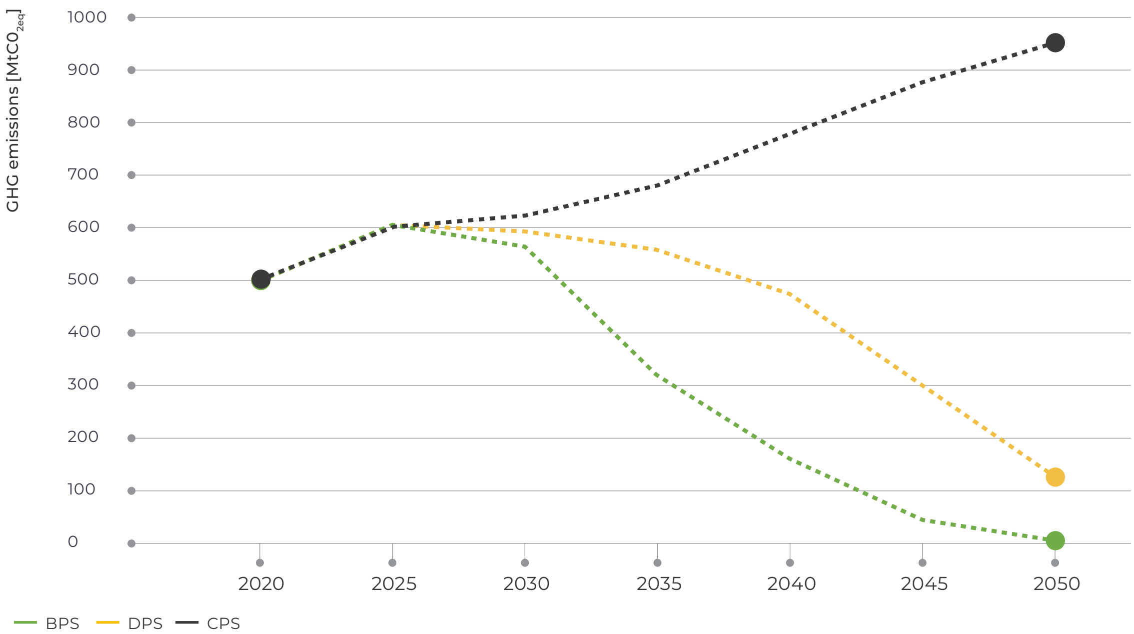


Figure 6: Emissions of the CPS, DPS, and BPS

Box 1

The LUT Energy System Transition Model is structured to provide an optimal set of technologies and capacities matched with the availability of resources in 8 regions in Indonesia (Sumatra, Java West, Java Central, Java East, Nusa Tenggara, Kalimantan, Sulawesi, Maluku and Papua). All sectors (power, heat, and transport) are integrated and optimized together in full hourly resolution. Generation, storage, transmission technologies operation is optimized for each hour to get least cost energy supply. Model structure can be seen in ANNEX E.

The LUT Energy System Transition Model is a linear optimisation tool that models a transition of the integrated power, heat and transport sectors on an hourly time scale for every 5-year time step from 2020 to 2050. Under specific constraints, the model defines an optimal cost structure and operation modes for each of the energy system's elements to provide a least-cost solution. The unique feature of the model is that it enables a global-local energy system transition towards 100% renewable energy for the power, heat and transport sectors. The LUT model has been applied on a global scale (Bogdanov et al., 2019), for Europe (Ram et al., 2018), Japan (Renewable Energy Institute, et al., 2021) but also for country studies comparable to Indonesia, such as for Bolivia (Lopez et al., 2021), Finland (Child et al., 2020), Turkmenistan (Satymov et al., 2021), and Kazakhstan (Bogdanov et al., 2021). A recent review study has rated the LUT model highest among all investigated long-term energy system transition models (Prina et al., 2020).

Input data in the LUT Energy System model:

- historical weather data for: solar irradiation, wind speed and hydro precipitation
- available sustainable resources for biomass and geothermal energy
- synthesised power load data
- efficiency/yield characteristics of RE plants
- efficiency of energy conversion processes
- capex, opex, lifetime for all energy resources
- min and max capacity limits for all RE resources
- nodes and interconnections configuration

A pathway to zero emissions by 2050

Indonesia today, as many countries around the globe, is at a watershed moment. The country is on a path of increasing its carbon footprint, which is expected to grow dramatically in the coming decade. Yet, technological innovation, the impact of climate change becoming more and more visible and global political commitments towards a zero carbon future provide what seemed unimaginable a decade ago: a real and unique opportunity to transform the energy system. As seen in Figure 9, there is still a mismatch between existing planning, the reality of the energy system, and where we need to be – in order to be in line with global climate change mitigation commitment.

This section lays out a pathway to zero emissions in the energy system, as depicted in the Best Policy Scenario, in three stages:

- **By 2030:** bending the greenhouse gas emission curve and peaking emissions.
- **By 2045:** removing a major share of emissions through energy system transformation.
- **By 2050:** achieving zero emissions through increase in green synthetic fuel production and elimination of residual emissions in the industry sector.

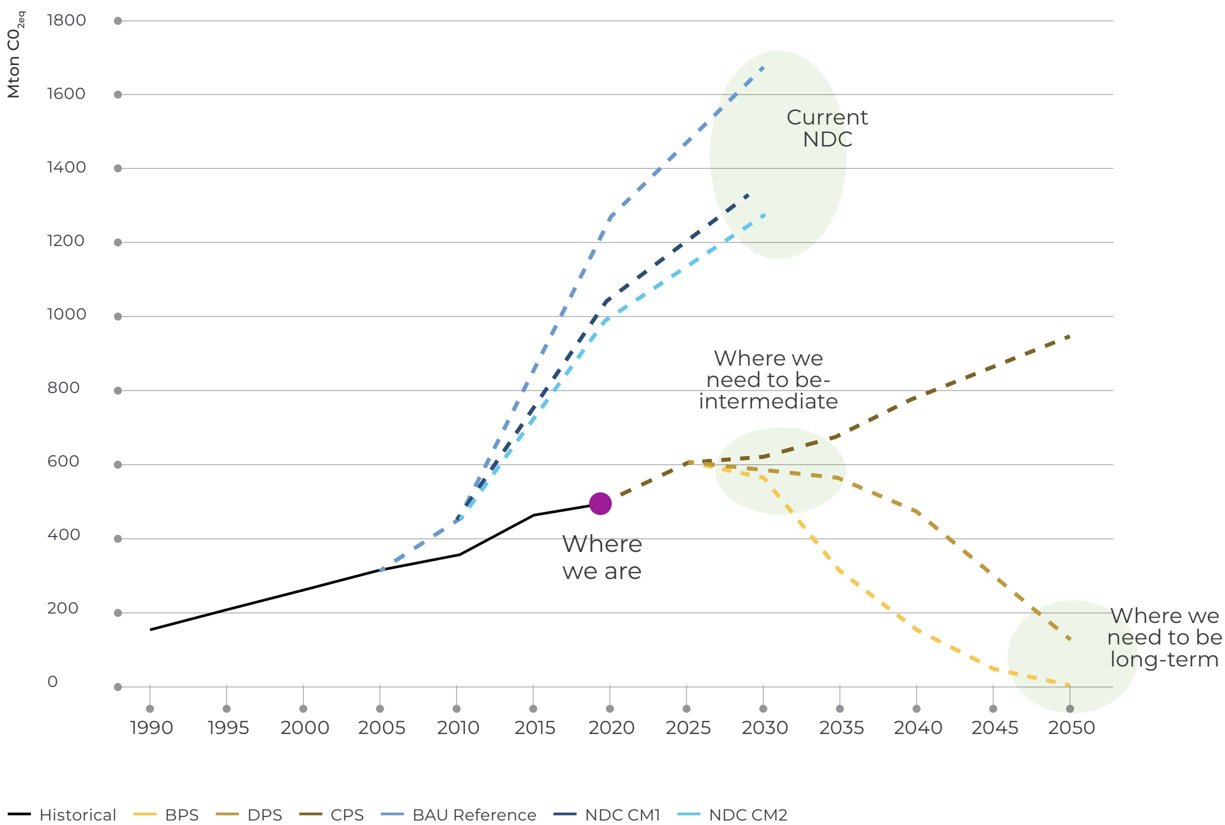


Figure 7: Historical emissions in the energy sector and emission reduction pathways in Indonesian NDC and this study

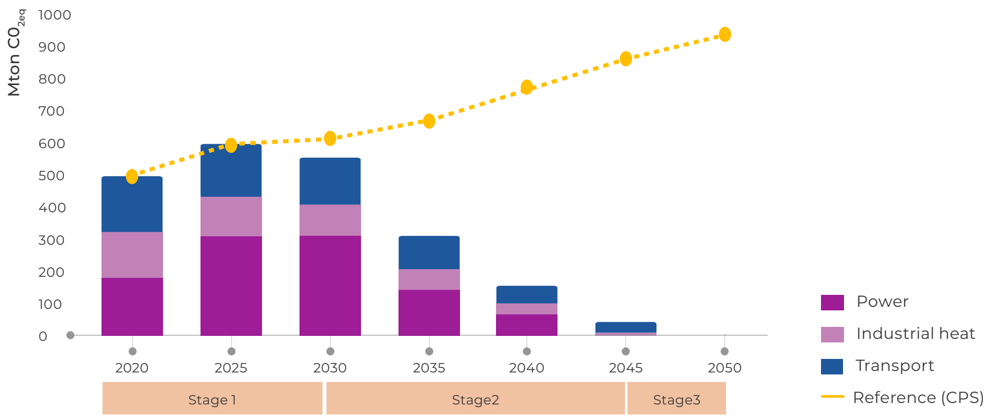


Figure 8: Emission reduction for each sector in the Best Policy Scenario

Step 1 (up to 2030): Bending the curve peaking GHG emissions

Similar to other emerging nations, Indonesia's energy consumption is expected to increase[2] in the next decade. This has implications for emissions from the energy sector. The first important step to carbon neutrality is to bend the emissions curve as soon as possible by decoupling emissions growth from economic growth. Low economic activity due to the pandemic has curbed GHG emissions, but structured changes will need to follow. Peaking emissions from the energy sector before 2030 is crucial to achieve. One of the primary means is to fill in the growing energy needs with low-carbon energy sources quickly. The power sector is the low-hanging fruit, but the transport and industry sectors must already follow suit.

Power sector: the first important step is to install renewables at scale and increase their share to 45% in the power sector. Along with other renewable energy sources, Indonesia would need to install 100 GW of solar PV in the next 10 years. Rooftop solar PV and prosumer systems are assumed at 2% of total demand in 2025, continuing the effort of one million solar rooftop initiatives. All of these efforts still only use 6% of the technical potential[3]. Solar PV will be one of the main contributors to energy supply not only due to its resource potential but also cost competitiveness, reaching a LCOE level at around USD 18/MWh by 2030, much lower than PV LCOE in 2020 at USD 53/MWh.

Power sector emissions will still increase to around 200 Mton CO_{2eq} due to the amount of fossil fuel in the current system. Around 11 GW of coal power plants are under construction, giving a total of 44 GW of coal power plants by 2030. However, due to decrease in CFPP utilization, the share of coal generation will fall from current levels of 60% to 45% in 2030, yet coal electricity production will still increase from 185 TWh to 355 TWh.

In addition, it is also important to take into account domestic energy trading and the needed infrastructure. The Java, Kalimantan, and Nusa Tenggara power systems will be interconnected by 2030 to ensure security of supply with a total transmission capacity of more than 3 GW (HVDC), mostly for exporting power to Java.

Transport sector: there is a change in trends as more people shift to public transport. Cycling is also becoming more mainstream. Similarly, 2 wheelers still play a central part in public mobility.

[2] The population across Indonesia is expected to grow steadily from 270 to 325 million, while the average energy demand per capita grows from around 6.9 MWh/person in 2020 up to over 9.0 MWh/person by 2050.
[3] Solar PV module efficiency is assumed to increase from what is today at 18% to 22% at 2030, with a specific capacity of 92 MW/km2.

In 2030, there will be more than 100 million new battery-powered electric motorcycles on the road. Electric cars will also start to emerge, with around 1.7 million vehicles; the government-led program is expected to amount to around 188 thousand electric busses by 2030. In total, electric vehicles account for 15% of energy demand from the transport sector. Meanwhile, fossil fuel share in liquid hydrocarbon demand declines to around 70% from almost 90% today.

As an important part of Indonesian energy policy, biofuel blending mandate is assumed to continue. Biofuel production is projected to grow almost 3-fold from 8.4 million kL today to 24.2 million kL in 2030, fulfilling 30% of the transport sector demand. With high penetration of solar PV, increased use of biofuels, and electrification of the transport and heat sectors, the national energy target of 23% of renewables by 2025 in primary energy will be well-achieved.

Step 2 (up to 2045): Decreasing carbon emission by around 92% between 2030 and 2045

By 2030, emissions have peaked. Decarbonization efforts continue in the next 15 years. In 2045, Indonesia will enter the golden generation (Indonesia Emas[4]). Low-carbon energy systems and infrastructure will be key strategies towards reaching the vision of the golden Indonesia. In this phase, emissions fall by up to 92%.

Power sector: All (100%) electricity generation comes from renewable energy resources by 2045. Electricity generation will grow enormously as electrification of all sectors continues with electrification accounting for around 2/3 of total power demand. Solar PV emerges as the bulk electricity provider by contributing to 88% of electricity generation in 2045, complemented by hydropower and geothermal energy. Hydropower supplies 6-12% and geothermal continues to increase and contributes around 6-10% of the total generation. As low-cost renewables, especially solar PV, gain traction in the energy system, coal utilization drops considerably and starts to lose attractiveness. At this stage, a large share of existing Indonesian coal power plants will reach more than 30 years[5] of operation.

The share of coal generation will rapidly decline from around 46% in 2030 to around 12% in 2035 and 4% in 2040 before reaching zero in 2045, indicating that coal retirement programs should be carried out from 2030 onwards.

Energy storage starts to become more relevant as the renewable energy share rises. As batteries become cost-effective, they emerge as the most significant energy storage by 2045 with their share at around 52% of total storage systems, followed by hydrogen at 37% and other storage systems at around 11%. Higher share of batteries will complement the higher penetration of renewable energy (particularly solar energy and diurnal role of batteries). The share of electricity demand covered by energy storage increases significantly from around 2% by 2030 to 29% by 2045. Major share of battery storage will come from utility-scale systems, and smaller share from commercial and industrial parks, and residential systems.

Transport sector: Battery electric vehicles will dominate road transport as battery-powered two-wheelers, cars, busses, and trucks amount to over 230 million vehicles on the roads by 2045. In total, battery electric vehicles account for 44% of energy demand from the transport sector. Meanwhile, fossil fuel share in demand for liquid hydrocarbon falls to 27%, mainly used in hard-to-abate maritime and aviation sectors. The use of fossil fuels in these sectors contributes to 80% of emissions in the energy sector in 2045.

While biofuel still maintains its share, synthetic fuels and hydrogen will start to gain its importance in marine and aviation. Electrolyzer

[4] Indonesia Emas is a goal that Indonesia, with its large share of productive generation in 2045, will become a well-developed country, free from corruption and poverty issues. The year is also 100 years of celebration of the country's independence.
[5] In 2020, the Ministry of Energy and Mineral Resources (MEMR) stated that coal power plants more than 20 years old operation, which is currently around 5.6 GW, should be replaced with renewables.

and Fischer-Tropsch installed capacities increase significantly from 2035 onwards and reach more than 180 GW by 2045, with a major share of water electrolysis along with CO_2 DAC as the basis for Fischer-Tropsch and hydrogen production. Building these dedicated renewables sites and electrolyzers may not only provide domestic needs but also present export opportunities to demand centres in China, South Korea, Japan, and Singapore.

Industry sector: Industry will use more electric heating. Over the next 15 years, between 2030-2045, electric heating should provide nearly 70% of the heat generated and be complemented by bioenergy (2%). Fossil-based heating decreases gradually to 3% while renewable fuels-based heating will contribute to a quarter of heat generation in 2045.

Step 3 (up to 2050): Decarbonizing the last miles

Thanks to renewables and a high degree of electrification, 90% of emissions will have been mitigated by 2045. While most emissions in the power sector are mitigated through solar PV, geothermal and hydropower, more decarbonization efforts will be needed in the transport and industrial sectors.

Power sector: Continue using 100% renewable energy. Solar PV remains the largest contributor to power generation, accounting for 88% of total generation. Meanwhile, electricity storage systems contribute to around 30% of electricity demand.

Transport sector: Most emissions that still occur in the aviation and maritime sectors will vanish near 2050. To fully decarbonize this sector, hydrogen consumption in the transport sector will need to double in five years. Liquid fuels (hydrogen and synthetic fuels) produced by renewable electricity contribute to 27% of the final energy demand in the transport sector in 2050.

Industry sector: Electric heating plays a significant role in the heat sector, with nearly 67% of heat coming from electric heating by 2050. The remaining heat comes from renewable-based hydrogen and synthetic methane as well as bioenergy to generate high-temperature process heat. Emissions from industrial heating reach zero by 2050. Heat demand increases steadily from around 700 TWh,th in 2020 to 811 TWh,th in 2050, mainly driven by higher demand for industrial process heat (91%) that is projected to grow moderately. Other demand comes from domestic water heating. Heat for fuel conversion is managed with excess heat and recovered heat in various processes.

Stage 1

Power:
- No new coal except 11 GW in the pipeline
- 100 GW of solar PV
- 2 GW of solar PV prosumers

Industry:
- Biomass and electric heating

Transport:
- Increase biofuel blending
- 70-100 million new electric motor

Stage 2

Power:
- 100% Renewables, Utility-scale Battery storage
- Coal retirement program
- Start installing 200 GW of electrolysers
- CO_2 storage and DAC to produce synthetic fuel

Industry:
- Biomass and electric heating
- Start use of synthetic fuel

Transport:
- 190 million new electric motorcycles
- 59 million cars, eletcric train

Stage 3

Power:
- Continue 100% of Renewables

Industry:
- Increase use of synthetic fuel
- Heat recovery management

Transport:
- Doubling electricity-based mathane and hydrogen production

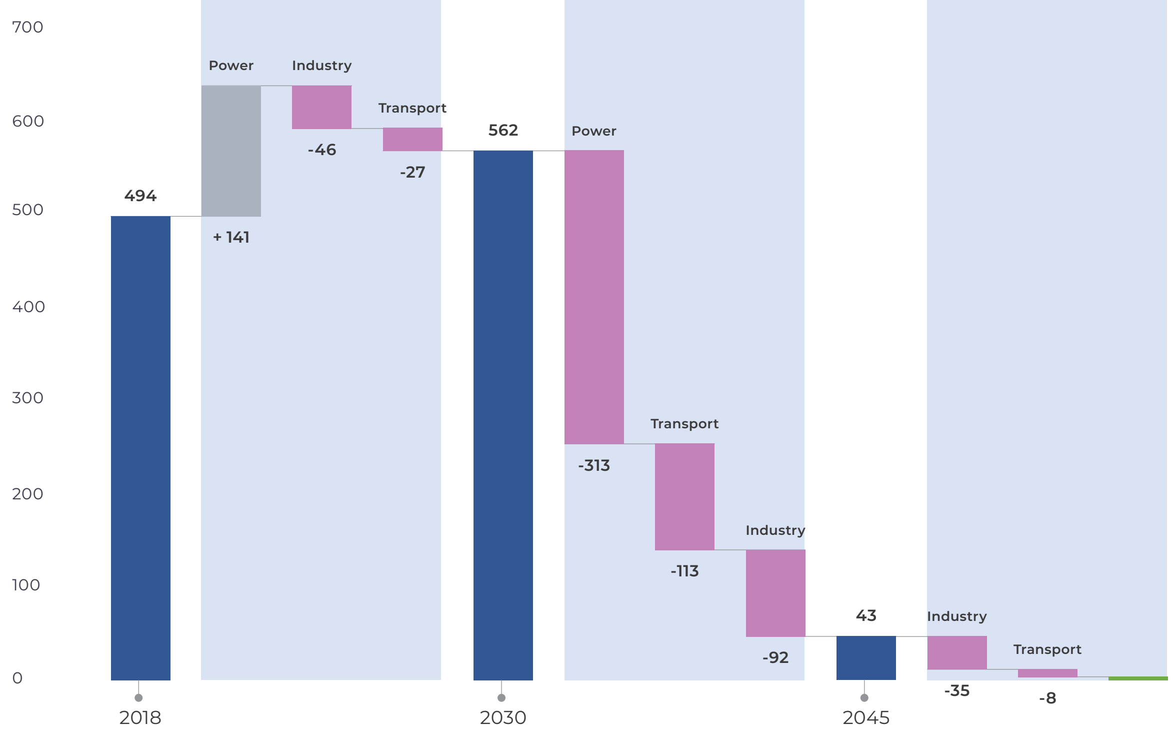


Figure 9: A pathway to zero emissions. (Note: increased emissions in the power sector from 2018 to 2030 due to growing demand and emissions from both existing and newly entering operation-fossil power plants. The model assumed that PV+battery is not yet cost-competitive with coal power in 2020 so a cost-optimal solution is reached with peak coal generation as observed in 2025.

Four pillars of the transition to a zero-emission energy system

To achieve a zero-emission energy system by 2050, the Indonesian government, utilities and stakeholders should focus on at least four areas.

1. Renewables

Our model shows that PV will emerge as the dominating source of energy, in particular from 2040 onwards. In the Best Policy Scenario (BPS), PV will contribute to around 88% of total electricity generation in 2050, followed by hydropower at 6% and geothermal at 5%. With all electricity coming from renewable sources, renewables capacity will significantly increase. PV installed capacity reaches 1,492 GW by 2050 with electricity generation as high as 2,602 TWhe, followed by hydropower capacity at 40 GW and geothermal capacity at 19 GW. While these non-PV renewables are quite miniscule in comparison, they still play an important role when it comes to balancing PV variability.

The remaining coal capacity in the country will inevitably become stranded as coal loses its competitiveness against renewable energy. Stranded coal assets without any utilization will peak in 2045 at around 53 GW and cost Indonesia USD 26 billion. This is as a result of new coal-fired power plants built between 2020 and 2025.

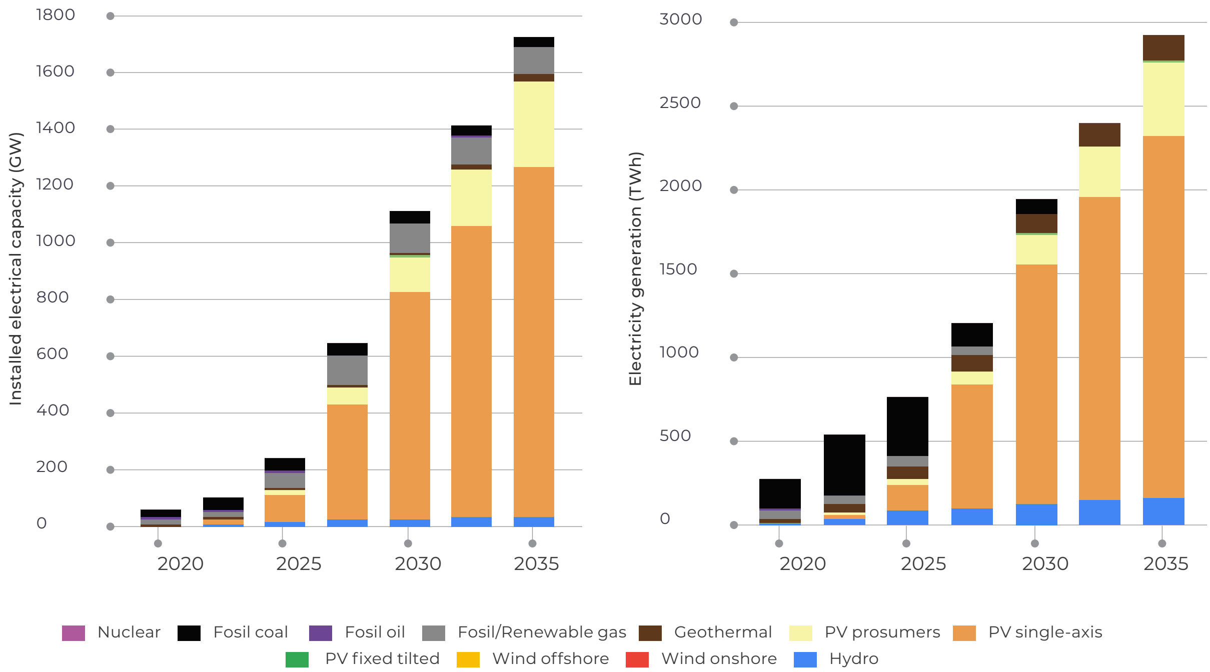


Figure 10: Installed capacity and generation

Indonesia has high PV potential evenly distributed throughout the nation. The total PV potential for Indonesia increases from about 1,400 GW in 2020 to 3,380 GW in 2050, assuming that efficiencies of PV modules will increase from only 18% in 2020 to around 30% in 2050. With 1,492 GW installed capacity in 2050, only 44% of the total potential is utilized which requires a total area (excluding forest and water) of 2.5% of the available land. Around 80% of solar PV is utility-scale, the remaining comes from rooftop solar PV in the residential, commercial and industrial sectors.

While concerns about the variability of PV are real, the model shows the security of supply is guaranteed despite high shares of solar generation. Compared to many other world regions, Indonesia has rather small seasonal or even daily variations in solar output as seen in the figures below. During the best solar week, peak of solar PV generation is around 1,000 GW during most of the hours in 2050, the system has excess generation during this week. During the worst solar week, the peak of solar generation is around 700 GW during most of the hours, import and export of electricity is observed to be highest during this period (seasonal balance).

The higher PV share during the day is balanced out by battery charge, power-to-fuels, power-to-mobility (EV charging), power-to-heat, and regional export. Hydropower plants are operated flexibly during this period while geothermal operates as baseload. At night, when solar PV is not available, battery discharge, hydropower, geothermal, biomass, and regional import will be dispatched to meet demand.

For energy potential and current load distribution, intraland electricity import-export is mandatory. In the BPS, nearly 760 TWh of electricity is exchanged across the country, with Sumatra and Nusa Tenggara as the major exporters, while Java is the major importer. The island of Java is assumed to remain the main energy consumer in Indonesia by consuming 80% of total energy in the country. With this condition, Java will need to import 4.6% of its demand by 2030, 45.5% by 2040 and 82.1% by 2050 under the Best Policy Scenario.

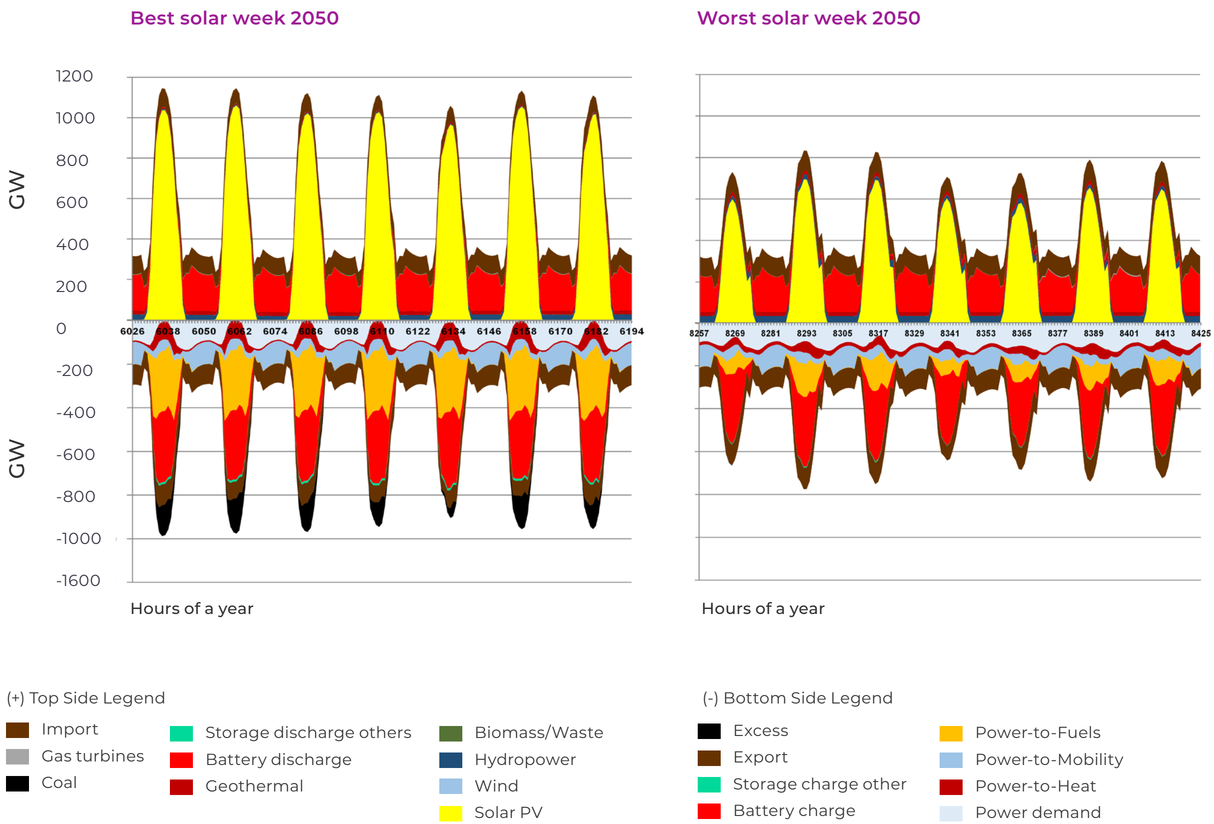


Figure 11: Hourly generation in best and worst solar weeks

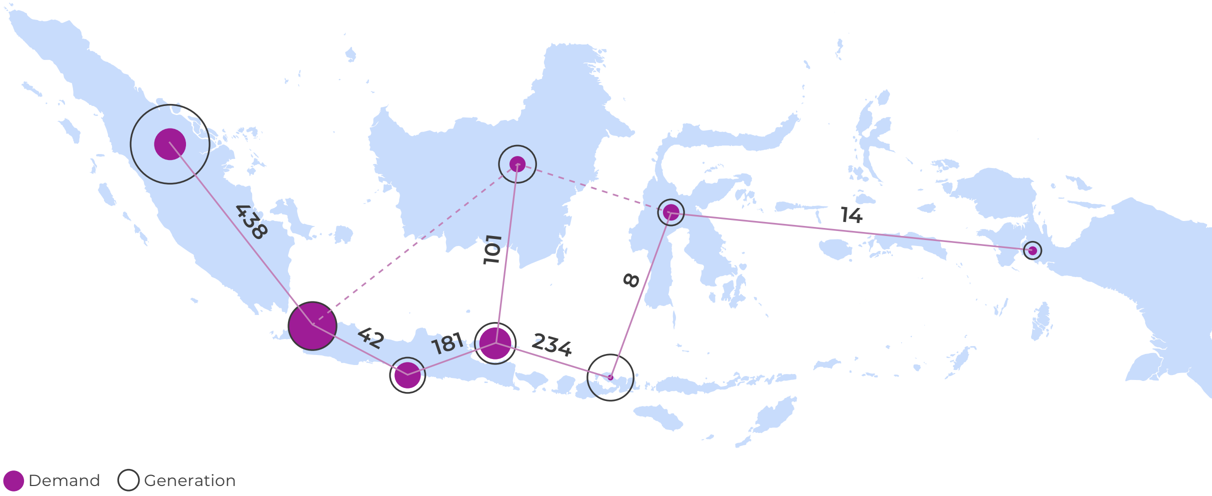


Figure 12: Illustration of annual imported and exported electricity in 2050 (in TWh)

To support this trading, Indonesia's grid capacity will need to expand. In all scenarios, interconnections between East Java and Bali will need to be expanded to Nusa Tenggara. The planned Java-Sumatra interconnection is very important to supply electricity to Java. The importance will increase after 2030 as capacity will need to increase from virtually zero in 2030 to around 50 GW by 2050, with utilization exceeding 97%. Interconnections between Java, Kalimantan, and other islands will be more important beyond 2030 as the energy system becomes more electricity-based.

However, since transmission grid projects usually take a long time to develop, it is very important to start planning decades before.

Realizing this intraland electricity transfer will demand action from the government, policy makers, regulators, and from Perusahaan Listrik Negara (PLN) as the utility that owns all transmission and distribution lines. Our model indicates that by 2050 an overall transmission capacity of 158 GW needs to be built to interconnect Indonesia from west to east.

Connection		2020	2025	2030	2035	2040	2045	2050
'Sumatra'	'Java - West'	0	0	0	6,104	10,685	36,170	51,802
'Java - West'	'Java - Central'	4,200	4,200	4,200	12,619	26,091	26,092	26,092
'Java - West'	'Kalimantan'	0	0	0	0	0	0	0
'Java - Central'	'Java - East'	4,200	4,200	4,200	13,199	23,087	26,089	30,486
'Java - East'	'Nusa Tenggara'	0	1	766	18,817	27,259	27,793	32,029
'Java - East'	'Sulawesi'	0	787	2,609	2,609	2,610	5,048	12,931
'Nusa Tenggara'	'Sulawesi'	0	0	612	1,505	1,505	1,505	1,505
'Kalimantan'	'Maluku and	0	0	3	509	509	509	509
'Sulawesi'	Papua''	0	0	831	2,536	2536	2,536	2,536
Total		**8,400**	**9,188**	**13,221**	**57,898**	**94,282**	**125,742**	**157,890**

Table 1: Grid capacity development in Indonesia (Note: inter-island connection is HVDC)

2. Electrification

This study reveals that comprehensive electrification will lead to increased energy efficiency due to lower conversion losses, lowering both the primary energy supply and greenhouse gas emissions (GHG) significantly. Since most emissions in the power sector come from coal, electrification of all sectors can bring about massive emission reductions only if all electricity generation comes from renewable sources. It is also worth noting that direct electrification is carried out whenever possible as it requires much less energy (higher efficiency). Indirect electrification is therefore needed for technology reasons (energy density, heat temperature, etc.)

By 2050, Indonesia needs to see a high level of direct and indirect electrification of more than 80% in all sectors (transport, heat, and power) to be able to achieve zero GHG emissions in the energy system by 2050. Specifically, direct electrification will cover 46% and 70% of energy demand in the transport and heat sectors, respectively. Meanwhile, indirect electrification through the production of synthetic fuels and hydrogen will make up 33%, and 27% of final energy demand in the transport and heat sectors, respectively.

In the transport sector, efforts to reduce the need to travel through better urban planning and to increase the use of public transport and non-motorized transport will help decarbonize the sector. However, motorized vehicles will remain one of the main transport modes in the future with around 288 million new EVs will be seen on the road in 2050. Electrification of vehicles will also become increasingly important to help the country's transport sector become carbon-free by 2050.

Our model shows that battery electric vehicles (BEV) should comprise 73% and 95% of newly sold passenger cars and light trucks (light duty vehicles) and newly sold motorcycles, respectively by 2050. Meanwhile, in other segments of road transport vehicles, BEVs will make up 90% (bus), 80% (medium duty vehicles), and 50% (heavy duty vehicles) of newly sold vehicles in the same period. The remaining share will use hydrogen, renewable-based synthetic fuels, and sustainably produced biofuels to drive fuel cell electric vehicles, plug-in hybrid electric vehicles, and internal combustion engines. The road transport modes such as motorcycles, cars, and buses are relatively easy to electrify, and thus should become the first priority of the Indonesian government.

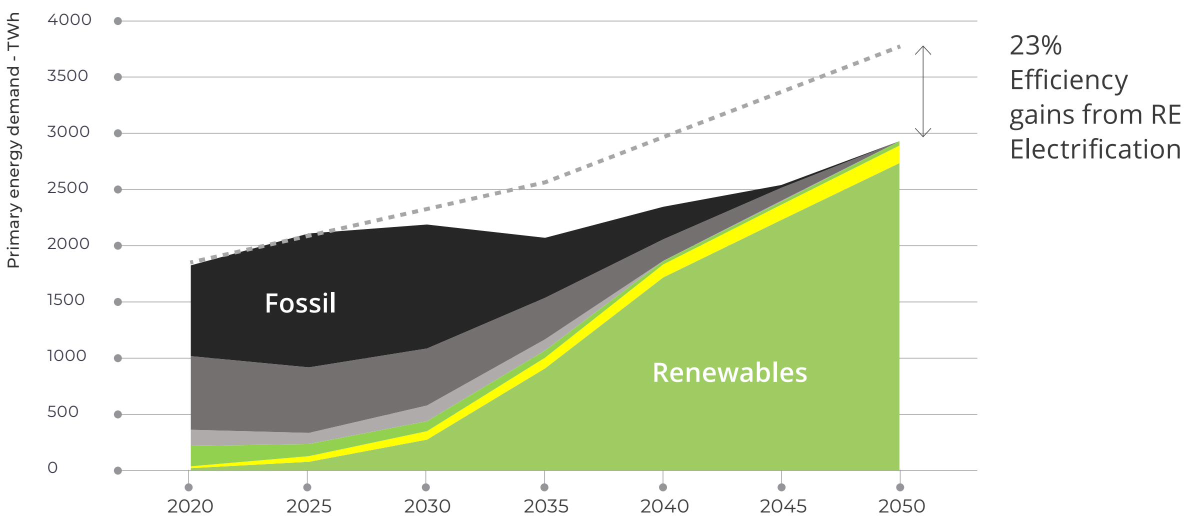


Figure 13: Development of primary energy demand and efficiency gains

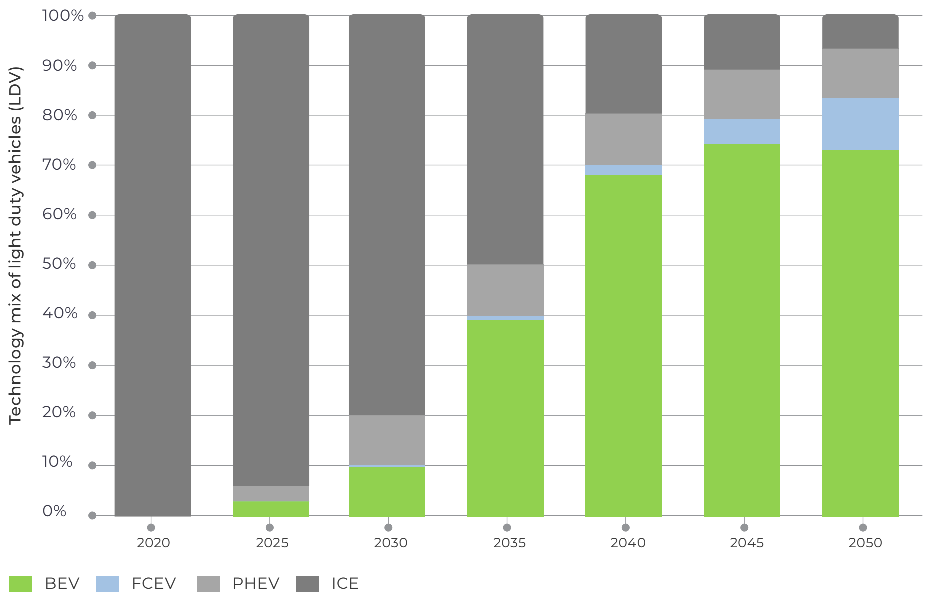


Figure 14: Technology mix of light duty vehicles (LDV)

Meanwhile, indirect electrification through the use of synthetic fuels will be key in decarbonizing the harder-to-abate sectors such as maritime, aviation, and some industrial processes (very high temperature process heat). Additionally, synthetic fuel conversion provides vital flexibility to the energy system via the power-to-fuels integration. By 2050, the fuel conversion capacities reach around 242 GW with electrolyzers making up for 95% of the capacities and the rest comes from Fischer-Tropsch. Greater capacities provide higher flexibility enabled by electrolyzers, but also add to the overall energy demand.

Overall, direct electrification creates demand of 429 TWh while indirect electrification to produce synthetic fuels creates an additional electricity demand of around 252 TWh by 2050 in the transport sector. Massive demand for renewables-based liquid fuels will kick-in from 2040 onwards up to 2050 with liquid fuels produced by renewable electricity covering around 27% of final energy demand in 2050. Hydrogen, specifically, will make up around 21% of final energy demand in 2050.

3. Decline in fossil fuel use

Fossil fuels have long dominated the Indonesian energy system by contributing to more than 90% of annual primary energy supply over the past decade (*Handbook Of Energy & Economic Statistics Of Indonesia, 2020*). However, fossil fuel utilization will drastically decline through the transition as fossil fuels are completely replaced by electricity and synthetic fuels along with some sustainable biofuels in all three scenarios by 2050.

To achieve the ultimate goal of a carbon-neutral energy system by 2050 in line with the target of limiting temperature rise to about 1.5°C, Indonesia needs to start limiting coal development. In the optimized model, any coal plants built after 2025 would not be utilized for more than 15-20 years. This foreshortening would seriously undermine the economics of such investments. Therefore, consideration on the economic viability of new coal-fired power plants is needed to avoid stranded assets in the near future.

Later on, a coal moratorium will be much more feasible; coal power generation loses its relevance with increasing competitiveness of renewables, in particular PV. In addition, carbon taxes will further accelerate the decline in coal-based power generation in the country, making coal power unaffordable. In our Best Policy Scenario (BPS), coal starts losing attractiveness from 2025 onwards as low-cost renewables (particularly PV and batteries) gain traction in the energy system. To avoid coal stranded assets, early decisions to stop building new coal plants are needed. If delayed, Indonesia would likely see higher stranded coal investments in the future.

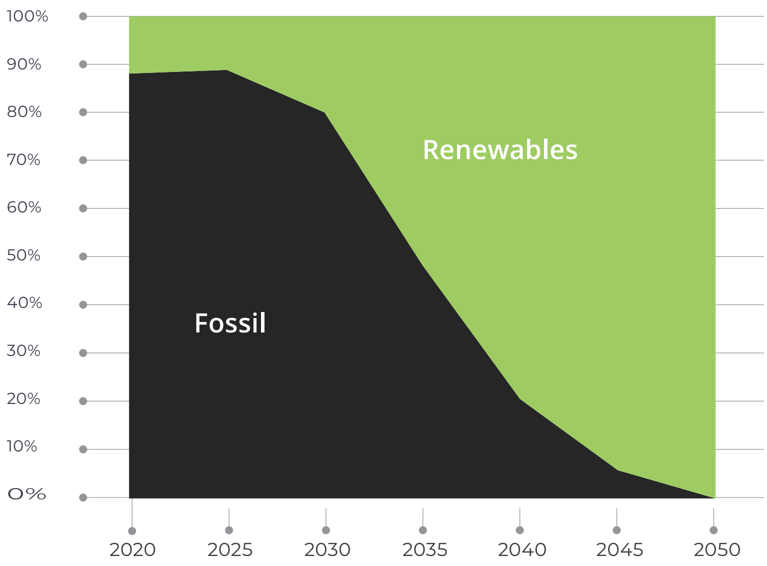


Figure 15: Indonesia's primary energy mix

The decline in fossil use will later reduce the overall GHG emissions from the energy system from around 502 $MtCO_{2eq}$ in 2020 to virtually zero in 2050. In contrast, under the business-as-usual scenario (CPS), Indonesia will see an increase in GHG emissions by 89% in 2050. The BPS will enable an early stabilization of emissions, followed by a steady decline and almost zero emissions in 2045. In addition to achieving climate targets, zero use of fossil fuels by mid-century will also help lower the number of people with air pollution-related Non-Communicable Diseases (NCDs) in the country.

4. Clean fuels

Clean fuels are one of the key parts of a decarbonized energy system. In this study, clean fuels used are sustainable biofuels, synthetic fuels, and hydrogen. These fuels along with electrification will completely replace fossil fuel use in both the transport and industry sectors. Biofuels are used in the transport sector and contribute most to fuel use in the sector at around 54%, with the remaining sourced from liquid hydrocarbons (Fischer-Tropsch), methane, and hydrogen. It is important to note that the model is conditioned to use all sustainable biofuel potential available to reflect government continuous support for biofuel programs.

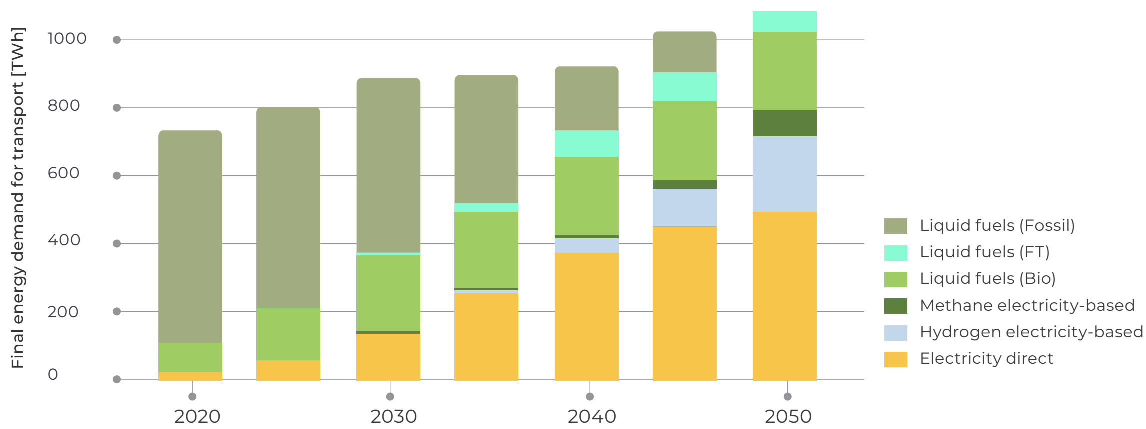


Figure 16: Final energy demand of the transport sector

While biofuels have become an important part of the Indonesian energy policy, concerns over production sustainability remain. Biofuel production itself requires far more land than PV for producing Fischer-Tropsch (FT) fuels due to considerably lower yield of energy crops compared to PV yield/km2 for converting the solar electricity. In the BPS scenario, biofuel potential grows from 88 TWh in 2020 to 229 TWh in 2030 and is assumed to stay constant until 2050 to ensure the sustainability of biofuel production. The land requirement increases from 2.5% (20,000 km2) to 6.4% (50,000 km2) of the total area (excluding area occupied by forest and water) from 2020 to 2030.

Meanwhile, synthetic fuels produced through the Fischer–Tropsch[6] process are used in the transport sector to replace fossil-based diesel and jet fuels. On the other hand, other renewable-based fuels such as synthetic methane and hydrogen are used as fuels for both vehicles and industrial heat generation. All of these synthetic fuels and hydrogen are produced domestically using renewable electricity. The electricity is used in water electrolysis as the basis for Fischer-Tropsch process and hydrogen production. With more countries around the world embracing hydrogen as part of their decarbonization strategies, Indonesia should also follow suit with this development.

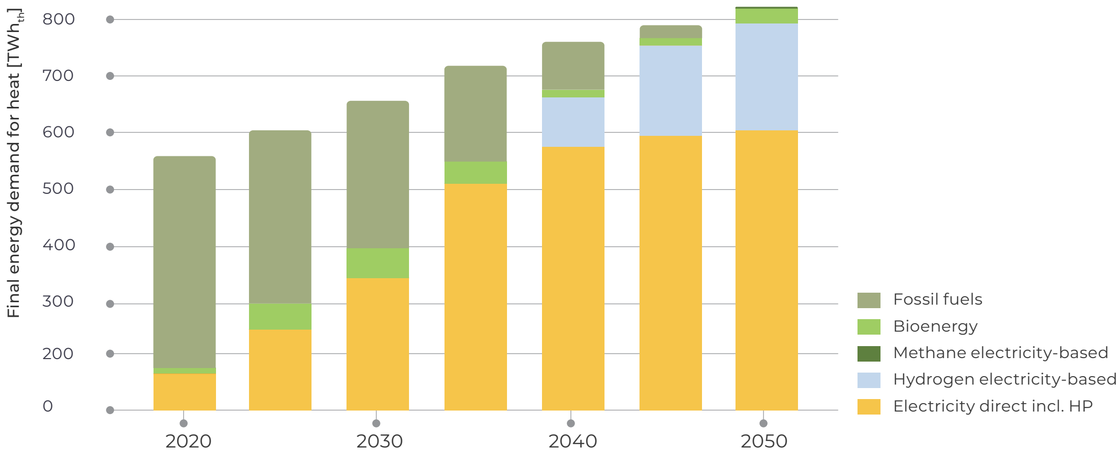


Figure 17: Final energy demand of the industry sector (heat)

[6] Fischer–Tropsch process is a process that converts a mixture of carbon monoxide and hydrogen into liquid hydrocarbons/fuels

Required investments to achieve zero emissions by mid-century

Continuing business as usual until solar PV technology costs have gone down significantly is understandable at first sight, but not without consequences. A stepwise decarbonization would require reduction of coal power plants in the pipeline. An immediate halt of new coal power plants is necessary to reduce the risk of stranded assets.

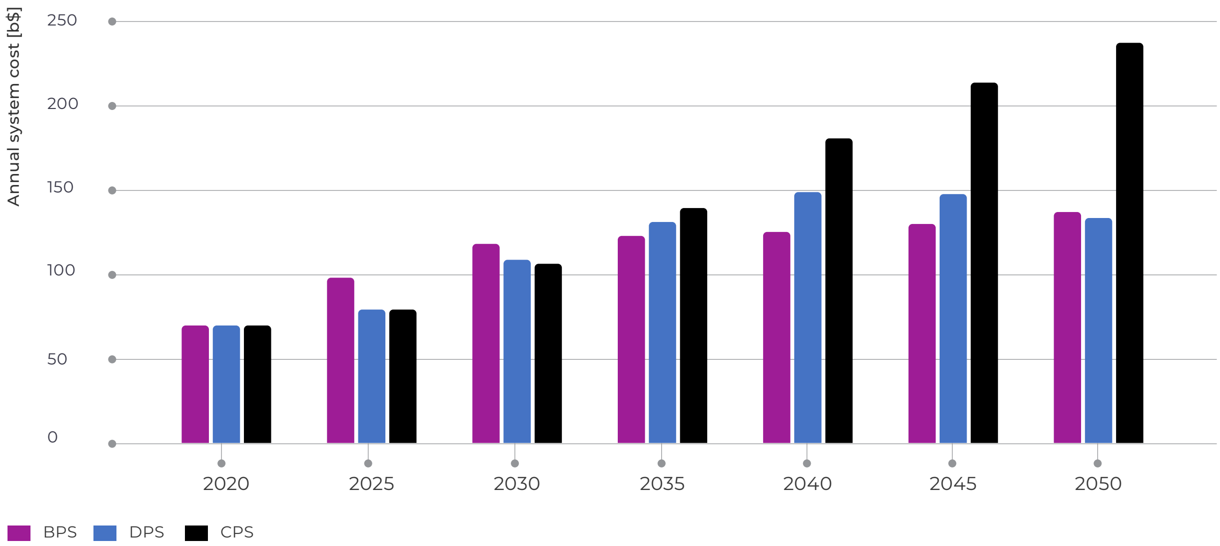


Figure 18: Annual system costs

Under most assumptions for future fuels[7] and CO_2 prices[8], cumulative annual system costs from 2020 to 2050 of the renewables-based energy system are 20% lower than costs of the energy system where fossil fuels dominate. Pathways towards carbon neutrality in the energy system will thus not require higher system costs than fossil-based pathways, making the vision more feasible to achieve than ever before. What does become evident when looking at annual system cost in five-year time steps is that, in order to initiate a transition in the 2020s, higher system costs occur in the next decade between 2020 and 2030. Meanwhile, from 2030 onwards, the trend changes with annual system costs becoming more attractive in comparison to both the DPS and CPS step by step.

When looking at the levelized cost of electricity (LCOE), two main findings are relevant: while power is more expensive for the decarbonization pathway up to 2030, it does become cheaper than both alternative scenarios from 2030 onwards. This is even true under the assumption of a lack of

[7] Coal price is at around USD 11-17/MWh_{th} (USD 89-134/ton) and gas price is at USD 24-44/MWh_{th} (USD 7-13/MMBTU)`
[8] The CO_2 emission price for BPS starts at around USD 10/ton CO_{2eq} in 2020, reaches about USD 50/ton by 2030, and gradually increases to USD 100/ton by 2050. For the CPS, the CO_2 emission cost starts only in 2030 at USD 10/CO_{2eq}, reaches USD 55/ton in 2040, and gradually increases to a similar USD 100/ton in 2050. The 2050 CO_2 price is similar under all scenarios due to the assumption that in 2050, a carbon price of USD 100 would likely be imposed.

GHG emissions cost. Considering current global trends to decarbonization, this is a highly improbable assumption. If GHG emissions cost is taken into account, CPS is 50% more expensive in 2050. Secondly, the LCOE calculation shows that a modernized renewables-based power system will be able to generate, already in the short term, electricity at prices comparable to those of today, and, in the mid to long run, at considerably lower costs

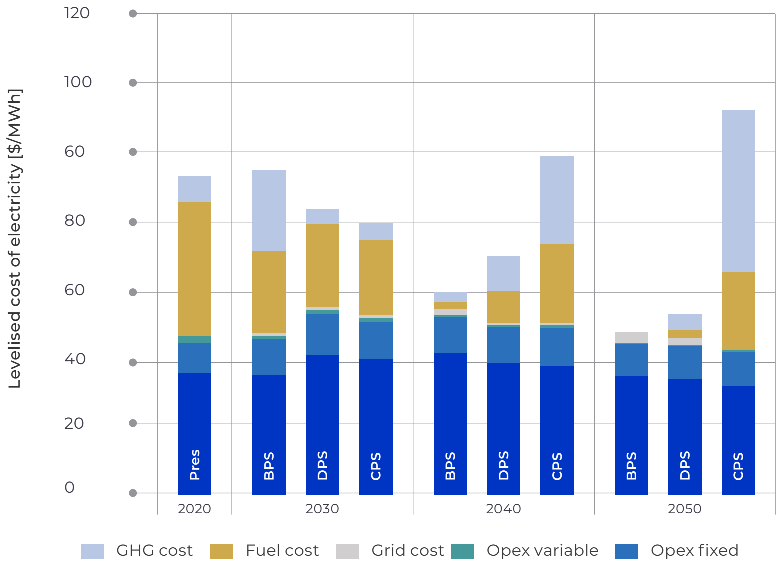


Figure 19: Levelized cost of electricity (LCOE)

Up to 2030, all scenarios require comparable investment costs with the Best Policy Scenario suggesting a shift from fossil investment to renewables investment. Due to renewables cost structure which usually requires high upfront investment, the annual investment needed in renewable based systems from 2030 onwards is higher compared to a fossil-based system. In the renewable based scenario, Indonesia will need an estimation of USD 20-25 billion investment per year from now through 2030. Through 2030-2040, the country will need an annual investment of USD 60 billion to ramp up decarbonization efforts.

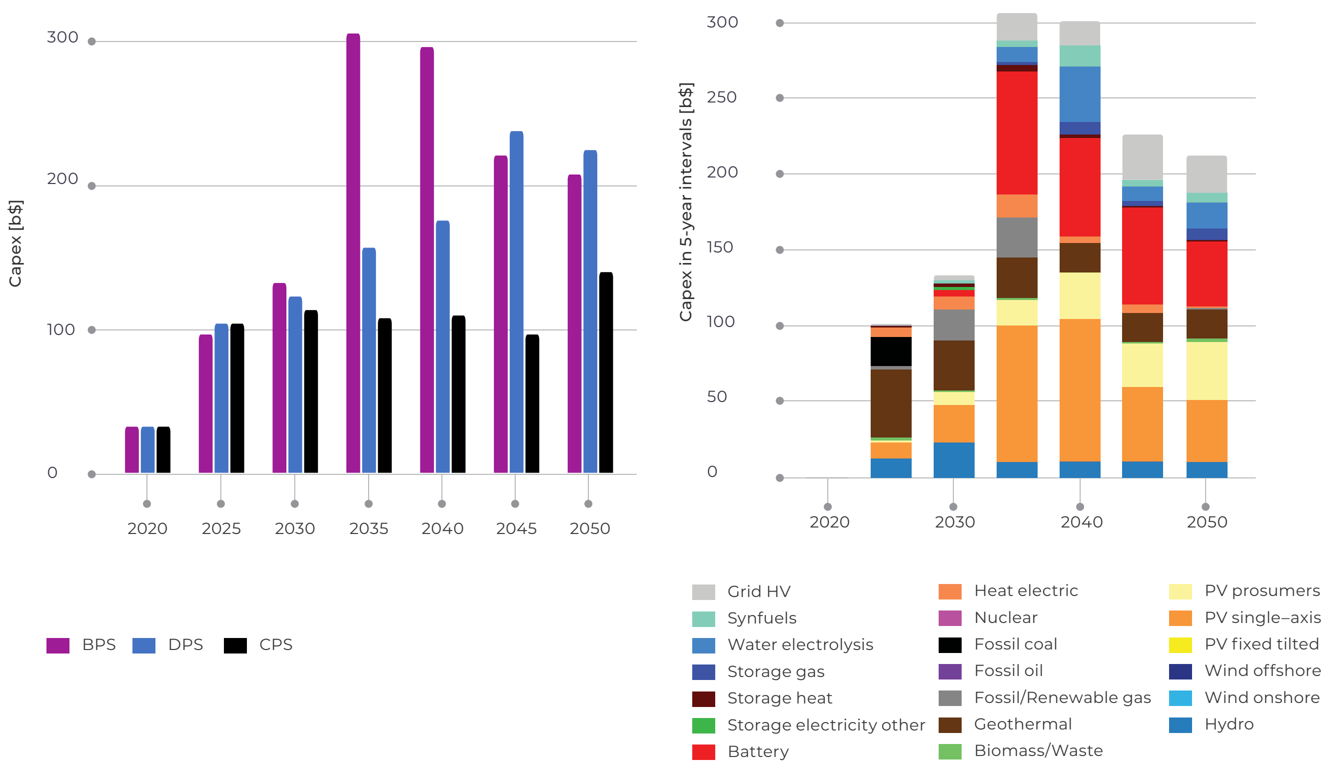


Figure 20: CAPEX cumulated with 5 years interval and CAPEX distribution in BPS scenario

Investments are well spread and channeled for different clean energy technologies. Investment in solar PV (including rooftop solar PV) will become the highest at around USD 2-7 billion per year for the next ten years. The solar PV investment will need to increase to USD 20-25 billion per year between 2030 and 2040, around a third of total investment needed in that period. With solar PV becoming the backbone of the energy system from 2030 onwards, investment in batteries will be crucial and reach as high as USD 13-16 billion per annum from 2030 to 2040. Geothermal and hydropower need to see annual investments of USD 7-8 billion and USD 2-5 billion respectively for the next ten years. Meanwhile, as grid integration intensifies from 2030 onwards Indonesia needs to see investment at around USD 3-4 billion per year between 2030 and 2040 and USD 5-6 billion per year from 2040 onwards. Lastly, investment in electric heating systems needs to ramp up to USD 1-2 billion for the next ten years while investment in electrolyzer is estimated at around USD 2-7 billion per year from 2030 to 2040.

The required investment grows due to growing energy demand in all sectors, decommissioning of old fossil capacity, and a shift toward renewable technologies. This projection may be on the high side compared to the past years, but it only corresponds to 5% of Indonesia's current GDP – quite a small number considering future economic growth. Besides achieving carbon neutrality, the programme will also improve people's quality of life by reducing noise and air pollution. Overall, the renewable-based energy system will benefit Indonesia in the long term considering the benefits mentioned above. Lower annual system costs and LCOE of renewables will make fossil-based energy systems no longer a viable option.

Capex in 5-year intervals [b$]	2025	2030	2035	2040	2045	2050
Hydro	12.5	23.7	11.2	11.0	10.9	10.9
Wind onshore	0.0	0.0	0.0	0.0	0.0	0.0
Wind offshore	0.0	0.0	0.0	0.0	0.0	0.0
PV fixed tilted	0.0	0.0	0.0	0.0	0.0	0.0
PV single–axis	11.3	24.4	89.3	93.9	49.5	40.3
PV prosumers	1.4	8.5	16.9	30.5	28.8	39.0
Biomass/Waste	1.4	0.9	0.9	0.0	0.7	2.2
Geothermal	45.5	33.6	27.2	19.6	19.2	19.0
Fossil/Renewable gas	1.7	20.0	26.6	0.0	0.0	0.6
Fossil oil	0.1	0.0	0.0	0.0	0.0	0.4
Fossil coal	19.3	0.0	0.0	0.0	0.0	0.0
Nuclear	0.0	0.0	0.0	0.0	0.0	0.0
Heat electric	6.0	8.6	14.7	4.0	4.8	1.0
Battery	0.0	4.8	81.2	65.1	64.5	42.4
Storage electricity other	0.7	1.5	0.0	0.0	0.0	0.0
Storage heat	0.9	2.5	4.4	2.1	0.6	1.4
Storage gas	0.0	0.1	2.5	8.7	3.9	7.6
Water electrolysis	0.0	0.0	9.3	36.6	9.0	16.3
Synfuels	0.0	2.3	4.0	13.8	4.7	6.4
Grids HV	0.5	2.8	18.7	16.1	29.3	24.6
Total	**101.3**	**133.7**	**306.9**	**301.4**	**225.9**	**212.1**

Table 2. CAPEX in 5-year intervals by technology (BPS scenario)

Co-benefits of deep decarbonization

Apart from reducing anthropogenic carbon emissions, deep decarbonization could bring important co-benefits such as the avoided costs of climate damages, increased energy efficiency, better air quality, avoided deaths and healthcare costs, more resilient energy systems, increased water availability and food security, as well as healthy ecosystems and rich biodiversity (Bos et al., 2019; IRENA, 2017). Data from Bappenas shows that coal-related air pollution alone has caused 7,480 premature deaths per year in Indonesia and cost the country USD 2.9 billion (Bappenas, 2019). With most major cities in Indonesia suffering from chronic congestion, the death toll from as well as the costs of air pollution would likely soar when including transport-related air pollution. Deep decarbonization in both power generation and road transport is therefore not only beneficial but also necessary.

With renewable energy becoming cheaper than fossil fuels, its use will also translate into lower energy expenditure and subsidies in the long run. Early coal phase-out will also avoid Indonesia from mounting stranded assets that might reach as little as USD 26 billion after 2040. Renewable energy is also key in electrifying Indonesia's rural areas that spread over the archipelago. Access to clean energy will bring new economic opportunities for rural people that oftentimes have no to limited access to electricity necessary in economic activities.

Deep decarbonization will also create new job opportunities in Indonesia. Job creation will increase over the transition period as Indonesia ramps up its renewable power generation. By 2030, the country will see more than 800,000 new direct jobs from the power sector, with around 67% of them coming from solar PV. The employment will continue to increase to more than 3.2 million jobs in 2050 with solar PV and batteries making up for 73% of total new jobs created in that year (see Figure 21).

It is important to note that the analysis only takes into account direct jobs in the power sector (power generation, transmission, and storage), meaning that job creation through the use of 100% renewable energy will likely create a higher number of jobs if indirect and induced jobs are included. This job estimate also excludes the jobs created when manufacturing electric vehicles, expanding public transport and retrofitting buildings, thus can be perceived as rather conservative.

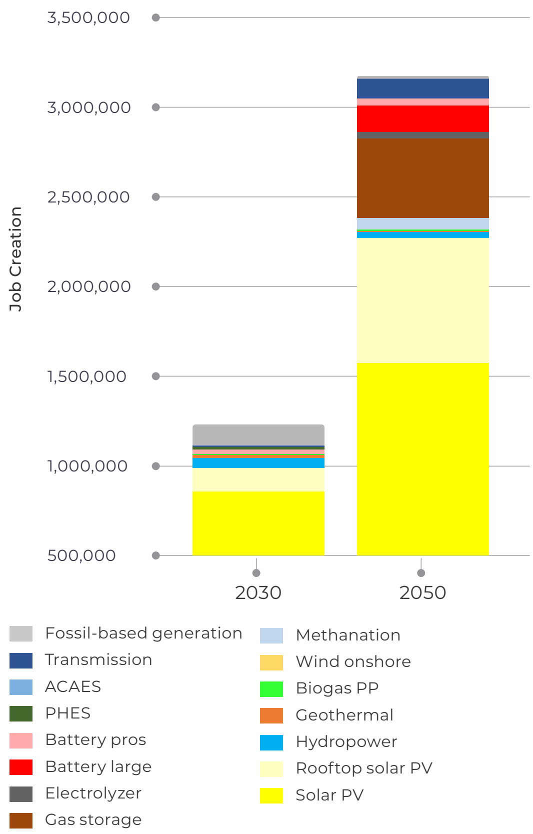


Figure 21: Job creation[9] through the use of 100% renewable energy.

[9] Jobs calculated are jobs in manufacturing, construction and installation, operation and maintenance, fuel supply, decommissioning and transmission. The calculation is using the methodology developed by LUT University (Ram et al., 2020).

Recommendations for policymakers

1. Take a bold decision now: Make deep decarbonization of Indonesia's energy system a top priority

This study shows that deep decarbonization of Indonesia's energy system by mid-century is both technically and economically attainable by changing the supply source from today's dominance of fossil fuels to 100% renewable energy. Such a pathway will reduce overall system cost for the next three decades by one fifth compared to a fossil fuel pathway. It will, at the same time, allow for a secure and reliable supply of energy in the country. Initiating such a profound energy system transformation will also bring tremendous economic opportunities at a time when, due to the pandemic, Indonesia direly needs it.

The sense of urgency regarding climate change mitigation efforts has risen rapidly in Indonesia with more and more hydrometeorological disasters occuring in Indonesia, reflecting the real risk and cost of climate change. The Indonesian government therefore must take bold moves to take action towards a zero-emission energy system. This might become a difficult decision particularly in the political sphere where the fossil fuel industry has considerable relevance for the economy of the country.

However, it is important to note that a successful transformation could bring major socio-economic benefits to Indonesia. A massive investment program in clean technologies such as renewable energy, electric vehicles, and modernized grid infrastructure will help the country leapfrog towards a modern, sustainable and globally competitive economy.

This will be felt also in the job market: **our analysis shows that at least 3.2 million new jobs will be created if the country transforms its energy system to a modern and sustainable zero emission supply by 2050.** The use of clean energy will bring clean air, improve overall public health and reduce health care costs. In contrast, sticking to the traditional fossil fuel pathway will require major investment in coal-fired power plants that would most likely become stranded assets in the 2030s in the face of cost-competitive clean energy.

Deep decarbonization, therefore, should be perceived as an opportunity rather than a threat to Indonesia's economy. To tap this opportunity, a bold political commitment is needed today as today's decision will ultimately determine the pace of the energy transition in Indonesia as well as the system cost. Political leadership to make deep decarbonization a national priority will provide much-needed direction to the market to take the right steps in line with the new global energy sector trend.

To show its strong political commitment, in a first and important step, the government has to increase its climate mitigation ambition under its Nationally Determined Contribution (NDC) that is currently highly insufficient to meet the Paris Agreement (Climate Action Tracker, 2020). With the COP26 approaching, the Indonesian government should not miss the opportunity to update and scale up its NDC target for 2030 as well as present a new, ambitious Long-Term Strategy for Low Carbon and Climate Resilience (LTS CCR) 2050. The recently released-LTS CCR 2050 drafted by the Ministry of Environment and Forestry (MoEF) has been perceived as less ambitious considering that the government only targeted to reach carbon neutrality by 2070 rather than 2050. A complete change of direction is therefore needed to put Indonesia on the frontline of the fight against climate change.

2. Ensure that the energy system planning reflects a clear decarbonization pathway

As a manifestation of a strong political commitment to deep decarbonization, energy planning should be carried out in a way that the planning minimizes the environmental impacts of both energy production and consumption in Indonesia. Considering that building power, gas and battery charging networks, as well as generation facilities for power plants, electrolyzers and other parts of the infrastructure is not achieved overnight and once constructed, the infrastructure is there to last for (and re-earn investment over) decades, policymakers need to ensure that today's planning is consistent with the long-term goal to achieve a zero emission energy system by mid-century. The following elements should be reflected in the upcoming, more ambitious plans for the power, transport and industry sectors.

Power sector

The existing national energy plan (RUEN) as well as RUPTL still put too much focus on fossil-based power generation despite the fact that a variety of analyses have demonstrated that high shares of renewable energy in the power grid can be achieved at low costs. Indeed, the power sector is of particular importance in decarbonization efforts, since it is easier to be decarbonized than transport and industry. It will play an important role also for these two sectors, as parts of transport and industrial energy supply will come from electricity in the future. Policymakers should thus feel encouraged to intensify the integration of renewable energy into Indonesia's energy system.

Today, only 14% of electricity generation comes from renewable sources. In the next ten years, around half of electricity generation needs to be sourced mainly from solar PV, hydropower, and geothermal. To achieve the target, annual growth of solar PV capacity (including rooftop solar PV) of 10 to 12 GW is required between 2020 to 2030. Meanwhile, in the same period, annual capacity growth of hydropower, geothermal, and biomass capacities should be in the range of 200 to 1600 MW. On top of that, the coal moratorium should start in 2025 at the latest. From 2025 onwards, the government needs to phase-out coal by shutting down the remaining coal-fired power plants, particularly power plants that are more than 15 years old.

The capacity of the inter-island grids would need to expand by around 5 GW by 2030. The expansion is mainly the new inter-island connections from Java to Kalimantan, Java to Nusa Tenggara, Nusa Tenggara to Sulawesi, and Sulawesi to Maluku and Papua that will help the integration of more renewables into the national grid. The capacity of sea cable infrastructure connecting these islands is ranging from 600 MW to 2.6 GW.

The inter-island interconnection will be essential to tap Indonesia's enormous renewables potential that is oftentimes distant from load centers. To minimize the need for new power stations and allow more distributed generation integrated into the grid, grid modernization should be carried out. The modernized grid will also help reduce peak load, increase renewable penetration, improve system security, and cut down operational costs (*US Department of Energy*, n.d.).

From 2030 onwards, electrification and sector coupling will become the new normal in the Indonesian energy sector. As a result, electricity demand significantly increases in the country. With the combination of renewable energy and battery becoming more competitive than fossil fuel power generation, all electricity supply in Indonesia could come from renewable sources by 2045. Meeting the growing electricity demand would translate into investment of up to 70 GW annually in solar PV, and up to 1 GW and 0.5 GW in hydropower and geothermal respectively between 2030 and 2045.

To ensure the reliability and security of power supply, battery system capacity would need to increase significantly after 2030 by around 20 GW per year. Additionally, Sumatra and Java as well as Kalimantan and Sulawesi should be interconnected by 2035 to allow electricity exchange between these islands. Nationally, an annual increase of 7 to 8 GW in transmission capacity would help achieve 100% renewable power generation by 2045. While the power sector will have been fully decarbonized by 2045, growth in renewable energy, energy storage systems, and transmission remains crucial to achieve zero emissions in the transport and industry sectors by 2050.

Transport sector

Current government target to increase penetration of electric cars to 2,200 and electric motorcycles to 2.1 million by 2025 is insufficient to meet the deep decarbonization target. At minimum, 10% of new cars and light trucks and 60% of new motorcycles sold in 2030 should be battery-powered, growing from virtually zero today. At the same time, the market share of battery electric vehicles in the bus, medium duty, and heavy duty vehicles segments should reach 50%, 19%, and 8% respectively. This will translate into 110 million of battery electric vehicles on the road in 2030. To realize this target, Indonesia needs to start building necessary infrastructure such as charging stations and conduct pilot projects to introduce electric buses and trucks to the market.

The government needs to ban all fossil-powered vehicles by 2050. In this period, battery-powered cars and motorcycles should make up for 73% and 95% of overall market share. The remaining share comes from other types of electric vehicles such as fuel cell electric vehicles (FCEV) and plug-in hybrid electric vehicles (PHEV) as well as internal combustion engines that use renewable-based fuels.

To date, however, no plans for hydrogen and synthetic fuel production have been put in place. This needs to change as the role of hydrogen and synthetic fuels in decarbonizing the harder-to-abate segments such as marine and aviation (and some industrial processes that require very high temperatures) will significantly increase after 2030. While the demand for hydrogen and synthetic fuels will come later, the government should start carrying out pilot projects and identifying potential demand and locations of required infrastructure throughout the country.

Industry (heat) sector

Most industrial process heat today is produced by fossil fuels. But in the next ten years, more than 40% of process heat needs to be produced by efficient electric heaters and heat pumps, triple today's number. Electric heating is particularly suitable for the production of low temperature heat. To encourage the use of electric heating, the government needs to impose stricter energy efficiency standards for industries.

The renewable-based fuels such as hydrogen and synthetic methane need to take a larger role in heat production (particularly the production of very high temperature heat) from 2040 onwards with their share reaching 29% in 2050. To meet the target, a roadmap on clean fuel production should be developed. The roadmap should clearly provide information about the infrastructure development plan (including production facilities and gas storage) required to meet future demand. Pilot projects in the industrial facilities carried out prior to 2040 will be prerequisite for the successful implementation of renewable-based heating in the industrial sector.

The implementation of pilot programs becomes important considering the risks and costs associated with the use of new technologies. In the industry sector, the use of electricity or hydrogen-based heat requires the industry to change its production processes and furnace designs. Considering that the industrial processes are usually highly integrated, any adjustments to one part of the process require adjustments to

3. Stimulate multi-stakeholder participation in decarbonization efforts

Deep decarbonization is possible for Indonesia. However, it certainly comes with tremendous challenges. It will, eventually, become a long, multifaceted, and complex process which demands participation of all state and non-state actors at the national, provincial, and local levels. Granted, the national government plays a key role in setting up the national target and long-term climate strategy. However, it is the provincial and local governments that will largely determine the final results of such a strategy. The national government therefore needs to ensure that there are no policy gaps between national strategies and provincial and local action plans.

The provincial and local governments, for instance, need to realign their local building codes with the new, more ambitious climate strategy set up by the central government. Provinces and cities have to provide necessary incentives to encourage building owners to comply with the new, stricter building codes. Other efforts, such as developing and integrating public transport, setting up bike lanes, deploying electric buses, using rooftop solar PV on government buildings, and installing EV charging stations, are also important to be taken by the provincial and local governments to reduce both greenhouse gas emissions and pollutants in the local areas.

Local initiatives such as 100% renewable energy islands, provinces, and cities will also accelerate the decarbonization pace. The Indonesian government should equip local governments with sufficient information about the costs and benefits of decarbonization as well as with technical assistance, policies, and incentives that can help local governments carry out the initiatives. Engagement with these local governments is also key to stimulate participation of different levels of government and help prepare action plans crafted for each local initiative.

Finally, participation of non-state actors such as business owners and individuals in decarbonization efforts should also be encouraged. For instance, the government should allow and even incentivize business owners and individuals to install rooftop solar PV on their facilities and houses. Recognizing that deep decarbonization requires enormous amounts of investment, the participation of the private sector and citizens will ease up the government's responsibilities. However, to increase participation of non-state actors, decentralization and democratization of energy infrastructure should be warranted by the government.

4. Put in place the right policies to realize the deep decarbonization target

This study has shown that deep decarbonization of Indonesia's energy system is technically and economically achievable. The size of the challenge should not obscure the fact that decarbonization will also bring enormous benefits and opportunities to Indonesia's economy: the creation of millions of new, sustainable and quality jobs, the improvement of public health (which will also imply a substantial reduction in health costs), and the establishment of a modern economy, which enable the country to compete in the growing world market for carbon-neutral products. To get there, the Indonesian government needs to put in place the right policies and regulations today and remove regulations and policies perceived as barriers to clean technology investments in the country.

Power sector: policies on Renewable Portfolio Standards (RPS), fiscal and non-fiscal incentives for renewable energy, Feed-in-Tariffs (FIT), renewable energy certificates, competitive tenders/auctions, and renewable energy funds should be put in place to encourage renewables development in the country. In addition to these policies, policies and regulatory certainty, the streamlining of PPA and the tender process will also help reduce risks for potential investors and thus mobilize private investment in renewable energy. The government should also expedite the enactment of the renewable energy law and Presidential Regulation on renewable energy tariff that contains Feed-in-Tariffs for small scale renewables that have been processed for more than one years since the initial consultation took place by the end of 2019.

Moreover, Indonesia needs to stop accepting new proposals to build new coal-fired power plants. The coal moratorium should be followed by a coal exit policy that sets forth the coal retirement mechanism (CRM) used to retire 15-to 20-year-old coal plants. The CRM can be combined with a sustainable energy transition mechanism (SETM) used to replace the old coal plants with a mix of energy efficiency, renewable energy and storage (Kanak, 2020). As fossil fuel phase-out will negatively impact regions that are heavily dependent on fossil fuels, the government has to help local governments diversify their economies, set up skill development programs for affected workers, and facilitate social dialogue among stakeholders (Gabriella & Simamora, 2020).

Reforms in energy subsidies and market structure are also needed. The government must stop providing subsidies to coal and other fossil fuels to create a level playing field for renewable energy. Instead, the subsidies can be repurposed to support green growth in Indonesia. In addition, policymakers also need to restructure the power market to allow increased participation of the private sectors and citizens in renewable generation (distributed generation) as well in power transmission development. The private participation will also attract new, innovative investors to come in and compete for best solutions, driving costs down.

Transport sector: policies on public transport expansion and integration, bike lanes, electric buses should be put in place to reduce the use of private vehicles, lower greenhouse gas emissions, and improve air quality. Meanwhile, to increase the EV ecosystem in Indonesia, the government should provide fiscal incentives such as direct subsidies, tax exemptions, carbon price as well as non-fiscal incentives such as charging infrastructure and free parking (Adiatma & Marciano, 2020). Most importantly, the government needs to set a policy on banning all fossil-based vehicle sales by 2050.

Fuel economy standards are also crucial in helping the automotive industry develop new technologies that are both efficient and clean. Meanwhile, financial support is needed to build infrastructure used to produce hydrogen and synthetic fuels necessary for reducing emissions from both the transport and industry (heat) sectors. To take full advantage of the shift to electric vehicles, the government also needs to prepare policies that support the development of the EV supply chain in the country.

Industry (heat) sector: policies on energy efficiency and energy management in industries will be key in decarbonizing the industry sector. Stricter energy efficiency standards will help encourage industries to shift to electric heaters and heat pumps that are more efficient than fossil-based heaters. However, the government also needs to provide incentives for industries carrying out decarbonization efforts. The incentives are necessary considering the risks associated with the retrofitting of production facilities. While hydrogen and synthetic methane will only be used in heat production after 2040, the government should start carrying out pilot projects and incentivize research and development of hydrogen and synthetic fuels in Indonesia earlier.

Environment: policies on air quality and environmental protection should be strengthened to reflect a more ambitious climate target in Indonesia. The government can start improving policy on emission standards for coal-fired power plants that is perceived as weak (ICEL, 2019). The standards need to be updated regularly and made stricter to discourage coal development in the country.

Overall, the integration of energy, industrial, financial, environmental, and fiscal policies is needed to reflect synchronous climate strategies in all segments of Indonesia's economy. The government should also make sure that policies on human development will equip local talents with skills needed in the new, green economy. Both the Long-Term National Development Plan (RPJPN) and the Medium-Term National Development Plan (RPJMN) should provide measured strategies to achieve Indonesia's climate commitment. On top of that, policy consistency should also be achieved at different levels of government with national and regional plans being orchestrated towards climate actions.

In line with this, the government should then focus efforts on aligning all energy plans with the new NDC and long-term climate strategy. Specifically, the National Energy Plan (RUEN) as well as the Regional Energy Plans (RUED) should reflect a new, more ambitious climate target of 2030 and 2050 and put in place detailed action plans necessary to achieve that target.

With policy playing a key role in determining the outcome of decarbonization efforts, policymakers need to reimagine the energy sector post-pandemic and take necessary measures to improve investment climate and achieve deep decarbonization by mid-century. The deep decarbonization therefore should be seen not only as a shift from fossil fuels to renewable energy but also as an opportunity to modernize and restructure the energy market, allow stakeholder and citizen participation in energy infrastructure ownership and investment, and set up new forms of socio-economic development (World Future Council, 2014).

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ANNEX A - Table key indicators in the Best Policy Scenario

Key indicators		2020	2025	2030	2040	2050	to 2030 p.a	2030 - 2050 p.a
GHG emssion (Mton CO_{2eq})	Power	180,1	315,6	313,2	66,3	0,0	13	-16
	Heat	147,2	123,1	100,9	34,7	0,0	-5	-5
	Transport	174,5	165,7	147,9	54,8	0,0	-3	-7
	Total	501,8	604,4	562,0	155,8	0,0	6	-28
Primary energy demand (TWh)	Total	1852,9	2141,3	2221,9	2382,3	2975,3	37	38
	Fossil gas	146,7	99,9	142,2	2,1	0,0	0	-7
	Fossil oil	665,8	592,7	515,4	194,8	0,0	-15	-26
	Fossil coal	820,7	1210,7	1120,5	294,3	0,0	30	-56
Electricity consumption	(TWh)	233,0	596,0	700,0	834,0	1213,0	47	26
	Share of	0,1	0,2	0,5	0,9	1,0	0	0
	Renewables	0,0	19,0	107,8	897,8	1492,9	11	69
	PV (GW)	0,1	0,1	0,1	0,1	0,0	0	0
	Wind	5,6	11,0	21,3	30,8	40,2	2	1
	Hydro	0,2	0,7	1,7	2,5	2,5	0	0
	Biomass/Waste	2,0	0,7	1,7	2,5	2,5	0	0
	Others RE	30,1	6,1	9,2	14,1	19,1	1	0
	Fossil Coal	30,1	44,1	44,1	41,2	38,2	1	0
Number of electric vehicle (million of units)	LDV	0,0	0,7	2,9	37,1	58,7	0	3
	2/3 wheeler	45,7	65,4	110,9	173,1	210,5	7	5
	Bus	0,0	0,8	2,4	7,0	9,6	0	0
	MDV	0,0	0,5	1,2	6,1	8,0	0	0
	HDV	0,0	0,0	0,1	0,6	1,2	0	0
Transport fuel demand (TWh)	Electricity	23,9	60,8	135,9	377,7	498,9	11	18
	Hydrogen	0,0	0,4	2,6	41,1	223,7	0	11
	Methane	0,0	0,1	0,5	5,6	72,0	0	4
	FT Fuels	0,0	0,0	5,6	75,2	62,9	1	3
	Biofuels	88,1	153,1	229,4	229,4	157,8	14	-4
	Fossil Fuels	626,1	592,7	515,4	194,8	0,0	-11	-26
Synthetic fuel	Electrolyser capacity (GW)	0,0	0,0	0,0	138,7	229,1	0	11
	CO_2 DAC (GW)	0,0	0,0	2,1	28,2	42,2	0	2
	Hydrogen use (TWh)	0,0	0,4	1,9	16,5	41,9	0	2

ANNEX B - Renewables Assumptions

Key indicators	Year	2020	2025	2030	2035	2040	2045	2050	Units
PV fixed tilted PP	Capex	899.8	602.8	305.8	260.7	227.7	202.4	182.6	USD/kWp
	Opex fix	16.17	11.66	6.27	5.5	4.95	4.4	4.07	USD/(kWp*a)
	Opex var	0	0	0	0	0	0	0	USD/kWh
	Lifetime	30	35	35	35	40	40	40	years
PV rooftop - residential	Capex	1100	943.8	786.5	684.2	606.1	545.6	498.3	USD/kW,el
	Opex fix	9.57	8.58	7.37	6.49	5.83	5.17	4.84	USD/(kW,el*a)
	Opex var	0	0	0	0	0	0	0	USD/kWh,el
	Lifetime	30	35	35	35	40	40	40	years
PV rooftop - commercial	Capex	863.5	683.1	501.6	432.3	379.5	338.8	308	USD/kW,el
	Opex fix	11.44	9.57	7.37	6.49	5.83	5.17	4.84	USD/(kW,el*a)
	Opex var	0	0	0	0	0	0	0	USD/kWh,el
	Lifetime	30	35	35	35	40	40	40	years
PV rooftop - industrial	Capex	699.6	531.3	361.9	309.1	269.5	238.7	216.7	USD/kW,el
	Opex fix	12.43	10.23	7.37	6.49	5.83	5.17	4.84	USD/(kW,el*a)
	Opex var	0	0	0	0	0	0	0	USD/kWh,el
	Lifetime	30	35	35	35	40	40	40	years
Wind onshore	Capex	1500.4	1300.2	1100	1061.5	1034	1006.5	990	USD/kW,el
	Opex fix	59.95	25.96	22	21.23	20.68	20.13	19.8	USD/(kW,el*a)
	Opex var	0	0	0	0	0	0	0	USD/kWh,el
	Lifetime	25	25	25	25	25	25	25	years
Hydro Dams/ reservoirs	Capex	2066.9	2066.9	2066.9	2066.9	2066.9	2066.9	2066.9	USD/kW,el
	Opex fix	39.6	39.6	39.6	39.6	39.6	39.6	39.6	USD/(kW,el*a)
	Opex var	0	0	0	0	0	0	0	USD/kWh,el
	Lifetime	50	50	50	50	50	50	50	years
Hydro Run-of River	Capex	2816	2816	2816	2816	2816	2816	2816	USD/kW,el
	Opex fix	84.48	84.48	84.48	84.48	84.48	84.48	84.48	USD/(kW,el*a)
	Opex var	0	0	0	0	0	0	0	USD/kWh,el
	Lifetime	50	50	50	50	50	50	50	years

ANNEX C - Coal Assumptions

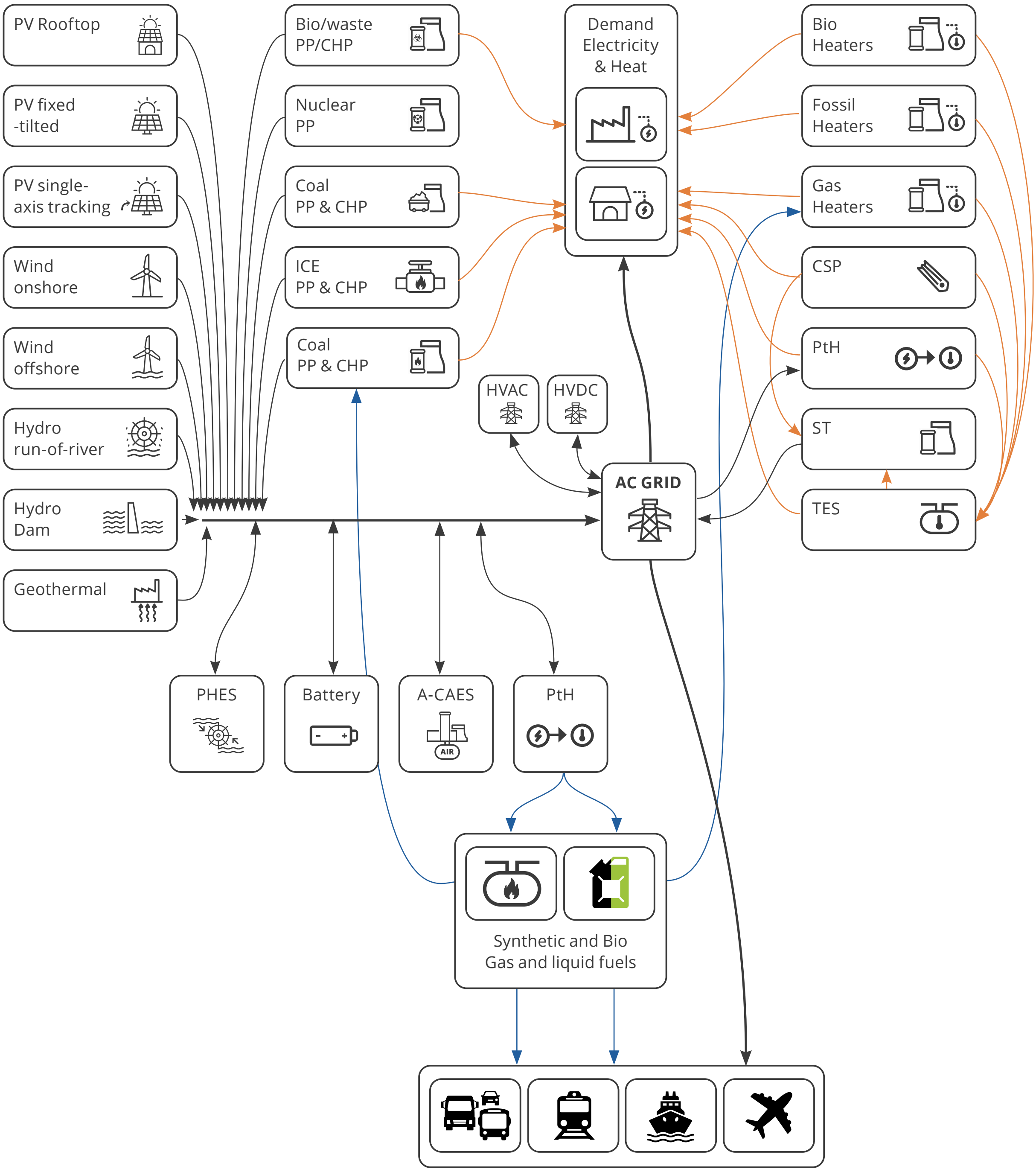
	Year	2020	2025	2030	2035	2040	2045	2050	Units
Hard Coal PP	Capex	1400.3	1380.5	1359.6	1349.7	1339.8	1329.9	1320	
	Opex fix	40.7	40.7	39.6	39.6	39.6	38.5	38.5	USD/kW,el
	Opex var	0.000121	0.000121	0.000121	0.000121	0.000121	0.000121	0.00011	USD/(kW,el*a)
	Lifetime	45	45	45	45	45	45	45	USD/kWh,el
	Efficiency	0.37	0.37	0.38	0.38	0.38	0.39	0.39	years

ANNEX D - Fuel Prices, WACC

	Year	2020	2025	2030	2035	2040	2045	2050	
Fuel prices	Coal	11.33	12.43	13.64	15.18	16.5	16.5	16.5	USD/MWh,th
	Light fuel Oil	43.89	49.61	55.33	54.78	54.23	54.23	54.23	USD/MWh,th
	fossil gas	24.53	33.11	35.97	39.71	44.22	44.22	44.22	USD/MWh,th
	Uranium	2.86	2.86	2.86	2.86	2.86	2.86	2.86	USD/MWh,th
GHG emissions*		9.9	35.2	49.5	62.7	74.8	88	100.1	USD/ton
WACC		10.0%	9.5%	9.0%	8.5%	8.0%	7.5%	7.0%	

*depends on the scenario, for BPS it starts from 2020 and for DPS and CPS it starts from 2030

ANNEX E - The schematic representation of the LUT Energy System Transition model



The LUT model has been applied across an integrated energy sector comprising power, heat and transport demand. Across the system, electricity (represented by black lines), heat (represented by orange lines) and hydrogen and synthetic fuels (represented by blue lines) are generated to produce power and heat.

Electricity is generated from multiple sources and distributed to meet power and heat demands. Excess electricity can be saved in the energy storage systems, e.g. batteries, pump hydro, and compressed air and/or used to produce hydrogen and synthetic fuels (indirect electrification). Produced clean fuels will be used in the transport and industry sectors.

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