Making Energy Transition Succeed

A 2023's Update on The Levelized Cost of Electricity and Levelized Cost of Storage in Indonesia

Imprint

Making Energy Transition Succeed:
A 2023's Update on The Levelized Cost of Electricity and Levelized Cost of Storage in Indonesia

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Foreword

It has been a challenging year for everyone. The COVID-19 pandemic, energy crisis, rising inflation, and climate crisis occur concurrently. While many people around the world, particularly in emerging economies, are facing rising energy costs due to Russia's invasion of Ukraine, Indonesians are relatively immune to this situation. Unlike other countries, we do not see the incremental cost of our energy bill, which includes electricity, LPG, and, to a lesser extent, gasoline. The main reason for this is because of the government's massive energy subsidies.

The total energy subsidy alone reached IDR 131.5 trillion or USD 9 billion in 2021, which is IDR 49.8 trillion or USD 3.4 billion for electricity via PLN. In addition to the subsidy, PT PLN received additional compensation in the amount of IDR 24.6 trillion (USD 1.77 billion). The total electricity subsidy was USD 5.1 billion.

As the price of fossil fuels skyrocketed in 2022, the subsidy amount increased dramatically. Originally, the subsidy budget was IDR 350 billion or USD 24 billion. However, by the end of 2022, the subsidy had reached its peak with electricity subsidies and compensation totalling IDR 551 trillion or USD 37 billion. The electricity subsidy and compensation totalled IDR 101 trillion (USD 6.82 billion).

With fossil fuels accounting for 87% of PLN generation, the majority of this subsidy actually goes to fossil fuels. The subsidy amount excludes coal subsidies in the form of a domestic coal price cap of USD 70/ton and a fossil gas price cap of USD 6/MMBtu. Despite the significant increase in fuel costs, the cost of electricity generated by coal and fossil gas plants remains low in this case.

Energy subsidies are one of the obstacles to the growth of renewable energy in Indonesia. Without all of these subsidies, electricity from coal generation could be three times as expensive as it is now, far more expensive than renewable electricity, such as solar PV or wind power with energy storage. The fossil fuel subsidies create an unfavorable incentive for utilities to maintain their fossil fuel assets, despite the fact that they are no longer economically competitive and are financially burdening the public.

More importantly, fossil fuel subsidies impede utilities like PLN to deal with stranded assets from its fossil fuel plants. Fossil fuel subsidies also make it impossible to accelerate the deployment of renewable energy and on the contrary, implement false solutions based on the intention of extending the use of coal, thus disrupting the transition to renewable energy in line with the Paris Agreement temperature goal. IESR first published the LCOE report and tool in 2019. This year we updated our tool with more technologies and the new economics of energy technology. IESR's 2023 Update of LCOE and LCOS shows that renewables have become more competitive than fossil fuels. Nevertheless, renewable energy adoption in Indonesia remains low due to the government's own policy of maintaining massive subsidies for fossil fuels. As Indonesia plans to achieve net-zero emissions by 2060 or sooner, and the power sector's emissions peak in 2030, energy subsidy and pricing reform should be prioritized. With that, the utility should move faster to deploy renewables and retire coal plants sooner.

Jakarta, 24 March 2023

Fabby Tumiwa
Executive Director

List of Abbreviations

BESS	: Battery Energy Storage Systems
BMS	: battery management system
BPP	: *Biaya Pokok Penyediaan (listrik)*
BOS	: balance of system
C & I	: commercial & industry
CAES	: compressed air energy storage
CAPEX	: capital expenditure
CCGT	: combined-cycle gas turbine
CCS	: carbon capture and storage
CFPP	: coal-fired power plant
Coal SC	: Coal Supercritical
Coal SubC	: Coal Subcritical
Coal USC	: Coal Ultra-supercritical
COD	: commercial operation date
DEN	: *Dewan Energi Nasional*
DMO	: Domestic Market Obligation
DoD	: depth-of-discharge
E/P ratio	: energy-to-power ratio
EPC	: engineering, procurement and construction
ESS	: energy storage systems
G20	: Group of Twenty
GHG	: greenhouse gasses
GW	: GigaWatt
GWh	: GigaWatt-hour
HBA	: *Harga Batubara Acuan*
HPP	: hydropower plant
HSD	: high speed diesel
IGCC	: integrated gasification combined cycle
IPB	: *Izin panas bumi*
ITF	: Indonesian Throughflow
kW	: kiloWatt
kWh	: kiloWatt-hour
LCOE	: levelized cost of electricity
LCOS	: levelized cost of storage
LCR	: local content requirement
LDS	: long-duration storage
LFP	: lithium iron phosphate
LIB	: lithium-ion battery
MEMR	: Ministry of Energy and Mineral Resources
MMBtu	: Metric Million British Thermal Unit
MSW	: municipal solid wastes
MW	: MegaWatt
MWh	: MegaWatt-hour
NCM	: Nickel-Cobalt-Manganese
NZE	: net-zero emission
O & M	: operational and maintenance
OCGT	: open-cycle gas turbine
OPEX	: operational expenditure
PHS	: pumped hydropower storage
PLN	: *Perusahaan Listrik Negara*
PNNL	: Pacific Northwest National Laboratory
PPA	: power purchase agreement
PV	: photovoltaics
RDF	: refuse-derived fuel
RE	: renewable energy
RTE	: round-trip-efficiency
RUPTL	: *Rencana Usaha Penyediaan Tenaga Listrik*
SMR	: Small Modular Reactor
tCO_2eq	: $tonCO_2$ equivalent
VGF	: Viability Gap Fund
VRE	: variable renewable energy
VRFB	: vanadium redox flow battery
WACC	: weighted average cost of capital
WKP	: *Wilayah Kerja Panas Bumi*

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Executive Summary

Replacing the greenhouse gasses-emitting power plants with renewable ones is necessary to achieve the net-zero emission goal. In Indonesia, however, renewables are still facing unfair competition with artificially cheap coal-fired power plants (CFPP) and the hesitance of the utility company to adopt more variable renewable energy (VRE) due to its intermittency. CFPPs are still reported as the cheapest source of bulk generation in Indonesia with a cost varying between $66 to $95/MWh, while many countries that previously relied on thermal power plants have been shifting into renewables and making their cost less than US$30 per MWh.

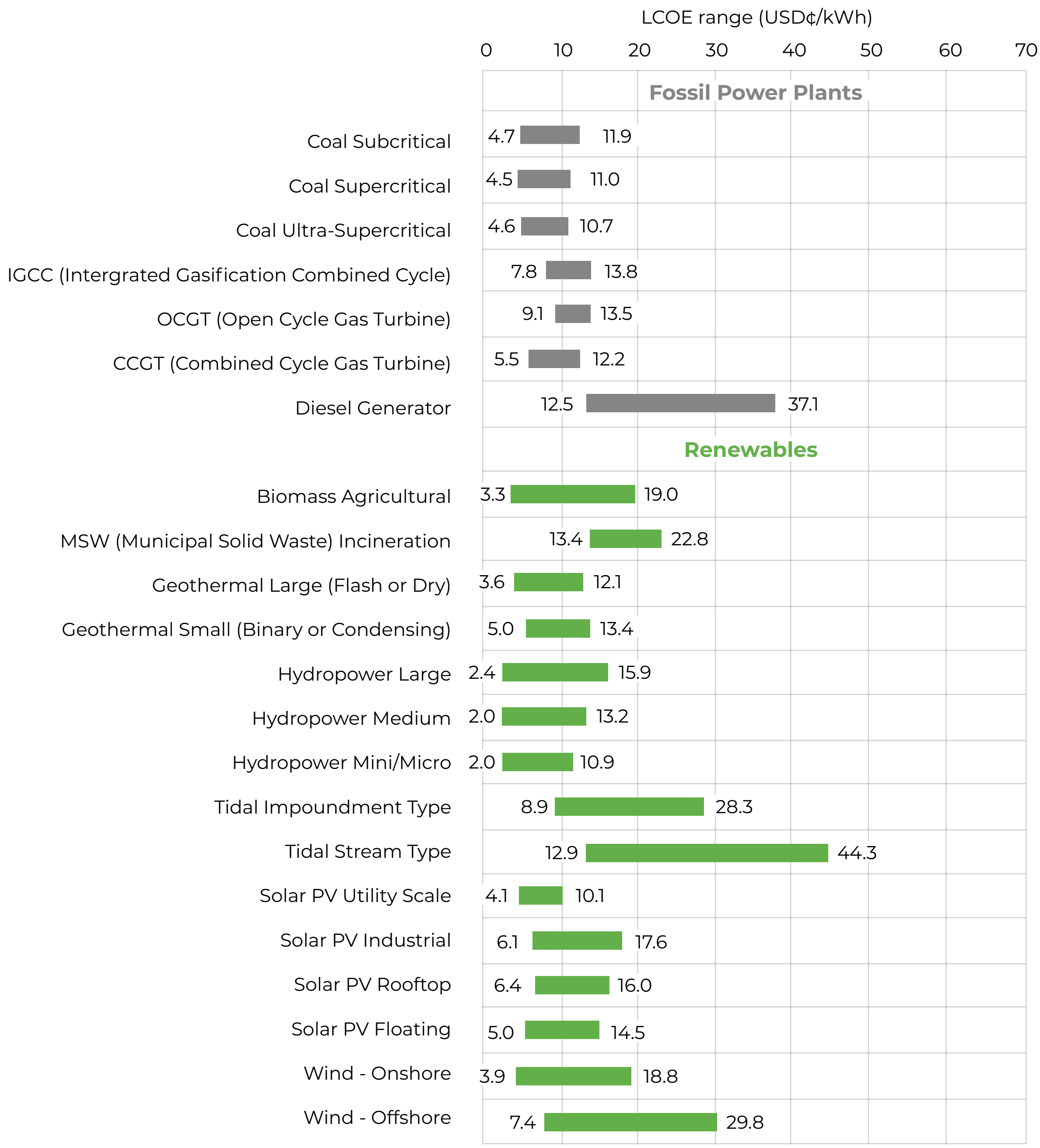
Understanding how to estimate the generation cost through levelized cost of electricity (LCOE) calculation and identifying its cost drivers is necessary for energy planners, renewable project developers, and citizens. LCOE is the price at which the generated electricity should be sold for the system to break even at the end of its lifetime. It is derived from dividing the total cost of a power plant by the total amount of generated electricity. Analogously, the cost of energy storage, often cited as a prerequisite for renewable energy integration, in different use cases through the levelized cost of storage (LCOS) calculation is obtained from the total costs incurred by an energy storage system (ESS) divided by its discharged energy over its entire lifespan. The analysis can be used to provide input, especially for policymakers, in providing the optimal stimulus or incentives needed to accelerate the development of prospective renewable energies (REs).

Institute for Essential Services Reform (IESR) published the first report on Indonesia's LCOE in 2019. Due to many factors influencing LCOE, such as technological advancement, cost, and regulations in the power sector that have changed since then, it is necessary to update the LCOE calculation based on the current circumstances. This report covers more technology options than the previous one, which can be used as an additional reference for readers. The analysis of the LCOE values also considers the implication of policies that have been implemented or are soon to be enacted, in addition to the trend of changes in technology prices. Furthermore, an updated LCOS from several ESS types is presented in this report to support the use of renewables in various cases.

The LCOE and LCOS value in this report is calculated specifically using the annuity method where the total cost is converted into an equivalent annual cost, while the electricity generation (or electricity discharge for ESS) value used is the average annual electricity generation (or annual discharge). Each technology has certain parameters that significantly affect LCOE or LCOS values; hence, the sensitivity analysis of several parameters is necessary. For LCOE outcomes, the policies that may affect parameter values are further discussed, including the impact of implementing carbon pricing, co-firing, and carbon capture technology (CCS) for fossil power plants. The effect of local content requirement (LCR) policies and intermittent technologies' installation requirements on the LCOE value of solar photovoltaics (PV) also becomes the focus of the discussion. In the case of LCOS, this report introduces various types of energy storage applications with varying costs.

What are the LCOE and LCOS for Indonesia?

Based on the recommended LCOE value, coal supercritical is the technology with the lowest cost today, under the condition that its fuel price follows Domestic Market Obligation (DMO) regulation with a coal price cap of US$ 70 per ton. Nevertheless, it is likely to become expensive because of the implementation of policies like carbon pricing that are effective this year and possibly a coal price increase if DMO's price is lifted. The cost of energy generated from fossil fuel power plants is very sensitive to changes in the fuel cost parameter value. The fuel costs component accounts for more than half of the LCOE of gas-fired power plants and even up to 71.4% of the LCOE of diesel generators. Meanwhile, the shares of the fuel cost component of CFPPs are relatively lower due to the DMO price of coal. When the assumption of a moderate market coal price of US$150 per tonne is taken into account to calculate the LCOE, instead of the DMO coal price, the LCOE of CFPPs will be around 10.7 to 11.9 cents per kWh.



Graph ES 1. LCOE from various electricity generation technologies

Among renewables, medium-scale hydropower plants have the lowest LCOE at 4.1 cents/kWh, followed by mini/micro hydropower plants and utility-scale solar PV with 4.9 cents/kWh and 5.8 cents/kWh, respectively. In calculating the LCOE value, this report does not include the land-use costs. However, due to high space requirements for hydropower plants and solar PV developments, the potential deviation of LCOE outcome from land-use cost incurrence must be recognized. While the estimated investment cost increase of medium-scale hydropower plants from land-use cost is about 6%, the land-use cost would affect utility-scale solar PV by around 18% and drive its LCOE value to 6.7 cents/kWh.

Moreover, the LCOE of renewables, except agricultural biomass power plants, is very sensitive to their financing. Changes in the weighted average cost of capital (WACC), and their CAPEX component make up a high share of the LCOE structure in the absence of the fuel cost component. Solar PV is one of the technologies most affected by the WACC value, where every 10% of WACC growth increases its LCOE by at least 7%. For agricultural waste biomass power plants, the LCOE of 6.4 cents per kWh is lower than that of municipal solid wastes -incineration at 17.1 cents per kWh. However, the earlier technology LCOE can only be reached if there is cheap biomass feedstock. Otherwise, the LCOE can be as high as 19 cents/kWh if a similar type of biomass (*i.e.*, wood chips) is obtained at the global market price today of US$160 per ton.

Table ES 1. LCOS from various ESS technologies in various applications

Applications (Scale)	Technology	Duration	LCOS (USD¢/kWh)
Primary response (100 MW)	Flywheels	0.25 hour	14.82
	LIB (LFP)		19.28
	LIB (NCM)		21.11
	VRFB		30.48
Secondary response (100 MW)	LIB (LFP)	4 hours	12.61
	LIB (NCM)		14.22
	VRFB		14.40
	PHS		8.65
Peaker replacement (100 MW)	LIB (LFP)		20.94
	LIB (NCM)		25.95
	VRFB		28.84
	PHS		23.89
Energy trade (100 MW)	LIB (LFP)	10 hours	22.85
	LIB (NCM)		27.63
	VRFB		26.03
	PHS		15.82
Power reliability (10 MW)	LIB (LFP)	10 hours	19.62
	LIB (NCM)		24.51
	VRFB		22.30
	Lead-acid		57.12
Long-duration storage (100 MW)	LIB (LFP)	100 hours	158.41
	LIB (NCM)		197.64
	VRFB		159.13
	PHS		35.47
	CAES		19.99

An ESS technology can have LCOS with different values depending on the type of application in the power system. Among the ESS options, flywheels is the least-cost option for an application that requires more than 8,500 cycles per year (*i.e.*, a primary response). For applications that require a moderate annual cycle and duration (*i.e.*, secondary response and peaker replacement), the choices are between batteries and pumped hydropower storage (PHS). Meanwhile, PHS and compressed air energy storage (CAES) are superior in applications with a duration longer than 10 hours,except for power reliability applications that mandate distributed energy storage systems (i.e., Battery Energy Storage Systems (BESS)). In this regard, lithium-ion battery-lithium iron phosphate (LIB-LFP) is currently the least-cost BESS option.

The Impact of Policy Implementation

Implementation of carbon pricing (cap, trade, and tax), CCS technology, and co-firing strategy are measures that could influence the LCOE of fossil power plants. The carbon pricing mechanism that can internalize carbon costs to the generation cost of power plants is still in the early implementation stage and will have a negligible impact on the LCOE. The high stipulated emission cap between 0.911 and 1.297 tCO_2eq/MWh and relatively low carbon price at around US$2/$tCO_2eq$ is insufficient to control GHG emissions from fossil fuel power plants. This is true for both reducing emissions and encouraging the development of renewable energy.

On the other hand, implementing CCS technology and co-firing CFPPs with biomass fuel are the two approaches that are expected to cut direct emissions from fossil fuel burning. The installation of CCS technology would increase the LCOE of power plants (*i.e.*, supercritical coal, integrated gasification combined cycle (IGCC), and combined-cycle gas turbine (CCGT)) by 27% to 84% due to the additional investment and operation costs (including fuel cost increase caused by lower system efficiency) requirements. In the case of co-firing, PLN has set an ambitious plan for the utilization of biomass for co-firing, which is targeted to cumulatively reach 10% of electricity generation by all CFFPs or about 9 million tons annually by 2025. However,the domestic feedstock supply chain uncertainty makes the utility nervous. The LCOE analysis shows that biomass co-firing can actually reduce LCOE (slightly) as long as the low-cost biomass feedstock is available at the preferred price of around US$40 per ton. Nevertheless, the cost of making CFPP electricity can go up by 79% if the feedstocks are brought in from other countries.

In different plans to reduce carbon emissions in Indonesia's power sector, solar PV is expected to play a significant role, and its capacity is expected to grow intensively in the next few years. Unfortunately, solar PV has not been able to compete with existing thermal power plants under current circumstances. There are at least two problems with using it: local content requirement (LCR) regulation and the need for solar PV plants to store energy to increase its reliability. To meet the LCR's requirements, in the case of utility-scale solar PV development, the investment cost increases by at least 12% due to the higher cost of local modules, which increases the LCOE to 6.23 cents/kWh. Also, developers will have trouble securing international project financing because domestic solar modules are not yet bankable.

On the other hand, the need for energy storage to address the intermittency of solar PV increases deployment costs, especially since ESS is still expensive. The LCOE of on-grid utility-scale solar PV is estimated to increase by at least 21.6% with BESS, while on the off-grid, the LCOE value can increase by five-fold.

In contrast to the impact of the stipulated policy, which increased the LCOE of solar PV, the LCOE of CFPPs is kept low due to the DMO policy with a coal cap price that is much lower than the market price. The LCOE from CFPP can increase by about 2.5 times without DMO. Even though this policy aims to keep electricity prices low, it makes stakeholders in the power sector less eager to switch to low-carbon technologies. With the cost of BESS and solar PV declining over time, it is projected that Solar PV with BESS could reach grid parity with coal plants from 2030 to 2033 under the subsidized coal price scenario.

Based on the findings in this report, the government and utility companies should:

- **Phase out CFPPs subtly but do not resuscitate emitting power plants.** Phasing out coal plants is a necessity to reach net-zero emission, but its replacement must be cost-competitive. The implementation of CCS and the co-firing could make CFPP reduce its emission over its lifetime, but its generation cost becomes uneconomical in the future due to additional investment and operation costs incurrence. Indonesia should instead be more proactive in preparing CFPP substitution with renewable power plants so that they can be more competitive from a cost perspective. In this regard, instruments such as carbon pricing can be used to urge emission reductions according to national targets and gradually remove coal and fossil gas subsidies in the near future to make the costs of thermal power plant generations reflect their true cost and could make renewable become more competitive.

- **Provide inclusive incentives and appropriate strategies for renewable deployment.** For renewable technology such as solar PV, the technology price is no longer an issue for utility scale installation, especially with its cost reduction projection. However, the implementation of regulations such as LCR in Indonesia is currently causing unfavorable conditions for the development of solar PV projects due to the limited capability of domestic solar PV manufacturers to produce high-quality and high-efficient solar modules at competitive prices. Consequently, project financing becomes difficult, and the cost of capital is higher. Therefore, the government should plan to ease LCR, build demand to attract tier-1 international solar manufacturers to set up production facilities in Indonesia, and develop solar PV's supply chain. For other renewable energy such as wind power, biomass, and hydro, low-cost financing facilities and risk mitigation instruments shall be provided by the government to lower the cost of finance of the project.

- **Identifying potential uses, quantifying needs, establishing development plans, and providing incentives for ESS deployment.** Although it is still relatively expensive today, ESS is a key technology to enable higher VRE's penetration in the power grid. Given the application of ESS in Indonesia is still in its infancy, the government must encourage piloting various ESS technologies and plan for short, medium, and long-duration ESS and its various applications, not limited to off-grid electrification. Firstly, a regulatory framework for ESS deployment shall be put in place, followed by updating the grid code to allow integration of ESS and renewable energy and removing barriers to ESS deployment. Secondly, PLN, as the largest utility, shall be encouraged to integrate various ESS applications in its system because apart from VRE integration purposes, ESS can be deployed for several roles in utility systems to increase the stability of the existing system. When the economics of VRE + ESS is competitive with the gas peaker plant, PLN could also substitute the gas peaker plant with a VRE+ESS plant that is less dependent on fossil energy. Thirdly, to make a business case for BESS application and to create a rapid demand in BESS aligned with the development of the battery industry, the government could incentivize the application of BESS with rooftop PV to reduce the impact of rooftop solar PV on the PLN's grid. Having such regulatory frameworks, pilot project initiatives, and business plans could create prospective demand for ESS, boosting investors, technology providers, and developers' confidence to supply new technologies and establish an ESS supply chain, and ultimately drive down the ESS cost in Indonesia.

1

The Importance of Analyzing Technology Costs Based on the Current Issues and Updates

Renewable energy technologies, especially solar photovoltaics (PV) and wind power, are getting cheaper. This has led countries worldwide to pledge to reach net-zero emissions. The global average power generation cost of solar PV and wind (average onshore and offshore) fell to 4.8 and 5.5 cents/kWh, respectively, which is a more than 60% decline within the past decade (IRENA, 2022). Several reports regarding generation costs have been published and updated annually, despite the fact that they generally only focus on a few popular technologies (BloombergNEF 2022a; Lazard, 2021).

Among various generation technologies, coal-fired power plants (CFPP) are still reported as the cheapest source of bulk generation in Indonesia, with a cost ranging from US$66 to US$95 per MWh. Meanwhile, many developing countries (e.g., India, Vietnam, South Africa, etc.), which previously relied on thermal power plants, have been shifting and making renewable energies (REs) cost less than US$30/MWh (BloombergNEF, 2022a). In this regard, understanding how the generation cost value is obtained through the levelized cost of electricity (LCOE) calculation and its cost components is necessary as an input to the analysis needed to provide the optimal policy support required to accelerate the development of prospective renewable energy. Similarly, the cost of energy storage in different use cases (on-grid or off-grid) that can be calculated through the levelized cost of storage (LCOS) should be assessed.

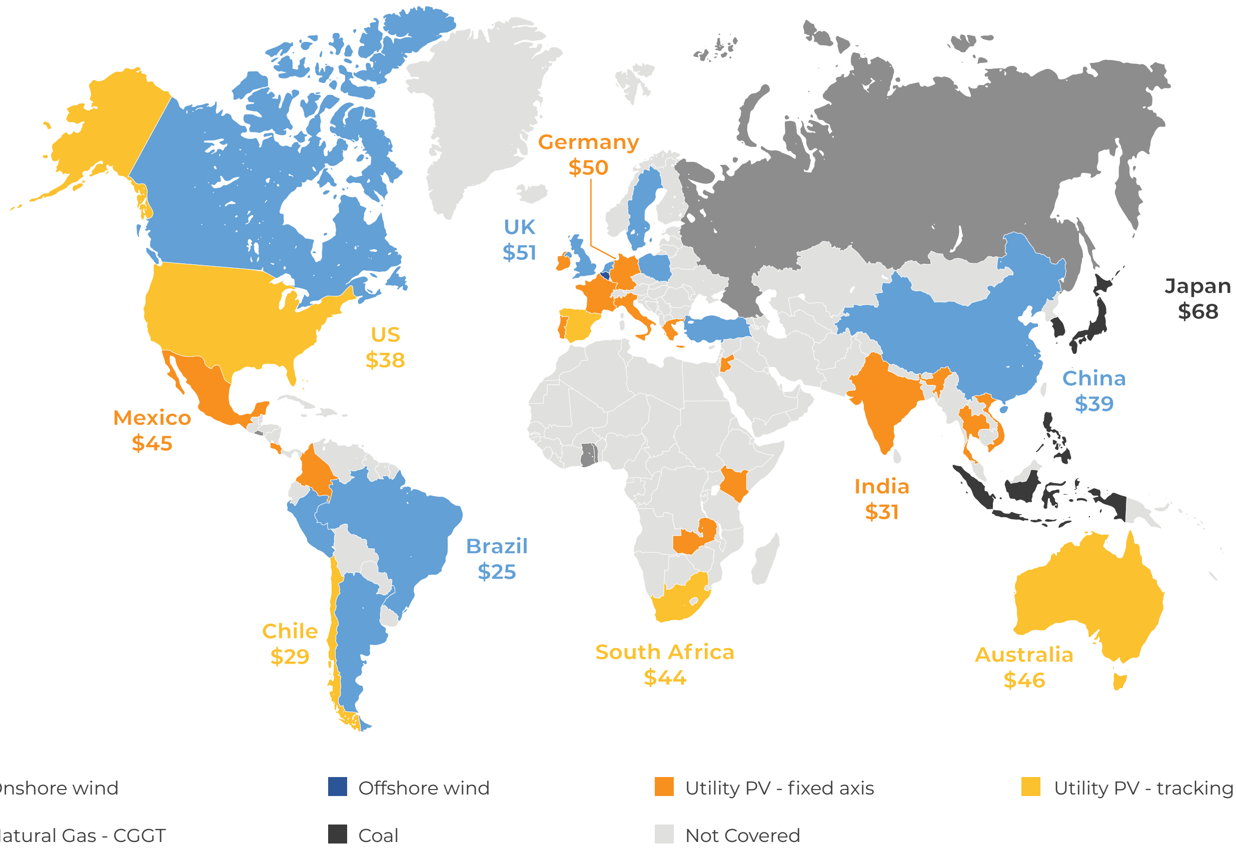


Figure 1. The map of several countries' lowest LCOE (US$/MWh) technologies
Source: (BloombergNEF, 2022a)

In the context of Indonesia, renewables are still facing unfair competition with artificially cheap CFPP and the hesitance of utility (i.e., PLN) to increase the uptake of variable renewable energy (VRE) due to intermittency problems. The generation cost of thermal power plants, in fact, can be higher, mainly due to the volatility of fuel prices. For instance, CFPP can only become a least-cost option with a DMO coal price cap regulation in place. On the other hand, as renewable energy technologies mature, they become more cost-effective, and many ideas have been put forward to deal with their intermittent nature. The Energy Storage System (ESS) is the most popular of these ideas. Moreover, the current lowest Power Purchase Agreement (PPA) price for solar PV is 5.6 cents/kWh, and wind in Sidrap is 10.9 cents/kWh, while there are record low bids of around 4 cents/kWh and 5.5 cents/kWh for solar and wind PV projects, respectively (IESR, 2022a). Mathematically, the PPA price will be equal to the LCOE without additional elements, such as PPA escalators (Miller et al., 2017).

IESR published a study report on Indonesian LCOE in 2019 (IESR, 2019). Due to many factors influencing LCOE, such as technological advancement and regulations in the power sector that have changed globally and nationally, it is necessary to update the LCOE study based on the current circumstances. To provide a comprehensive, up-to-date overview of the LCOE of various types of power plants, this report also evaluated the cost drivers of several technologies that consider the implication of policies that have been implemented or are soon to be enacted in addition to the trend of changes in technology prices.

Along with figuring out how much different power plants cost to make, the cost of energy storage in different use cases is also shown. The higher integration level of VREs would make the role of energy storage more crucial. Thus, evaluating the LCOS is essential. Currently, the use of ESS is limited in Indonesia. Meanwhile, ESS has broad technology options, which make it superior in specific applications. Here, the costs of ESS technologies are discussed in more detail based on the application-specific LCOS and, hence, can be used as a reference in future planning.

Compared to previous reports, the current report highlights the context of Indonesia more deeply, including unique potential (in terms of natural resources) and technological development constraints. Also, this report covers more technology options, which can be an additional reference for readers. There are 26 types of power generation technologies and seven types of energy storage technologies covered in this report.

The generation technologies covered are from conventional fossil generators (coal and gas-fired power plants), popular renewables (solar PV and wind), as well as types of potential power plants in Indonesia, such as geothermal and tidal. On the other hand, the energy storage analyzed includes three types of electrochemical batteries (lithium-iron phosphate (LFP) and nickel-manganese-cobalt (NMC) types of lead-acid battery, as well as vanadium redox flow batteries (VRFB)), flywheels, pumped hydropower storage (PHS), and compressed air storage (CAES). These technologies are among the ESS options that have been advanced in terms of technology development and capacity deployment. Batteries and flywheels represent distributed ESS that are more independent in terms of site selection. Meanwhile, PHS and CAES are bulk ESS technology that are more dependent on geographical conditions.

For the LCOE values, changes that have occurred in recent years are analyzed based on value changes in the driving parameters. Meanwhile, projections of the parameter values are used to forecast future LCOE values for 2030 and 2050. Each technology has certain parameters that significantly affect LCOE; hence, the sensitivity analysis of several parameters is necessary. Policies that may affect parameter values are further discussed. It includes the impact of implementing carbon pricing, co-firing, and carbon capture and storage (CCS) technology for fossil power plants. On the other hand, the effect of local content requirement (LCR) policies and intermittent technologies' installation requirements on the LCOE value of solar PV is also the focus of the discussion.

In the case of LCOS, the discussion focus is slightly different from that of LCOE. Rather than digging into the causes (i.e., policy implementation) and historical changes in parameter values, this report focuses on introducing various types of energy storage applications where costs can vary. Nevertheless, this report still highlights the sensitivity of LCOS parameters that are influential to the LCOS of ESS in certain applications. The limited deployments and the absence of specific regulations governing ESS are the reasons for the different focus of discussion for LCOS. Besides, to the best of the authors' knowledge, literature discussing LCOS in Indonesia is still very limited.

2 Levelized Cost of Electricity (LCOE)

The LCOE calculation is used as a standard tool to determine the generation cost of various technologies. It can be defined as the price at which the electricity should be sold for the system to break even at the end of its lifetime, derived from the total cost of a power generation technology divided by the generated electricity. The results show what each technology looks like in a certain place, with its own technical and financial parameters. It can be easily compared, which can help businesses or policymakers make investment or planning decisions faster.

There are several ways to calculate the LCOE, each with its advantages, namely the discounting method, the annuity method, and the financial model method (IESR, 2019). The LCOE in this report is calculated specifically using the annuity method. It allows simple LCOE recalculation and comparison of the sensitivity of different parameters that affect the LCOE outputs, and the total cost is converted into an equivalent annual cost while the electricity generation value used is the average annual electricity generation. The annuity method LCOE formula is shown in Equation 1 in Appendix 1.

Financial parameters are used to calculate the construction and operating costs of power plants. The parameters are: 1) a total investment cost, also known as an overnight cost; 2) a cost of capital using the weighted average cost of capital, or WACC; 3) a fixed O & M cost; 4) a variable O & M cost; 5) a fuel cost; and 6) a CO_2 cost. To determine how much electricity power plants generate, engineers use technical parameters like technical lifetime and capacity factor. In addition, the technical parameters of fuel efficiency and CO_2 emissions of thermal power plants are also taken into account to calculate the LCOE output. The parameter values to calculate the LCOE are mainly extracted from the Technology Data for the Indonesian Power Sector report by Dewan Energi Nasional (DEN) published in 2021 (Danish Energy Agency et al., 2021) and refined with the most recent data from other related market studies (BNEF, IRENA, etc.) as well as surveys with the association, project developers, and PLN. The WACC assumption is estimated through surveys and interviews with related stakeholders over the value of debt and equity and the cost of debt and equity. The unique values of parameters used to calculate the LCOE of various generation technologies are compiled in Appendix 1.

The investment cost ($/kW) presented in this report consists of all costs such as the equipment, permit, feasibility study, engineering, procurement and construction (EPC), etc. Land-use costs can indeed influence the LCOE outcome. However, the value is very project-specific, depending on the location and type of technology. For instance, the land-use cost of solar PV, which requires high space (m^2/kW capacity), can increase the pre-land-use investment cost by about 20%. Even though it is high, specifically for ground-mounted solar PV, the environmental footprint is relatively small, and the land used still has a high value for resale. More details will be discussed in the solar PV subchapter. In the calculation of investment costs, land-use costs and the project owners' pre-development costs are not included (Danish Energy Agency et al., 2021). Instead, it is spread out annually using the WACC as the annuity factor. WACC is used instead of the standard discount rate to capture the financing cost in the calculation. Generation technology output degradation is not considered and is supposed to be represented by technical lifetime and constant capacity factor parameters. The carbon cost (if applied) is calculated from the CO_2 emissions of the respective thermal power plant multiplied by the carbon price parameter.

In addition to power generation technologies, parameters for co-firing and CCS technologies are also introduced. These technologies affect the financial and technical parameters of certain power plants. When applied, co-firing options affect the CO_2 emission and fuel cost parameters of all coal-fired power plants. Meanwhile, CCS technology affects the investment cost, CO_2 emissions, and fuel efficiency of coal supercritical, IGCC, and CCGT power plants.

The LCOE sensitivity analysis in this report is carried out by adjusting the value of certain parameters individually, whether financial or technical, to understand certain technologies' LCOE key drivers. For instance, the sensitivity analysis with a range of 20% of the WACC parameter (10% is the default value) will result in LCOE outputs of 8% and 12% WACC. These LCOE outputs are then compared to the one with the default parameter. Parameters that are considered to play a significant role as LCOE drivers are highlighted in this report and become the subject of discussion.

To anticipate the possibility of differences in the cost components of the parameters for calculating LCOE, this report is supplemented with the IESR LCOE tool that readers can use to adjust parameter values (e.g., investment cost) that are more suitable to their circumstances. Regardless, the power plants' LCOEs also vary depending on the scale, operational protocols, and policy regulations, which may influence the value of the investment cost, amount of electricity generated, and operational cost, respectively. Hence, the LCOE of each technology is commonly presented within a range. In chapters 3.1.1 and 3.2.1, the LCOE ranges of several types of thermal power plants and renewables, respectively, are shown and compared with the LCOE ranges in 2019.

In the subsequent chapter, the recommended LCOE value is used for discussion as the wide range of LCOE of each technology would make it difficult to measure and compare the economics of technologies. The recommended LCOE is assumed to have a realistic value and is not the average of the high-end and low-end LCOE. It is rather derived from the typical value of individual LCOE parameters. All parameters for calculating LCOE are in Appendix 1, including those for calculating low-end and high-end LCOE. In the following chapter, the recommended LCOE, denoted as LCOE, of each technology is presented and compared based on their category. Also, the trend and facts regarding each technology are briefly discussed.

2.1. Thermal Power Plants

2.1.1. LCOE Changes of Main Thermal Power Generation Technologies

Coal and gas-fired power plants are the main thermal power plant technologies employed in Indonesia, covering about 83.1% of the country's total power generation energy mix in 2020 (MEMR, 2023; PLN, 2021). However, these conventional power plants' generation costs are envisaged to increase in the future due to the volatility of fuel prices, the implementation of carbon pricing, and the need to invest in carbon capture technology (IEA, 2020).

Figure 2 shows that between 2019 and 2022, the high-end LCOEs of typical power generation technologies in Indonesia are steadily increasing. Notably, the high-end LCOEs of coal-fired power plants (CFPPs) in 2022 are higher than in 2019. This is mainly due to the different considerations of the fuel cost parameter in the calculation. The capped and global market coal pricing of up to US$150 per ton were employed in the 2022 calculation, while the 2019 calculation only employed the average global market coal pricing from 2017 to 2018. The most significant increase in high-end LCOE is observed in CFPP with subcritical coal technology, which increased to 11.85 cents/kWh, or 46%, compared to the 2019 LCOE. Notably, it may further increase to around 20.3 cents/kWh if the recorded high coal price, according to Coal Price Reference (*Harga Batubara Acuan*; HBA), at US$330 per ton in October 2022, is applied. Having low efficiency, the subcritical CFPP is prone to the change in the fuel pricing schemes in the 2022 LCOE, hence the staggering increase. Similarly, the high-end LCOE of gas-fired power plants, i.e., open-cycle gas turbine (OCGT) and combined-cycle gas turbine (CCGT), in 2022 are also extended, mainly due to high gas prices in addition to the lower efficiency assumptions for OCGT.
In contrast, the low-end LCOE of corresponding technologies is observed with slight changes relative to

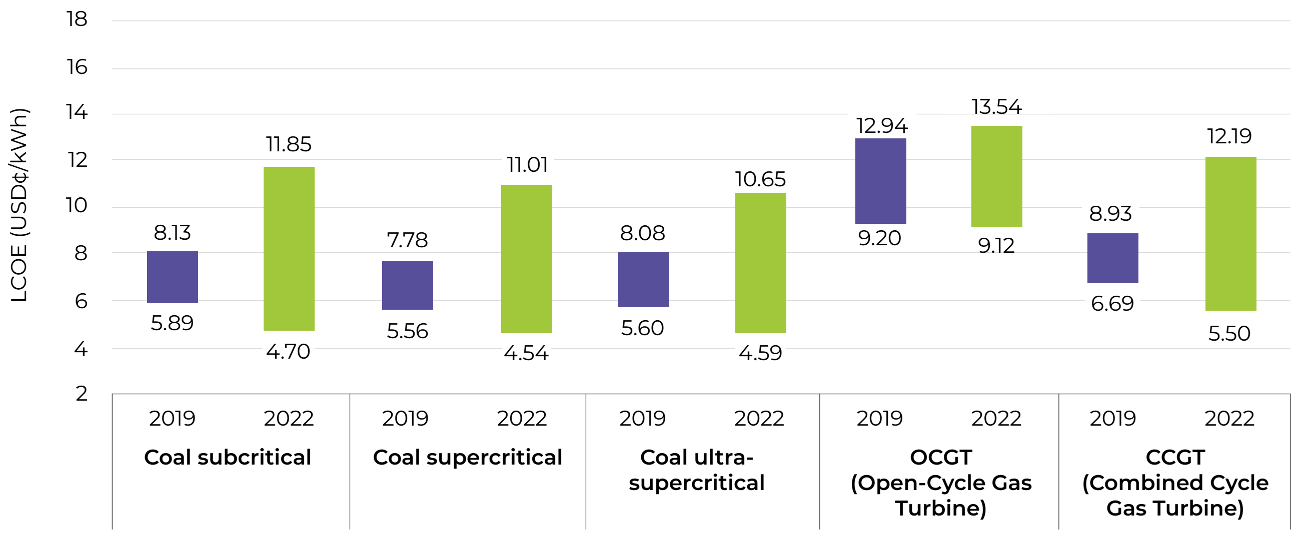


Figure 2. The LCOE range changes from 2019 to 2022 of main thermal generators in Indonesia. The higher values represent high-end costs, while the lower values represent low-end costs

the 2019 estimate, possibly due to the power plants' higher capacity factor. Despite the maturity of these technologies and the slight cost reduction of technology included in CAPEX (Danish Energy Agency et al., 2021), these conditions have unsurprisingly insignificant impact on the change of estimated low-end LCOE. For these technologies, the change of LCOE in the upcoming years could solely be more influenced by the operating costs (including fuel cost) and optimization of power plants' efficiency and capacity factor.

2.1.2. Overview of Thermal Power Plants LCOE

a) Coal-Fired Power Plant (CFPP) and Integrated Gasification Combined Cycle (IGCC)

CFPPs have been the main power generation in Indonesia. CFPP can be classified into three different technologies, namely subcritical coal, supercritical coal, and ultra-supercritical coal. Apart from the three CFPPs technologies, integrated gasification combined cycle (IGCC) is another type of technology that requires coal as fuel. In IGCC, coal is initially converted into a synthesis gas (syngas), then fires in the power block that is very similar to a combined cycle gas power plant, making the efficiency of IGCC superior to CFPPs.

Most of the CFPPs in Indonesia are subcritical, while several new power plants currently under development adopt supercritical and ultra-supercritical technologies that are considered more efficient and produce lower emissions than the subcritical ones. To date, CFPPs are still the cheapest power plant technology in the country, having a calculated LCOE that is lower than the national Electricity Generation Basic Cost (*Biaya Pokok Penyediaan (listrik)*; BPP) of 7.05 cents/kWh, as shown in Figure 3. The LCOE of CFPP and IGCC ranges from 5.7 to 8.3 cents/kWh, with supercritical coal being the lowest and IGCC being the highest (Figure 3). Although ultra-supercritical coal and IGCC fuel cost components are lower due to their superior efficiency, their investment costs are 8.6% and 42% higher than supercritical coal. In the next few years, the LCOE of new CFPP is expected to not experience significant changes. Learning rates from matured CFPP in Indonesia are much lower than that of emerging solar PV technology (Danish Energy Agency et al., 2021). IGCC will experience the largest reduction in future LCOE. Nevertheless, it will still be hovering above the current LCOE of the CFPPs.

In the long term, CFPP will not be the least-cost option in Indonesia. Compared to the LCOE projection

of the new utility-scale PV in 2050, which is below 3 cents/kWh, the operational cost of CFPP will be higher, ranging between 3.12 - 3.45 cents/kWh. Given CFPPs CO_2 emissions, generally estimated between 670-1200 tCO_2eq/GWh (Coal Industry Advisory Board, 2019), the implementation of carbon tax in the upcoming years will definitely increase their operating costs. Similarly, several studies also suggested that unabated IGCC CO_2 emissions are similar to those of supercritical CFPPs (Cormos et al., 2020; IPCC, 2014). The impact of the carbon price on CFPP's LCOE value will be further discussed in Section 4.1a.
The government's commitment to achieving NZE was reflected in the stipulation of Presidential Decree

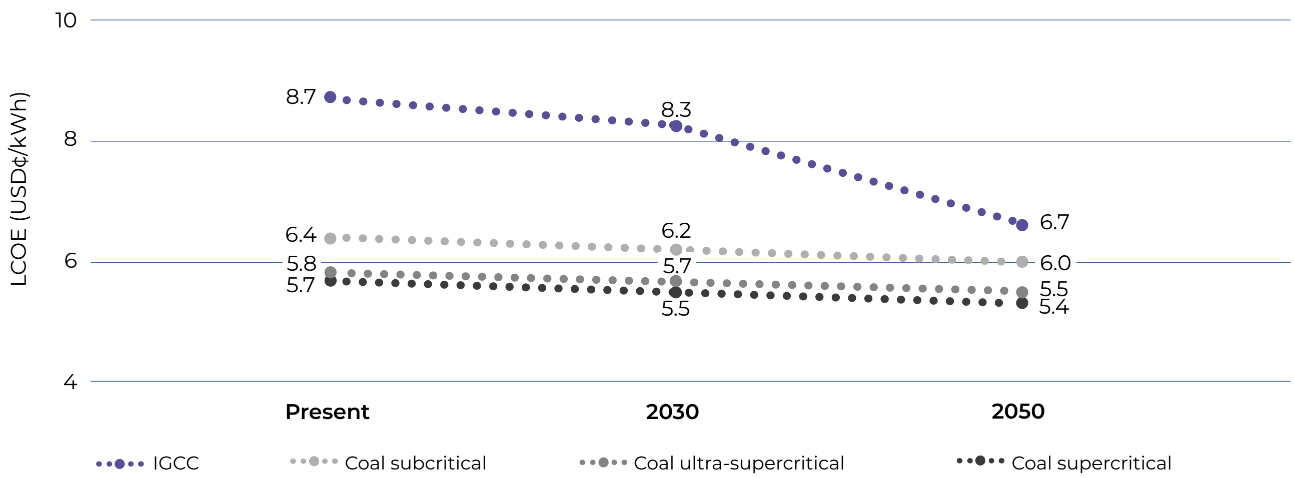


Figure 3. Recommended LCOE of coal-fired power plants. Recommended values refer to the LCOE calculation using the most realistic parameter values (e.g., a coal price cap of US$70/ton)

112/2022, which mandated the acceleration of renewable energy development and deployment in the power sector. However, the development of clean energy is currently hampered by the number of existing CFPP fleets as well as those in the pipeline. To overcome this, the decree also included an article that specifically limits the entire CFPP fleet[1] operations to 2050. Consequently, this will further increase the LCOE of the newly developed CFPP due to its lower operational years than its typical operating lifetime, which could be over 30 years.

b) Natural Gas-fired[2] and diesel generator power plants

Despite being relatively cleaner than coal, natural gas-fired power plants have been underutilized compared to CFPPs due to mainly the availability and low costs of coal, with the share of gas in the power generation mix being less than 16.8% compared to coal (67.21%) in 2022 (MEMR, 2023).

Meanwhile, the diesel generator is a technology that is no longer relevant to be developed on a large scale. Diesel generators were indispensable for electrifying several regions in Indonesia, particularly those that are far from the main utility grid and have marginal electricity demand for coal-fired or gas-fired power plants to be built. Today, besides being an uneconomical option, diesel generators are also a technology that produces high emissions of at least 553 tCO_2eq/GWh (JCM, 2017), thus subjected to the carbon tax.

The present LCOE of gas-fired power plants is 10.8 and 7.7 cents/kWh for OCGT and CCGT, respectively.

[1] Existing fleet and in the pipeline prior to the enactment of the decree.

[2] Excluding gas engine power generation.

Although the technology capital cost is relatively low, the capacity factor (CF) and fuel cost are the main drivers of their higher LCOEs than CFPPs counterparts. Gas-fired power plants have a low capacity factor of around 35%, and gas fuel costs 2.5 times more than coal to generate the same amount of electricity in Indonesia (PLN, 2021). Similar to CFPP, gas-fired power plant technology has matured since the 1990s (Rubin et al., 2015), and the decrease in capital costs in the future would not result in a notable LCOE reduction. Meanwhile, the increase in fuel efficiency is expected to be the main factor in lowering the LCOE of gas-fired power plants in the future.

Diesel generators, on the other hand, are a type of thermal power plant with the highest LCOE, reaching 13.2 cents/kWh. The high fuel cost became the main LCOE driver despite the low capital cost of technology. In practice, the generation cost of diesel generators is even higher due to expensive fuel transportation costs, amounting to 30% of the fuel price. On top of that, diesel generators in 200 locations are reported to have an average generation cost of around 24 cents/kWh in 2020 (PLN, 2020).

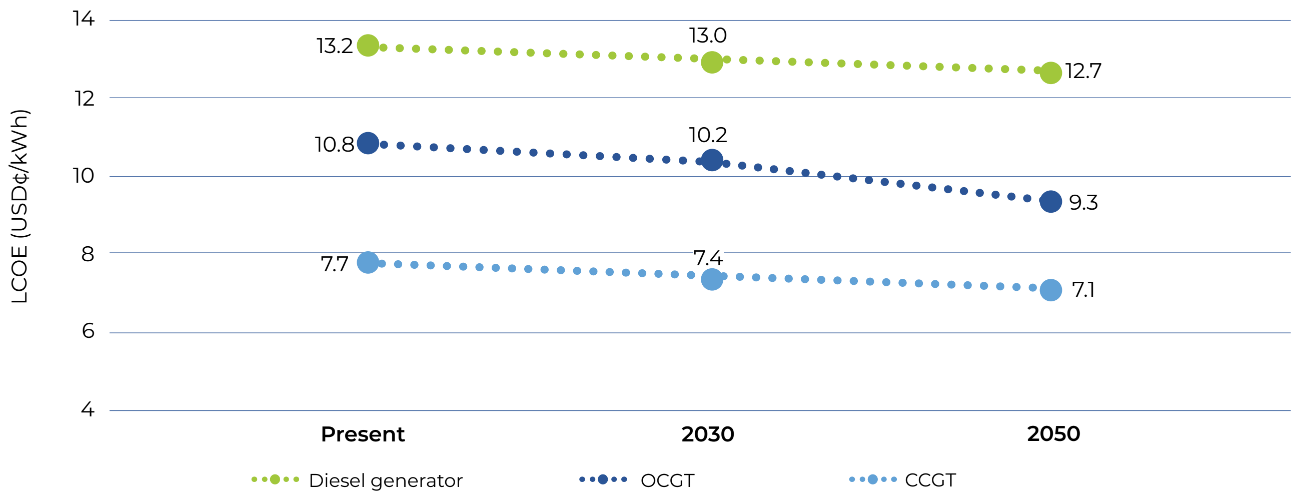


Figure 4. Recommended LCOE of gas-fired power plants and diesel generator

Gas-fired power plants and diesel generators could have different prospects in the future. The installed capacity of the former could possibly grow with the restrictions of CFPP and the increasing need for fast-response power plants to accommodate renewables' intermittency, unlocking the grid's flexibility. However, their large deployment could be challenging, given the gas price volatility and the projection that Indonesia will become a net gas importer in 2030 due to the decline in domestic production (IEA, 2022d). For the diesel generator, PLN has no plan to add diesel generator capacity in the latest RUPTL. Instead, it plans to carry out the de-dieselization program to beam, replaced by renewables, with the expected Commercial Operation Date (COD) no later than 2025.

c) Nuclear power plant

Nuclear power plants are one of the most reliable low-carbon technologies, with an estimated capacity factor of 85% (IEA, 2020). They can be operated most of the year, making them a clean alternative for baseload power generation. The fuel cost is relatively low, with a mere difference of around $0.1 for each MWh of electricity compared to the cost of coal in Indonesia (see Appendix 1) (IEA, 2020; PLN, 2021). Despite being a low-carbon technology, nuclear power plants are actually not renewable. The heat generated by the nuclear fuel to generate the steam that drives the turbine will stop as soon as the radioactive fuel runs out.
To date, Indonesia has not used nuclear energy to generate electricity. The geographical condition of

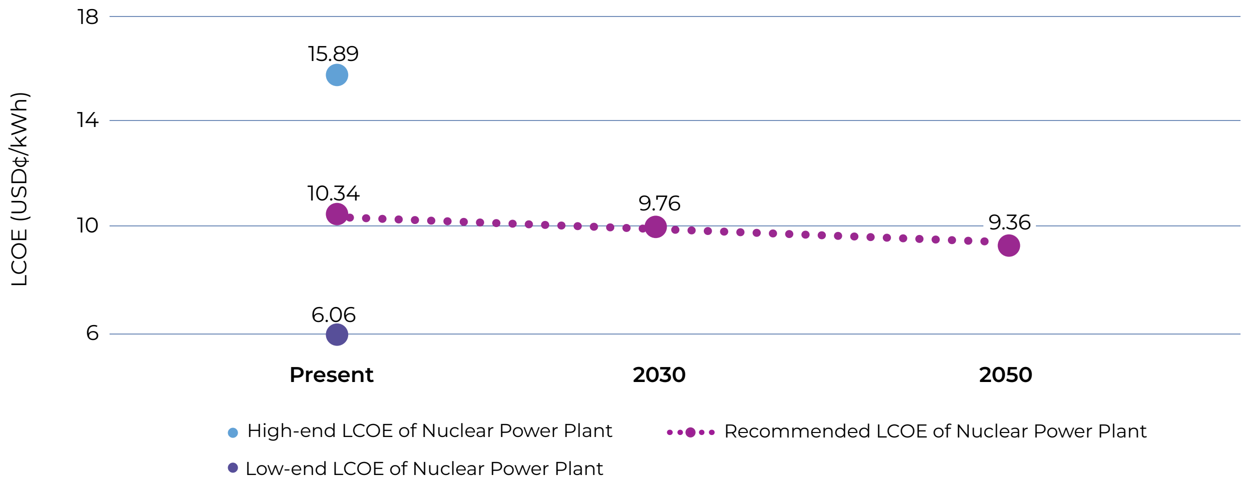


Figure 5. Recommended LCOE of nuclear power plants

Indonesia, which is prone to natural disasters such as earthquakes, used to be the reason. Nuclear power plants are often associated with a high risk of accidents, although modern nuclear plants have earthquake-proof designs. Regardless, the nuclear power plant project has a very high risk of cost overrun caused by construction delay, which the public may disapprove of and hamper the project's development (Sokolski, 2011). It has a high sensitivity to project interest rates, which will be discussed in Chapter 2.1.3b. Nevertheless, plans for developing nuclear power plants are being re-examined in Indonesia, considering the need for low-carbon technology to meet the country's net-zero emission (NZE) target by 2060.

Unlike other technologies described in this report, MEMR has not yet included nuclear power plants in the Indonesian generation technology catalog (Danish Energy Agency et al., 2021); hence, the values of parameters for their LCOE calculation are adopted from global reports (IEA, 2020, 2022b). The recommended LCOE of nuclear power plants is 10.34 cents/kWh, while the LCOE ranges are from 6.06 to 15.89 cents/kWh. This value is relatively higher than CFPPs and CCGTs but still lower than diesel generators. The kind of technology a nuclear power plant adopts has a significant impact on its LCOE. Globally, the investment cost of this technology ranges from $2800 to $6600 for each kW of capacity in 2022. Meanwhile, in recent government planning, nuclear energy is expected to generate around 31 GW of electricity by 2040, with a projected investment requirement of about $6.9 billion per GW (IESR, 2022c). The nuclear technology that is being sought by the government and utilities is the Small Modular Reactors (SMRs), which are currently not yet built or commercially available. Therefore, it is difficult to determine its cost, both CAPEX and OPEX, and other costs associated with reliability and risk profiles.

2.1.3. Sensitivity of Thermal Power Plants LCOE

a) Fossil fuel price

The fuel cost component (cents/kWh) is a great contributor to the LCOE structure of existing thermal power plants. As shown in Figure 6, more than half of the LCOE of gas-fired power plants comes from fuel costs. In the case of diesel generators, it even takes up to 71.4% of the share. Meanwhile, the shares of the fuel cost component of CFPPs are relatively lower due to the Domestic Market Obligation (DMO) regulation price of coal at $70 per ton. To generate the same amount of electricity, the natural gas and diesel fuel consumption costs about 2.5 and 4.5 times higher, respectively.

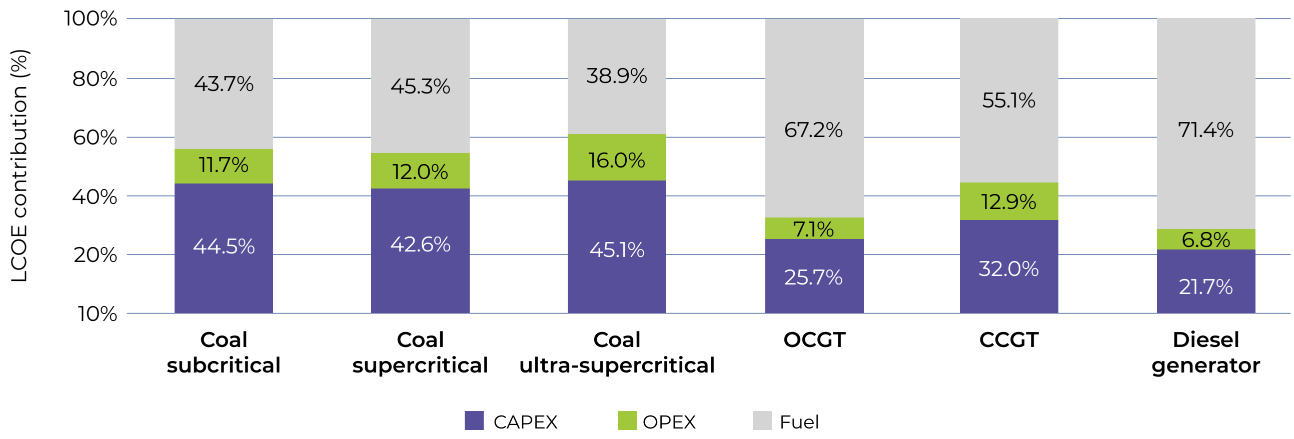


Figure 6. Thermal power plants LCOE component breakdown

The efficiency of thermal power plants also has an impact on the LCOE in addition to the cost of the fuel. The fuel conversion process in low-efficiency technology generates high energy losses; hence, fuel consumption becomes higher to obtain the desired electrical output. CCGT has the highest fuel efficiency at 56%, while subcritical coal has the lowest efficiency at 34% (Danish Energy Agency et al., 2021).

Although a less efficient subcritical coal technology has higher fuel costs of 2.8 cents/kWh than the supercritical one (2.58 cents/kWh), the share of the fuel cost component of the latter in its LCOE is surprisingly a few degrees higher than the subcritical one. Apparently, the higher investment and operational cost of subcritical coal drive down its share of the fuel cost.

On the other hand, the high share of a fuel cost component in supercritical coal's LCOE structure indicates that the influence of coal price (US$/MWh) fluctuation becomes even more prominent on the LCOE outcome compared to other CFPP technologies. Among the LCOE calculation parameters for supercritical coal technology, the fuel cost has the second-highest sensitivity, after the capacity factor. When a 20% sensitivity range value is applied to the parameters, a 20% increase in fuel price implies a 9.1% increase in LCOE. The value is higher than the subcritical one, where the LCOE only increases by 8.7% for the same percentage of the sensitivity range. These imply the notable role of coal DMO pricing in minimizing the generation cost of CFPPs. Scenarios in which coal prices for CFPPs are not regulated by the DMO, *i.e.*, follow global market prices, will be further explored in Chapter 4.

b) WACC of thermal power plant

As revealed in this study, the LCOE value was found to be more sensitive to changes in the cost of capital (i.e., WACC), particularly for a high investment-cost generation technology. Nevertheless, this does not apply when two technologies with different LCOE components are compared. For example, supercritical coal technology has an investment cost almost twice that of utility-scale solar PV ($1400/kW vs. $790/kW), yet the CAPEX share contribution to LCOE (with 10% WACC) is only 42.6% in the supercritical coal compared to the utility-scale PV at 85%. The cause is clearly due to the large contribution of the supercritical coal fuel cost component in its LCOE, as discussed earlier. Therefore, the sensitivity of LCOE to WACC thus depends on the CAPEX contribution to the LCOE, while the changes are greatly influenced by how capital-intensive a technology is ($/kW). In the case of CFPPs, the CAPEX component's (investment cost with 10% WACC) contribution to LCOE stretches between 42.6% and 52.1%. Accordingly, with an increase in WACC of 12%, the LCOE growth is only 7-8% or around 0.4 cents/kWh. Furthermore, a comparison of the LCOE sensitivity to WACC of several thermal technologies is presented in Figure 7.

Amongst these technologies, the LCOE sensitivity to WACC of nuclear power plants shows a very distinctive trend. The LCOE of nuclear power plants increases significantly more than that of other technologies as the WACC increases. A 20% change to the default WACC of 10% causes the LCOE to increase by about 1.14 cents/kWh (11.03%) relative to the baseline LCOE. Despite having a fuel component, the CAPEX of nuclear power plants presents a strong dominance, similar to that of renewables. Given the high risk of the project, the WACC has long been a big hurdle for the development of nuclear power plants.

Meanwhile, the nuclear power plant project is necessarily promoted with a low WACC. The proportion of CAPEX (with 10% WACC) in the nuclear power plant LCOE could reach 63.3%. This number could increase since nuclear projects have a history of going over budget and taking longer to build than planned. Consequently, such projects are very costly, mainly due to the additional interest payment period. So, building nuclear power plants in Indonesia would require a strong commitment to making it easy to obtain low-interest loans for projects. Also, it is very important to be ready for many aspects like government licensing and certification procedures in order to avoid cost overruns caused by project delays.

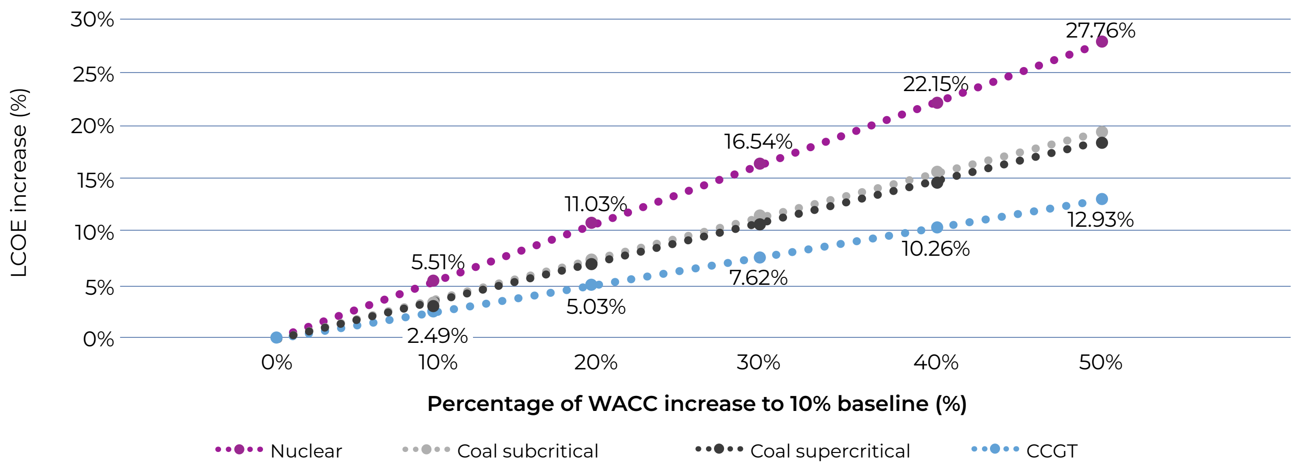


Figure 7. Increased of LCOE of thermal power plants with every 10% increase of WACC

2.2. Renewables

2.2.1. LCOE Changes of Main Renewable Technologies

Globally, the cost of developing renewable energy plants has decreased. Through innovation in R & D and mass production, several technologies, like solar PV, are getting cheaper and cheaper. Geothermal and hydropower power plants, for example, have become more mature over time, leading to their technology costs decreasing. However, for this technology, the project development and land acquisition costs increase, making the overall investment cost mostly the same.

Compared to thermal power plants, the low-end LCOE of renewables has decreased significantly compared to the estimation for 2019 by more than 30%, as shown in Figure 8. The increase in the lifetime of renewable technologies is one of the causes of changes in LCOE, besides the decline in technology prices globally. The high LCOE estimates of solar PV and hydropower have decreased, while those of geothermal and wind power have increased. The updates to the estimated investment cost values for the four technologies have an impact on changes in the low-end and high-end LCOE (Danish Energy Agency et al., 2017, 2021).

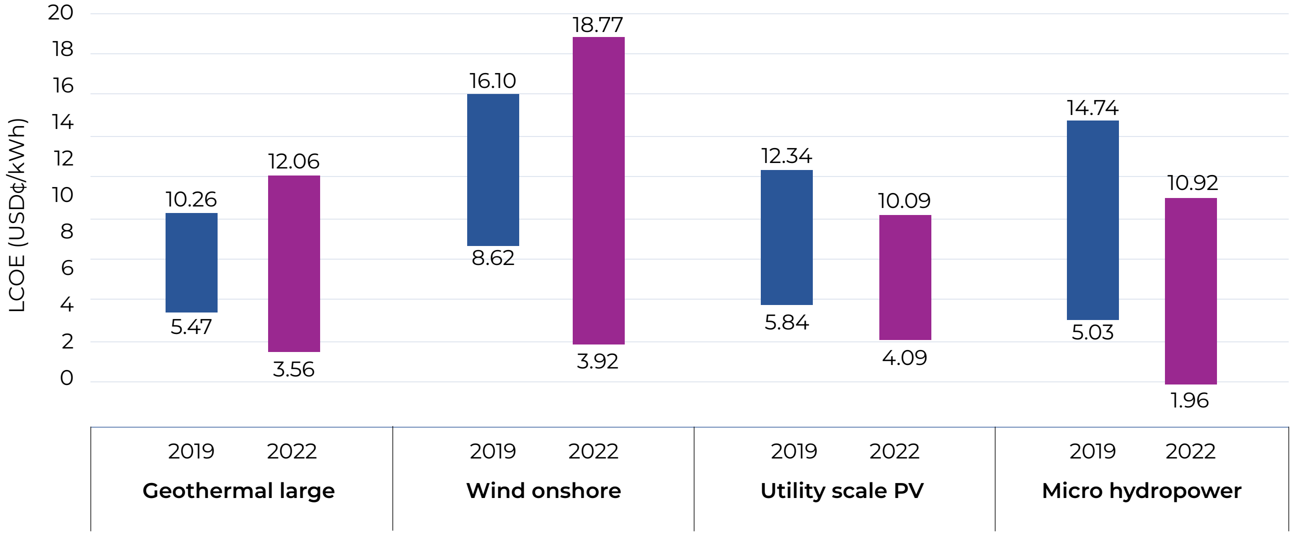


Figure 8. LCOE range changes from 2019 to 2022 for several renewable technologies in Indonesia. The higher values represent high-end costs, while the lower values represent low-end costs

In addition to the four renewable technologies above, this chapter also discusses LCOE of biomass power plants with different fuel types, as well as tidal electricity generation technology for the first time. The LCOE projections for each renewable energy source in the coming years are also determined. Some of these projections are expected to be comparable to Indonesia's average cost of power generation today.

2.2.2. Overview of Renewables LCOE

a) Biomass (Agricultural and Municipal Solid Waste (MSW))

Indonesia is a country that is rich in biomass resources, both from crops and from solid wastes that are scattered in various regions of Indonesia. Nationally, the biomass potential reaches between 30.73 and 32.65 GW, with palm oil being the most abundant source type (around 40%) and Sumatra and Kalimantan being the most abundant areas (Danish Energy Agency et al., 2021; IESR, 2021). In 2019, the use of biomass for electricity generation reached about 1.9 GW, with its use mainly in the industrial sector (Danish Energy Agency et al., 2021).

The recommended LCOE of an agricultural biomass power plant is relatively low at 6.4 cents/kWh, which is less than half that of a MSW power plant, as shown in Figure 9. However, it should be noted that the LCOE range is very wide. The low-end LCOE of agricultural biomass power plants is as low as 3.3 cents/kWh, while its high-end reaches 19.05 cents/kWh. The significant difference is mainly due to the price of biomass feedstock (see Appendix 1b). Meanwhile, the fuel efficiency of biomass power plants is lower than that of CFPPs because biomass has a lower heating value than coal, resulting in a typical efficiency of around 15–35%. In comparison, the efficiency of CFPPs is higher than 35% (Danish Energy Agency et al., 2021).

Wood chips at US$40 per tonne are assumed to be the recommended fuel price parameter value for an agricultural biomass power plant. This price includes costs for biomass materials, processing, and short-distance transportation (IESR, 2022c). For the low-end LCOE, the fuel price is assumed to come from the wood chips transport and processing costs of only US$14.6 per ton. Meanwhile, the global price of wood chips at US$ 160/ton is used for high-end LCOE calculations (Soojin Kim et al., 2022; Vu Dinh Thung, 2022). The availability of biomass feedstock for agricultural biomass power plants is a big challenge, which will be discussed further in chapter 2.2.3a.

On the other hand, the LCOE of an MSW-incineration power plant ranges from 13.4 cents/kWh to 22.8 cents/kWh. Although the used RDF fuel price is relatively low (IPEN, 2022; Prihandoko et al., 2022; Ummatin et al., 2018), the investment costs of up to $7000/kW drive the high-end LCOE. For an MSW-incineration power plant to be built, it would need extra tools like control for carcinogenic exhaust gases. Although waste-to-energy technology (i.e., MSW power plants) is expensive, its development would have environmental benefits. In 2017, Indonesia was estimated to produce around 64 million tons of municipal solid waste per year, which includes 60% food waste, 14% plastic waste, 9% paper waste, and others (USAID, 2021). The use of solid waste for power generation will be in line with efforts to reduce waste, especially waste plastic, which is targeted to be reduced by 30% by 2025.

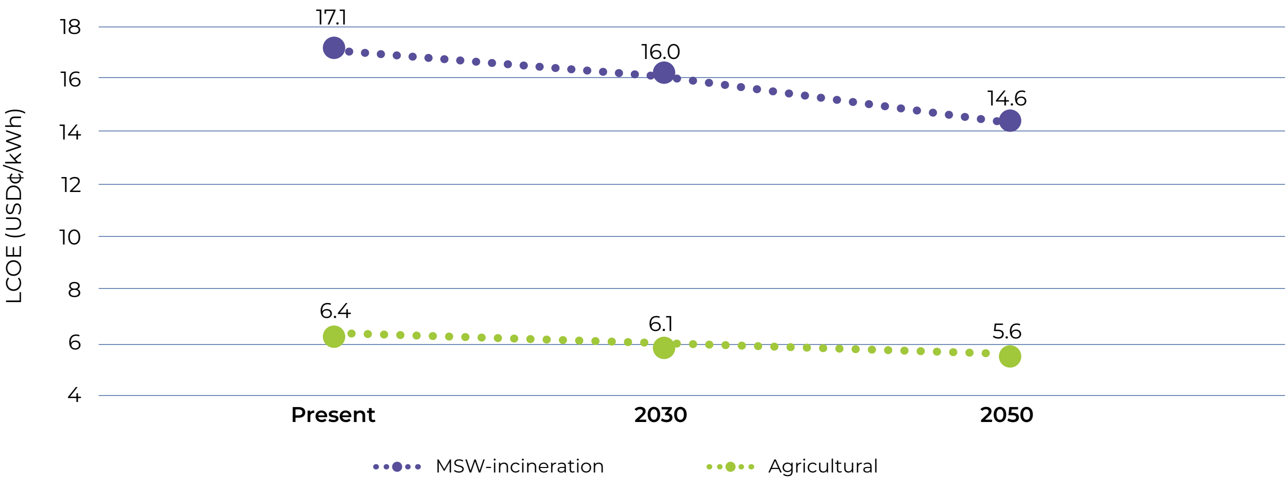


Figure 9. Recommended LCOE of biomass power plants

In the upcoming years, the LCOE of biomass power plants is not expected to undergo a notable reduction. The investment cost decline will be low due to the maturity of their key components, namely boilers and steam turbines. Therefore, the LCOE of the biomass technology plant will depend on the availability and price of the feedstock. The sensitivity of the change in fuel cost to the LCOE of biomass power plants will be further discussed in the following subchapter. The biomass utilization strategy for CFPP co-firing will also be discussed in more detail in Section 4.1c.

b) Geothermal (Large and Small)

Indonesia is one of the few countries that has the resources and skills to use geothermal energy, with an installed capacity of about 2.3 GW by 2021. The more energy that can be taken out of the geothermal reservoir, the more electricity can be generated. Indonesia has many geothermal resources above 225 ^{0}C (high-temperature category). It allows developers to adopt flash or dry technology, which requires relatively lower investment costs than binary cycle technology with low temperatures.

Geothermal energy can be a generation technology option with a firm output and replace fossil-fuel power plants due to its working mechanism, which allows it to operate with a high capacity factor. The theoretical capacity factor of geothermal power plants in Indonesia is very high, around 90%. Geothermal power plant is also classified as a low-carbon technology that is assumed to produce no emissions, even though there is a small release of CO_2 and H_2S from geothermal reservoirs, around 42–73 gCO_2/kWh from testing at three sites in Indonesia (Danish Energy Agency et al., 2021). However, the location of geothermal sources, which are generally far from electricity loads, naturally causes high construction costs for power plants and transmission lines.

The LCOE of geothermal power plants is 6.8 cents/kWh and 8.5 cents/kWh for large and small types, respectively. The one classified as large type is a geothermal power plant with flash or dry technology, which has a capacity per unit of around 55 MW, while the small type uses binary technology with a generating capacity of around 10 MW. In estimating the LCOE of the two technologies, the CF used is the same, which is 80%. However, the investment cost of large geothermal plants is 20% lower than their counterparts. For small geothermal, the investment cost is $5000/kW, making it one of the most expensive options in this report after tidal and MSW-incineration power plants. The need for the exploration process, site characterization, and drilling (often referred to as "subsurface cost”) is uncertain and could further increase the cost of developing geothermal power plants.

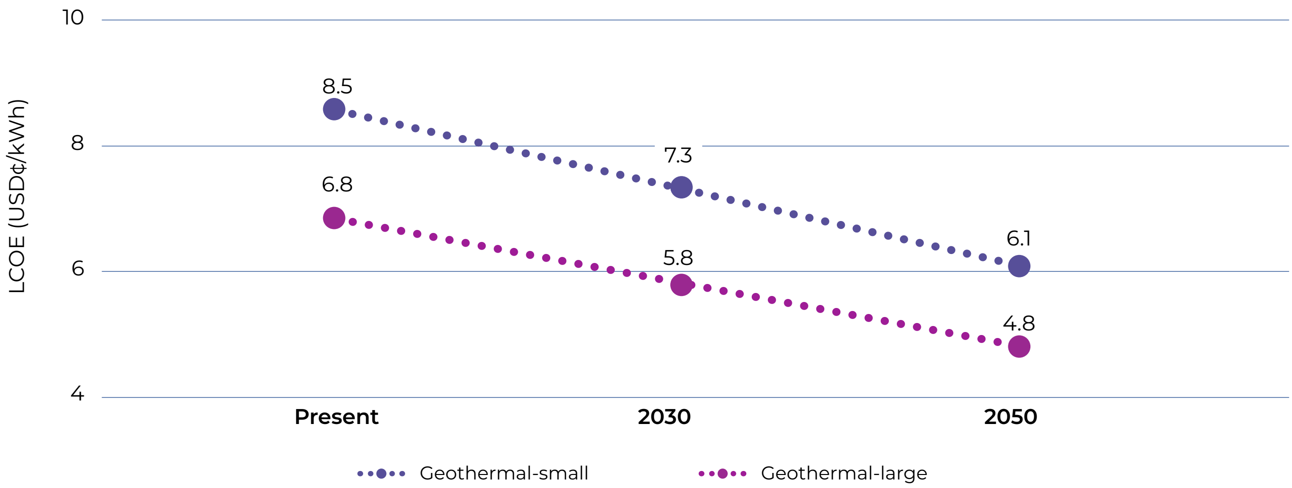


Figure 10. Recommended LCOE of geothermal

Based on the projected parameters values (Danish Energy Agency et al., 2021), the LCOE from geothermal power plants will significantly decline. Large and small geothermal power plants are projected to have LCOEs of 4.8 and 6.1 cents/kWh, respectively, by 2050. Investment costs for both technologies are expected to decline by about 29%. By that time, geothermal will be a cheaper option than thermal power plants. However, it should be noted that the geothermal power plant project development mechanism is regulated in Government Regulation 7/2017, which requires the ownership of *Wilayah Kerja Panas Bumi* (WKP) and *Izin Panas Bumi* (IPB) permits. In addition, the sale of electricity from geothermal power plants, according to the recent Presidential Decree 112/2022, is through a direct appointment (not a tender). Nevertheless, the decree also states that the government can provide support, such as by facilitating project financing as well as project derisking.

c) Hydropower

Hydro power plants (HPP) are a type of renewable technology with the highest utilization rate in Indonesia. In terms of total installed capacity, hydropower has a share of 8.23%, with a capacity of about 6.7 GW in 2022 (MEMR, 2023). The total hydropower potential in Indonesia is estimated at 94.5 GW (Danish Energy Agency et al., 2021).

Based on their architecture, hydropower plants can be divided into three types: reservoir, run-off-river, and pumped storage hydropower types. The latter type consumes electricity to pump water from one reservoir to a higher reservoir, which is the working scheme of the ESS. Hence, its electricity cost will be explained in Chapter 3. The reservoir type requires the construction of a dam to store water, while the other types can rely on the flow of water. The run-off-river type HPP does not require a long construction time to build a dam, but its generation depends on natural availability. Besides its architecture, HPP is often classified based on its scale. There is no internationally recognized standard definition for hydropower scale, but mini/micro HPP usually has a capacity of less than 1 MW, medium scale has a range of tens to one hundred megawatts, and large-scale HPP typically has a capacity of more than 100 MW (Danish Energy Agency et al., 2021). Most large-scale HPPs use a reservoir architecture, although some HPPs are based on run-off rivers or use a combination architecture.

Among the technologies presented in this report, hydropower plants are one of the cheapest options for generating electricity. As shown in Figure 11, the LCOE is as low as 4.1 cents/kWh for the medium-scale HPP, while the large HPP has an LCOE of 7.9 cents/kWh, both if the land-use cost is not included. For medium-scale HPP, land-use cost is estimated to increase the investment cost by at least 6.1%, escalating the LCOE to about 4.36 cents/kWh. Although the LCOE of power plants commonly declines as the scale increases, large HPPs have a higher LCOE because their capacity factor of 36% is much lower than that of medium and mini/micro HPPs, both with CF of 76%. CF is associated with the type of HPP utilization, in which HPPs with a reservoir are commonly employed as peaking power plants in the power system. Nevertheless, the LCOE of HPP in different scales is still relatively low and can be competitive with CFPPs as a baseload power plant.

HPPs also offer flexibility because of their rapid ramp rates. At a high utilization rate (i.e., high CF), HPPs LCOE can be competitive with peaker gas-fired power plants. One of the favorable factors driving down the LCOE of HPPs is the length of their technical lifetime, which is possibly more than 50 years.

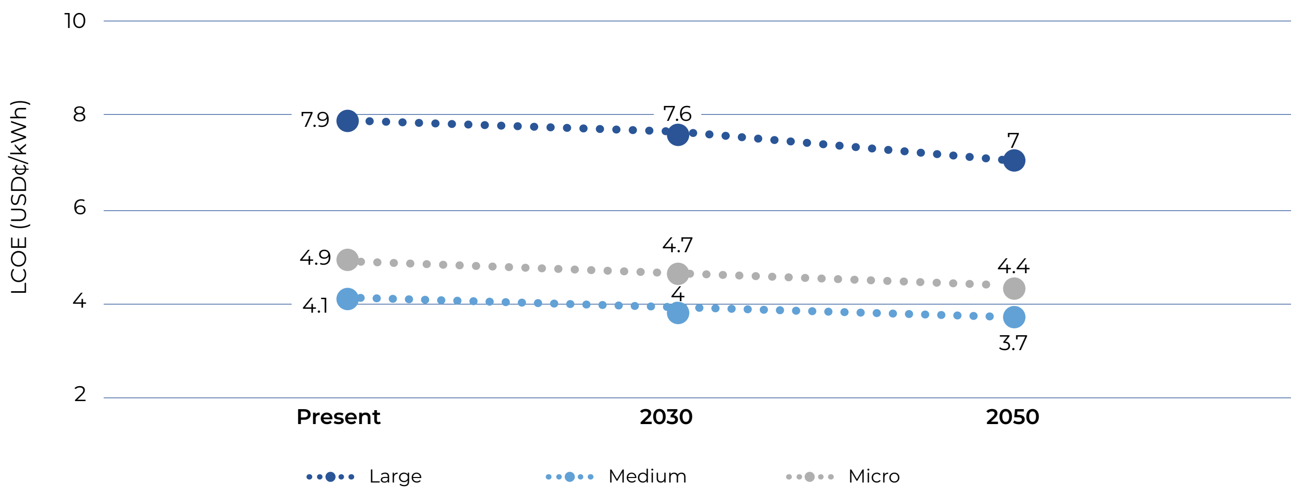


Figure 11. Recommended LCOE of hydropower power plants

Hydropower is one of the oldest power generation technologies in the world and has gone through many advancements; hence, the price of technologies such as HPPs' turbines will not change much and affect LCOE. Rather than the equipment cost, the further decline will probably be influenced by changes in the installation cost, where about 70% of the nominal investment costs come from. To achieve the energy mix target in Indonesia, HPP is still the primary option, as indicated by the plan to install an additional 10.4 GW of HPPs before 2030 in PLN's RUPTL, the highest (25.6%) among other renewables.

d) Tidal (Impoundment and Stream types)

Tidal energy is a part of ocean energy that has around 1,200 TWh/year of electricity generation potential. Indonesia is said to have an advantage in tidal energy utilization due to the presence of Indonesian Throughflow (ITF), which can be exploited in addition to tidal current. Several tidal power plant project initiatives with a total capacity of 197 MW have been conducted in Indonesia (IESR, 2022c). This capacity is considerably high given that, up until now, the installed capacity of tidal power plants globally has only reached 532 MW (IRENA, 2020).

There are two types of tidal power generation technology, namely impoundment and stream types. The first has similarities with HPP because it requires the construction of a barrier to trap water that can be released to rotate the turbine and produce electricity. The tidal stream type, on the other hand, uses the energy of the water flow, which is similar to how wind turbines work. Tidal energy is relatively more predictable than solar PV and wind. The capacity factor of the tidal power plants is estimated to reach 40%.

The LCOEs of tidal power plants are high, mainly due to their high investment costs. The impoundment type has an LCOE of 20.7 cents/kWh, while the LCOE of the stream type reaches 31.2 cents/kWh. Generally, the construction of tidal power plants should be robust and require more expensive corrosion-resistant materials as they are situated at sea. The investment cost per kW capacity of the stream type is unsurprisingly lower than the impoundment type that requires a large structure for a seawater barrier. However, the stream type is reported to have an O & M cost that is about four times higher than its counterpart and accounts for 35% of its LCOE.

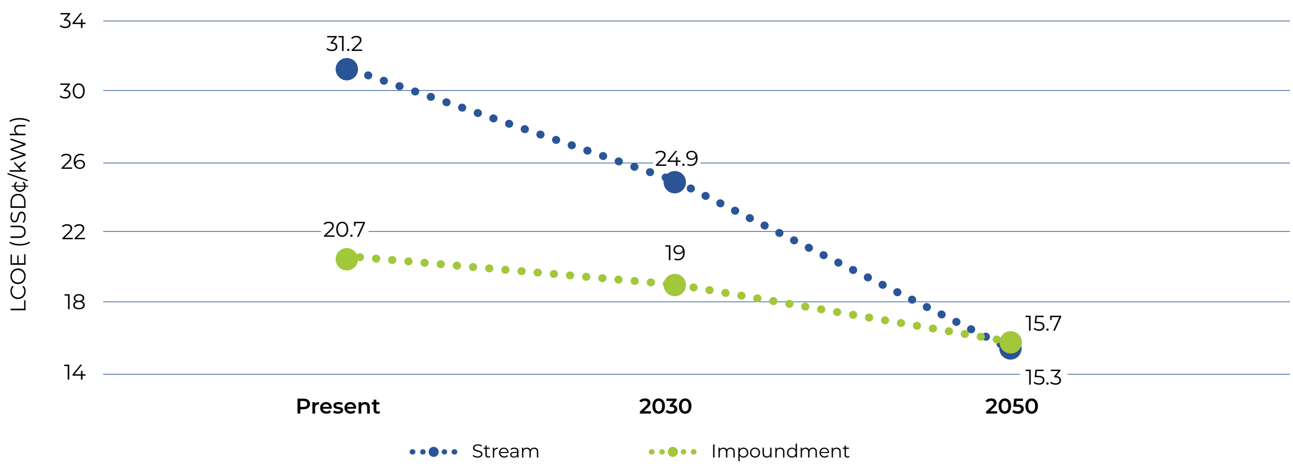


Figure 12. Recommended LCOE of tidal power plants

Along with the increase in the installation of tidal power plants, the technology LCOE is projected to decrease, especially for the stream type. The stream type technology is still in the pre-commercialization stage and currently at a low level of deployment (about 2% of the total installed tidal power plant capacity). The cost of technology and O&M stream-type tidal are projected to have a higher degree of decline, and the LCOE will be lower than the impoundment type in 2050. Notably, the 150 MW stream-type tidal power plant project that has been developed in Indonesia since 2015 is expected to start operating by 2024, opening up more opportunities for similar projects. Although the LCOE is still higher than other renewables, the development of tidal power plants could be a solution for electrification in off-grid coastal areas where the cost of electricity generation could be high.

e) Wind

Globally, the wind turbine is one of the fastest growing renewable technologies, in terms of the number of installed capacity, with a remarkable cost decline. Although it is suggested that the technical potential of wind power (onshore at 100 m hub height) reaches at least 19.8 GW of capacity (IESR, 2021), wind energy in Indonesia is still under-utilized. The installed capacity of wind power plants is no more than 154 MW in 2022 (MEMR, 2023), and its electricity costs, based on PPAs of around 10 cents/kWh, are much higher than the global weighted average LCOE of 3.3 cents/kWh (IRENA, 2022).

Technically, the average wind speed in Indonesia is less than 7.5 m/s (low wind), ranging around 3–7 m/s (Rahmadi et al., 2017). Thus, it is presumed unable to firmly produce electricity at full rated power. Nonetheless, some areas, such as southern Sulawesi and southern Kalimantan, have moderately adequate wind characteristics to develop wind power plants.

Wind turbines can be put on land or in the water to collect wind energy and turn it into electricity. Offshore wind power plants generally use large turbines to maximize wind potential, making the capacity factor about 20% higher than their onshore counterparts. As a drawback, the investment and O & M costs of offshore wind are naturally higher. The higher cost are due to the need for sturdy power plant construction to sustain harsh offshore environments and more complex infrastructure, as well as accessibility challenges for operation and maintenance.

The calculated LCOE of offshore wind is 3.8 cents/kWh higher than onshore, as shown in Figure 13. Despite having a high capacity factor of up to 48%, the investment cost and O & M costs of offshore wind are about 2.3 and 1.2 times higher, respectively, compared to onshore wind. Nonetheless, with an LCOE of 7.5 cents per kWh, onshore wind power plants are not yet competitive with thermal power plants in Indonesia.

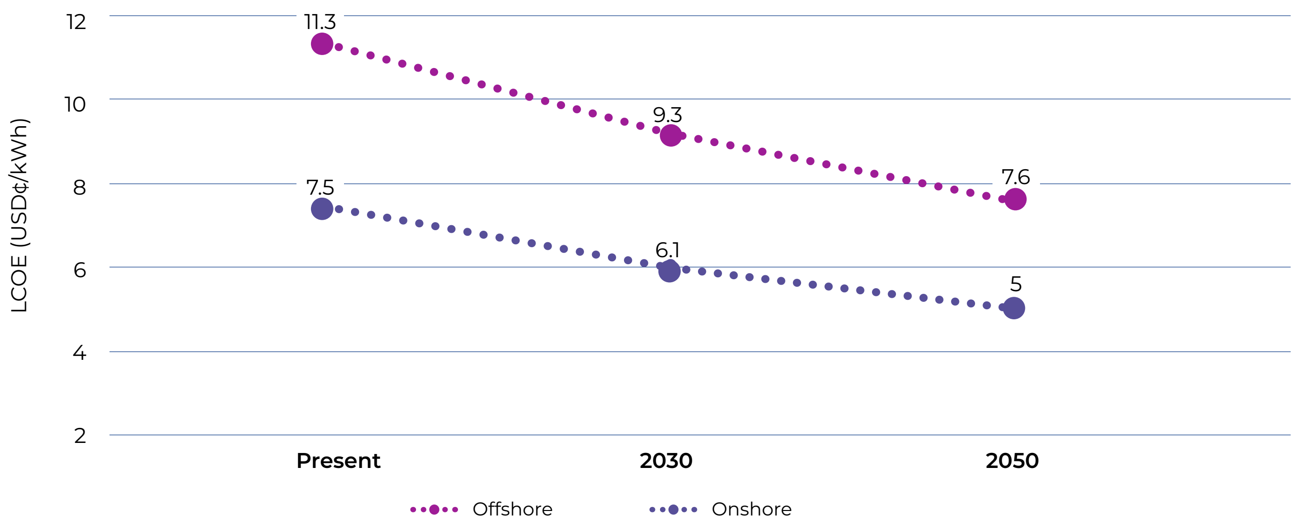


Figure 13. Recommended LCOE of wind power plants

Based on the projected parameter values, the LCOE of onshore and offshore winds in 2050 will decrease to 5 cents/kWh and 7.6 cents/kWh, respectively. The decrease is driven by the increase in the capacity factor of wind turbine technology. Besides, the investment costs of both wind power plant technologies are expected to decline by about 28% in 2050.

In Indonesia, the development of wind power plants seems to be less prioritized. PLN, for example, plans to add only around 600 MW of capacity by 2030. Regardless, a record-low bid of 5.5 cents/kWh won the 70 MW Tanah Laut wind power plant tender in 2022. The bid is about half of the previous lowest PPA price. The wind power plant, equipped with 10 MW of battery energy storage (BESS) to compensate for wind power intermittency, is planned to operate in 2024. The success of the project may inspire the development of more wind power plants, increase the competitiveness of its generation costs, and boost the wind energy mix beyond the initial plan.

f) Solar PV

Solar PV is one of the power generation technologies that requires the shortest time for construction (less than a year); hence, more intense utilization will help Indonesia achieve its energy mix target, which has been progressing slowly. However, the development of solar PV projects in Indonesia faces various challenges that will be discussed later. Even though the potential for solar energy in Indonesia is thought to be 7,714 GW (IESR, 2022c), very little of it is being used at the moment. In 2022, the installed solar PV capacity only reached 270 MW, much lower than the initial target of 893 MW (MEMR, 2023). Based on the recent auctions for large-scale solar PV projects, there was a record low for bids of 3.6 cents/kWh (IESR, 2022a), lower than the global LCOE of solar PV in the last two years of around 4.5 cents/kWh (BloombergNEF, 2022a), suggesting increasing cost competitiveness of solar PV in Indonesia.

The types of solar PV power plants evaluated in this report are utility-scale PV, commercial and industry (C & I) solar PV, rooftop PV, and floating PV; each has a different cost due to its system configuration and scale. Utility-scale PV is usually developed at a large capacity of at least 10 MW. Here, it refers to a ground-mounted type of PV that is connected and supplies electricity to the utility grid.

Meanwhile, floating PV has substantial differences in configuration and cost components, making it a category of its own despite having similarities in scale and the end-user of electricity. Additionally, the quantity and variety of users can set C & I and rooftop PV apart. Rooftop PV, typically a few kW in scale, is usually installed above residential houses. The scale of C & I PV can reach hundreds of kW; thus, its installation is not only situated on the roofs of buildings. In addition to saving money, solar PV in the commercial and industrial sectors are one of the best ways to cut down greenhouse gas emissions from industrial processes.

The LCOE of utility-scale PV is 5.8 cents/kWh for the assumed capacity scale of at least 10 MW, while 5 kW-scale rooftop PV has an equivalent cost of 9.8 cents/kWh, as shown in Figure 14. Floating PV does have a higher expected CF than utility-scale solar PV on the ground (21% vs. 19%) because it gets more sunlight and stays warmer. However, the higher investment cost requirement for additional components of the floating system, such as floaters, anchors, etc., still makes the LCOE floating PV about 0.55 cents/kWh higher than its counterparts.

The difference between the investment costs of rooftop and utility-scale solar PV is about 67%, the former being higher at $1320/kW. The economy of scale indeed helps to drive down the utility-scale solar PV investment cost per kW, for instance, through more efficient labor and installation costs as well as equipment delivery.

Figure 14 also includes the LCOE of utility-scale solar PV with a land-use cost component to the total investment cost. The investment costs dataset used for calculating LCOE here does not include land-use costs due to lack of data (Danish Energy Agency et al., 2021). However, given the space requirement for a solar PV project reaching 14 m^2/kWp, more than 100 times the need for thermal power plants, it is necessary to discuss this. Assuming a land acquisition cost of US$10/m^2, which is quite in line with the price of non-urban land by zone value (BHUMI.atrbpn, n.d.), there will be an increase of about 18% in the total investment cost. Consequently, the present LCOE for utility-scale PV will increase by around 15.1%, while the increase is estimated to reach 28.6% in the projected LCOE in 2050.

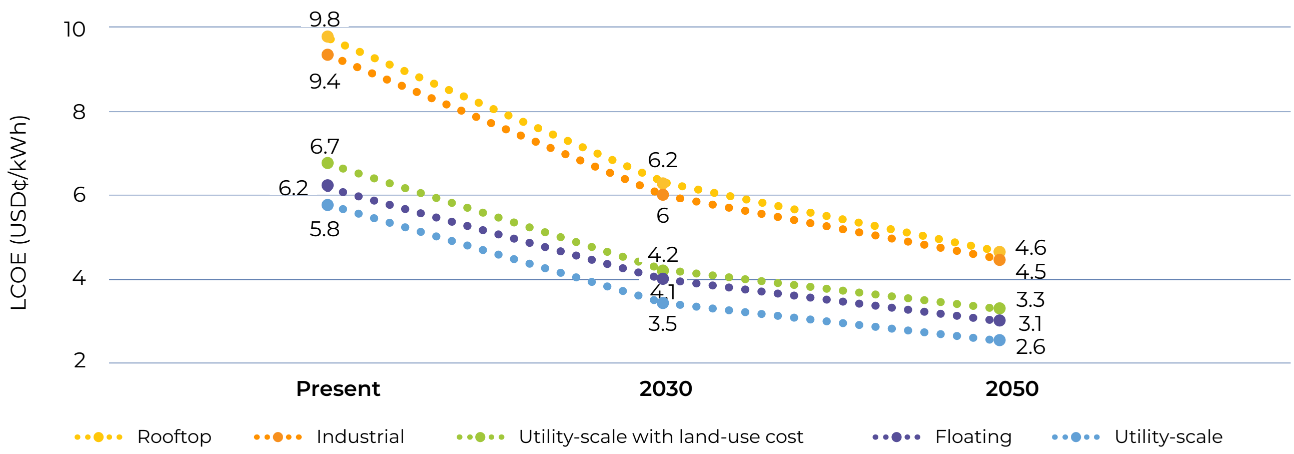


Figure 14. Recommended LCOE of solar PV power plants

The cost projection based on the learning rate of solar PV suggested that Indonesia will keep up with the global LCOE decline of solar PV even though there will be a delay for a few years. By 2050, the LCOE of the four types of solar PV will be less than 5 cents/kWh, while the utility-scale LCOE will reach 2.6 cents/kWh. Notably, domestic manufacturers of solar PV should be able to produce the components at competitive prices with the global market to drive down the LCOE. Unfortunately, the price of domestic modules is still 30–45% higher than the imported ones (IESR, 2022a), and the implementation of the local content requirement for the development of solar PV could be a great barrier to increasing the capacity of solar PV. The impact of LCR requirements on the LCOE of solar PV and its countermeasures will be further discussed in Chapter 4.

2.2.3. Sensitivity of Renewables LCOE

a) Biomass Feedstock Price

An agricultural feedstock-fueled biomass power plant can be very cheap if the feedstock is obtained at a low cost. According to PLN's Director Regulations No. 1/2020 and 4/2022, the price of biomass for utility power generation is capped at the coal price of US$70 per ton. When the recommended US$40/ton feedstock is available, the LCOE value is also relatively low at 6.4 cents/kWh, with 42% of the LCOE coming from the fuel cost component. However, because of the uncertainty in the feedstock supply chain, it is possible that the demand for biomass fuel cannot be met without using other feedstocks or importing the feedstock, especially for privately-owned biomass power plants. Notably, most of the biomass feedstock will also be allocated for the CFPP co-firing program, which requires about 2.2 million tons of feedstock by 2023 (IESR, 2022c).

In case the expected biomass feedstock is not met, the LCOE value of a biomass power plant with the foregoing recommended parameters, which involves wood chips substitution for palm kernel shell with an FOB market price of US$131.4 per ton (Argusmedia, 2023), will reach 11.67 cents/kWh with a fuel cost component contribution of 68.31%. The high share of fuel costs will result in a high sensitivity of the LCOE to fuel cost value changes. As shown in Figure 15, the LCOE of biomass power plants using alternative feedstocks has a higher sensitivity.

In this regard, the development of the biomass feedstock supply chain is very important to ensure the fulfillment of the power sector needs. If the price of biomass is set below US$70 per ton, it is necessary to ensure that there are alternative types of feedstock within the price range because, historically, the price of a type of feedstock can have high fluctuations.

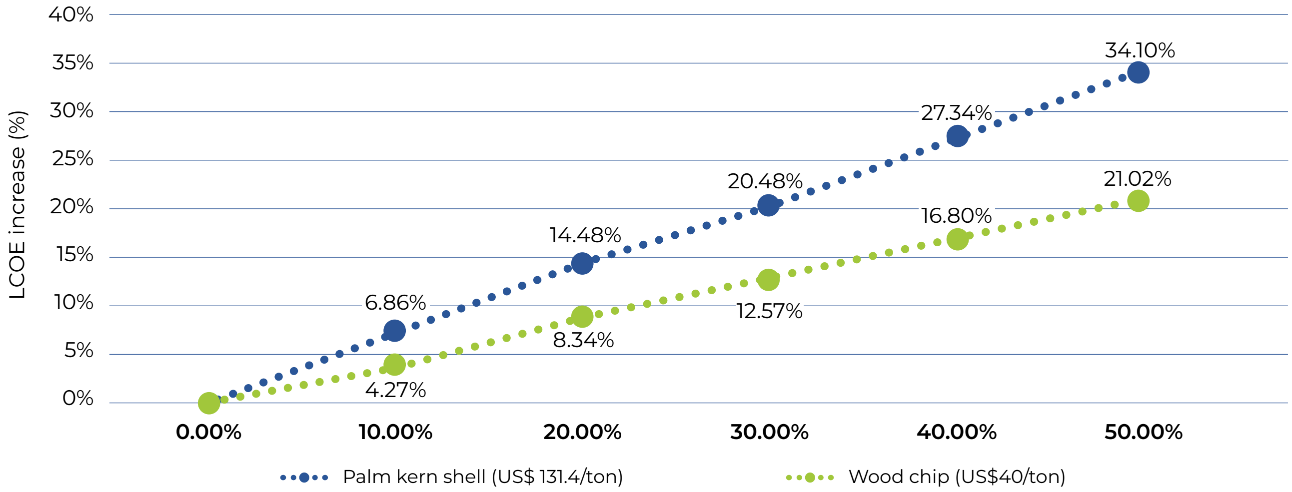


Figure 15. The LCOE of biomass agriculture with different biomass feedstock changes with fuel costs increase

b) WACC of Solar PV

In the absence of the fuel cost component, the cost of investment becomes an important parameter that influences the LCOE of solar PV. A sensitivity test to a 20% change in WACC, for example, will have an impact on an increase in LCOE of 15.3% or a decrease of 14.7%. Although the sensitivity of solar PV to changes in the investment cost and capacity factor is still higher, these two parameters are mainly influenced by price trends and technological advancement globally. On the other hand, the WACC is a parameter that can be manipulated by the government through policy schemes.

Although the cost per kW of installation is relatively low ($790/kW), utility-scale solar PV is one of the renewable generation technologies with the highest WACC sensitivity, as shown in Figure 16. In Indonesia, the cost of investment for solar PV projects is still high. A uniform default WACC of 10% is used to calculate the LCOE of all technologies in this report, which can be assumed a moderate value, as suggested by some reports (AIGCC, 2021; IRENA, 2022). Solar PV projects are considered high-risk, and the WACC could be higher, especially for those who use domestic modules, which are not yet bankable.

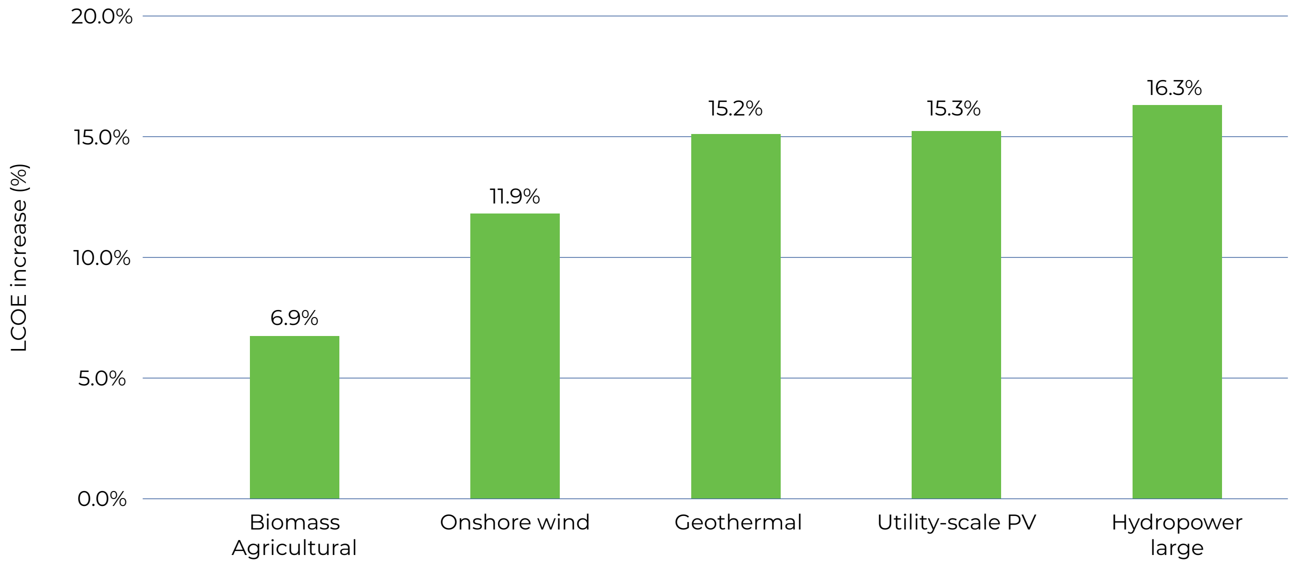


Figure 16. Sensitivity of various renewables LCOE to 20% increase in WACC

With a low WACC, solar PV has the potential to be the least-cost power generation technology option. As a point of comparison, the utility-scale PV's LCOE with a WACC of 9.7% will offset the LCOE of supercritical coal. LCOE will further decrease with a lower WACC, as shown in Figure 17. On the other hand, the increase in WACC drives LCOE even higher. For instance, when the WACC of utility-scale solar PV is 15%, the LCOE is increased to 8 cents/kWh (39% from the baseline of 5.8 cents/kWh). Meanwhile, there will only be a 35% decrease in LCOE with a 50% decrease in WACC.

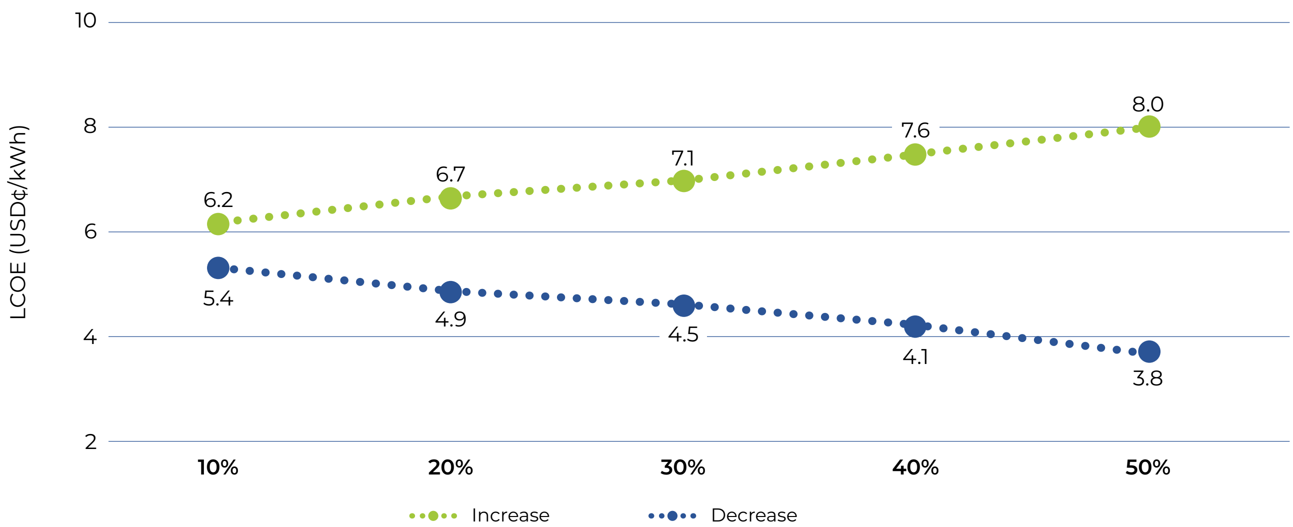


Figure 17. LCOE of utility scale solar PV in different changes of WACC

3 Levelized Cost of Storage (LCOS)

Whereas LCOE is generally used to decide whether a generation technology has economic feasibility, in the case of energy storage, the LCOS is instead used as the measure. Analogous to its LCOE counterpart, LCOS is based on similar elements: CAPEX, OPEX, and energy output. However, the annual cost might also include the charging cost, which depends on the round-trip efficiency of the storage technology and is comparable to the fuel cost in LCOE. In LCOS, the term "energy output" or "generated electricity" can be replaced with the discharge of ESS. Since ESS can have different scales and durations, the investment cost of the same ESS technology might also have different values. The LCOS in this report is calculated by the annuity method, as shown in Equation 2 in Appendix 1. The classification and definition of financial and technical parameters of ESS are mainly adopted from Pacific Northwest National Laboratory's (PNNL) report (Mongird et al., 2019; PNNL, 2022), and the values of all the technical and financial parameters used to calculate LCOS in this report are shown in Appendix 2.

The investment cost to calculate LCOS includes the financial parameters of the costs of: 1) energy ($/kWh) and power components ($/kW); 2) the balance of the system (BOS; $/kWh); 3) system integration ($/kWh); 4) grid integration ($/kW); 5) controls and communication (C&C; $/kW); 6) engineering, procurement, and construction (EPC; $/kWh); and 7) project development ($/kWh). Given that financial parameters exist in different units of $/kW and $/kWh, the latter has to be multiplied by the ESS energy-to-power ratio to calculate the LCOS. For example, if the BOS cost of 4-hour duration pumped hydropower storage is $100/kWh, it must be calculated as $400/kW to be added to the total investment costs. In the case of OPEX, a single variable O & M cost value is applied to each ESS technology and multiplied by the amount of electricity output. Meanwhile, the fixed O & M costs vary depending on the scale and type of ESS.

The technical parameters that will determine the output of the ESS include the parameters derived from the intrinsic characteristics of ESS (whose values are determined by technological capability) and the parameters whose values are specific to the type of ESS application, namely:

1) Duration (hours), also called the rated energy-to-rated power ratio of the ESS.
2) Round-trip-efficiency (RTE; %), the ratio between electricity output (discharge) and input (charge) which is naturally less than 100% due to electrical losses.
3) Cycle life (#), the total sequence of the charge-discharge process provided by ESS before reaching the end of life.
4) Calendar life (years), the maximum period after which the ESS reaches the end of life regardless of operating conditions.
5) Depth of discharge (DoD; %), the amount of electricity discharged as a percentage of the rated energy capacity.
6) Annual cycles (cycles/year), the total number of charge-discharge processes an ESS goes through in a year.

In the case of DoD, the value is usually kept within a certain range to maintain the durability of the ESS. In operating lithium-ion batteries, for example, the DoD is usually kept around 70–90% to prevent the degradation of battery energy materials, which would reduce the number of cycles. Meanwhile, the value of the annual cycles varies depending on the type of ESS application. In this report, LCOS is evaluated for six types of applications with different annual cycles ranging from 40 to 15,000 cycles per year. Since the durability of an ESS is highly dependent on how often it is used, especially batteries, a corresponding cycle life (years) that considers both calendar life and cycle life relative to an application's annual cycle number is used to calculate the value of LCOS.

The type of application is also used to determine the charging value. The applications evaluated are primary response, secondary response, peaker replacement, energy trade, power reliability, and long-duration energy storage (LDES). Except for energy trade and long-duration storage applications, where a charging cost of 3 USD/kWh is used as the default value, the charging costs are not included. The electricity to charge the ESS is assumed to be free from the excess VRE generation. The reason for calculating the charging cost for those two applications is because the results of the output of the LCOS calculation for energy trade and long-duration storage applications are expected to be used as a reference when a buying and selling electricity scheme from privately owned ESS becomes available. This is done to demonstrate how much the charging cost contributes to the LCOS.

As for LCOE analysis, the LCOS sensitivity analysis is used to observe the effect of changing parameter values on the LCOE output. This analysis reveals that the LCOS value of a particular ESS technology is affected differently due to its unique parameters, such as its configuration (scale and duration), operation (number of annual cycles), technology performance improvements (calendar life improvement), etc.

Due to the limited project experience and information on the supply chain in Indonesia, the financial parameters (CAPEX and OPEX) values used in this report are extracted from the global ESS projected cost, mainly from the PNNL which has been actively evaluating the cost of various ESS (Mongird et al., 2019; PNNL, 2022; Schmidt et al., 2019). In addition, data associated with technical parameters is also refined with several related publications that are suitable for the application context in Indonesia.

3.1. Energy Storage Technologies

In the last few years, the global capacity of energy storage has increased, mainly due to the higher utilization of renewable energy. The ESS is one of the keys to curbing the intermittency issue of VRE. Moreover, ESS can also be utilized for a wider range of uses in power systems, such as maintaining the reliability and stability of the power grid. The estimated total power capacity of the global ESS is more than 160 GW by the end of 2021 and is expected to continue to grow along with the increasing commitment of several countries in achieving the NZE target (IEA, 2022e).

The high demand for ESS is accompanied by an extended list of the types of ESS technologies that are intensively being developed. There are at least three different types of technologies that can be used to classify these ESS: mechanical, thermal, and electrochemical. As of now, more than 90% of all ESS capacity comes from mechanical PHS, the most mature ESS technology. However, the growth of PHS capacity could be outpaced by electrochemical batteries ESS which is projected to have 387 GW/1,143 GWh of new ESS installed by 2030 (BloombergNEF, 2022b).

The increasing interest in BESSs is likely driven by their flexibility features. While PHS installations require certain geographical conditions, BESS is a more suitable option to support scattered VRE power plants. When it is feasible, however, PHS would be a much cheaper option, particularly for long-duration storage. Therefore, ESS technology should indeed be evaluated based on its utilization. In addition to PHS and batteries, flywheels and CAES technology are also evaluated in this report. Those four technologies were chosen because they can represent different roles of ESS technologies in power systems.

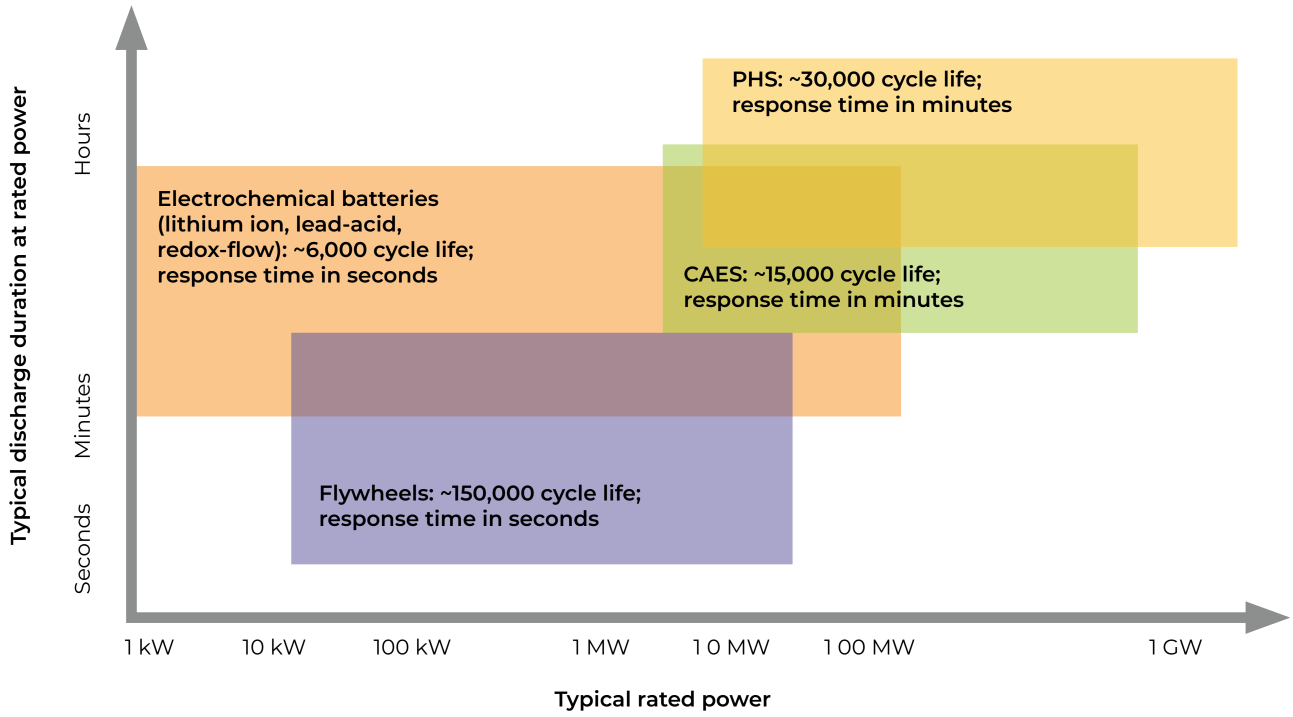


Figure 18. Typical characteristics of energy storage technologies

Intrinsically, each ESS technology possesses different merits and limitations. Flywheels, for example, have a peculiarly low discharge duration while theoretically having unlimited cyclability. Meanwhile, CAES can have a much longer discharge duration with sufficiently high cyclability, but it takes a longer time to discharge electricity due to its working mechanism. Typical characteristics of ESS discussed in this report are illustrated in Figure 18.

Generally, ESS in a project is denoted by the type of technology, power capacity, and energy capacity (e.g., VRFB 1 MW/8 MWh or PHS 100 MW/400 MWh). The ratio between energy and power capacity (E/P ratio) is used to describe how long an ESS can release electricity while still putting out its rated amount of power. A higher E/P ratio means higher electricity output in each cycle (which drives down the LCOS) at the expense of higher energy component costs.

To decide the most appropriate type of ESS for one or multiple applications in a power system, the technical requirements should be first evaluated. Table 1 shows the typical technical requirements of ESS for the different applications discussed in this report. After an ESS meets the applications' technical criteria, the unique parameters of the ESS, such as RTE and DoD, and the corresponding life cycle will determine the economics of the ESS, represented by its LCOS value.

Although the LCOS value of each ESS technology will be proportional to its investment cost, an ESS with a low investment cost per installed capacity ($/kW) is not always the most economical technology option for particular applications in power systems. In the use of ESS to maintain grid stability (e.g., primary response), for example, due to a long corresponding cycle life, flywheels can have a lower LCOS than batteries even though their investment cost ($/kW) is about ten times higher. Meanwhile, PHS and CAES would not be appropriate technology options for such application because they do not meet the response time requirement, even though they would have the advantage of long cyclability.

Table 1. Different energy storage applications and technical requirements
Source: IESR analysis and Schmidt et al. (2019)

	Primary response	Secondary response	Peaker replacement	Energy trade	Power reliability	Long-duration storage
Minimum response time	<10 seconds	No specific requirement	No specific requirement	No specific requirement	<10 seconds	<10 seconds
Power scale (MW)	1 – 100	10 – 100	1 – 100	1 – 100	1 – 10	1 – 100
Duration (hours)	0.25 – 1	0.25 – 10	2 - 6	2 - 10	2 - 10	100h
Application annual cycle	15,000	1,000	350	350	365	40

3.2. Application specific LCOS

The value of energy storage technologies must be reviewed depending on the type of application. Globally, each ESS role already has its estimated value in the form of LCOS value (Lazard, 2020; World Energy Council, 2016), although it can be different for each country. LCOS can be used as a reference for measuring the economics and determining selling prices for ESS services (e.g., for the ancillary services market), analogous to LCOE as a reference for PPA pricing. For applications where ESS is integrated with power generators or grids, ESS would be assumed economical if electricity costs were lower than pre-ESS costs; the LCOS of ESS, which acts as a peaker power plant substitution, for instance, needs to be competitive with LCOE peaker gas turbines. Given the wide use of ESS in the power sector, it is important to present the results of LCOS calculations that are application-specific based on recent financial and technical data and compare the LCOS values of different ESS technologies. The calculated LCOS is shown in Figures 19 and 25. The detailed parameters are available in Appendix 2.

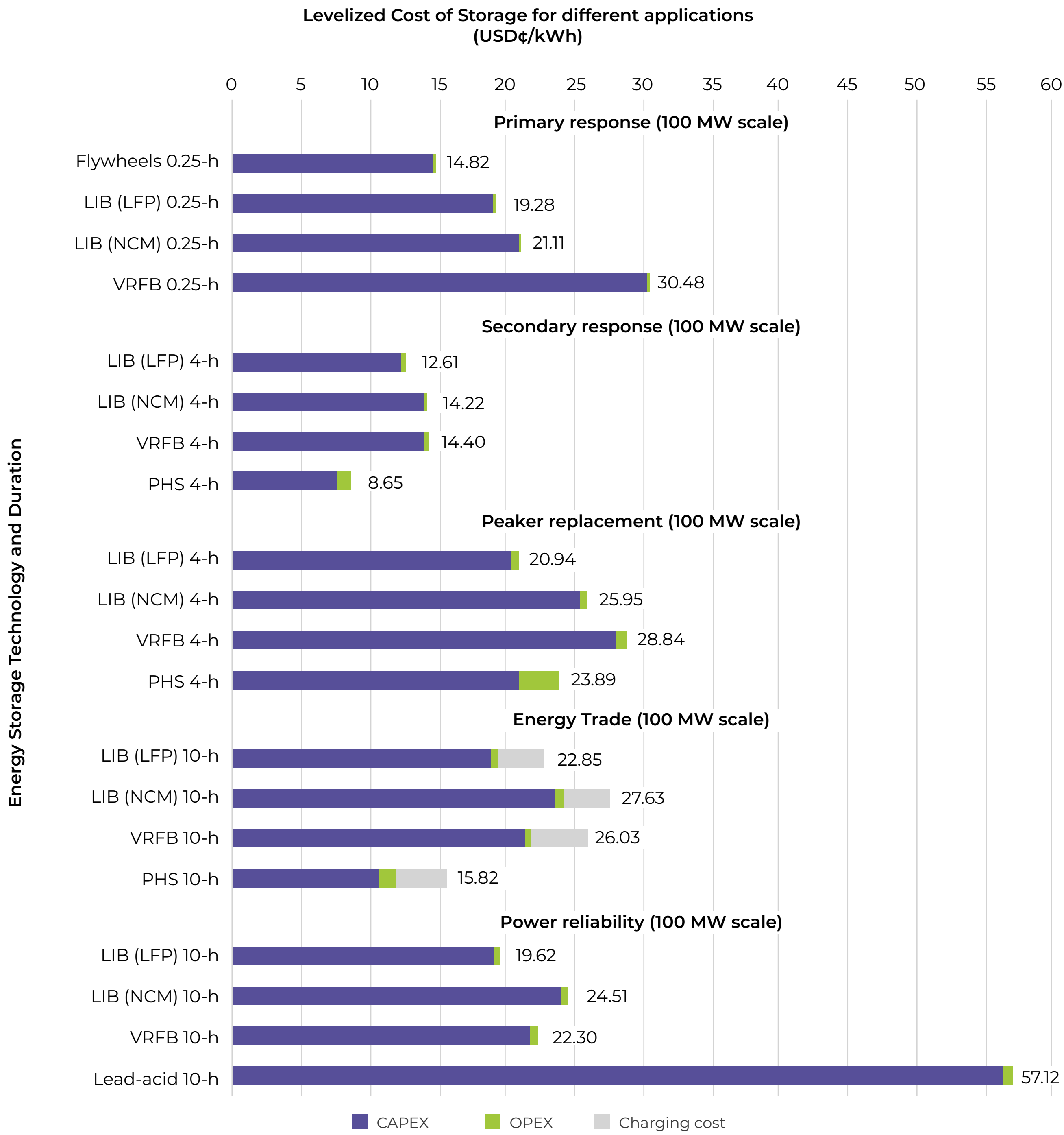


Figure 19. The LCOS of several ESS technologies in different applications

In addition to the comparison of ESS LCOS values, the sensitivity of their parameter values to the respective LCOS are analyzed, similar to the LCOE sensitivity analysis. However, the analyses are carried out on LCOS outcomes in different applications, each highlighting one parameter whose value changes would influence the ESS LCOS outcomes. The parameters discussed include the number of the annual cycle, scales and durations (which affect investment costs), charging costs, calendar life, and round-trip efficiency. Recognizing the sensitivity of the ESS parameters would be critical in Indonesia, which is still in the early stages of adoption and has not specified the criteria for the required ESS. The ESS deployment plans, should have a list of sensitive parameters for choosing technology, scale, and the best way to run it.

a) Primary Response

ESS technologies that are commonly employed for primary response applications are those with high cycle lifetime characteristics. In several reports, this type of application is also known as frequency regulation, whereby the electrical energy stored in the ESS can be used to automatically correct and stabilize system frequency during changes in load or generation. In this regard, the ESS must also have a fast response and is generally designed with a short-duration configuration.

In addition to the fast response time capability, batteries or flywheels are ESS technologies often found in charge of regulating system stability because they also have the flexibility to be built in island systems that typically have more variable demand than a centralized system; hence, the primary response capability of ESS is critical. Assuming that the primary response ESS operates 15,000 cycles a year, flywheel technology is an option with the lowest LCOS of 14.82 cents/kWh. At the same scale (100 MW/25 MWh), the LFP-type lithium-ion battery (LIB) has the lowest LCOS, with 19.82 cents/kWh among batteries, as shown in Figure 19. The low LCOS of the flywheel is due to its very high cycle lifetime, which makes it have an estimated operating time (i.e., corresponding cycle life) of almost ten years, while all batteries technically reach end-of-life and need replacement in less than a year. In the case of VRFB, even though it has a higher corresponding cycle life (and can be cycled more frequently) than LIBs, component costs that are twice those of a LIB are the cause of the high LCOS value.

If ESS technologies operate only half as the times previously assumed, the LCOS of the flywheels will be higher than LIB-LFP (21.7 cents/kWh vs. 19.7 kWh). It indicates that the LCOS of flywheels is very sensitive to the number of annual cycles. As shown in Figure 20, the change is most significant for flywheels, whether the number of cycles increases or decreases. Through analysis of annual cycle changes, it is found that flywheels and LIB-LFP have an equivalent LCOS of 19.6 cents/kWh when both ESS are operating at 8500 cycles annually. In this regard, flywheels could be the least-cost option only if, for the primary response application, the ESS is planned to be cycled more than 8,500 times a year the ESS is planned to be cycled more than 8,500 times a year.

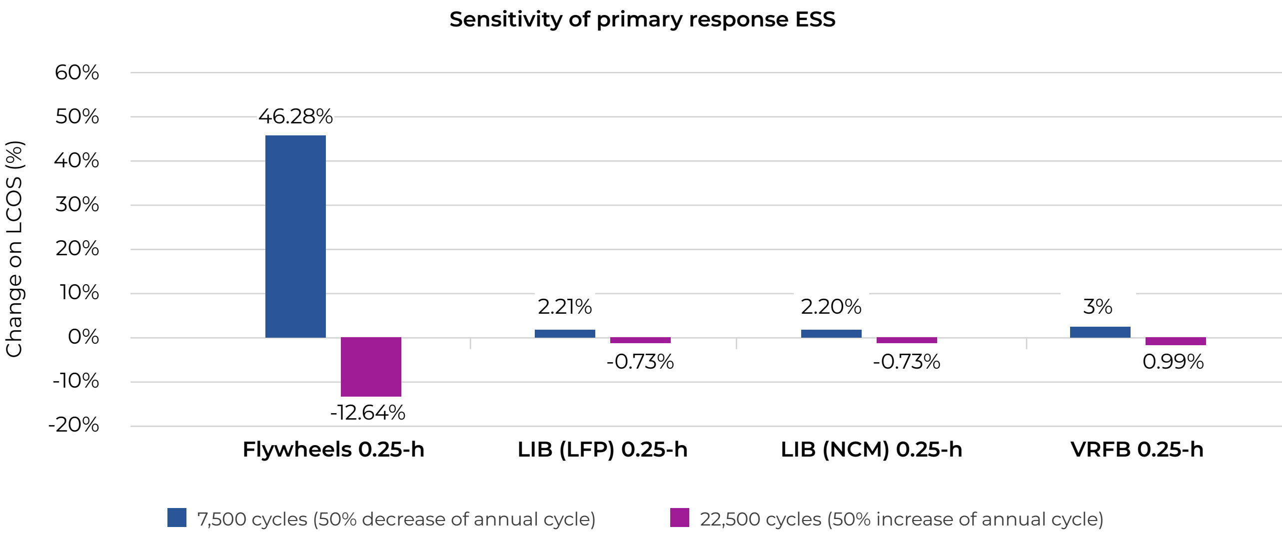


Figure 20. Sensitivity of primary response application LCOS to the number of annual cycles. The change values are compares to LCOS with 15,000 annual cycles

b) Secondary Response

Compared to primary response applications, the use of ESS for secondary responses has less strict response time requirements, and the ESS are usually cycled less frequently. The ESS for these applications can be operated automatically or manually and is frequently used to correct and firm up inaccuracies in renewables forecasts. The minimum ESS scale is typically more than 10 MW, higher than some other types of applications. The reason should be related to their assignment of ESS for a secondary response application that includes load following to anticipate unmet load that requires high power. In this application, PHS technology meets not only the technical requirements but also the technology option with the lowest LCOS at 8.65 cents/kWh, as shown in Figure 19. Although the total investment cost per kW of PHS is higher than batteries, the corresponding cycle life of PHS, which is 4 to 5 times longer, is the driver of a low LCOS value.

Notably, longer-duration ESS, despite requiring higher investment costs, could have lower LCOS values due to the economy of scale in general and particular ESS advantages. It should be noted that each ESS investment cost comprises the cost of power and energy components. For instance, the power component of a PHS is the turbine, and the energy component is the reservoir. Consequently, increasing the energy capacity of PHS is much cheaper than batteries because the energy component of the batteries is associated with relatively expensive energy materials (*i.e.*, anode and cathode precursors). Meanwhile, PHS and VRFB benefitted from their decoupled power-energy capability to scale up the duration (IESR, 2022b). The duration of PHS and VRFB can be longer by enlarging the reservoir or electrolytes tank of VRFB without the expenses for power components (additional turbines for PHS and reactor size for VRFB). The decoupling capability is responsible for the high LCOS sensitivity to the increased E/P ratio (*i.e.*, duration) of PHS and VRFB. As shown in Figure 21, the LCOS values of the two types of ESS underwent significant changes when the duration was increased. Besides the individual characteristics, the economy of scale also contributes to the decrease in the LCOS values of longer-duration ESS. The cost of the energy component per kWh of VRFB, in particular, is about 20% lower in a 10-hour configuration than the cost in VRFB of a 4-hour duration system. Meanwhile, the difference in PHS is only about 6%, suggesting the significance of the economy of scale emerging ESS technology component.

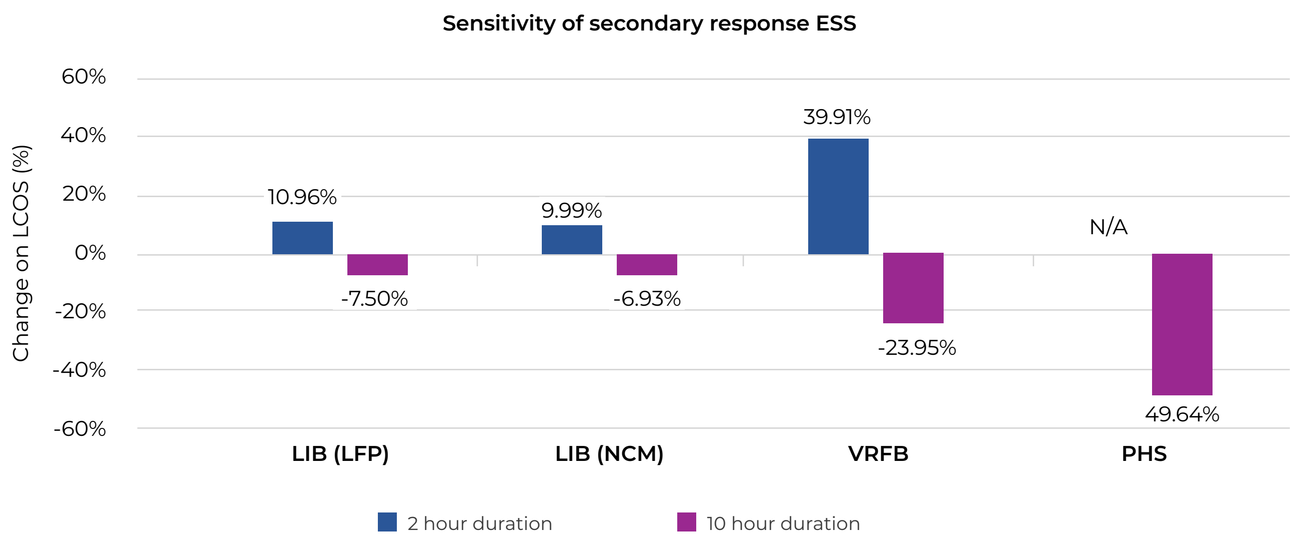


Figure 21. Sensitivity of secondary response application LCOS to the ESS E/P ratio. The change values are compared to LCOS with 4 hour duration

c) Peaker Replacement

One of the key roles of ESS in a power system is as a load/generation shifter. In power grids that may consist of various types of power plants, ESS can provide bulk electricity when electricity demand is high and store electricity supply when demand is low. This utilization can make ESS an alternative to peaker power plants which usually have high generation costs. In parallel, ESS is also one of the solutions for integrating large-capacity VREs. ESS can reduce the curtailment of VRE generation and absorb generated excess electricity for charging, making a power grid with high VRE penetration remain efficient.

Assuming that ESS will have 350 annual cycles, the estimated LCOS of several types of ESS with a scale of 100 MW/400 MWh for peaker replacement applications ranges from 20.94 - 28.84 cents/kWh, as shown in Figure 19. LIB-LFP is the technology with the lowest LCOS, while VRFB is the highest. The average LCOS value of this application is still relatively high; even the high-end LCOE of the OCGT power plant (with a 35% capacity factor) is still lower at 17.35 cents/kWh. Nonetheless, the projected lower technology price is expected to make the LCOS of ESS for peaker replacement more competitive. For example, the LCOS of the LIB-LFP is expected to decline to 15.89 cents/kWh by 2030 (future LCOS projections of several ESS are also provided in the IESR web tool). Besides, ESS deployment would provide the integration of cheap renewables, by curtailing and correcting the VREs output, which could eventually lower the average utility power grid generation cost.

Similar to scaling up the ESS duration, the economy of scale affects the LCOS of ESS at different power scales. The LCOS values mentioned are the estimated LCOS in the highest ESS scale in this report (100 MW). Meanwhile, on a smaller scale of 1 MW and 10 MW, excluding PHS, for which the data is unavailable, the estimated LCOS value of each technology will be higher, as shown in Figure 22. The percentage of increase in LCOS of batteries is relatively on par.

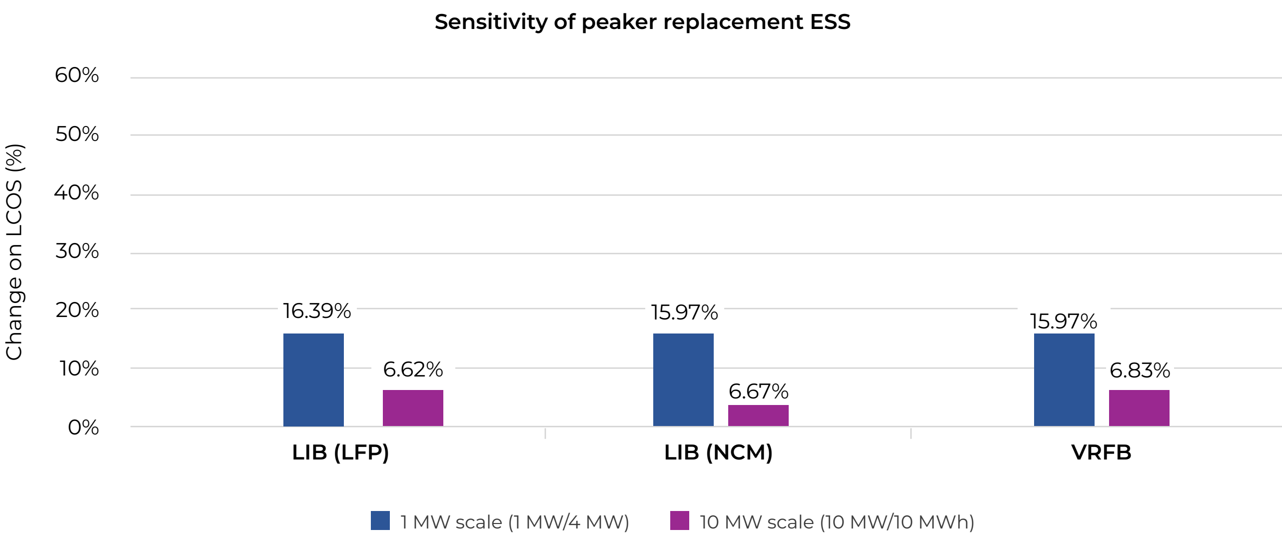


Figure 22. Sensitivity of peaker replacement application LCOS to the scale of ESS. The change values are compares to LCOS with 100 MW scale (100 MW / 400 MWh)

d) Energy Trade

A notable difference in the LCOS value calculation for energy trade applications is the introduction of a charging cost component. The LCOS outcome, with the inclusion of charging cost in this application, can give a picture of the minimum price for selling electricity stored in ESS as the owner of the energy storage asset. In some aspects, the energy trade application is similar to the well-known energy arbitrage application of ESS, where the owner of the ESS stores the electricity in ESS when the tariff is cheap, and then exports/sells it when the tariff is high. However, the concept of energy arbitrage does not generate revenue in Indonesia, given the regulation of flat electricity rates. Against this, the energy trade practice is that the ESS owner might harvest energy from various types of power plants (*i.e.*, cheap renewables) to be stored in ESS first and then sold as bulk electricity supply through such a power purchase agreement.

Round-trip efficiency is a major contributing factor to the high charging cost of ESS. At the charging rate of 3 cents/kWh, the contribution of the charging cost LCOS component ranges from 12.6-24.3% of LCOS values where the highest is observed in the LCOS of PHS. This is due to the relatively lower RTE at 78% than LIBs at 86%. Regardless, PHS on the scale of 100 MW/1,000 MWh (10-hour duration) still has the lowest LCOS for energy trade applications, as shown in Figure 19. Interestingly, the LCOS of VRFB is lower than LIB-NCM, verifying the advantage of the decoupling property of VRFB for the long-duration application mentioned earlier.

The calculated charging cost LCOS component value of VRFB, which has the lowest RTE among other ESS at 73%, is higher than that of PHS with 4.11 cents/kWh and 3.85 cents/kWh, respectively. However, the CAPEX value (cent/kWh) of VRFB is much larger. Hence, the LCOS value of PHS would be the most affected by the charging cost. The sensitivity analysis on the cost for charging per kWh confirmed the sensitivity of the PHS LCOS value to the change in charging cost, as shown in Figure 23.

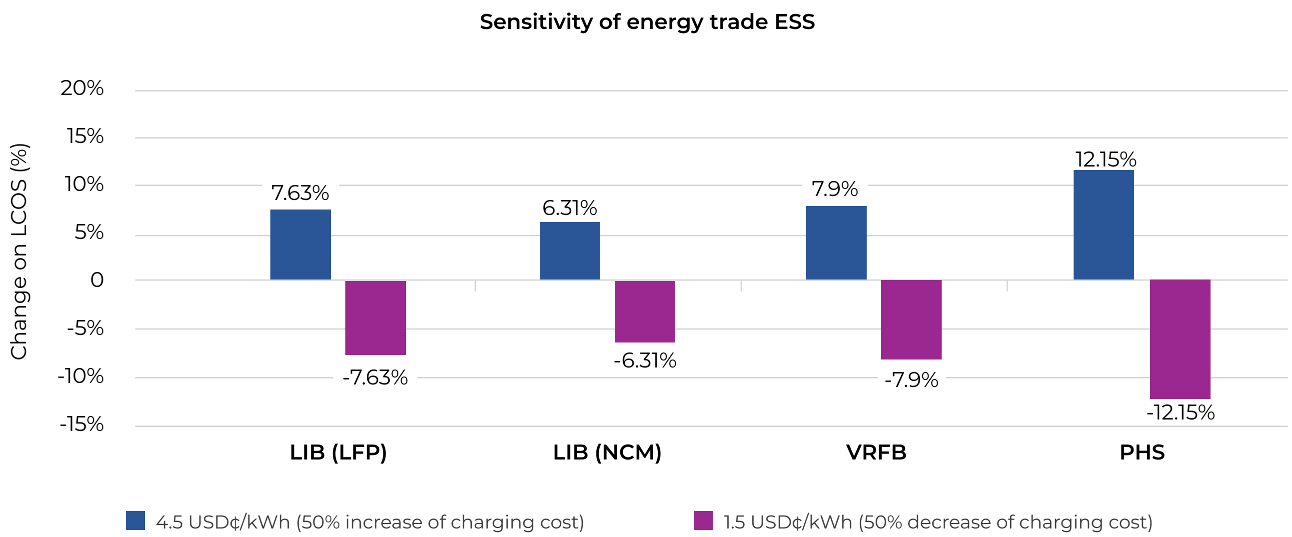


Figure 23. Sensitivity of energy trade application LCOS to the charging cost. The change values are compares to LCOS with charging cost of 3 USD¢/kWh

e) Power Reliability

Power system reliability application requires a fast-shifting source of electricity that can operate for a sufficiently long duration during the absence of primary resources, such as ESS installation to support VREs in an off-grid system, to ensure the electricity demand of off-grid systems is met 24/7. Moreover, off-grid ESS may need a storage technology that is easy to assemble and flexible to be installed in several geographic conditions. From the available options, flywheels and PHS would not be appropriate ESS for this application. Flywheels' energy capacity and duration are simply too low, while PHS has geographical condition requirements. The lead-acid battery can instead be used as it meets some off-grid system's ESS criteria.

In power reliability application, the number of annual cycle assumptions is 365 cycles/year, and the ESS is charged with the daily excess power generation. The lead-acid battery has about 20-30% lower DoD than other batteries and has a cycle lifetime about three times lower. As a result, it came out as the most expensive ESS based on its LCOS, which is over 57.11 cents/kWh. Nevertheless, other technology options are also still expensive, with the lowest LCOS value being close to 20 cents/kWh (LIB-LFP).

One of the reasons for the high LCOS of ESS in power reliability applications is the low utilization in terms of the number of annual cycles. The value comes from the assumption that ESS is coupled with solar PV, where ESS will undergo a single charge-discharge process daily. As mentioned earlier, the LCOS calculation uses the corresponding cycle life value, in which the value depends on whichever is shorter between nameplate calendar life and specific cycle life (ESS age is based on cyclability and intensity of use). Consequently, among four batteries, only lead-acid batteries have a corresponding lifetime that is not based on their calendar life. In other words, other batteries can be operated for 1-6 years longer if calendar life is ignored.

When ESS's calendar life is 50% longer, there will be significant changes in LCOS, as shown in Figure 24. LIB-NCM and VRFB are the two technologies significantly affected, with a LCOS decrease of 11.72% and 11.28%, respectively. The decrease occurs due to the LCOS parameter of corresponding lifetime, which increases from 13 years to 17.25 years for LIB-NCM and 16 years to 22.7 years for VRFB. Meanwhile, the LCOS of lead-acid battery is not affected by the change of calendar life at 50% ranges due to the corresponding cycle life being less than 6 years (*i.e.*, calendar life value after a 50% decrease applied).

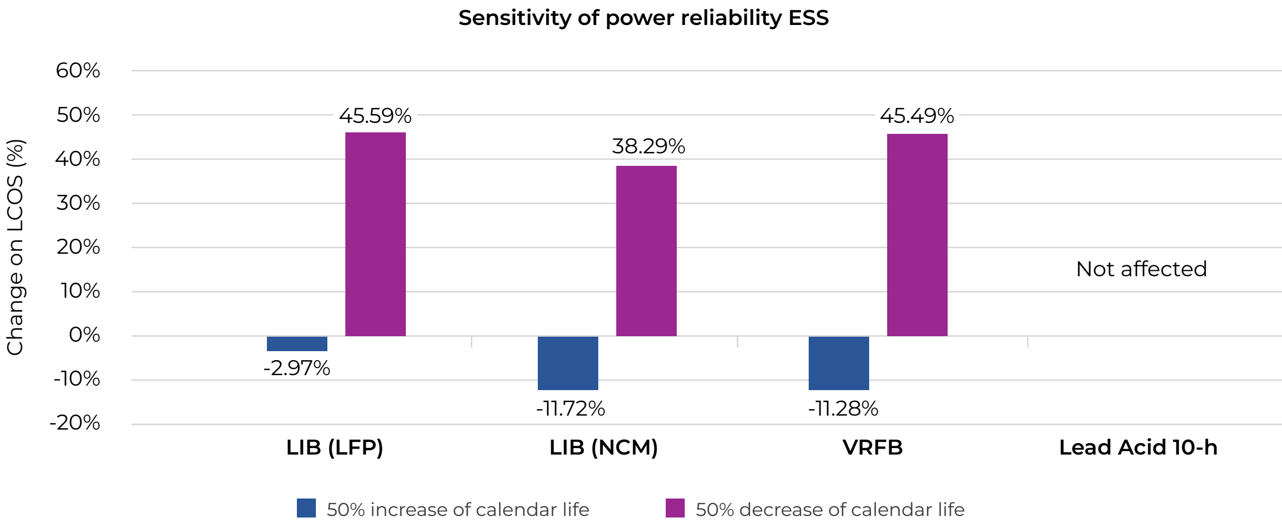


Figure 24. Sensitivity of power reliability application LCOS to the calendar life. The change values are compares to LCOS with default calendar life: 12 years (lead-acid battery), 13 years (LIB-NCM), and 16 years (LIB-LFP and VRFB)

f) Long Duration Storage

In this report, long-duration application storage (LDS) options are ESS that can have a discharge duration of more than 100 hours. LDS is generally prepared to mitigate power system disruption (of electricity supply) due to lengthy extraordinary circumstances, such as natural disasters. In several parts of the world, for example, LDS can also be used for resource adequacy when the solar PV yields low sun intensity and cannot produce sufficient electricity supply, such as during the winter season.

Based on the storage technology options, mechanical types of ESS, such as PHS and compressed air storage (CAES), are favored options for LDS applications. The cost for capacity expansion of these technologies is typically much lower than that of the electrochemical batteries, except for batteries like VRFB which is benefitted from having decoupled power-energy properties. As the operating capacity of LDS would be too high to be charged with the current excess VRE generation in Indonesia, the charging cost of 3 cents/kWh assumption is applied.

As shown in Figure 25, CAES and PHS are the two ESS with the lowest LCOS at 20 cents/kWh and 35.5 cents/kWh, respectively. Even with the low RTE that makes the CAES charging cost almost double that of PHS, the low total investment cost of CAES drives down its LCOS. On the other hand, the 100-hour duration LDS batteries with the lowest LCOS is LIB-LFP at 158.4 cents/kWh, followed by VRFB with a difference of less than a cent. The current level of battery energy components costs is the reason for their high LCOS.

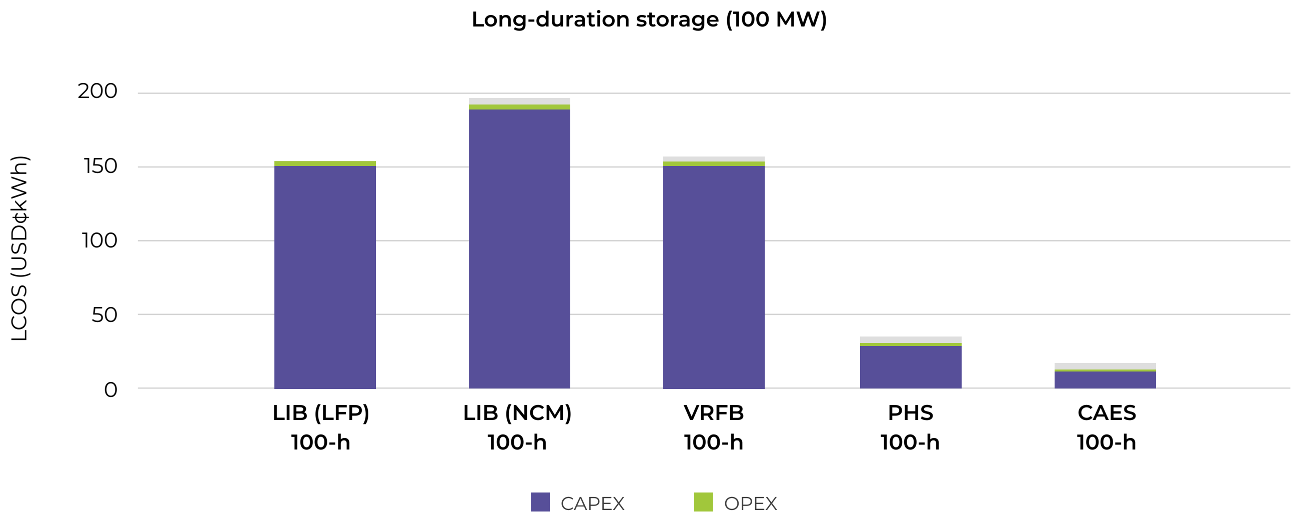


Figure 25. LCOS of various ESS for long-duration storage application

Similar to energy trade applications, the RTE is one of the technical parameters that significantly affect the LCOS value of LDS ESS. Among the options, the RTE of CAES is the lowest with 44%, resulting in the charging cost component contributing to 34% of its LCOS at the 3 cents/kWh rate. The sensitivity of CAES LCOS to changes in RTE is very high compared to other technologies, as shown in Figure 26. If technological advancements can somehow increase the RTE by 5%, the LCOS of CAES would decline by more than 10%.

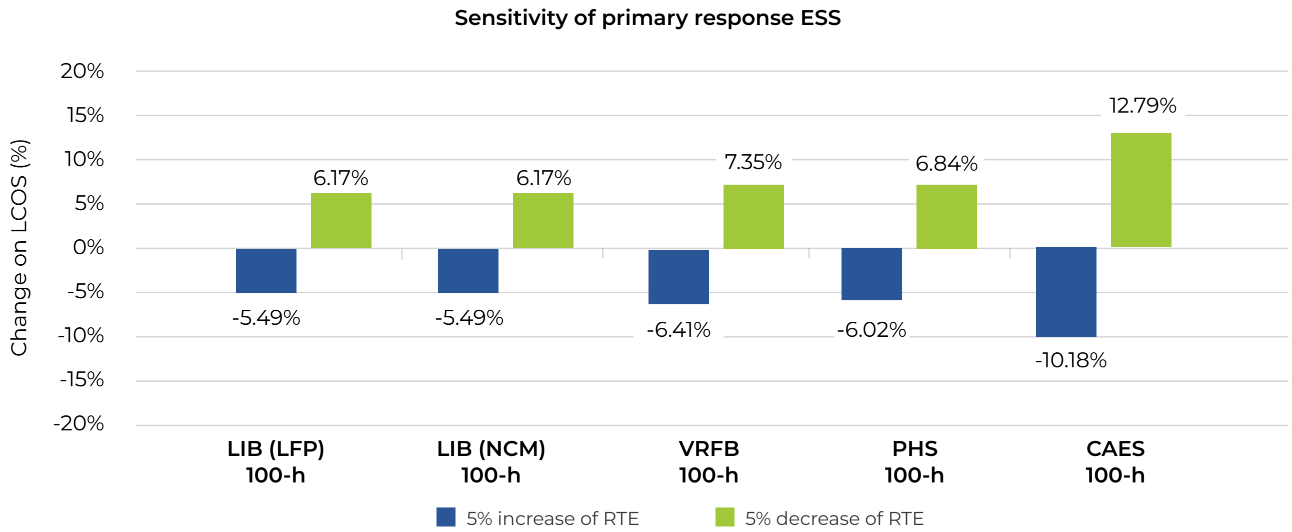


Figure 26. Sensitivity of long-duration storage application LCOS to the ESS round-trip efficiency. Sensitivity of power reliability application LCOS to the calendar life. The change values are compares to LCOS with default RTE: 44% (CAES), 73% (VRFB), 76% (PHS), and 86% (LIBs)

4 The Impact of Policies on the LCOE

4.1. Carbon Pricing and Abatement Measures

a) Carbon Pricing

Carbon pricing is a mechanism that captures the externalities of a process or activity, the greenhouse gas (GHG) emissions, and binds them to their sources through a price based on the carbon dioxide (CO_2) emitted. The implementation of carbon pricing is expected to encourage GHG emitters to reduce their carbon emissions activities with emissions abatement or low-carbon technologies. A penalty is subjected to those failing to maintain their emissions below certain limits. Therefore, the magnitude of carbon price could be a decisive factor that drives the transformation of major emitting sectors, such as industry, power plants, and transportation.

The Harmonization of Tax Law (Law No. 7/2021) indicates that carbon pricing for tax purposes and carbon trading will be fully implemented in 2025. The carbon cap and trade are already tested for the CFPP, whilst the carbon tax is set to be IDR 30,000/ton CO_2e ($2/tonne CO_2e, approximately) in 2023 and will be evaluated periodically. The stipulation of carbon pricing will undoubtedly affect the LCOE of fossil fuel power plants as the result of higher operational expenditure. However, the current emissions cap, ranging between 0.911 and 1.297 tCO_2eq/MWh, is close to the technical assumption of the maximum CO_2 emissions factor used in this report at 1.34 tCO_2eq/MWh. Thus, the quantity of carbon to be traded or later subjected to tax is relatively marginal compared to the total emissions.

With the price only at $2/t$CO_2$eq, the effect of internalizing carbon costs will cause an insignificant increase on the LCOE of CFPPs, which will increase around 0.13-0.24 cents/kWh, assuming the carbon cap to be zero, as shown in Figure 27. If the pricing level is further increased to $54, as referred from other G20 countries (Climate Transparency, 2021), the carbon price component could increase the LCOE, particularly the supercritical coal, close to twofold the baseline, making it higher than the national BPP and also competitive with rooftop PV. To use carbon pricing as one of the instruments in driving decarbonization, its pricing should therefore be adjusted to the agenda of low-carbon power plant technology development.

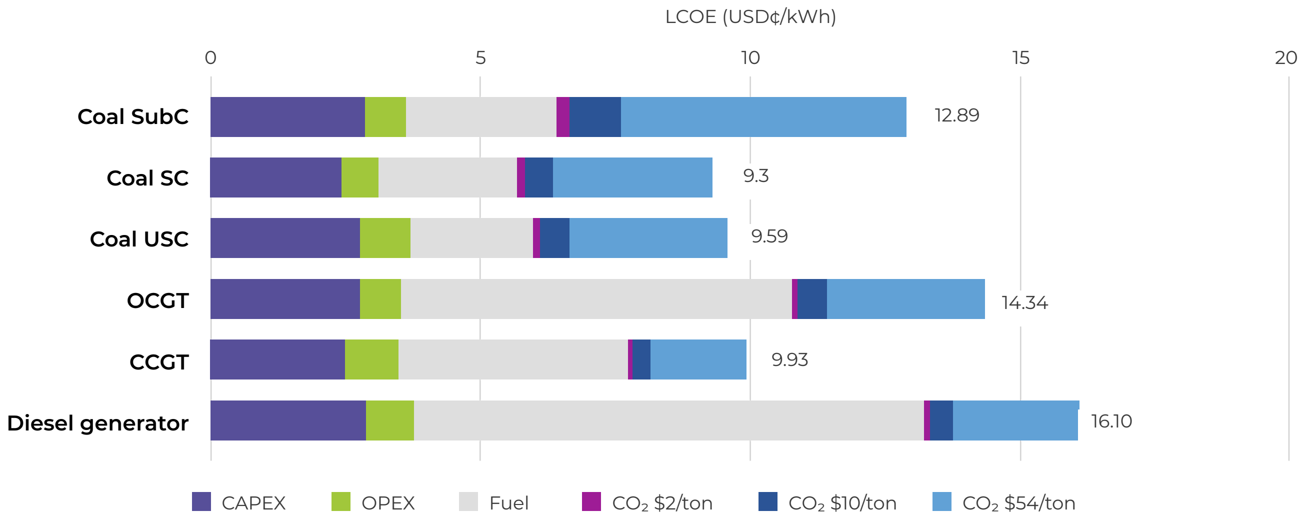


Figure 27. LCOE of various thermal power plants with CO_2 prices applied and emission cap is zero

b) Carbon Capture and Storage (CCS)

The use of carbon emissions control at power plants through the adoption of CCS technology might help Indonesia in pursuing the NDC target. It could also have an impact on the carbon cost reduction of fossil power plant units. Such technology will increase the CAPEX due to the additional investment needed for the CCS component at the start of the project. As shown in Figure 28, the LCOE of CCS-equipped supercritical CFPP with $54/t$CO_2$eq tax is 10.85 cents/kWh, which is 14% higher than its LCOE without CCS. Although CCS is expected to reduce up to 90% of the emissions, its installation would increase the investment cost for each kW of capacity to almost double. Moreover, installed CCS will incur additional O & M costs on the power plant; this auxiliary component also has an impact on reducing the system efficiency of power plants, hence increasing the fuel costs. Apart from being expensive, several deployed CCSs are also reported to be unable to meet the capture target (IEEFA, 2020).

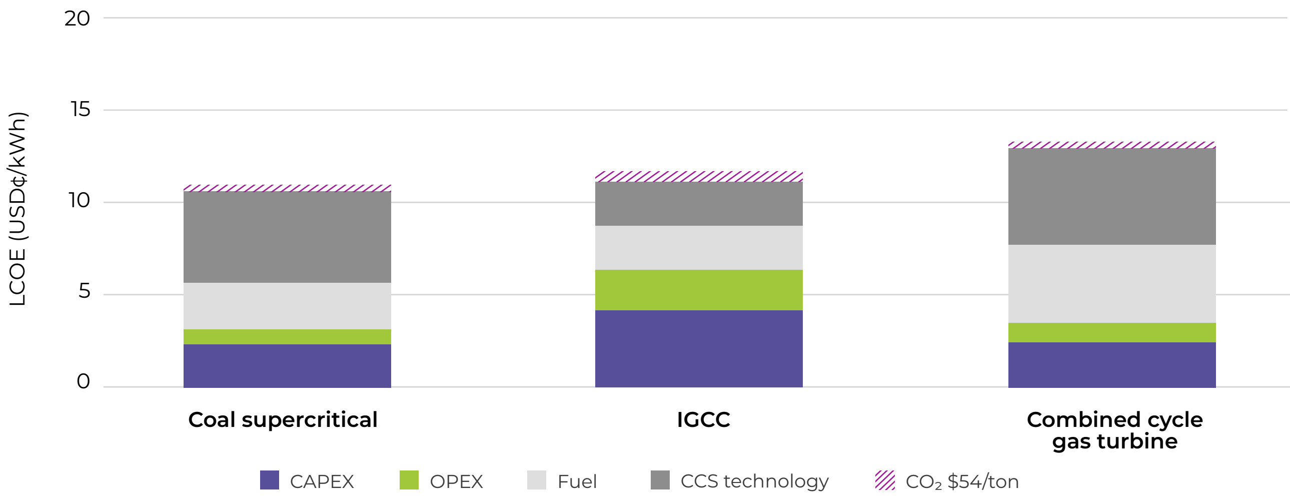


Figure 28. LCOE of various thermal power plants with CCS technology and CO2 prices applied

c) Co-Firing

In addition to the CCS solution, the current approach to reducing fossil fuel power plant emissions is by substituting fossil fuels with carbon-neutral fuels, i.e., biomass. In Indonesia, PLN has implemented a co-firing strategy for several of its CFFP units. The company has even developed a medium-long-term plan to increase the percentage of annual co-firing biomass mix to about 10% by 2025, with an estimated required biomass feedstock of 9 million tons per year (IESR, 2022c). PLN also envisions that co-firing could be a cheap solution to reduce CFPP emissions. However, it would require the availability of low-cost biomass feedstock that meets the requirements in terms of maximum moisture, calorific value, and minimum organic compositions for co-firing.

As mentioned previously in chapter 2.2.3a, this ceiling price is much lower than the global biomass feedstock prices, which could reach more than US$100/ton, e.g., wood chips and pellets can cost above $160/ton (Vu Dinh Thung, 2022). With a limited supply chain of biomass feedstock for the power sector, meeting co-firing targets will be a tough challenge. For example, this year, PLN has just confirmed the supply of 0.6 million tons of biomass feedstock to meet the target of 2.2 million tons by 2023 without detailing where it is or its sustainability (IESR, 2022c).

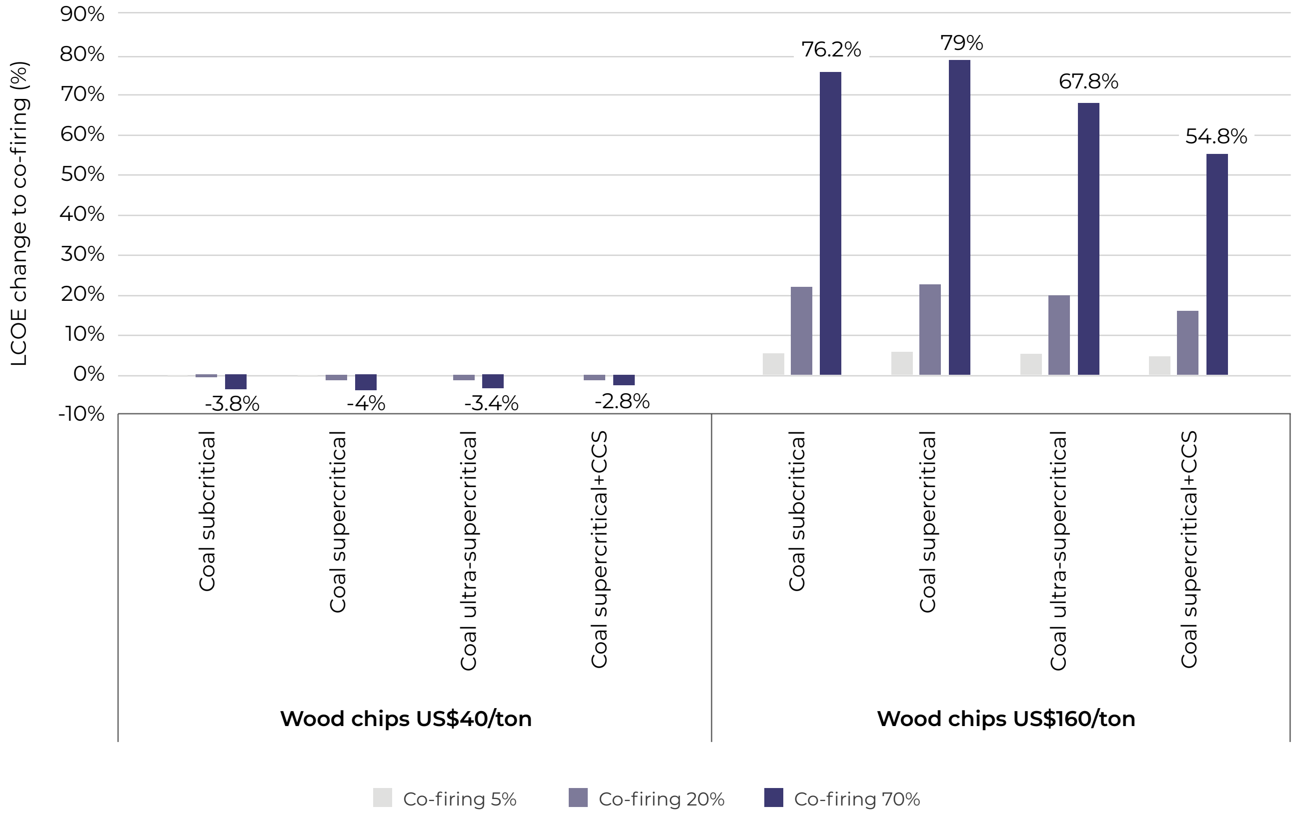


Figure 29. CFPPs LCOE sensitivity at different percentages of co-firing and different feedstock

Assuming the market price of wood chips is US$160 per ton, Figure 29 shows that the LCOE of CFPPs can increase by 3.9% to 79% from the baseline CFPPs, depending on the type of technology and the percentage of co-firing. Meanwhile, when the feedstock that costs well below the coal price is used, the LCOE reduction is around 0.2% to 4%. The LCOE of supercritical coal is the most sensitive to the implementation of co-firing because its CAPEX component contributes the smallest to its LCOE compared to other coal generation technologies. The results indicate that the potential cost savings from the implementation of co-firing are relatively small, while the unavailability of cheap feedstock could significantly increase the generation cost.

Besides ensuring low-cost feedstock availability, the implementation plan for co-firing should also consider carbon pricing, and vice versa, to manage the value of LCOE. If carbon pricing is set at US$54/ tCO_2eq (Figure 30), supercritical and ultra-supercritical coal would be economical when 70% co-firing with low-cost biomass is feasible. Otherwise, the inability to synchronize the co-firing development with carbon price changes (which can be market-driven) makes the co-firing strategy economically ineffective.

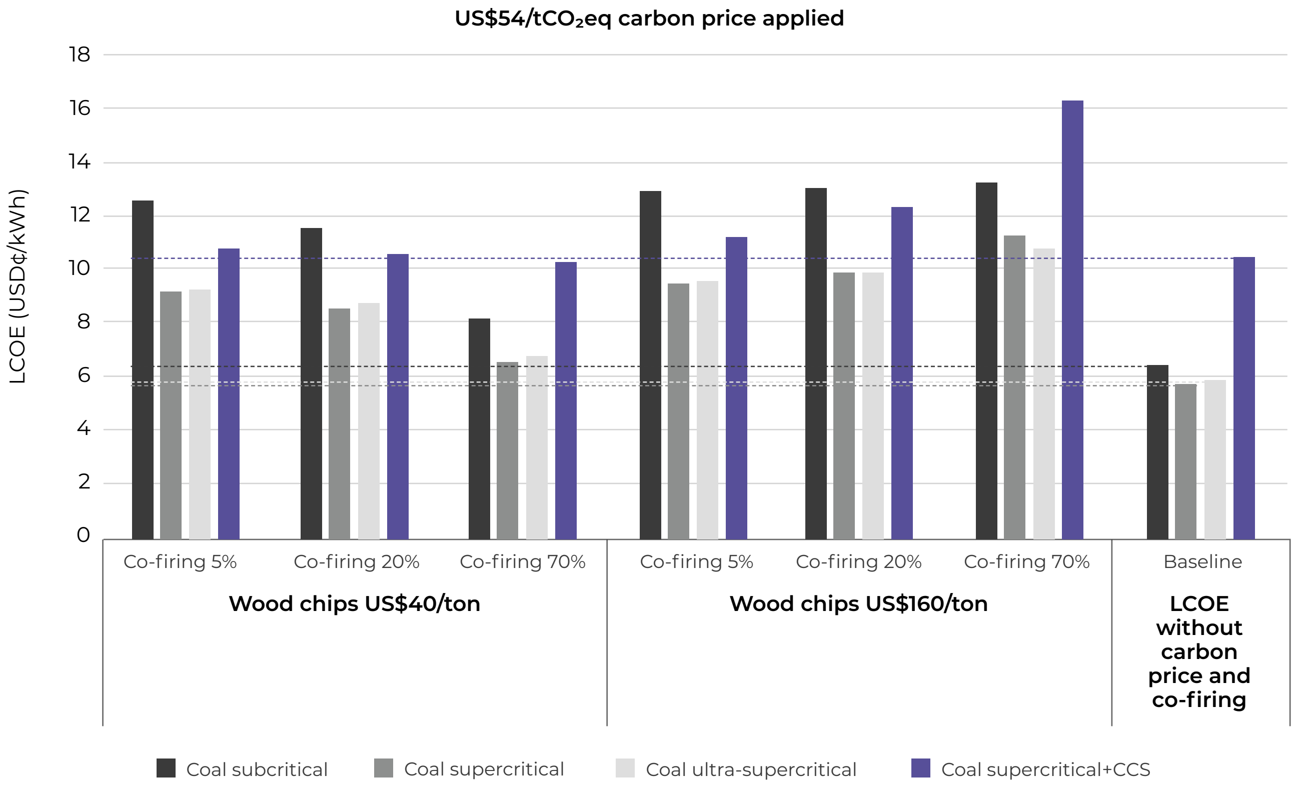


Figure 30. CFPPs LCOE at different percentage of co-firing with applied carbon price of US$54/t$CO_2$eq

4.2. Domestic Market Obligation (DMO) of Coal

A DMO policy with a specific ceiling price for coal fuel is used to maintain the security of supply for CFPP in the power sector as well as to keep the generation costs low to provide affordable electricity. The latest policy that regulates the fulfillment of domestic coal needs is the Minister of Energy and Mineral Resources Decree No.139.K/HK.02/MEM.B/2021, which states that coal mining industries must sell coal domestically at a minimum of 25% of their planned annual production. The regulation also set the coal cap price at US$70/ton of coal with certain specifications and used for electricity generation that serves the general public. Yet, the implementation of the DMO regulations caused problems due to the volatility of the coal price in the market. When the market price of coal is above US$70/ton, historically, many companies have been reluctant to commit to DMO (TEMPO, 2022), and government had to put an abrupt stop on coal export due to the shortage of domestic supply.

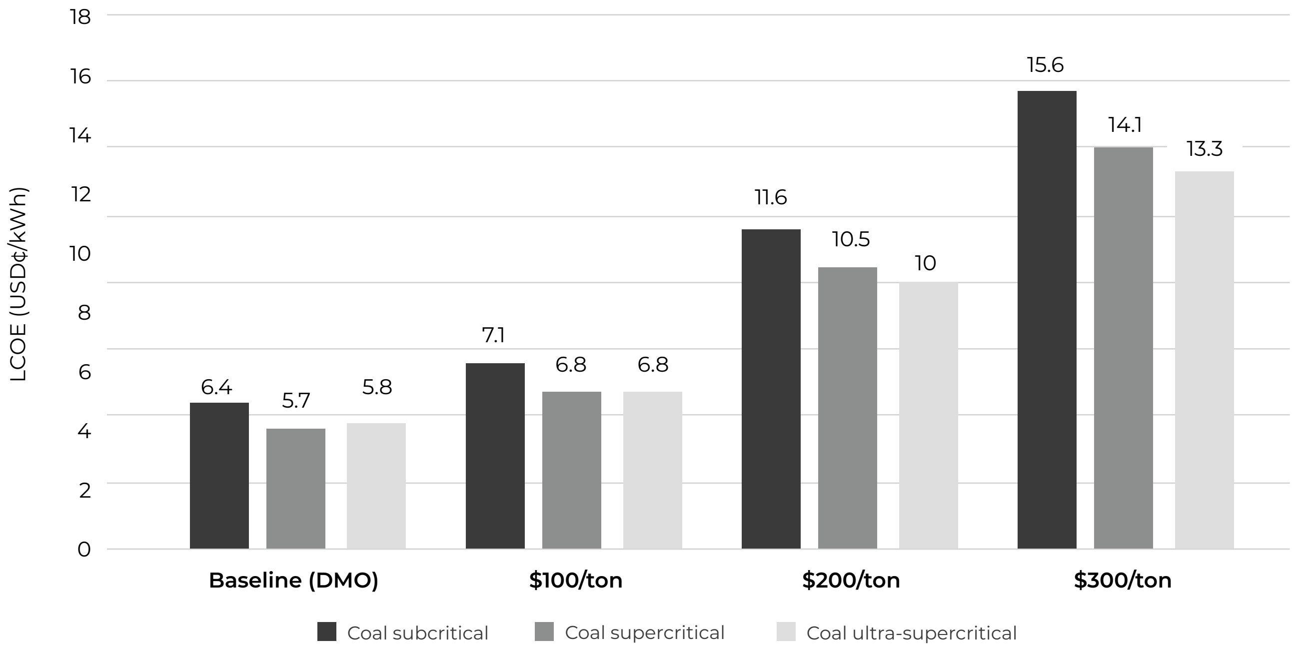


Figure 31. The LCOE of CFPPs with different price of coal

The LCOE of CFPPs would almost triple the baseline without the DMO regulation if the recent coal price around US$300/ton were applied. To illustrate the magnitude of CFPPs' LCOE dependency on the coal price, the LCOEs of several types of CFPPs are compared, as shown in Figure 31. This measure has indeed made coal electricity generation cheap in Indonesia, but in the long run, the cost is borned by the citizens. Its generation cost is often considered a benchmark for renewable energy generation's competitiveness. CFPP's large contribution to the electricity system is driving the national BPP close to its LCOE, which is relatively low. As a result, it is difficult for renewables developers to meet the reference price set for low-emission power plants, thereby causing the slow growth of renewables in Indonesia and becoming a hurdle to reaching NZE's ambition.

4.3. Local Content Requirements (LCR) on Solar PV

Apart from the difficulty of competing with 'subsidized' thermal power plants, the development of renewable power plants in Indonesia faces several boundaries, one of which is the LCR regulation. As renewables are still a fairly new technology in Indonesia, there is not yet a good supply chain in place. For example, Indonesia's solar PV industry has only been able to assemble PV modules with parts brought in from other countries. Meanwhile, the development of solar PV projects now requires the use of domestic services and components with an LCR value of up to 45.9%, whereas for the PV module, the LCR reaches 40% (IESR, 2022d). PV module manufacturers in Indonesia have been able to fulfill these requirements. Unfortunately, domestic modules still cannot compete with imported modules in terms of price, quality (i.e., how well they work), and how easy they are to finance. The price of domestic modules is at least 30% more expensive than foreign modules (IESR, 2022a). As a result, the investment cost for developing solar PV is higher and increases the solar PV LCOE.

Figure 32 shows that the LCOE of solar PV will go up by about 8% from the baseline if solar PV modules make up 40% of the total investment cost, and the price goes up by 30% if they are made in the country. Moreover, domestic PV modules are considered not yet bankable, affecting high interest rates. In Indonesia, no PV module manufacturer obtained a tier-1predicate, which requires several conditions to be met, such as the PV module must be used for six projects with capacities above 1.5 MW funded by six different banks (BloombergNEF, 2020). From the point of view of domestic module manufacturers, it is difficult for them to meet the demand because the demand is still low, which means that the development of domestic manufacturing is currently in a negative cycle.

Government intervention is needed to induce domestic demand for solar PV installation through competitive LCOE with CFPPs and overcome the LCR challenge. An example of an effort that can be done is through the viability gap fund (VGF) policy. The VGF should be considered because renewable projects can help government programs reach their emission reduction goals and grow domestic industries. The VGF support is regulated under the Ministry of Finance Regulation No. 143/PMK.011/2013 and is given in the form of a construction grant for an infrastructure project, which is a form of VGF known as a capital grant scheme. The alternative, as well as the second form of VGF, is an equity financing scheme. Compared to the earlier scheme, the equity financing scheme requires less capital and gives a return over the lifecycle of the project. In the second scheme, the government may take the equity with a lower expected return. In the case of solar PV projects, VGF equity financing will significantly help developers, considering the high sensitivity of the cost of investment (i.e., WACC) for solar PV projects, as discussed in Section 3.2.3, and the tendency for higher interest rates in projects with LCR modules.

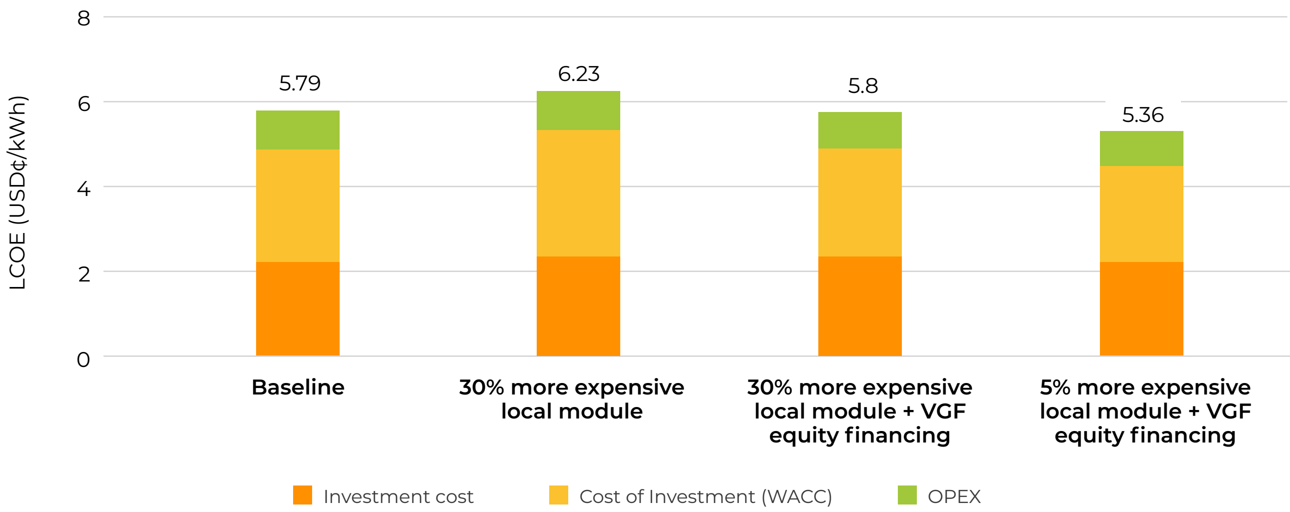


Figure 32. LCR and incentive impact on utility scale PV LCOE

Providing VGF to solar PV projects with a local module that is 30% more expensive can make the LCOE offset the baseline LCOE of solar PV, as shown in Figure 32. The total investment cost of the more expensive "LCR" solar PV project is $884/kW. Meanwhile, the WACC with VGF is 8.82%, which can be obtained if the government takes 50% of equity from a 30:70 equity-debt ratio (10% cost of debt and 25% tax rate) on the one hand. On the other hand, the development of the PV module supply chain is expected to make domestic PV module prices competitive. The IEA indicates that the cost of producing PV modules in ASEAN countries is potentially only 5% higher than that of modules manufactured in China (IEA, 2022c). If solar PV module costs increase by 5% from the baseline and VGF equity financing is provided, the LCOE of solar PV would fall to 5.36 cents/kWh, lower than CFPPs.

It is important to note that under LCR regulations, incentives for developing projects like VGF should be combined with incentives for improving solar PV components. This is because the use of domestic components of low quality would not provide a performance guarantee that would convince the financier to fund the project, regardless of whether the VGF is given. The LCOE reduction scenario in Figure 32 cannot happen unless the necessary condition is met, which is the availability of high-quality domestic solar PV components. Hence, incentives to improve the quality of domestic products are also an important factor to increase the competitiveness of solar PV LCOE with the stipulated LCR regulations.

4.4. VRE Integration Requirement

One of the challenges to increasing the share of renewable energy in power systems is the cost of variability integration which could be higher than the cost of renewable technologies themselves, which are needed because VREs' intermittency may disrupt system stability. There are different types of integrators, but in this discussion, the evaluation of the integrator costs is represented by the LCOS of BESS, which can be added directly to the LCOE of VRE (i.e., solar PV).

According to the grid code (MEMR Regulation 20/2020), the storage requirement for utility VRE installations is 10% of the capacity of VRE power plants. In such a requirement, the type of utilization of BESS would be primary or secondary response applications because other applications, such as load/generation shifting, typically need high capacity or longer discharge duration storage. The requirement in the grid code is currently reasonable for the current low VRE penetration level in Indonesia. However, with the future high VRE share to reach decarbonized power systems, updating the grid code is necessary because, on a system with high VRE, BESS can have a role in optimizing VRE generation (reducing curtailment and load shifting).

The LCOE of solar PV equipped with BESS is still higher by about 5% compared to the national BPP in Indonesia (7.05 cents/kWh), as shown in Figure 33. The solar PV LCOE addition (from 10% of BESS LCOS) is based on BESS with 1000 annual cycles and a 1-hour E/P ratio configuration LIB-LFP. Nonetheless, for the PV+ battery LCOE for the on-grid system, the cost contribution of the battery is relatively small, around 21.6%.

In an off-grid system, however, the BESS takes more than 77% of the LCOE system because the system is assumed to entirely relies on a PV + battery alone. BESS in the off-grid system needs to have a long storage duration, and the calculation result (Figure 33) is based on the 10 MW/100 MWh LIB-LFP type BESS with a discharge duration of 10 hours cycled 365 times/year. It should be noted that the BESS duration requirement will vary depending on the system's specific profile. In a hypothetical system with 10 MW solar PV, the 100 MWh capacity (10 hours duration) should be able to provide 2 days of autonomy (the period that the energy can supply the site's loads without any support from generation sources). This prediction is based on a 46 MWh ideal daily output of 10 MW solar PV with a 19% capacity factor.

The resulting LCOE of a PV + battery is unsurprisingly almost twice that of the diesel generator reference LCOE of 13.2 cents/kWh. However, it should be noted that in real applications, the generation cost of diesel generators could be higher, mainly due to the volatility of diesel fuel prices and also fuel transportation costs. In other words, the actual fuel cost is much higher than the reference of 0.45 cents/kWh (PLN, 2021). Therefore, the LCOE of low-emission systems might have been competitive at the particular sites.

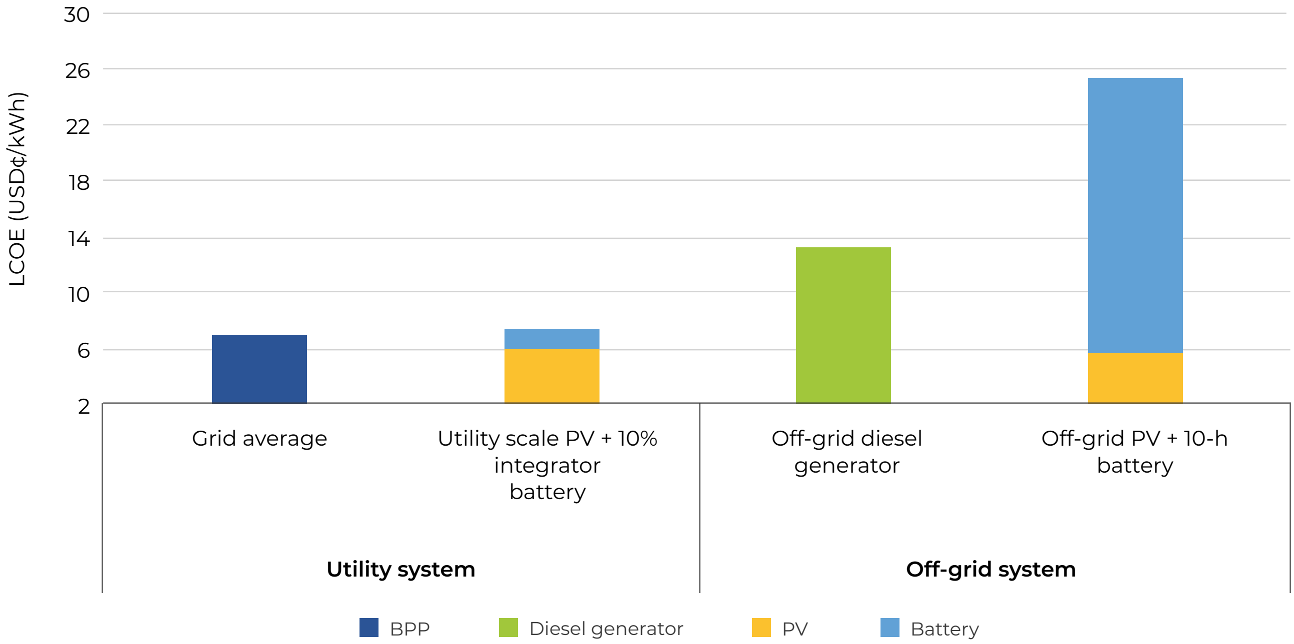


Figure 33. LCOE comparison between thermal power plants and renewables for on-grid and off-grid system

The reduction in the investment cost of BESS (US$/kW) will have a very significant impact on its LCOS, as shown in Figure 34, which shows changes in the LCOS of different BESS technologies on a scale of 10 MW/100 MWh. The LCOS value of LIB-LFP could fall to 10.03 cents/kWh when the investment cost drops by half from the current assumption. Therefore, the BESS ecosystem and industry should be established to make the price of the equipment that makes up the investment cost cheaper. The domestic demand for BESS is huge, with a projected BESS requirement of at least 56 GW of power capacity by 2060. Notably, the supply chain would be different with batteries for EVs, which are being intensively cultivated in Indonesia recently, because BESS consists of different types of components (e.g., battery packing, battery management system (BMS), and balance of system (BoS)) (IESR, 2022c).

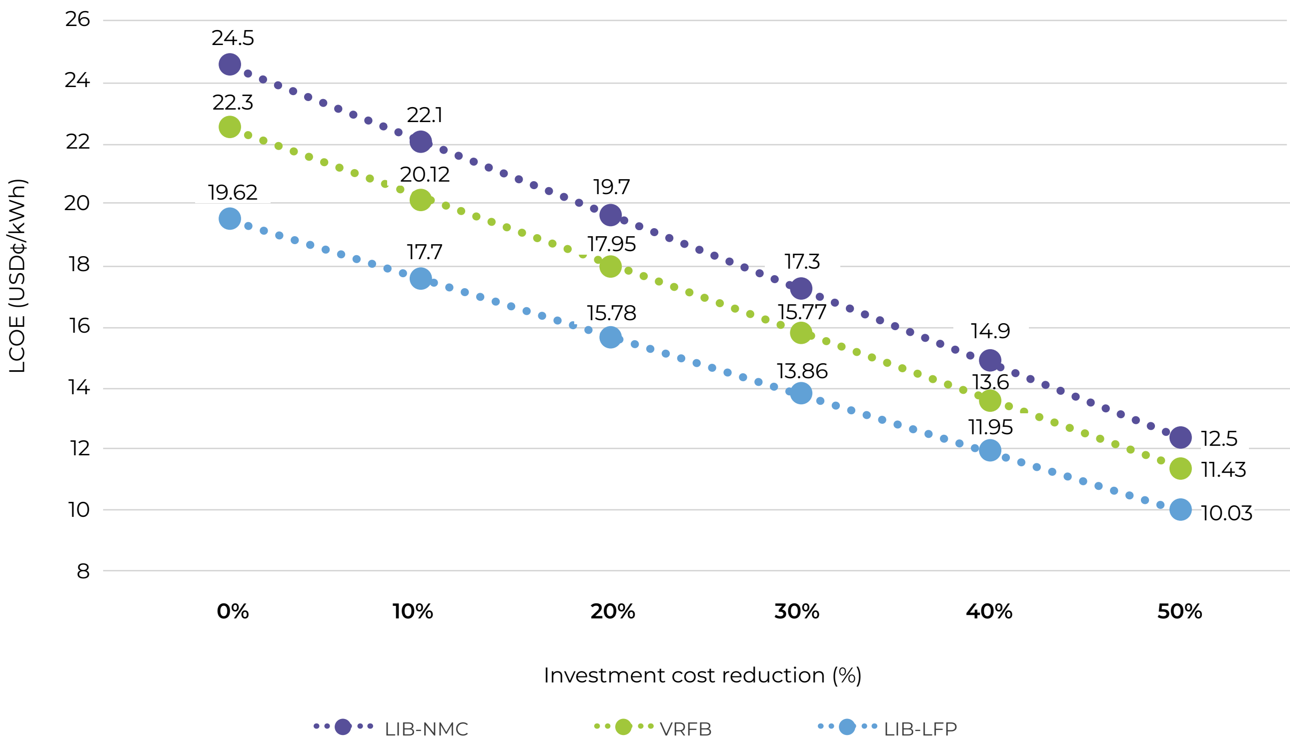


Figure 34. LCOS reduction of different BESS (10 MW/100 MWh) for off-grid application with the decline of investment cost

5 Key Takeaways

5.1. Summary

1. **The generation costs of conventional thermal power plants are expected to be no longer competitive in the future.** To date, they are still the least cost options, represented by the LCOE value of supercritical coal CFPP at 5.7 cents/kWh. However, these matured technologies potentially become more expensive due to the potential increase in fuel prices and the impact from more stringent policy for GHG emission reduction. The fuel cost component (cents/kWh) is inarguably the greatest contributor to the LCOE structure of existing thermal power plants, except for CFPPs where the price of coal is preserved much below the market price through the coal DMO price cap. Otherwise, their LCOE would be less content.

2. **The increased global capacity of renewables, particularly solar PV and wind, is align with the decline of the technology cost and target to meet net zero.** It is demonstrated by the low-end LCOE value of solar PV and wind at around 4 cents/kWh. The continuing technical improvement efforts and increasing economies of scale are expected to drive down their LCOE value further. For most renewables, the CAPEX component makes up a high share of the LCOE structure in the absence of the fuel cost component. Thus, the WACC becomes important. The high WACC value will escalate their LCOE values. Meanwhile, low-cost feedstock supply uncertainty for biomass power plants may force the use of alternative or import feedstocks that will dramatically increase their LCOE.

3. **ESS can have various roles in a power system with different storage costs.** Among candidates with competitive investment cost (US$/kW), an ESS with characteristics that fulfill the technical requirements and suit a peculiar application's operational parameters will have the lowest LCOE value. Flywheels is the least-cost option for an application that requires more than 8,500 cycles/year (i.e., primary response). For applications that require moderate annual cycle and duration (i.e., secondary response and peaker replacement), the choices are between batteries and PHS. Meanwhile, PHS and CAES are superior in applications with a duration longer than 10 hours, except for power reliability applications that mandate distributed energy storage systems (i.e., BESS). In this regard, LIB-LFP is currently the least-cost BESS option.

4. **Carbon pricing can be a powerful instrument to manage and reduce GHG in the power sector.** However, the currently stipulated emission cap between 0.911 and 1.297 tCO_2eq/MWh is not much different from the technical assumption of the maximum CO_2 emission factor (in this report). Hence, the quantity of carbon traded or later taxed is still relatively very small. The CO_2 cost component in LCOE structure for tax is negligible with the current cap and carbon price ($2/$tCO_2eq$). Even if the carbon price is applied to the actual CO_2 emitted (without cap), the LCOE of CFPPs would only increase around 0.13 to 0.24 cents/kWh.

5. **CO_2 abatement strategies could result in a significant increase in fossil power plants' LCOEs.** The LCOE increase due to the installation of CCS technology is between 27% to 84%. Several installed CCSs are also reported to be unable to meet the capture target, raising the question of whether CCS is the right solution for reducing CO_2 emissions. On the other hand, biomass co-firing would be a more affordable strategy to cut GHG emissions from coal burning than CCS if the biomass feedstock can be obtained under the regulated price. However, there is a concern regarding the availability of low-cost feedstock supply. It is found that the LCOE of CFPPs can increase between 3.9% to 79%, depending on the type of technology and the percentage of co-firing, when feedstock at a global market price is used.

6. **Solar PV is facing unfair competition from CFPPs.** The CFPPs' electricity would not be cheap without DMO that cap the coal price for the power sector at US$70/ton. Meanwhile, the average reference price of coal in the past two years was around US$216/ton, which peaked at over US$320/

ton in 2022. At a coal price of US$300/ton the LCOE of CFPPs (subcritical, supercritical, and ultra-supercritical coals) would increase by 130% to 144%. The LCR requirement hampers the development of solar PV projects in terms of competitiveness against CFPPs. Domestic solar PV modules are still unable to compete with imported modules in terms of price, quality (i.e., sizing and efficiency), and bankability, thus naturally increasing the LCOE of solar PV. In utility-scale solar PV projects in which more expensive domestic modules are used, the LCOE would increase by at least 8%. The figure potentially becomes higher given bankability issues that may increase the cost of capital (i.e., WACC).

7. **The cost of ESS as the VREs integrator drives the LCOE value of PV + battery higher than that of the existing systems.** Although the battery cost for grid-tied solar PV installation is low, the LCOE (PV + battery) is 21.6% higher than the national BPP of 7.05 cents/kWh. In off-grid that naturally requires higher capacity ESS, estimated LCOE of a PV + battery is almost twice that of the reference LCOE of a diesel generator of 13.2 cents/kWh. The investment cost reduction of ESS, through the use of lower-cost equipment, will be the key to minimizing the gap.

5.1. Recommendations

1. **Formulate the utilization strategy of carbon pricing, CCS, and co-firing that aligns with Indonesia's decarbonization target.** Carbon pricing can be used as an instrument to control emissions from GHG emitters as well as drive transitions through the development of renewable power plants. The revenues from carbon tax levied on fossil generators can be used to incentivize the development of renewables. To make a significant impact, however, the cap for carbon pricing must be low, even close to zero, while the carbon price should be high. When the carbon price is US$ 54/ tCO_2eq, for example, LCOE rooftop solar PV can be competitive with CFPPs. CCS should be considered a last-ditch effort. CCS can directly reduce GHG emissions, but the additional costs for its installation, based on the current CCS technology cost, will make power plants' LCOE uneconomical. In the case of co-firing, biomass feedstock should be available at a low cost to align with the NZE plan, otherwise, co-firing will not be a cost-efficient measure. It must be noted that biomass feedstock availability must be considered as a crucial issue beforehand. Constructive collaborations of stakeholders in Indonesia to downstream biomass products are required to ensure feedstock sustainability.

2. **Evaluate the renewables deployment bottlenecks and provide more impactful incentives.** Facilitating projects with low financing costs should be one of the solutions to increase renewables competitiveness, given the high sensitivity of WACC to the LCOE of renewables. However, other major roadblocks, specifically, must be addressed. For instance, an incentive such as the land provision would expedite project development, especially for renewables with sizable space requirements (e.g., solar PV and hydropower plants). In the case of solar PV, the LCR regulation should be discussed further since Indonesia is still establishing demand to set up production facilities of tier- solar PV modules. LCR is currently making solar PV project financing difficult due to the high price of domestic modules that are also not yet bankable, meanwhile, the domestic industry will not grow without sufficient demand.

3. **Prepare the regulations and development roadmap of ESS to welcome high penetration of VREs in the future power system.** Currently, the quantity (in terms of power and energy capacity) of required ESS and its potential roles in the power system has yet to be specified. Meanwhile, the high cost of ESS, particularly BESS, is often used as an excuse for slow VRE penetration. The intention to adopt ESS should be articulated with the ESS development roadmap, pilot project initiatives, and readiness of regulatory framework, which could create prospective demand that attracts investors, technology providers, and developers to supply new technologies and establish an ESS supply chain and drive down the ESS cost, consequently.

Initially, stakeholders of power systems, especially PLN and MEMR, need to evaluate the grid conditions to determine the potential roles of ESS in the short to long-term grid development plans. Simultaneously, the government needs to prepare regulations related to ESS, such as standardizing various types of technology, and rules for installation and operation, which may require updating the grid code to accommodate ESS.

As the largest utility company, PLN should initiate several pilot projects that use ESS with different technologies to find the best practice, the most suitable technology, and how to operate it according to the needs of the utility system. Besides VRE integration (on-grid and off-grid) purposes, ESS can be used for several roles in utility systems to increase the stability of the existing system, such as frequency regulation, peak shaving and load leveling, black start, system upgrade deferral, etc. Moreover, PLN should also consider using VRE + ESS plants to replace peaker gas power plants to reduce reliance on fossil energy. Regardless, business cases for BESS deployment are necessary to create rapid demand in BESS aligned with the development of the battery industry. For example, the government could incentivize the application of BESS with rooftop PV, which could also reduce the impact of rooftop solar PV on the PLN's grid, allowing more installation of rooftop solar PV.

Appendix

1. LCOE Calculation

a) Formula

$$LCOE_{Annuitizing} = \frac{Annual\ (Cost)}{Annual\ (Output)}$$

$$= \frac{(Annual\ CAPEX + Annual\ OPEX + Annual\ Fuel\ Cost)}{Annual\ (Output)}$$

$$= \frac{(CRF * C_t + (Annual\ Fixed\ O\ \&\ M + Variable\ O\ \&\ M\ Cost * Annual\ Output) + Fuel\ Cost * Annual\ Output)}{Output\ over\ lifetime \div Years\ of\ lifetime}$$

$$Capital\ recovery\ factor\ (CRF) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

i = interest rate (or WACC)

n = number of annuities (or project lifetime)

C_t = Total investment (or total capital cost)

Equation 1. LCOE Formula

b) Financial Parameters

Table appendix 1. Financial parameters of calculated LCOE

Type	Technology	Financial parameters												LCOE (USDcent/kWh)			Note
		Investment cost ($/kW)			Fix O & M ($/kW/year)			Var O & M ($/MWh)			Fuel cost ($/MWhtherm)						
		Low	Rec.	High	Low	Rec.	High	Low	Rec.	High	Low	Rec.	High	Low	Rec.	High	
Fossil power plants	Coal SubC	1000	1650	1700	34	45.3	56.6	0.09	0.13	0.16	9.52	9.53	20.41	4.7	6.41	11.85	1,2
	Coal SC	1050	1400	1750	30.9	41.2	51.5	0.09	0.12	0.15	9.53	9.53	20.41	4.54	5.68	11.01	1,2
	Coal USC	1140	1520	1910	42.5	56.6	70.8	0.08	0.11	0.14	9.53	9.53	20.41	4.59	5.83	10.65	1,2
	IGCC	2160	2400	3500	56.1	60	68.4	7.9	12	15	9.52	9.53	20.41	7.82	8.71	13.77	1,2
	OCGT	650	770	1200	17.4	23.2	29	0.11	0.11	0.11	20.47	23.9	27.3	9.12	10.78	13.54	1,2
	CCGT	650	690	1000	17.6	23.5	29.4	1.73	2.3	2.88	20.47	23.9	27.3	5.5	7.74	12.19	1,2
	Diesel Generator	700	800	900	8	8	8	6.4	6.4	6.4	42.5	42.5	141.77	12.46	13.22	37.1	1,2
Non-fossil power plants	Biomass Agricultural	1300	2000	2250	35.7	47.6	59.5	2.3	3	3.8	3.03	8.34	33.26	3.29	6.39	19.04	1,3
	MSW Incineration	5100	6800	7000	195	243.7	304.6	18.1	24.1	30.2	5.88	5.88	5.88	13.37	17.1	22.83	1,3
	Geothermal Large	2700	4000	5750	37.5	50	62.5	0.19	0.25	0.31	0	0	0	3.56	6.79	12.06	1
	Geothermal Small	3800	5000	6300	48.8	65	81.3	0.28	0.37	0.46	0	0	0	4.96	8.53	13.44	1
	Hydropower Large	1650	2080	2250	28.3	37.7	47.1	0.49	0.65	0.81	0	0	0	2.37	7.91	15.9	1
	Hydropower Medium	1400	2290	5200	22	41.9	41.9	0.38	0.5	0.63	0	0	0	1.98	4.15	13.16	1
	Hydropower Mini/Micro	1200	2700	4000	39.8	53	66.3	0.38	0.5	0.63	0	0	0	1.96	4.94	10.92	1
	Tidal Impoundment	2900	5500	7500	23.4	70.8	72	0	0	0	0	0	0	8.94	20.65	28.3	1
	Tidal Stream	3000	5300	7100	93	283	412	12	12	12	0	0	0	12.94	31.19	44.3	1
	Solar PV Utility Scale	700	790	1200	10.8	14.4	18	0	0	0	0	0	0	4.09	5.79	10.09	1
	Solar PV Industrial	1050	1190	1800	10.8	14.4	18	0	0	0	0	0	0	6.13	9.38	17.64	1
	Solar PV Rooftop	1150	1320	2000	10.8	14.4	18	0	0	0	0	0	0	6.37	9.76	16	1
	Solar PV Floating	830	890	1430	12.2	16.2	20.3	0	0	0	0	0	0	5.04	6.21	14.5	1
	Wind - Onshore	1200	1500	2350	30	60	70	0	0	0	0	0	0	3.92	8.36	18.77	1
	Wind - Offshore	2400	3500	3700	58.2	72.6	78.2	3.4	5.5	5.8	0	0	0	7.35	11.31	29.85	1
	Nuclear	2800	4300	6100	-	-	-	9.7	17.5	26.4	5	9.5	13.9	6.06	10.34	15.89	4,5

Notes:

1. Investment cost, fixed O & M, and variable O & M costs are based on the Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021). The report did not include the land-use and pre-development costs. The investment costs presented here are before accounting for 10% of WACC of LCOE calculations.
2. For CFPPs, low-end and recommended fuel cost assumptions are derived from the reference price stated in the RUPTL 2021-2030 of US$70 per ton for coal with a calorific value of 6,322 kcal/kg. The assumption of a high-end fuel cost of US$150 per ton is used to represent the moderate market price of coal which is above the cap price. For OCGT and CCGT, fuel costs are obtained from the natural gas price assumed in RUPTL between US$6 to US$8/MMBtu. Low-end and recommended fuel costs of diesel generators are derived from RUPTL assumption on high speed diesel (HSD) price of US$ 0.45/L. Meanwhile, high-end fuel cost is based on the domesticHSD fuel price of US$1.5/L in March 2023. To calculate LCOE, the price of each fuel is converted to US$/MWh units.
3. Agricultural biomass fuel costs are obtained from interviews that were previously reported in Indonesia Energy Transition Outlook 2023 (IESR, 2022c). The recommended LCOE fuel cost assumption uses feedstock prices, transportation, and costs for processing feedstocks. In contrast, only the costs for transportation and processing of feedstocks are calculated for the low-end LCOE. The price of fuel from the MSW power plant is obtained from various references, based on the price of refuse-derived fuel and its transportation with a total cost of US$27 per tonne (IPEN, 2022; Prihandoko et al., 2022; Ummatin et al., 2018).
4. The investment costs of nuclear power plants are obtained from the World Energy Outlook (IEA, 2022b). The recommended investment cost is the average value between the lowest and the highest reported investment cost.
5. The O & M and fuel costs of nuclear power plants are obtained from the Projected Costs of Generating Electricity (IEA, 2020). The recommended O & M and fuel costs are derived from averaging the lowest and the highest value of the corresponding costs, respectively.

b) Technical Parameters

Table appendix 2. Technical parameters of calculated LCOE

Type	Technology	Technical parameters												Plant size (MWe)			Note
		Technical lifetime (years)			Fuel efficiency (%)			Capacity factor (%)			CO_2 emission factor (tCO_2/GWh)						
		Low	Rec.	High	Low	Rec.	High	Low	Rec.	High	Low	Rec.	High	Low	Rec.	High	
Fossil power plants	Coal SubC	40	30	25	37	34	29	73.6	70	58	880	1200	1340	200	150	100	1,3,6
	Coal SC	40	30	25	40	37	33	73.6	70	58	670	670	940	800	600	300	1,3,6
	Coal USC	40	30	25	45	42	40	73.6	70	58	670	670	860	1200	1000	700	1,3,6
	IGCC	30	30	30	40	40	40	70	70	70	741.75	757	817		150-200		1,2,4,,6
	OCGT	25	25	25	33	33	33	35	35	35	540	540	706	65	50	35	1,2,4,6
	CCGT	30	25	20	61	56	39	50	35	34.2	349	404	493	800	600	200	1,2,6
	Diesel Generator	25	25	25	47	45	43	35	35	35	533	533	533		20		1,2,4,6
Non-fossil power plants	Biomass Agricultural	31	25	19	35	31	25	90	90	70	-	-		50	25	1	1,2,,6
	MSW Incineration	25	25	25	30	28	26	90	90	70	-	-			22		1,2,6
	Geothermal Large	50	30	20	30	15	5	100	80	70	-	-		500	110	30	1,2,6
	Geothermal Small	50	30	20	12	10	6	100	80	70	-	-		30	20	5	1,2,6
	Hydropower Large	90	50	40	97	95	85	95	36	20	-	-		2000	150	100	1,2,6
	Hydropower Medium	90	50	40	97	95	85	95	76	50	-	-		100	50	20	1,2,6
	Hydropower Mini/Micro	90	50	40	90	80	70	95	76	50	-	-		10	5	1	1,2,6
	Tidal Impoundment	120	40	30	95	90	85	40	35	35	-	-		300	30	10	1,2,6
	Tidal Stream	30	25	20	97	90	87	40	33	33	-	-		400	10	1	1,2,6
	Solar PV Utility Scale	40	35	25	-	-	-	23	19	17	-	-			10		1,2,6
	Solar PV Industrial	40	25	25	-	-	-	22	17.7	14	-	-			0.1		1,2,6
	Solar PV Rooftop	40	35	25	-	-	-	23	17.7	17	-	-			0.005		1,2,6
	Solar PV Floating	40	25	25	-	-	-	22	21	14	-	-			10		1,2,6
	Wind - Onshore	35	27	25	-	-	-	45	34	20	-	-			70		1,2,6
	Wind - Offshore	35	27	20	-	-	-	50	47.9	20	-	-			240		1,2,6
	Nuclear	60	60	60	38	34	32	85	85	85	-	-			-		5

Notes:

1. Technical lifetime and power plants scale are based on the Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021)
2. Fuel efficiency and capacity factor are based on the Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021)
3. CF for high-end LCOE calculation of CFPPs are based on the Scaling Up Solar in Indonesia: Reform and Opportunity report (BloombergNEF & IESR, 2021). Recommended CF is an assumption from Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021). Meanwhile, CF for CFPPs low-end LCOE are derived from RUPTL 2021-2030 by comparing the annual electricity production (TWh) and installed capacity of CFPPs.
4. Low and high efficiency of the technologies are assumed equivalent to the recommended efficiency value and based on Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021).
5. Technical parameters of nuclear power plants are based on the Projected Costs of Generating Electricity (IEA, 2020).
6. The value of power plant size is not calculated in the LCOE calculation but rather to give an idea of how large the typical scale of a power plant is.

d) CCS and Co-firing

Table appendix 3. Parameters of CCS and Co-firing

Type	Technology	Financial parameters						Note
		Fuel efficiency impact (%)	Resulting CO_2 emission (tCO_2/GWh)	Resulting fuel cost (USD/ MWh)	Additional fixed O & M ($/kW/year)	Additional var O & M ($/MWh)	Additional investment Cost ($/kW)	
		Rec.	Rec.	Rec.	Rec.	Rec.	Rec.	
CCS	Coal SC	-8	73.7	-	41.8	3.1	1950	1,2
	IGCC	-8	105.56	-	8.9	5.3	950	1,2
	CCGT	-8	52.52	-	9	1.2	1150	1,2
5% Co-firing	Coal SubC		1140	9.47	-			3,4
	Coal SC		636.5	9.47	-			3,4
	Coal USC		636.5	9.47	-			3,4
20% Co-firing	Coal SubC		960	9.29				3,4
	Coal SC		536	9.29				3,4
	Coal USC		536	9.29				3,4
70% Co-firing	Coal SubC		360	8.69				3,4
			201	8.69				3,4
	Coal USC		201	8.69				3,4

Notes:

1. Efficiency impact, additional investment cost, additional fixed O & M cost, and additional variable O & M cost from CCS installation are based on the Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021).
2. CO_2 reduction is obtained from CO_2 emission factor of each technology (tCO_2/GWh) minus the percentage of reduction based on the Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021).
3. CO_2 reduction is obtained from CO_2 emission factor of each technology (tCO_2/GWh) minus the percentage of co-firing implemented.
4. The resulting fuel cost is obtained from blending x% (x is the percentage of co-firing) of recommended biomass that cost US$8.33/MWh with recommended CFPPs fuel price at US$9.53/MWh.

e) Projection

Table appendix 4. Projected parameters value for LCOE calculation

Type	Technology	Financial parameters						Technical parameters						LCOE (USDcent/kWh)		Note
		Investment cost ($/kW)		Fix O & M ($/kW/year)		Var O & M ($/MWh)		Technical lifetime (years)		Fuel efficiency (%)		Capacity factor (%)				
		2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	
Fossil power plants	Coal SubC	1600	1550	43.9	42.6	0.12	0.12	30	30	35	36	70	70	6.21	6.04	1,2,3,5
	Coal SC	1360	1320	40	38.7	0.12	0.11	30	30	38	39	70	70	5.52	5.37	1,2,3,5
	Coal USC	1480	1430	54.9	53.2	0.11	0.1	30	30	43	44	70	70	5.68	5.51	1,2,3,5
	IGCC	2210	2040	58.2	56.4	11.6	0.13	30	30	41	43	70	70	8.25	6.67	1,2,3,4
	OCGT	730	680	22.5	21.8	0.11	0.11	25	25	35	39	35	35	10.2	9.29	1,2,3,4
	CCGT	660	610	22.8	22.1	2.23	2.16	25	25	59	60	35	35	7.39	7.11	1,2,3,4
	Diesel Generator	800	800	8	7.76	6	5.8	25	25	46	47	35		12.98	12.68	1,2,3,4
Non-fossil power plants	Biomass Agricultural	1820	1600	43.8	38.1	2.8	2.4	25	25	31	31	90	90	6.07	5.65	1,2,3,4
	MSW Incineration	6300	5600	224.8	193.5	23.4	22.6	25	25	29	29	90	90	16.02	14.57	1,2,3,4
	Geothermal Large	3440	2840	43	35.5	0.22	0.18	30	30	16	17	80	80	5.94	4.82	1,3,4
	Geothermal Small	4300	3550	55.9	46.2	0.32	0.26	30	30	11	12	80	80	7.34	6.06	1,3,4
	Hydropower Large	2000	1850	36.2	33.6	0.62	0.58	50	50	95	95	36	36	7.61	7.04	1,3,4
	Hydropower Medium	2200	2040	40.2	37.3	0.48	0.45	50	50	95	95	76	76	3.99	3.7	1,3,4
	Hydropower Mini/Micro	2590	2400	50.9	47.2	0.48	0.45	50	50	80	80	76	76	4.74	4.39	1,3,4
	Tidal Impoundment	5100	5100	62.5	35.7	0	0	40	50	90	90	35	40	19.05	15.7	1,3,4
	Tidal Stream	4600	3400	230	114	9	7	25	30	92	95	35	37	24.93	15.34	1,3,4
	Solar PV Utility Scale	560	410	10	8	0	0	40	40	-	-	22	22	3.49	2.59	1,3,4
	Solar PV Industrial	840	620	10	8	0	0	25	25	-	-	19	19	6.03	4.49	1,3,4
	Solar PV Rooftop	940	690	10	8	0	0	40	40	-	-	19	19	6.25	4.62	1,3,4
	Solar PV Floating	660	480	13.5	11.3	0	0	25	25	-	-	24	24	4.1	3.05	1,3,4
	Wind - Onshore	1280	1080	51	43.2	0	0	30	30	-	-	35	36	6.09	5	1,3,4
	Wind - Offshore	2980	2520	61.7	52.3	4.8	3.9	30	30	-	-	49	51	9.26	7.59	1,3,4
	Nuclear	3875	3575	-	-	17.5	17.5	60	60	34	34	85	85	9.76	9.36	6,7,8

Notes:

1. Investment cost, fixed O & M, and variable O & M costs are based on the Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021). The report did not include the land-use and pre-development costs. The Investment costs presented here are before accounting for 10% WACC of LCOE calculations.
2. Fuel cost is assumed equivalent with today's recommended fuel costs.
3. Technical lifetime and power plants scale are based on the Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021).
4. Fuel efficiency and capacity factor are based on the Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021).
5. CF for high-end LCOE calculation of CFPPs are based on the Scaling Up Solar in Indonesia: Reform and Opportunity (BloombergNEF & IESR, 2021). Recommended CF is an assumption from the Technology Data for the Indonesian Power Sector report by DEN, published in 2021 (Danish Energy Agency et al., 2021). Meanwhile, CF for CFPPs low-end LCOE are derived from RUPTL 2021-2030 by comparing the annual electricity production (TWh) and installed capacity of CFPPs.
6. The investment costs of nuclear power plants are obtained from the World Energy Outlook (IEA, 2022b). The recommended investment cost is the average value between the lowest and the highest reported investment cost.
7. The O & M and fuel costs of nuclear power plants are obtained from the Projected Costs of Generating Electricity (IEA, 2020). The recommended O & M and fuel costs are derived from averaging the lowest and the highest value of the corresponding costs, respectively.
8. Technical parameters of nuclear power plants are based on the Projected Costs of Generating Electricity (IEA, 2020).

2. LCOS Calculation

a) Formula

$$LCOE_{Annuitizing} = \frac{Annual\ (Cost)}{Annual\ (Output)}$$

$$= \frac{(Annual\ CAPEX + Annual\ OPEX + Annual\ Charging\ Cost)}{Annual\ Discharge}$$

$$= \frac{(CRF*C_t + (Annual\ Fixed\ O\ \&\ M + Variable\ O\ \&\ M\ Cost*Annual\ Discharge) + Charging\ Cost*\ Annual\ Discharge)}{Discharge\ over\ lifetime \div Years\ of\ lifetime}$$

$$Capital\ recovery\ factor\ (CRF) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

i = interest rate (or WACC)

n = number of annuities (or project lifetime)

C_t = Total investment (or total capital cost)

Equation 2. LCOS Formula

b) LCOS Parameters

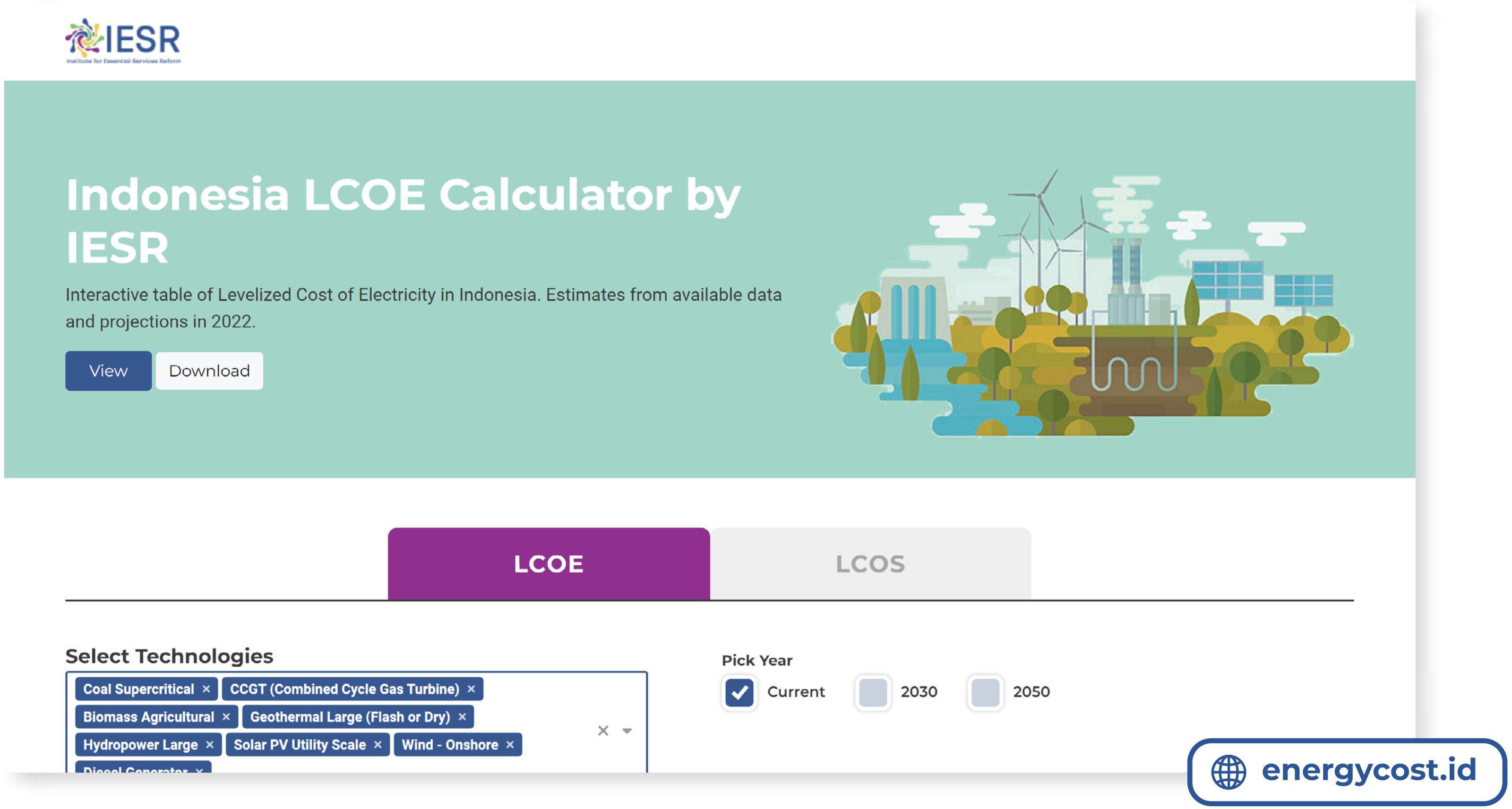
Table appendix 5. Parameters of calculated LCOS

Type	Technology	Financial parameters						Technical parameters						LCOE (USDcent/kWh)		Note
		Investment cost ($/kW)		Fix O & M ($/kW/year)		Var O & M ($/MWh)		Technical lifetime (years)		Fuel efficiency (%)		Capacity factor (%)				
		2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	2030	2050	
Fossil power plants	Coal SubC	1600	1550	43.9	42.6	0.12	0.12	30	30	35	36	70	70	6.21	6.04	1,2,3,5
	Coal SC	1360	1320	40	38.7	0.12	0.11	30	30	38	39	70	70	5.52	5.37	1,2,3,5
	Coal USC	1480	1430	54.9	53.2	0.11	0.1	30	30	43	44	70	70	5.68	5.51	1,2,3,5
	IGCC	2210	2040	58.2	56.4	11.6	0.13	30	30	41	43	70	70	8.25	6.67	1,2,3,4
	OCGT	730	680	22.5	21.8	0.11	0.11	25	25	35	39	35	35	10.2	9.29	1,2,3,4
	CCGT	660	610	22.8	22.1	2.23	2.16	25	25	59	60	35	35	7.39	7.11	1,2,3,4
	Diesel Generator	800	800	8	7.76	6	5.8	25	25	46	47	35		12.98	12.68	1,2,3,4
Non-fossil power plants	Biomass Agricultural	1820	1600	43.8	38.1	2.8	2.4	25	25	31	31	90	90	6.07	5.65	1,2,3,4
	MSW Incineration	6300	5600	224.8	193.5	23.4	22.6	25	25	29	29	90	90	16.02	14.57	1,2,3,4
	Geothermal Large	3440	2840	43	35.5	0.22	0.18	30	30	16	17	80	80	5.94	4.82	1,3,4
	Geothermal Small	4300	3550	55.9	46.2	0.32	0.26	30	30	11	12	80	80	7.34	6.06	1,3,4
	Hydropower Large	2000	1850	36.2	33.6	0.62	0.58	50	50	95	95	36	36	7.61	7.04	1,3,4
	Hydropower Medium	2200	2040	40.2	37.3	0.48	0.45	50	50	95	95	76	76	3.99	3.7	1,3,4
	Hydropower Mini/Micro	2590	2400	50.9	47.2	0.48	0.45	50	50	80	80	76	76	4.74	4.39	1,3,4
	Tidal Impoundment	5100	5100	62.5	35.7	0	0	40	50	90	90	35	40	19.05	15.7	1,3,4
	Tidal Stream	4600	3400	230	114	9	7	25	30	92	95	35	37	24.93	15.34	1,3,4
	Solar PV Utility Scale	560	410	10	8	0	0	40	40	-	-	22	22	3.49	2.59	1,3,4
	Solar PV Industrial	840	620	10	8	0	0	25	25	-	-	19	19	6.03	4.49	1,3,4
	Solar PV Rooftop	940	690	10	8	0	0	40	40	-	-	19	19	6.25	4.62	1,3,4
	Solar PV Floating	660	480	13.5	11.3	0	0	25	25	-	-	24	24	4.1	3.05	1,3,4
	Wind - Onshore	1280	1080	51	43.2	0	0	30	30	-	-	35	36	6.09	5	1,3,4
	Wind - Offshore	2980	2520	61.7	52.3	4.8	3.9	30	30	-	-	49	51	9.26	7.59	1,3,4
	Nuclear	3875	3575	-	-	17.5	17.5	60	60	34	34	85	85	9.76	9.36	6,7,8

Notes:

1. The number of cycles per year assumption, that vary for each application, is an IESR analysis inspired by the Projecting The Future Levelized Cost of Electricity Storage Technologies report (Schmidt et al., 2019).
2. The value of charging cost is based on IESR assumption. It is by default applied to energy trade and long-duration storage applications due to implementation considerations (commercial sales of energy for energy trade that should consider electricity costs and LDS as a back-up energy source which requires LDS to always be fully charged).
3. Investment cost, fixed O & M, and variable O & M costs are based on the 2022 Grid Energy Storage Technology Cost and Performance Assessment report (PNNL, 2022).
4. RTE, DoD, and cycle lifetime (based on DoD) are based on the Projecting the Future Levelized cost of Electricity Storage Technologies report (Schmidt et al., 2019).
5. Corresponding cycle life is a parameter that is assumed by IESR to calculate LCOS. Its value is derived from considerations of calendar life, cycle lifetime, and annual cycle based on the type of ESS application.

3. IESR LCOE and LCOS Webtool Description



The IESR LCOE and LCOS Webtool is an interactive web page that displays the results of the cost of electricity generation and the cost of electricity for energy storage systems calculations of various technologies in Indonesia. The webtool can be accessed through the energycost.id and biayaenergi.id domains (for page in Bahasa Indonesia). It is expected that the information on the webtool can be used as a reference for stakeholders and developers and investors in the decision-making process and project financing, respectively. Additionally, the information is expected to provide insights and references regarding LCOE and LCOS in Indonesia for academia, international institutions, and readers in general.

On the front page of the webtool, the LCOE calculation results (in units of US$ cents/kWh) for several types of power generation technologies are displayed based on the recommended default parameter values (currently most realistic) obtained from several references. Webtool users can select multiple technologies [1] from a total of 26 existing technology options and compare their current LCOE values, as well as their projected values in 2030 and 2050 by ticking the desired year [2]. Automatically LCOE and its components, namely CAPEX (capital expenditure, accounting investment cost, and cost of capital), OPEX (operational expenditure, including fixed O & M and variable O & M costs), fuel costs, and CO2 cost will be displayed on the recommended LCOE chart [3], after selecting the technology. In addition to the recommended LCOE values, webtool users can also determine the estimated lowest and highest LCOE values of each selected technology on the LCOE range chart [4]. Furthermore, the calculation results can also be seen in the form of a data table [5] where the values can be sorted. Charts and data in tables can be downloaded as images [6] or spreadsheets [7].

The interactive features on the webtool allow users to adjust default parameter values for the selected technologies to users' preferences. The adjustable parameters are grouped in the policy analysis section [8] and technology analysis [9]. Policy analysis includes WACC, fuel prices (in % increase or decrease for value in units of US$/MWh), and CO_2 prices (which affect fossil generation technology) settings. Moreover, policy analysis includes the options to incorporate CCS technology (affecting supercritical coal, IGCC, and CCG technologies) and co-firing strategy on CFPP technologies (subcritical coal, supercritical coal, and ultra-supercritical coal). Meanwhile, in the technology analysis section, users can set the parameter values of each selected technology individually by selecting the technology for which parameters are intended to be modified [10]. The webtool will display the default value of each technology for parameters of investment cost, technical lifetime, capacity factor, and fuel efficiency, where the users can adjust each value. The LCOE calculation results that are set by users can also be compared with the present range of LCOE and LCOE values recommended by the IESR on the LCOE range chart [4].

Figure appendix 1. LCOE webtool interface

To access the LCOS calculator, users can click the LCOS section on the main webtool page [11]. Essentially, the display and features of the LCOS web tool resemble those of LCOE. However, on the LCOS front page, the calculation results displayed are for energy storage systems application as a substitute for peaker generators (peaker replacement) with an ESS scale of 100 MW. It aims to introduce the IESR LCOS webtool feature which has classified the types of ESS usage based on its operating parameters. Definitions of several ESS applications and parameter terms can be seen on the glossary page and examples of different parameter values can be seen in the assumptions table of the About webtool page. The ESS application types available on the LCOS webtool are primary response, secondary response, peaker replacement, energy trade, power reliability, and long-duration storage. If one of these types of applications is selected [12], the LCOS webtool automatically applies parameter values according to the type of operation of the application type like the number of annual cycles [13], and several types of ESS that do not meet the general criteria for the application (i.e., minimum response time and duration) will be eliminated in the technology choice section [14]. If users prefer the LCOS calculation that is not limited by the type of application, users can select unspecified in the ESS application options.

In the LCOS policy analysis section [15], users can set WACC, charging fees, and the number of annual cycles (for unspecified applications). While in the technical analysis section [16], parameter values that can be changed are investment costs, calendar life, cycle lifetime, and round-trip efficiency of each technology with different durations.

From the main webtool page, users can access the About Webtool page [17] which comprises a brief description of the webtool, the calculation methodology, and the assumptions used. The terms and abbreviations used in the webtool are described on the glossary page [18].

Figure appendix 2. LCOS webtool interface

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