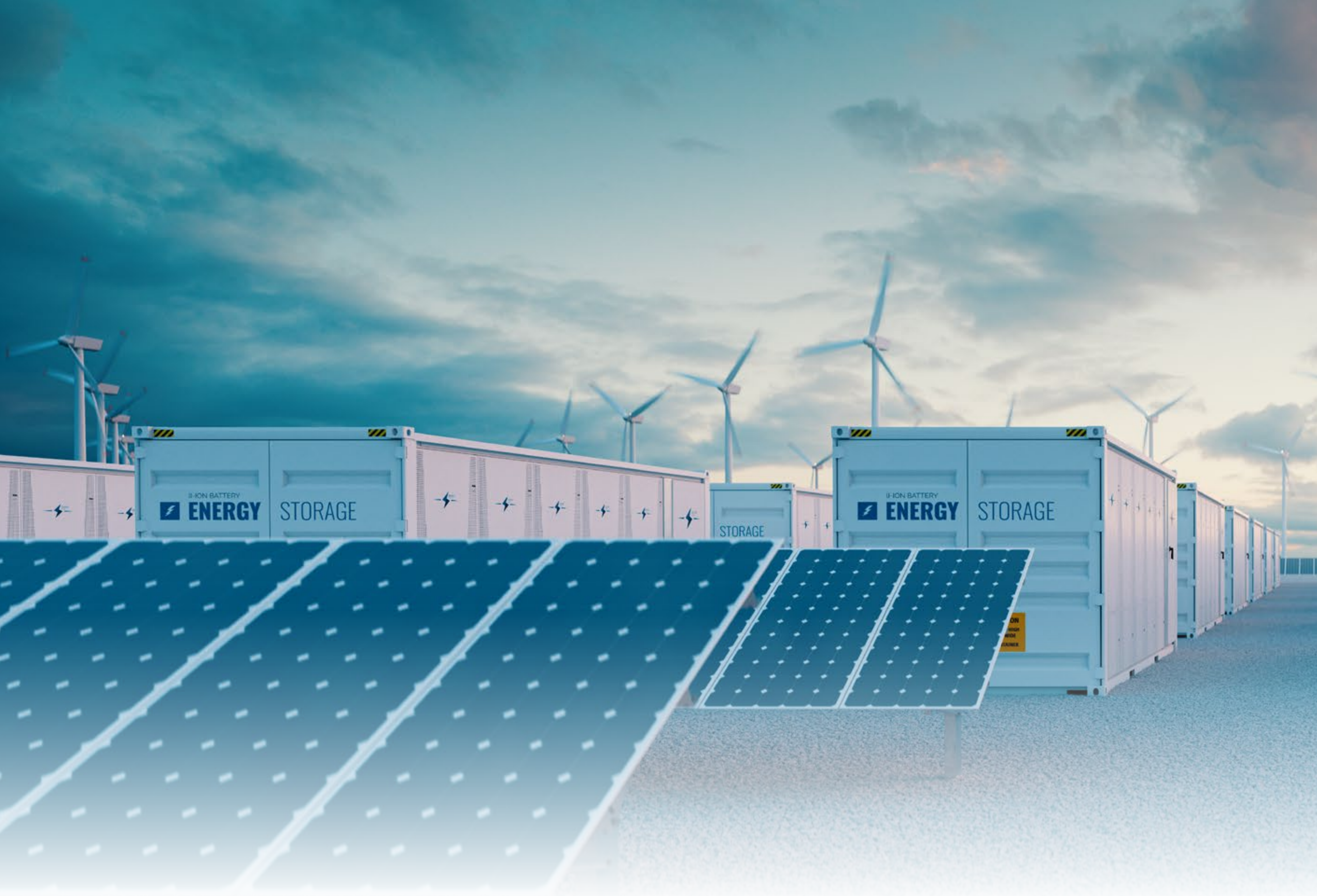
IESR
Institute for Essential Services Reform

Powering the Future:
An Assessment of Energy Storage Solutions and The Applications for Indonesia

2024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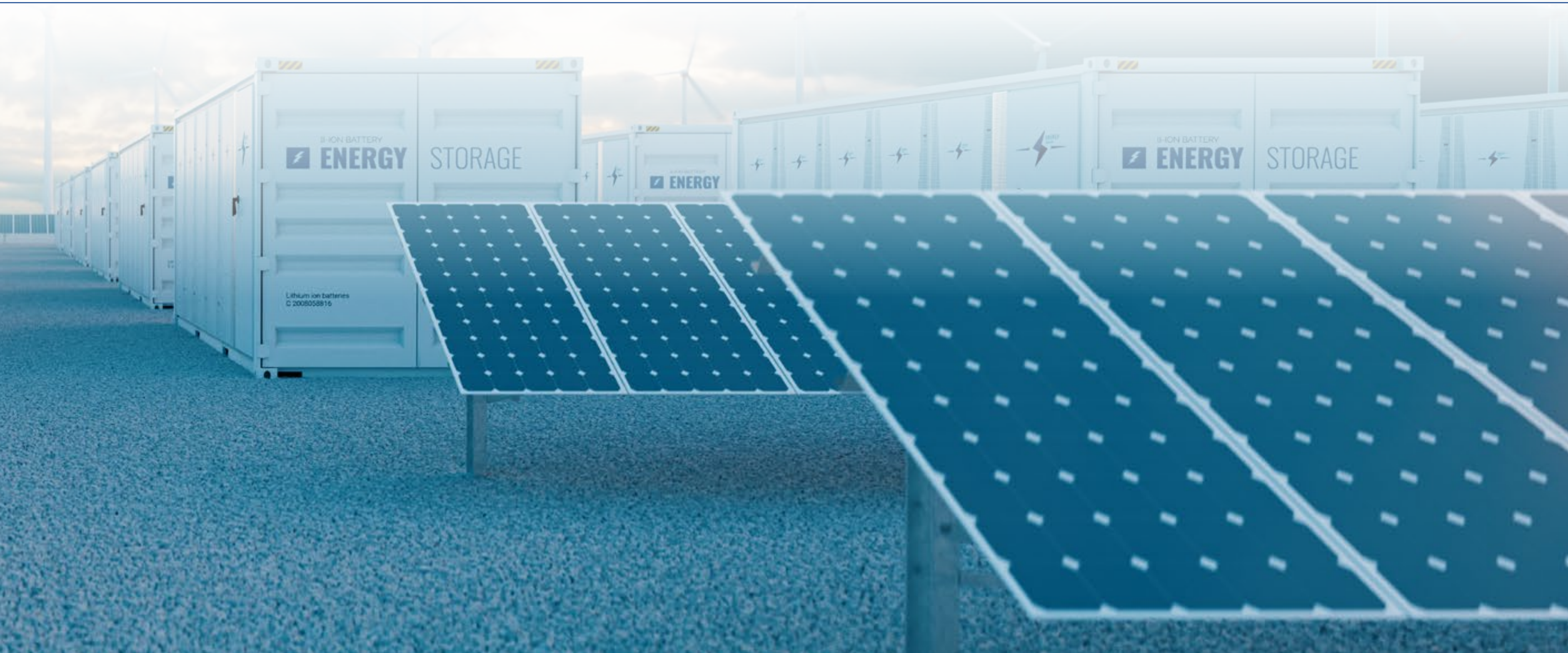

Imprint

Powering the Future: An Assessment of Energy Storage Solutions and The Applications for Indonesia

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Foreword

Energizing Indonesia's Sustainable Future

As Indonesia embarks on its energy transition, the need for sustainable and reliable power has never been more critical. Our archipelagic nation, endowed with abundant renewable resources, faces distinct challenges in balancing rising energy demand and rapid economic growth with environmental responsibility. In this context, energy storage systems (ESS) emerge as a pivotal solution, poised to transform our power sector and accelerate the path towards a low-carbon future.

In recent years, we have witnessed significant global advancements in energy storage technologies. These systems, ranging from advanced lithium-ion batteries to innovative pumped hydro storage solutions, are becoming increasingly sophisticated, efficient, and cost-effective. In Indonesia, promising pilot projects and growing interest from both the public and private sectors signal a shift in our energy paradigm.

The importance of energy storage within our national energy strategy cannot be overstated. As we pursue the ambitious target of achieving 23% renewable energy in the national energy mix by 2025, and an even more ambitious goal of net-zero emissions in the power sector by 2050, energy storage stands as a crucial pillar of this transition. ESS addresses one of the key challenges of variable renewable energy sources, such as solar and wind—their intermittency.

By efficiently storing excess energy during peak production periods and releasing it when demand increases or production decreases, ESS mitigates the variability inherent in renewable energy sources. This capability not only enhances grid stability but also significantly strengthens the integration of renewables into our power system. It enables us to fully exploit the potential of our solar-rich equatorial regions and the wind resources along our extensive coastlines, converting these natural assets into reliable power sources for our growing economy.

Furthermore, energy storage plays a vital role in our efforts to decarbonize the power sector, which contributes significantly to national carbon emissions. ESS reduces dependence on fossil fuels by facilitating higher levels of renewable energy integration. It provides a cleaner alternative to traditional peaker plants, which typically rely on diesel or natural gas to meet sudden spikes in electricity demand. Instead, stored renewable energy can be swiftly deployed, offering a carbon-free solution to grid balancing and peak shaving at a price competitive with conventional gas-peaker plants.

The benefits of adopting energy storage extend beyond environmental considerations. For our thousands of islands, many of which still depend on expensive and polluting diesel generators, energy storage systems (ESS), when paired with renewable energy, offer a pathway to energy independence and an improved quality of life. It promises more reliable access to electricity, lower energy costs, and new economic opportunities in remote areas.

In urban centers and industrial zones, energy storage can improve power quality and reliability, which are crucial for our expanding digital economy and manufacturing sector. By providing ancillary services such as frequency regulation and voltage support, ESS contributes to a more resilient and robust grid infrastructure, capable of meeting the demands of our rapidly developing nation.

Looking ahead, the role of energy storage in Indonesia's energy landscape is poised to expand significantly. Globally, investments in research and development are increasing, manufacturing capabilities are growing, and regulatory frameworks are evolving to recognize the value of storage. The development of an electric vehicle ecosystem in Indonesia has spurred research into nickel-based batteries and battery manufacturing, which could enhance the application of battery energy storage systems (BESS) across the country.

Indonesia stands to benefit from these technological innovations by incorporating them into our energy system as soon as possible. Power system planning requires a paradigm shift from a unidirectional, centralized model to one that is more flexible, distributed, and sustainable. Moreover, the widespread adoption of energy storage technologies will require ongoing policy support, innovative financing mechanisms, and capacity building across the sector. It is also essential to address the environmental and social impacts of battery production and disposal to ensure that our pursuit of clean energy does not create new environmental challenges.

This report comes at a pivotal moment, offering insights into the current state of energy storage in Indonesia, its potential impacts, and the pathways for its integration into our energy systems. It serves not only as a technical document but also as a call to action for policymakers, industry leaders, and citizens alike.

IESR sincerely thanks all those who contributed to the creation of this report, especially the policymakers, industry leaders, experts, and ESS installers who kindly shared their insights and experiences. This report comes at a pivotal moment, offering insights into the current state of energy storage in Indonesia, its potential impacts, and the pathways for its integration into our energy systems. It serves not only as a technical document but also as a call to action for for both stakeholders and citizens.

As we embark on this transformative journey, we must recognize energy storage not just as a technological solution but as a cornerstone of our sustainable development strategy. It is the key to unlocking the full potential of our renewable resources, advancing our transition to a low-carbon economy, and ensuring energy security for generations to come.

Indonesia stands on the brink of an energy revolution. With strategic investments, supportive policies, and collaborative efforts, we can harness the power of energy storage to build a cleaner, more resilient, and prosperous future for all Indonesians. Let this report guide us in that endeavor, as we write the next chapter in Indonesia's energy story—one of innovation, sustainability, and shared prosperity.

Jakarta, October 2024

Fabby Tumiwa

Executive Director

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List of terms and abbreviations

ACS : American Chemical Society
AEMFC : Anion Exchange Membrane Fuel Cell
AFC : Alkaline Fuel Cells
ASEAN : Association of Southeast Asian Nations
BECCS : Bioenergy with Carbon Capture and Storage
Behind-the-meter : Customer-sited energy storage installation
BESS : Battery Energy Storage System
BG : Biomass Gasification
Blue hydrogen : Hydrogen is derived from fossil fuels, while CO_2 emissions generated are captured with CCS/CCUS and not released to atmosphere
BNEF : Bloomberg New Energy Finance
CAES : Compressed Air Energy Storage
CAPEX : Capital expenditures
CC : Combined Cycle
CCS : Carbon Capture and Storage
CCUS : Carbon Capture Utilization and Storage
Close-loop : Pumped hydropower storage configuration includes two reservoirs isolated from any free-flowing water source
CNESA : China Energy Storage Alliance
CNG : Compressed Natural Gas
CAGR : Compound Annual Growth Rate
COP28 : Conference of the Parties 28
DAC : Direct Air Capture
DER : Distributed Energy Resource
DOE : Department of Energy
EBA : European Biogas Association
EBET : *Energi Baru Energi Terbarukan*
EES : Electrochemical Energy Storage
EIA : Energy Information Administration of United States
ERIA : Economic Research Institute for ASEAN and East Asia
ESG : Environment, Social, and Governance
ESS : Energy Storage System
EU : European Union
EV : Electric Vehicles
FC : Fuel Cell
FCEV : Fuel Cell Electric Vehicle
FESS : Flywheel Energy Storage System
FoMO : Fear of Missing Out
Front-of-the-meter : Energy storage installation on generation and transmission level
GHG : Green House Gasses
GHP : Green hydro gen plants or plants for producing hydrogen
GoI : Government of Indonesia

Gray hydrogen : Hydrogen is derived from fossil fuels, while CO_2 emissions generated are released into the atmosphere.

Green hydrogen : Hydrogen generated from water electrolysis powered with electricity generated from renewable energy

GT : Gas Turbine

GW : Giga Watt

GWh : Giga Watt-hour

GWR : Guinness World Records

HRS : Hydrogen refueling station

ICCT : International Council on Clean Transportation

IDR : Indonesian Rupiah

IEA : International Energy Agency

IHA : International Hydropower Association

IKN : *Ibu Kota Nusantara*

IRENA : International Renewable Energy Agency

JETP : Just Energy Transition Partnership

KEN : *Kebijakan Energi Nasional*

Kg : Kilogram

Km : Kilometer

kW : Kilo Watt

kWe : Kilo Watt Equivalence

kWh : Kilo Watt-hour

LCE : Lifecycle Carbon Emission

LCOE : Levelized Cost of Electricity

LCOS : Levelized Cost of Storage

LDES : Long-duration Energy Storage

LFP : Lithium-ferro phosphate or Lithium-iron phosphate

LIB : Lithium-ion Battery

Li-ion : Lithium-ion

MCFC : Molten-Carbonate Fuel Cells

MEMR : Ministry of Energy and Mineral Resources of Indonesia

MMT : Million metric tonnes

MoI : Ministry of Industry of Indonesia

MoU : Memorandum of Understanding

MP3EI : *Masterplan Percepatan dan Perluasan Pembangunan Ekonomi Indonesia* or Masterplan for the Acceleration and Expansion of Indonesia's Economic Development

MW : Mega Watt

MWh : Mega Watt-hour

Na-S : Natrium-Sulfur or Sodium-Sulfur

NDC : Nationally Determined Contributions

NMC : Nickel Manganese Cobalt

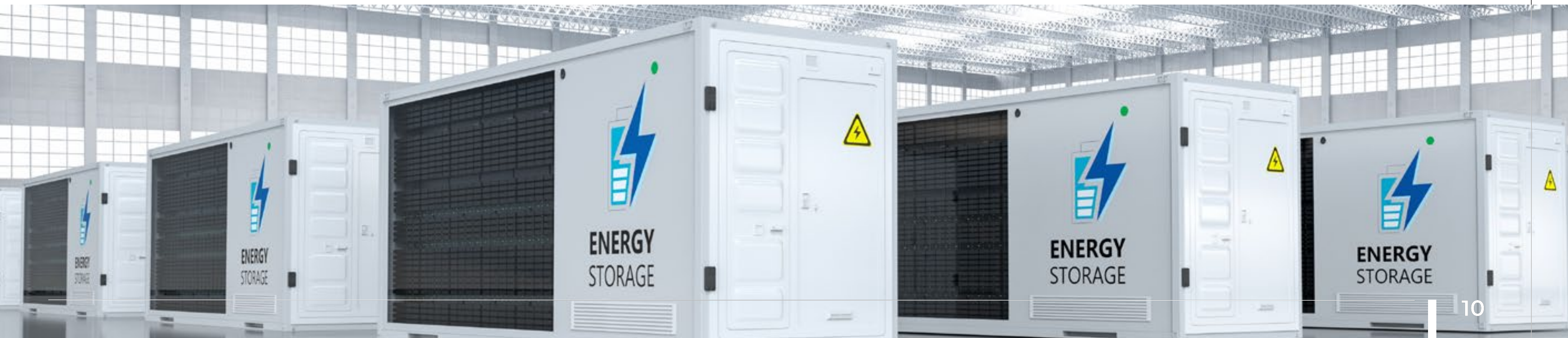
NZE : Net Zero Emission

Open-loop : Pumped hydropower storage configuration that has a permanent hydrologic connection to a natural water body

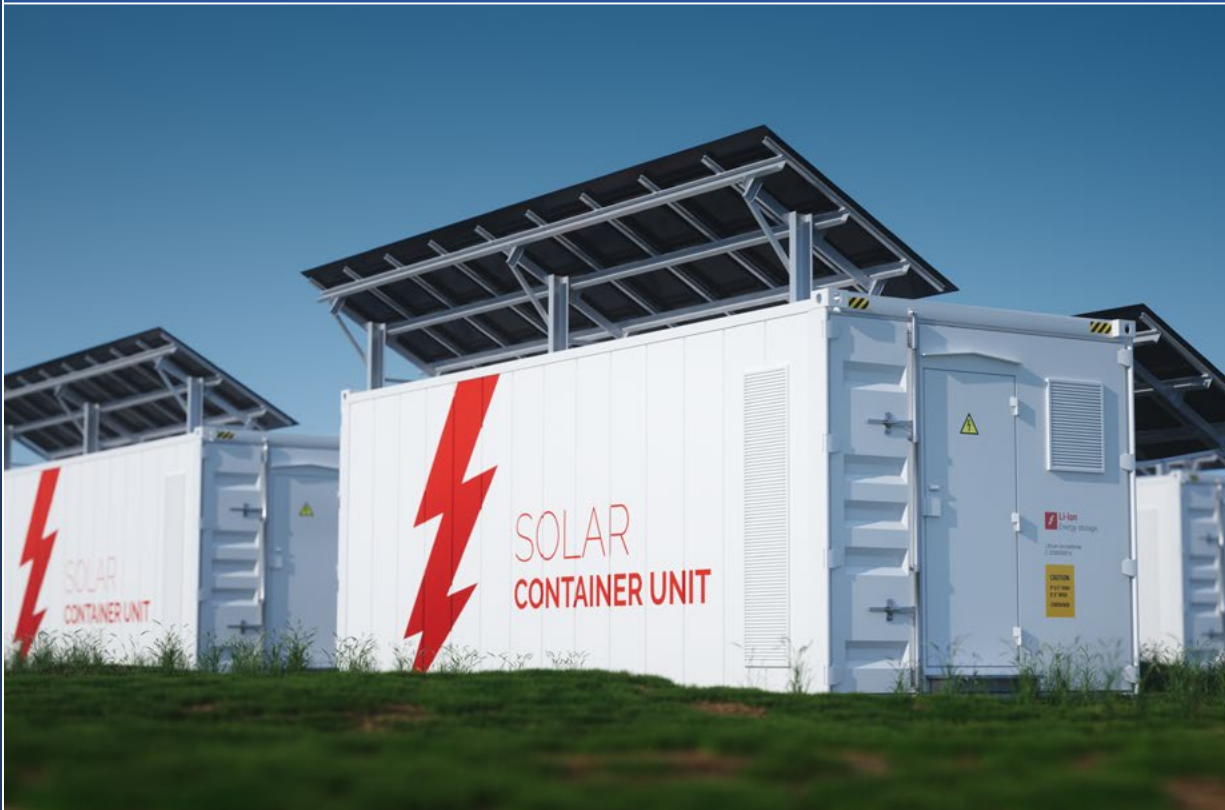
ORC : Organic Rankine Cycle

PAFC : Phosphoric Acid Fuel Cells

PEMFC	: Proton exchange membrane fuel cell
PLN	: *Perusahaan LIstrik Negara* or the state-owned electricity company of Indonesia
PP	: Pyrolysis Plasma
PHS	: Pumped Hydropower Storage
PV	: Photovoltaics
R&D	: Research and development
RE	: Renewable Energy
RFB	: Redox Flow Battery
RKEF	: Rotary Kiln-Electric Furnace
RPJMN	: *Rencana Pembangunan Jangka Menengah Nasional* or National Medium-Term Development Plan
RPJPN	: *Rencana Pembangunan Jangka Panjang Nasional* or National Long-term Development Plan (RPJPN)
RUEN	: *Rencana Umum Energi Nasional* or National Energy Plan of Indonesia
RUKN	: *Rencana Umum Ketenagalistrikan Nasional* or National Electricity Plan of Indonesia
RUPTL	: *Rencana Usaha Penyediaan Tenaga Listrik*
SAIDI	: System Average Interruption Duration Index
SAIFI	: System Average Interruption Frequency Indeks
SMR	: Steam Methane Reforming
SNI	: *Standar Nasional Indonesia* or Indonesian national standards
SOFC	: Solid Oxide Fuel Cells
TESS	: Thermal Energy Storage System
TRL	: Technology Readiness Level
USD or US$	: United States dollar
V2G	: Vehicle to Grid
VRE	: Variable Renewable Energy
VRFB	: Vanadium Redox Flow Battery
WHRS	: Waste Heat Recovery System
WNA	: World Nuclear Association



Executive Summary

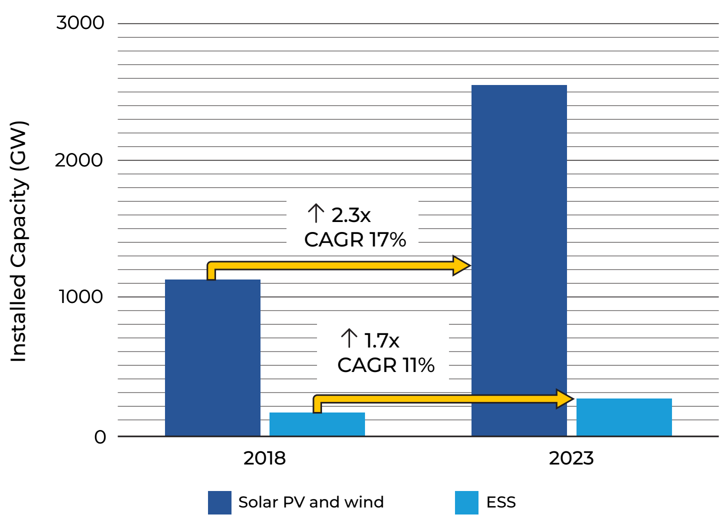


- Key drivers behind the growth of energy storage system capacity
- Global trends in energy storage system installations and technology advancements
- Current and projected capacity of energy storage systems and hydrogen in Indonesia
- Readiness for energy storage system adoption in Indonesia
- Challenges in the development of storage technology in Indonesia

Executive Summary

- Energy storage technologies are needed to transform fossil fuel-based power systems as solar PV and wind energy penetration rises worldwide. In addition to refining mature technologies, decarbonization has spurred the development of cheaper energy storage solutions like electrochemical storage and hydrogen conversion.

The Installed Capacity Growth of Energy Storage System Compared to Solar PV and Wind



- The installed capacity of energy storage systems has seen significant growth in recent years, driven by the rapid expansion of solar PV and wind power plants, which now account for over 13% of the global energy mix. Between 2018 and 2023, the compound annual growth rate (CAGR) for the two variable renewable energy (VRE) and energy storage system (ESS) capacity was 17% and 11%, respectively. The most notable increase was in battery energy storage systems (BESS), which experienced a remarkable CAGR of over 65% during this period.

- The enhanced capacity of storage and advancements in technology have improved the economic feasibility of energy storage, rendering it beneficial not only for facilitating the integration of variable renewable power generation into the grid but also as a valuable asset for grid strengthening. At the generation and transmission level, storage is being utilized more frequently for generator ramping, offering competitive options to gas peaker plants, deferring transmission and distribution (T&D), and even providing black start services. On the consumer side, energy storage systems are increasingly recognized as a cleaner and more cost-effective alternative to generators for backups , while also providing opportunities for savings on electricity bills.

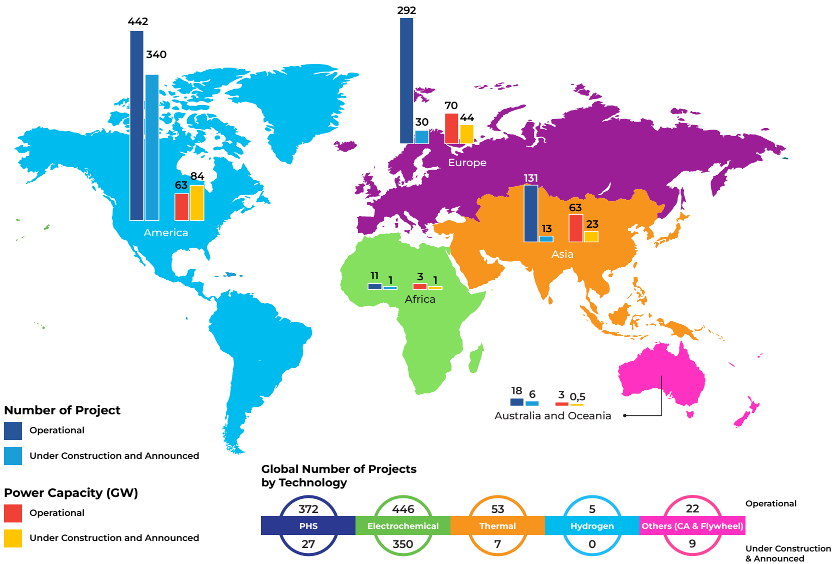
- The functions of energy storage are contingent upon the design and regulations of the electricity market. Presently, diverse applications of energy storage are more popular in areas with competitive electricity markets, including the United States, Australia, and much of Europe. Not all energy storage technologies are appropriate for every application, impacting their economic feasibility. Currently, electrochemical batteries are predominantly suited for medium-duration applications, whereas mechanical storage technologies such as pumped hydro storage (PHS) and compressed air energy storage (CAES) are superior for long-duration uses.

Executive Summary

- Over the past three years, battery energy storage system (BESS) capacity has nearly doubled and pumped hydro storage (PHS) capacity has grown by 5 GW. PHS capacity addition is expected to accelerate, reaching 35 GW in 2024. According to the US DOE database, 390 energy storage system (ESS) projects are under construction or announced worldwide, totaling 152 GW.

- As countries strive for net-zero emissions by 2050, ESS installations are expected to rise. COP28's goal of tripling renewable energy capacity by 2030 requires 1,500 GW of installed ESS capacity (excluding hydrogen storage), with 80% coming from BESS, according to the IEA.

The global map of energy storages systems installation



- Global investment in BESS doubled to $40 billion in 2023, indicating an exciting prospect for energy storage. The US, China, and Europe have accounted for 90% of global BESS spending over the past two years. BESS is preferred for its fast construction times, but future development plans must consider battery cell supply chain issues and critical mineral price volatility, which raised BESS costs in 2022. Thus, countries adopting BESS must be able to manufacture components domestically at competitive prices, if possible.

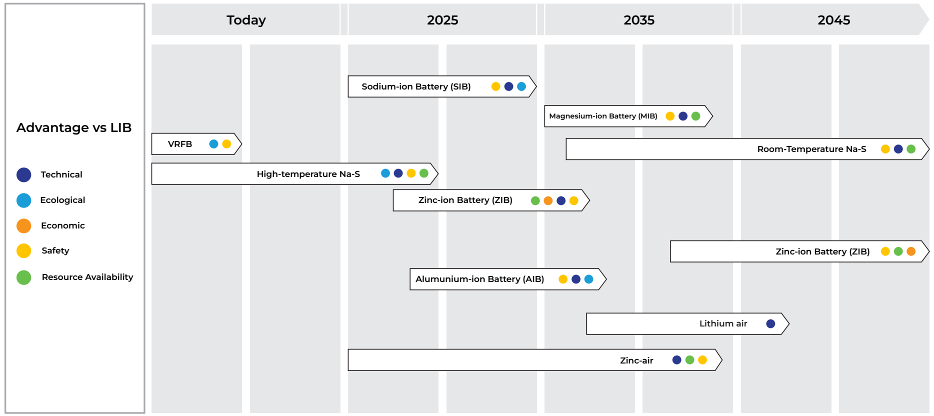
- The high cost of energy storage has led to new approaches like sector coupling. Instead of buying new BESS, electricity consumers can connect their EV batteries to the electricity grid to store excess solar PV generation and use them as backup power. This method increases the value of owning an EV and maximizes battery use, reducing energy storage waste. Notably, vehicle-to-grid (V2G) schemes, which allow EV owners to ‘sell’ electricity from their vehicles, are being developed in several countries. For V2G to work, improvements are needed in business models, regulations, grid strength, and infrastructure. Additionally, data will play a key role in V2G, making data protection and cybersecurity important factors to address.

- Besides V2G, Power-to-Gas (P2G) with hydrogen is another promising sector coupling scheme. This method generates cheap hydrogen from surplus electricity, which can be stored and converted into electricity using fuel cells or combustion engines. Hydrogen can also replace fossil fuels in transportation and industry.

Executive Summary

- The role of energy storage in power grids is rapidly evolving due to the integration of VRE and shifting consumer behavior, resulting in a wide range of applications, each with distinct technical requirements. Although PHS and BESS currently dominate the market, this variety of roles is driving innovation and the development of new technologies. For example, in the off-grid solar PV market, which is primarily served by electrochemical LIB, some of the market is being captured by flow batteries and even small-scale closed-loop PHS. In the industrial sector, BESS are being paired with supercapacitors and flywheels to improve performance.

Electrochemical Energy Storage Technology Development Roadmap



- Several technologies, such as flow batteries and high-temperature sodium-sulfur batteries, are technically advanced but still face limited market demand and growth. However, there is a shift in the market from short-duration storage (around 2 hours) to longer-duration storage, especially for energy-shifting purposes, where lithium-ion (LIB)-based ESS becomes more expensive. Non-lithium batteries are projected to represent over 10% of the stationary storage market by 2025, up from less than 5% in 2021. This trend is being driven by the increasing maturity of alternative batteries, like sodium-ion, which are entering the pre-commercial phase. Additionally, some well-established technologies are being revisited and improved as demand signals grow.

- In battery research, experts have forecasted the commercialization timelines for various alternatives to lithium-ion technology and outlined their advantages over the current standard. Sodium-based metal-ion batteries are expected to be the first to enter the energy storage market, capturing market share from lLIB, with magnesium, zinc, and other metal-ion options following. More experimental technologies, such as lithium-air and polymer flow batteries, are predicted to enter the market later. Additionally, mechanical storage solutions are gaining renewed attention, with innovations like underground or seawater-based PHS systems being explored.

- For seasonal storage, hydrogen is emerging as the most promising option, although its economics are relatively complex. A stationary bi-directional fuel cell represents the basic configuration of a hydrogen storage system for power systems, comprising three main technologies: electrolyzers for hydrogen production, hydrogen storage mediums, and fuel cells for converting hydrogen back into electricity. Research on these technologies primarily focuses on improving system efficiency and exploring new materials. Widespread commercialization of hydrogen storage for the power sector is anticipated after 2030, largely driven by the availability of low-cost power generation technologies.

Executive Summary

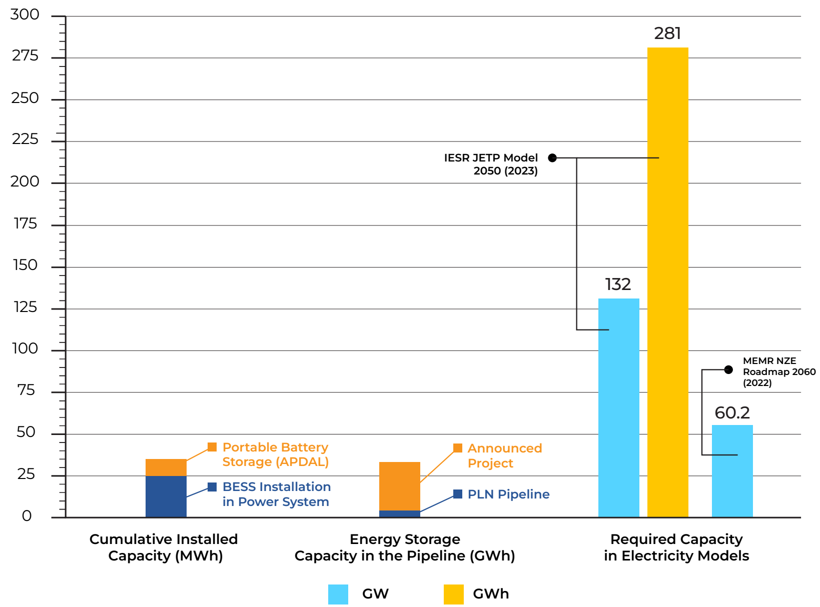
- Energy storage will be a crucial asset in transforming Indonesia's power sector toward achieving net zero emissions (NZE). With solar and wind expected to make up 77% of the total installed generating capacity (421 GW of solar PV and 94 GW of wind), at least 60.2 GW of energy storage will be required. However, widespread adoption remains a challenge due to the slow progress in renewable energy development. Most growth has been in dispatchable hydro and geothermal sources, with variable renewable energy (VRE) making up only 5.5% of the total installed renewable capacity and no large-scale energy storage systems currently operational.

- Some of the early adopters of ESS technology are private sectors and remote areas supported by grants to improve electricity access. Of the 25 identified BESS projects with capacities exceeding 100 kWh, 13 were developed by PLN, while the rest were implemented by private industries, hotels/ resorts, and conservation areas. The private sector adopted medium-scale BESS as early as 2015, with many relying on costly diesel generators. On the other hand, the residential sector connected to the grid still has not yet seen significant benefits from BESS installations. BESS installations initiated by foreign donors and the government have faced challenges with maintenance, and many units have reportedly been damaged.

- Indonesia's energy storage capacity will increase 1,000-fold with the announced ESS projects. In RUPTL 2021–2030, PLN plans only 4.2 GW of pumped hydro storage (PHS) and limited BESS deployment for diesel conversion. Upper Cisokan PHS, scheduled for completion in 2027, will be the first large-scale ESS to strengthen the grid. The government's roadmap predicts BESS adoption after 2034 as VRE penetration rises and battery prices fall. With 29 GWh of planned projects, electricity export schemes to Singapore could accelerate BESS deployment.

- Hydrogen technology is being promoted across all sectors and will strengthen the country's energy security. A 2023 National Hydrogen Strategy outlined the government's hydrogen development strategy. Indonesia produces 254 tons of renewable hydrogen annually from 23 green hydrogen plants (GHPs). Depending on the progress of announced projects, renewable hydrogen production could reach 2 million tons.

Installed energy storage capacity, announced projects, and required capacity to reach NZE in Indonesia



Executive Summary

Existing Characteristics That Present Opportunities for Energy Storage System Adoption in Indonesia

Characteristics	Description
Several isolated systems with limited energy sources	- In certain remote areas, particularly those with limited energy resources and no grid connection, access to electricity is often restricted to lighting. - Electricity generation using a solar PV plus storage system can be more cost-effective than fossil fuel generators like diesel generators.
Inferior power system reliability and efficiency in smaller systems	- There is potential to increase system efficiency based on the low system load factor, particularly in several small systems. - The higher-than-average level of system interruptions in small systems suggests potential for ESS implementation as a backup power source or for deferring transmission and distribution (T&D) upgrades. - Systems with high VRE penetration levels are beginning to be impacted by the variability of VRE output.
Low flexibility in current generation mix to accommodate rapid VRE integration	- The plan to significantly expand VRE capacity to reach the final net zero emissions (NZE) target will require large-scale, versatile energy storage to facilitate rapid VRE integration. - The number of existing grid assets that can be operated with flexibility is limited.

Executive Summary

- While certain technical characteristics of the current power system are not yet ideal for large-scale energy storage development, there are still important opportunities for deployment that should be maximized as a first step toward expanding their role in Indonesia's power grid. Several factors are limiting the large-scale adoption of ESS in Indonesia, including the slow growth of VRE capacity, the low urgency to use ESS as a peaker asset, and the focus on developing other grid-strengthening assets that serve similar functions in current plans. Indonesia's main grids are in Phase 1 of the energy transition, where VRE integration has little impact on system stability, reducing the immediate need for ESS to support VRE. The slow growth in electricity demand and peak load also has been met by increased generation capacity. Moreover, PLN's RUPTL indicates that about 48% of planned power sources until 2030 are fast-response assets, further limiting the role ESS might play in this space.

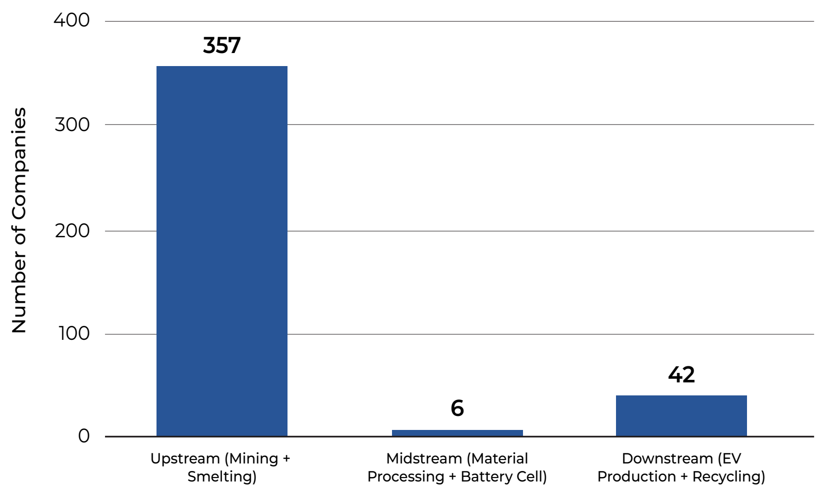
- Key opportunities for the initial deployment of ESS include the role to improving electrification level and addressing the low reliability and efficiency of small grids. Indonesia has many isolated power grids with limited energy resources and incomplete electrification. From the 99.78% electrification level in 2023, about 3% of this still only provides basic lighting, classified as Tier-1 electricity access. The reliability of Indonesia's power systems, especially outside Java, is reflected in the reported SAIDI and SAIFI values, which averaged 8.17 hours and 5.93 outages per consumer, respectively, in 2023. Additionally, low load factors in these systems have persisted, highlighting the need for efficient peak control assets, with ESS emerging as a practical solution.

- In addition to technical factors, the readiness of the policy framework is crucial for driving demand and determining the economic viability of ESS development. Currently, long-term planning documents for the power sector do not fully recognize the diverse roles and benefits of different types of stationary ESS, and the market structure and regulations do not yet provide a strong enabling environment. The implementation plan primarily views ESS as a bulk electricity source and a supporting component of VRE. However, by adjusting electricity tariffs for ESS assets, offering incentives to installers, and clearly defining the various roles of energy storage within the power system, opportunities for value-stacking schemes can be created. These schemes can significantly enhance the economic feasibility of ESS. Beyond closing regulatory gaps, establishing a transparent and efficient procurement framework is necessary to reduce development risks and build investor confidence in ESS projects.

Executive Summary

- Indonesia's ambition to build an EV battery supply chain faces significant challenges. The shift away from nickel-based batteries by EV manufacturers and ESG concerns in mining areas are hindering the industry's growth. The dominance of RKEF smelters in Indonesia does not align with the government's plan to develop a comprehensive EV battery supply chain. The middle stream is also lacks of attention and the development is sluggish compared to upstream and downstream sector. ESG practices are also a major issue, impacting investor interest. Notably, the limited domestic demand for batteries has constrained the production capabilities of local manufacturers. Furthermore, to compete globally, diversifying battery technologies is crucial, especially for large-scale battery systems, as current capacities remain insufficient to challenge international competitors.

Approximate Number of Companies in EV Battery Supply Chain



- The capability in handling used EV batteries, besides producing the new ones, is important for Indonesia to optimize the battery remaining values, reduce costs in BESS, and minimizing environmental impacts. This is also an important moves for Indonesia to show their position as a key player in the regional battery manufacturing industry.

- Indonesia has vast renewable energy resources totaling 3,698 GW, with the potential to support at least 185 GWh of green hydrogen production. With the lowest potential production cost (on-site) at USD 1.9/kg and it may lower in the future, Indonesia holds a highly competitive position in the global market. This advantage allows it not only to meet domestic demand but also to become a global hydrogen exporter. However, hydrogen adoption in the country is still in its early stages. Market demand has not yet been established, and the technology for hydrogen production and consumption is still developing. Additionally, the ecosystem for hydrogen adoption is far from ideal, with high capital costs for renewable energy power plants and electrolyzers being the main obstacles. Investments from industry players are currently on hold, as they wait for clearer government targets on hydrogen adoption. This highlights the need for stronger political will to drive Indonesia toward becoming a global leader in green hydrogen production and technology.

Recommendation

- Energy storage is a critical component to decarbonize power systems. Energy storage enables high level integration of variable renewable energy and could make the system more flexible, green, and efficient. Indonesia is currently in the early stages of adopting energy storage. To accelerate energy storage deployment in the Indonesian power system, key actions are needed to address existing opportunities and challenges, including:

1. **Tapping into the limited but existing opportunities for deploying energy storage systems (ESS)** is vital for expanding their role in Indonesia's power sector. At present, the greatest potential for ESS deployment lies in smaller and/or isolated systems, as well as in industrial or large scale commercial solar rooftop PV with BESS. Alongside these initial efforts, improving access to affordable ESS technologies, particularly batteries, and building the expertise of power sector stakeholders will be essential in laying the foundation for broader, large-scale implementation in the future.

2. **Improving the regulatory framework and establishing legal certainty** to adequately compensate ESS for the value it can provide, reducing development risks, and boosting investor confidence in ESS initiatives are imperative. Planning for energy storage systems should be well integrated with power transmission, distribution, and generation planning in Indonesia, aligning with the increasing installation of VRE. Besides setting capacity targets, planning documents should outline the full range of potential ESS roles. Currently, they primarily focus on smoothing and capacity firming without fully exploring technologies beyond BESS (Battery Energy Storage Systems) and PHS (Pumped Hydro Storage). Once these planning documents are updated, additional regulations will be necessary, including revisions to the grid code to reflect the latest technical capability. Additionally, policy support for long-duration energy storage should be explored further.

3. **Taking the best practices from other countries**. Nations such as the US, China, UK, and Australia, and which have significant ESS deployments, follow similar strategies: supportive policies that focus on three key areas—strong market signals, innovative revenue mechanisms, and enabling regulations that include industry support and R&D investment. These countries have set specific capacity targets for ESS and variable renewable energy (VRE) and have introduced carbon pricing, tender schedules, and procurement frameworks. Additionally, various ESS roles have been developed into value-stacking schemes, enhancing the economic feasibility of ESS ownership.

4. **Enhancing the economics of energy storage projects** can be achieved by adjusting electricity tariffs for ESS assets, providing incentives to installers, and clearly outlining the roles of energy storage in the power system to enable value-stacking. Furthermore, removing fossil fuel subsidies for utilities would create a more level playing field for VRE and storage, enabling their combination to deliver economically competitive, dispatchable power and serve as a viable alternative to gas and coal power plants.

5. **Conducting pilot projects to test various ESS technology options**. Experience in developing ESS projects in Indonesia is still very limited, and local expertise needs to be strengthened. Through planning, the government should encourage utilities to test various emerging energy storage technologies to better understand their characteristics, performance, and interoperability within the power system. Financial support or grants should be made available for these pilot projects, with funding extended not only to utilities but also to research institutions and universities.

6. **Enabling innovative sector coupling approaches**. The Vehicle-to-Grid (V2G) scheme, for instance, exemplifies how decarbonization efforts in the transport sector can benefit the power sector by reducing the need for costly investments in new batteries. However, technical improvements to the grid network are necessary to support V2G. Moreover, clear policies and business models must be established to make V2G both feasible and attractive. Beyond V2G, the power-to-x concept, particularly using hydrogen as a versatile energy feedstock, should also be further developed.

7. **Establishing a storage technology ecosystem and R&D roadmap**. Variations in ESS installation costs across countries are driven by factors such as project size, labour costs, and the availability of a strong technology supply chain. China currently leads in this area due to relatively low soft costs and advanced hardware manufacturing, particularly in lithium iron phosphate (LFP)-based LIB cells. As Indonesia begins to develop its battery ecosystem, it must anticipate market shifts, such as the rise of sodium-ion battery (SIB) technology, which is expected to capture a share of the LFP-based LIB market. To remain competitive, Indonesia's domestic industry development strategy must align with R&D efforts that keep pace with global technological advancements.

8. **To ensure responsible mining practices for mineral extraction and prepare for battery recycling and reuse**, Indonesia must enforce robust ESG standards, particularly in upstream activities, to secure international market access and support its ambition of becoming a regional battery hub. National regulations should adopt frameworks such as the Initiative for Responsible Mining Assurance (IRMA). Moreover, urban mining, which involves recovering materials from old batteries, needs to be developed, especially as nickel reserves are expected to be depleted within 6 to 34 years. This will help Indonesia maintain its strategic position as a regional hub. In the interim, while awaiting sufficient battery waste and advancements in recycling technology, repurposing waste EV batteries into BESS offers a promising business model for the country.

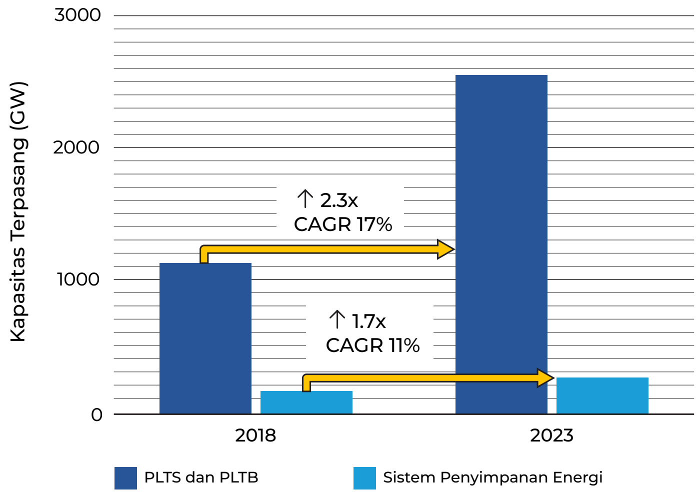

ENERGY
STORAGE SYSTEM

Ringkasan Eksekutif

- Dengan meningkatnya penggunaan energi surya dan angin secara global, teknologi penyimpanan energi menjadi sangat penting untuk mentransformasikan sistem kelistrikan yang masih bergantung pada bahan bakar fosil. Selain mengembangkan teknologi yang sudah matang, upaya dekarbonisasi mendorong pencarian teknologi penyimpanan energi jenis baru yang lebih terjangkau, seperti penyimpanan elektrokimia baru dan teknologi konversi hidrogen.

- Kapasitas instalasi sistem penyimpanan energi telah meningkat pesat dalam beberapa tahun terakhir, didorong oleh pertumbuhan cepat pembangkit listrik tenaga surya dan angin, yang kini menyumbang lebih dari 13% dari bauran listrik global. Antara tahun 2018 dan 2023, *compound annual growth rate* (CAGR) untuk *variable renewable energy* (VRE) dan *energy storage system* (ESS) masing-masing mencapai 17% dan 11%. Pertumbuhan terbesar terlihat pada *battery energy storage systems* (BESS), yang mengalami CAGR lebih dari 65% selama periode ini.

Pertumbuhan Kapasitas Sistem Penyimpanan Energi dibandingkan dengan Tenaga Surya PV dan Angin

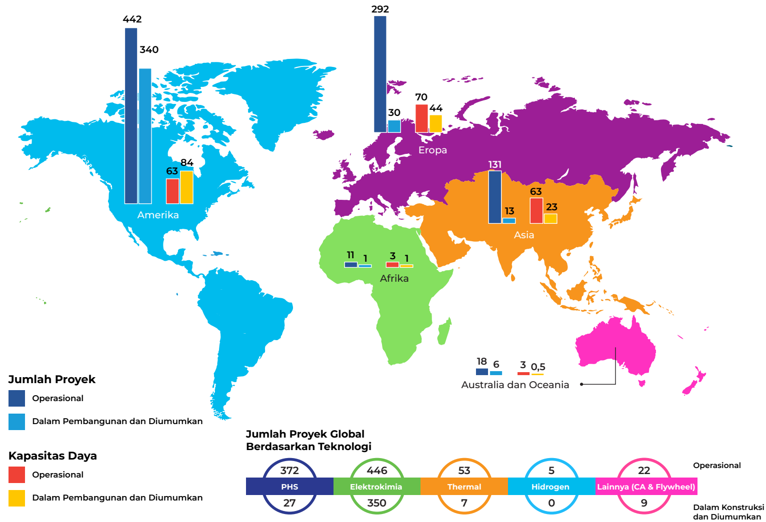


- Peningkatan jumlah proyek dan penelitian yang terus berlangsung telah membuat penyimpanan energi semakin layak secara ekonomi. Teknologi ini tidak hanya berguna untuk mendukung pembangkit energi terbarukan yang bersifat *variable*, tetapi juga sebagai aset untuk memperkuat jaringan listrik. Di tingkat pembangkit dan transmisi (*front-of-the-meter*), penyimpanan energi semakin banyak digunakan untuk membantu proses ramping pembangkit, menjadi alternatif yang kompetitif dibandingkan pembangkit listrik tenaga gas *peaker*, menunda investasi transmisi dan distribusi (T&D), hingga sebagai aset pemulihan darurat (*black start*). Sementara itu, di sisi konsumen (*behind-the-meter*), sistem penyimpanan energi (ESS) semakin banyak dipakai sebagai cadangan energi yang lebih bersih dan terjangkau dibandingkan genset, serta untuk menghemat tagihan listrik.

- Peran penyimpanan energi sangat bergantung pada desain pasar listrik dan aturan yang berlaku di setiap wilayah. Saat ini, penggunaan penyimpanan energi lebih umum di daerah yang memiliki pasar listrik kompetitif, seperti AS, Australia, dan sebagian besar Eropa. Secara teknis, tidak semua teknologi penyimpanan energi cocok untuk setiap fungsi, yang memengaruhi kelayakan ekonominya. Saat ini, baterai elektrokimia biasanya paling baik digunakan untuk penyimpanan jangka menengah, sementara teknologi penyimpanan mekanis seperti *pumped hydro storage* (PHS) dan *compressed air energy storage* (CAES) lebih cocok untuk aplikasi jangka panjang.

Ringkasan Eksekutif

Peta Global Instalasi Sistem Penyimpanan Energi



- Pertumbuhan tahunan *battery energy storage system* (BESS) hampir dua kali lipat dalam tiga tahun terakhir, sementara kapasitas *pumped hydro storage* (PHS) meningkat sekitar 5 GW per tahun selama periode yang sama. Penambahan kapasitas PHS diperkirakan akan semakin cepat, dan bisa mencapai rekor 35 GW pada tahun 2024. Menurut database Departemen Energi AS, saat ini ada sekitar 390 proyek *energy storage system* (ESS) di seluruh dunia yang sedang dibangun atau diumumkan, dengan total kapasitas mencapai 152 GW.

- Laju instalasi ESS diperkirakan akan terus meningkat seiring dengan semakin kuatnya komitmen negara-negara untuk mencapai target emisi nol bersih pada tahun 2050. Menurut IEA, untuk mencapai target COP28 dalam melipatgandakan kapasitas energi terbarukan pada tahun 2030, diperlukan kapasitas ESS terpasang sebesar 1.500 GW (tidak termasuk penyimpanan hidrogen), dengan sekitar 80% di antaranya berasal dari BESS.

- Prospek pengembangan penyimpanan energi sangat menjanjikan dengan peningkatan investasi global di BESS melampaui $40 miliar pada tahun 2023, dua kali lipat dari tahun sebelumnya. Selama dua tahun terakhir, sebagian besar investasi BESS terkonsentrasi di Amerika Serikat, Tiongkok, dan Eropa, yang bersama-sama menyumbang sekitar 90% dari total investasi global. Meski BESS menjadi preferensi karena waktu pembangunannya yang cepat, rencana pengembangan ke depan juga harus mempertimbangkan tantangan rantai pasokan sel baterai dan fluktuasi harga mineral penting, yang mendorong kenaikan biaya BESS pada tahun 2022. Karena itu, kemampuan memproduksi komponen secara lokal dengan harga bersaing akan menjadi kunci bagi negara-negara yang ingin mengadopsi BESS.

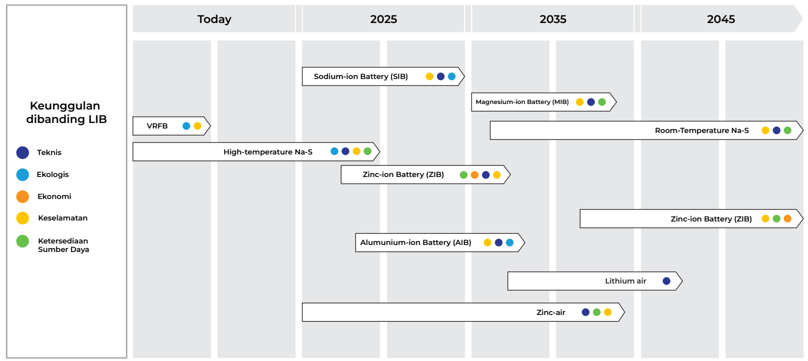
- Tingginya biaya penyimpanan energi telah memicu pendekatan baru, seperti *sector coupling*. Alih-alih membeli BESS baru, konsumen listrik dapat menghubungkan baterai kendaraan listrik (EV) mereka ke jaringan untuk menyimpan kelebihan energi dari panel surya dan menggunakannya sebagai cadangan. Cara ini meningkatkan nilai kepemilikan EV, memaksimalkan penggunaan baterai, dan mengurangi limbah penyimpanan energi. Skema *vehicle-to-grid* (V2G), yang memungkinkan pemilik EV untuk “menjual” listrik dari kendaraan mereka, sedang dikembangkan di beberapa negara. Agar V2G berhasil, dibutuhkan peningkatan pada model bisnis, regulasi, kekuatan jaringan, dan infrastruktur. Selain itu, data akan menjadi sangat penting dalam V2G, sehingga perlindungan data dan keamanan siber juga perlu diperhatikan.

- Pendekatan *sector coupling* lain yang menjanjikan selain V2G adalah *Power-to-Gas* (P2G), terutama dengan menggunakan hidrogen. Metode ini memanfaatkan kelebihan listrik untuk menghasilkan hidrogen murah, yang kemudian dapat disimpan dan dikonversi kembali menjadi listrik menggunakan teknologi *fuel cell* atau mesin pembakaran. Hidrogen juga bisa menjadi pengganti bahan bakar fosil di sektor transportasi dan industri.

Ringkasan Eksekutif

- Peran penyimpanan energi dalam jaringan listrik sedang mengalami perkembangan pesat karena integrasi *variable renewable energy* (VRE) dan perubahan perilaku konsumen. Hal ini memunculkan berbagai aplikasi dengan kebutuhan teknis yang berbeda-beda. Saat ini, *pumped hydro storag*e (PHS) dan *battery energy storage systems* (BESS) mendominasi pasar, tetapi keragaman peran ini mendorong inovasi dan pengembangan teknologi baru. Misalnya, di segmen panel surya *off-grid*, yang sebagian besar menggunakan baterai elektrokimia lithium-ion (LIB), juga terdapat penggunaan *flow batteries* dan PHS skala kecil dengan sistem *close-loop*. Di sektor industri, BESS dapat dipadukan dengan superkapasitor dan *flywheels* untuk meningkatkan kinerjanya.

Peta jalan Pengembangan Teknologi Penyimpanan Energi Elektrokimia Global



- Beberapa teknologi, seperti *flow batteries* dan baterai natrium-sulfur bersuhu tinggi (HT Na-S), sudah cukup maju secara teknis, tetapi masih menghadapi tantangan permintaan pasar dan pertumbuhan yang terbatas. Namun, terjadi pergeseran pasar dari penyimpanan durasi pendek (sekitar 2 jam) ke penyimpanan durasi lebih lama, terutama untuk aplikasi pengalihan energi *(energy-shifting)*, yang mana ESS berbasis lithium-ion (LIB) menjadi lebih mahal. Diperkirakan, baterai non-lithium akan menyumbang lebih dari 10% dari pasar penyimpanan stasioner pada tahun 2025, naik dari kurang dari 5% pada tahun 2021. Tren ini didorong oleh semakin matangnya teknologi alternatif, seperti baterai natrium-ion (SIB), yang kini memasuki fase pra-komersial. Selain itu, beberapa teknologi yang sudah ada mulai ditinjau ulang dan diperbaiki seiring meningkatnya permintaan.

- Dalam penelitian baterai, para ahli telah memperkirakan jadwal komersialisasi untuk berbagai alternatif teknologi lithium-ion dan memproyeksikan keunggulan masing-masing dibandingkan dengan standar saat ini. Baterai ion-logam berbasis natrium diperkirakan akan menjadi yang pertama memasuki pasar penyimpanan energi, merebut pangsa pasar dari LIB, diikuti oleh opsi ion-logam lainnya seperti magnesium dan seng. Teknologi yang lebih eksperimental, seperti baterai lithium-udara dan baterai aliran polimer *(polymer-based flow batteries)*, diprediksi akan muncul di pasar pada tahap berikutnya. Selain itu, solusi penyimpanan mekanis juga mulai mendapatkan perhatian kembali, dengan adanya inovasi seperti sistem PHS bawah tanah atau berbasis air laut yang sedang dieksplorasi.

- Untuk penyimpanan musiman *(seasonal storage)*, hidrogen muncul sebagai pilihan paling menjanjikan, meski aspek ekonominya cukup kompleks. Sel bahan bakar dua arah *(bi-directional fuel cell)* yang stasioner merupakan konfigurasi dasar dari sistem penyimpanan hidrogen untuk jaringan listrik. Sistem ini terdiri dari tiga teknologi utama: elektroliser untuk produksi hidrogen, media penyimpanan hidrogen, dan *fuel cell* untuk mengubah hidrogen kembali menjadi listrik. Penelitian tentang teknologi ini terutama berfokus pada peningkatan efisiensi sistem dan pengembangan bahan baru. Komersialisasi besar-besaran penyimpanan hidrogen untuk sektor kelistrikan diperkirakan akan terjadi setelah tahun 2030, terutama didorong oleh ketersediaan teknologi pembangkit listrik yang lebih murah.

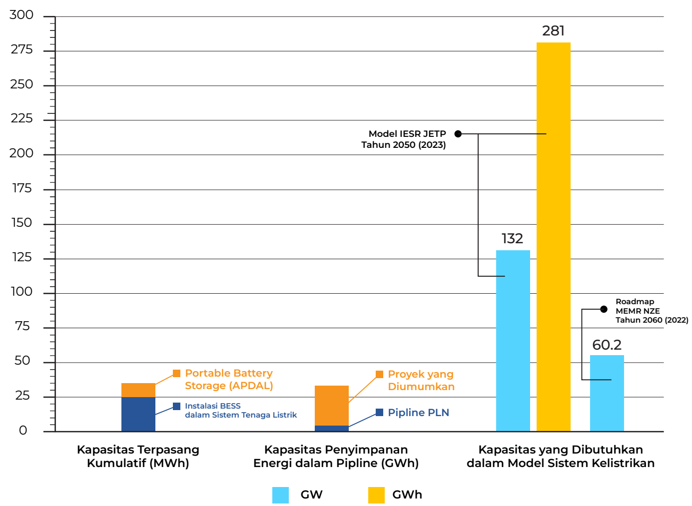
Ringkasan Eksekutif

- Penyimpanan energi akan menjadi aset penting dalam mengubah sektor kelistrikan Indonesia untuk mencapai *Net-Zero Emission* (NZE). Dengan proyeksi bahwa tenaga surya dan angin akan menyumbang 77% dari total kapasitas pembangkit terpasang (421 GW dari solar PV dan 94 GW dari angin) pada tahun 2060, setidaknya 60,2 GW penyimpanan energi akan diperlukan. Namun, adopsi yang luas masih menghadapi tantangan karena kemajuan yang lambat dalam pengembangan energi terbarukan. Sebagian besar pertumbuhan saat ini terjadi pada sumber energi hidro dan geotermal yang bersifat *dispatchable*, sedangkan *variable renewable energy* (VRE) hanya menyumbang 5,5% dari total kapasitas terbarukan yang terpasang, dan saat ini tidak ada sistem penyimpanan energi besar yang beroperasi.

- Beberapa pelopor inisiatif instalasi teknologi *energy storage system* (ESS) berasal dari sektor swasta dan daerah terpencil yang didukung oleh hibah untuk meningkatkan akses listrik. Dari 25 proyek *battery energy storage system* (BESS) yang teridentifikasi dengan kapasitas lebih dari 100 kWh, 13 proyek dikembangkan oleh PLN, sementara sisanya oleh industri swasta, hotel, dan kawasan konservasi. Sektor swasta yang selama ini bergantung pada generator diesel yang mahal telah mulai menggunakan BESS skala menengah sejak tahun 2015. Disisi lain, sektor rumah tangga yang terhubung ke jaringan listrik belum mendapatkan manfaat dari instalasi BESS. Proyek yang diprakarsai oleh donor asing dan pemerintah sering menghadapi tantangan dalam pemeliharaan, dan banyak unit dilaporkan mengalami kerusakan.

- Proyek ESS yang diumumkan diharapkan dapat meningkatkan kapasitas penyimpanan energi terpasang di Indonesia hingga 1.000 kali lipat. Saat ini, RUPTL PLN 2021–2030 hanya merencanakan 4,2 GW untuk *pumped hydro storage* (PHS) dan penggunaan BESS yang terbatas, terutama untuk program konversi diesel. Upper Cisokan PHS, yang sedang dibangun dan dijadwalkan selesai pada tahun 2027, diharapkan menjadi ESS berskala besar pertama yang memperkuat jaringan listrik. Menurut peta jalan pemerintah, adopsi BESS yang lebih luas kemungkinkan akan terjadi setelah tahun 2034 seiring meningkatnya penetrasi VRE dan turunnya harga baterai. Namun, skema ekspor listrik ke Singapura bisa mempercepat penerapan BESS, dengan kapasitas proyek yang direncanakan sudah mencapai sekitar 29 GWh.

Kapasitas Penyimpanan Energi yang Terpasang, Proyek yang Diumumkan, dan Kapasitas yang Diperlukan untuk Mencapai *Net-Zero Emission* (NZE) di Indonesia



- Teknologi hidrogen diharapkan menjadi aset kunci untuk memperkuat ketahanan energi negara dan sedang dipromosikan untuk digunakan di semua sektor. Pada tahun 2023, pemerintah merilis Strategi Hidrogen Nasional, dan saat ini negara ini memproduksi hidrogen terbarukan dari 23 *green hydrogen plants* (GHP) dengan *output* tahunan sebesar 254 ton. Melihat ke depan, berdasarkan kemajuan proyek yang diumumkan, kapasitas total produksi hidrogen terbarukan diperkirakan akan mendekati 2 juta ton.

Ringkasan Eksekutif

Karakteristik yang ada yang memberikan peluang untuk penerapan sistem penyimpanan energi di Indonesia

Ciri-ciri	Deskripsi
Beberapa sistem terisolasi dengan sumber energi terbatas	- Di beberapa daerah terpencil, terutama yang memiliki sumber energi terbatas dan tidak terhubung ke jaringan, akses terhadap listrik sering kali terbatas hanya untuk penerangan. - Pembangkitan listrik menggunakan sistem solar PV ditambah penyimpanan bisa lebih *cost-effective* dibandingkan dengan generator bahan bakar fosil seperti generator diesel.
Keandalan dan efisiensi sistem tenaga yang rendah di sistem kecil	- Ada potensi untuk meningkatkan efisiensi sistem berdasarkan faktor beban sistem yang rendah, terutama di beberapa sistem kecil. - Tingkat gangguan sistem yang lebih tinggi dari rata-rata di sistem kecil menunjukkan potensi untuk penerapan ESS sebagai sumber daya cadangan atau untuk menunda pembangunan sistem transmisi dan distribusi (T&D). - Sistem dengan tingkat penetrasi VRE yang tinggi mulai terpengaruh oleh variabilitas *output* VRE.
Fleksibilitas rendah dalam bauran pembangkitan saat ini untuk mengakomodasi integrasi VRE yang cepat	- Rencana untuk memperluas kapasitas VRE secara signifikan untuk mencapai target *net zero emissions* (NZE) akhir akan memerlukan penyimpanan energi yang besar dan serbaguna untuk memfasilitasi integrasi VRE yang cepat. - Jumlah aset jaringan yang ada yang dapat dioperasikan dengan fleksibilitas terbatas.

Ringkasan Eksekutif

- Meskipun beberapa aspek teknis dari sistem kelistrikan saat ini belum sepenuhnya mendukung pengembangan penyimpanan energi berskala besar, masih ada peluang besar untuk penerapannya yang perlu dimaksimalkan sebagai langkah awal dalam memperluas perannya di jaringan listrik Indonesia. Beberapa faktor yang membatasi penggunaan *energy storage systems* (ESS) berskala besar di Indonesia antara lain pertumbuhan *variable renewable energy* (VRE) yang lambat, rendahnya urgensi untuk ESS sebagai aset peaker, dan fokus pada pengembangan aset penguat jaringan lain yang memiliki fungsi serupa. Jaringan listrik utama di Indonesia saat ini berada pada Tahap 1 transisi energi, di mana integrasi VRE tidak berdampak signifikan pada stabilitas sistem, sehingga mengurangi kebutuhan mendesak akan ESS untuk mendukung VRE. Selain itu, pertumbuhan permintaan listrik dan beban puncak yang lambat telah diatasi dengan peningkatan kapasitas pembangkit. Rencana Umum Penyediaan Tenaga Listrik (RUPTL) PLN menunjukkan bahwa sekitar 48% sumber pembangkit yang direncanakan hingga tahun 2030 adalah aset yang bersifat *fast-response*, yang semakin membatasi peran ESS.

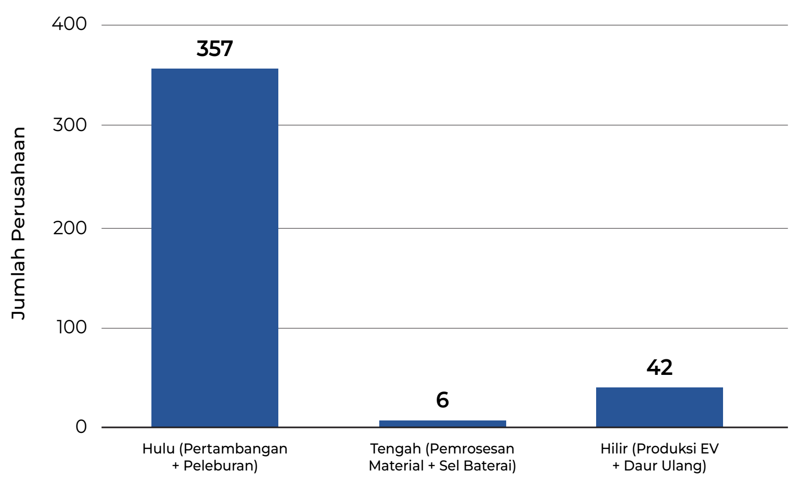
- Peluang kunci untuk penggunaan awal ESS meliputi kebutuhan peningkatan tingkat elektrifikasi dan perbaikan keandalan serta efisiensi dari jaringan kecil. Indonesia memiliki banyak jaringan listrik terisolasi dengan sumber daya energi yang terbatas dan tingkat elektrifikasi yang masih rendah. Dari tingkat elektrifikasi sebesar 99,78% pada tahun 2023, sekitar 3% hanya merupakan pencahayaan dasar, yang dikategorikan sebagai akses listrik Tingkat 1. Keandalan sistem kelistrikan di Indonesia, terutama di luar Jawa, dapat dilihat dari nilai SAIDI dan SAIFI yang dilaporkan, dengan rata-rata masing-masing mencapai 8,17 jam dan 5,93 pemadaman per konsumen pada tahun 2023. Selain itu, rendahnya faktor beban di sistem ini menunjukkan perlunya aset pengendalian puncak (*peaker*) yang efisien, di mana ESS bisa menjadi solusi yang praktis.

- Di samping faktor teknis, kesiapan kerangka kebijakan juga sangat penting untuk mendorong permintaan dan menentukan kelayakan ekonomi pengembangan ESS. Saat ini, dokumen perencanaan jangka panjang untuk sektor kelistrikan belum sepenuhnya merekognisi berbagai peran dan manfaat dari berbagai jenis ESS stasioner, dan struktur pasar serta regulasi yang ada belum memberikan dukungan yang kuat. Rencana implementasi saat ini lebih memandang ESS sebagai aset sumber *bulk electricity* dan komponen pendukung untuk VRE. Namun, dengan menyesuaikan tarif listrik untuk aset ESS, memberikan insentif kepada para pemasang, dan mendefinisikan secara jelas berbagai peran penyimpanan energi dalam sistem kelistrikan untuk memungkinkan skema penumpukan nilai, kelayakan ekonomi ESS dapat ditingkatkan. Selain menutup kesenjangan regulasi, penting untuk membangun kerangka pengadaan (*procurement framework*) yang transparan dan efisien guna mengurangi risiko pengembangan serta membangun kepercayaan investor terhadap proyek ESS.

Ringkasan Eksekutif

- Indonesia menghadapi sejumlah tantangan besar dalam upayanya membangun rantai pasokan baterai untuk *electric vehicle* (EV). Produsen EV mulai beralih dari penggunaan baterai berbasis nikel, dan kekhawatiran terkait *environmental, social, and governance* (ESG) di area pertambangan juga menghambat pertumbuhan industri ini. Dominasi smelter RKEF di Indonesia tidak sejalan dengan rencana pemerintah untuk menciptakan rantai pasokan baterai EV yang komprehensif. Selain itu, sektor midstream kurang mendapat perhatian, dan perkembangannya jauh lebih lambat dibandingkan dengan sektor hulu dan hilir. Masalah ESG menjadi perhatian utama yang mengurangi minat investor. Di samping itu, permintaan domestik terhadap baterai masih terbatas, sehingga menghambat kapasitas produksi produsen lokal. Untuk bersaing di pasar global, diversifikasi teknologi baterai sangat penting, terutama untuk sistem baterai berskala besar, karena kapasitas yang ada saat ini masih belum cukup untuk menghadapi kompetitor internasional.

Perkiraan Jumlah Perusahaan dalam Rantai Pasokan Baterai EV



- Kemampuan untuk mengelola baterai EV bekas, selain memproduksi baterai baru, menjadi hal penting bagi Indonesia. Ini akan membantu mengoptimalkan nilai sisa baterai, menekan biaya dalam *battery energy storage systems* (BESS), dan mengurangi dampak lingkungan. Langkah ini juga penting bagi Indonesia untuk memposisikan diri sebagai pemain utama dalam industri manufaktur baterai di kawasan ini.

- Indonesia memiliki sumber daya energi terbarukan yang melimpah, dengan total mencapai 3.698 GW dan potensi untuk memproduksi hidrogen hijau minimal 185 GWh. Dengan biaya produksi terendah sebesar USD 1,9/kg, yang mungkin akan turun di masa mendatang, Indonesia memiliki posisi yang sangat kompetitif di pasar global. Keunggulan ini memungkinkan Indonesia tidak hanya untuk memenuhi permintaan domestik tetapi juga menjadi eksportir hidrogen global. Namun, adopsi hidrogen di Indonesia masih dalam tahap awal. Permintaan pasar belum terbentuk, dan teknologi untuk produksi dan penggunaan hidrogen masih dalam pengembangan. Selain itu, ekosistem untuk adopsi hidrogen belum ideal, dengan biaya modal yang tinggi untuk pembangkit listrik berbasis energi terbarukan dan elektroliser menjadi hambatan utama. Saat ini, investasi dari pelaku industri terhenti karena menunggu kepastian dari pemerintah mengenai target adopsi hidrogen. Hal ini menunjukkan perlunya komitmen politik yang lebih kuat agar Indonesia dapat menjadi pemimpin global dalam produksi dan teknologi hidrogen hijau.

Rekomendasi

- Penyimpanan energi sangat penting untuk mentransformasi sistem tenaga listrik agar lebih fleksibel dan efisien dalam mengintegrasikan lebih banyak energi terbarukan. Saat ini, Indonesia masih dalam tahap awal adopsi penyimpanan energi. Untuk mempersiapkan penggunaannya secara luas, ada beberapa langkah penting yang perlu diambil untuk mengatasi peluang dan tantangan yang ada, antara lain:

    1. **Memanfaatkan peluang yang tersedia untuk menerapkan *energy storage systems* (ESS)** sangat penting untuk memperluas perannya dalam sektor energi Indonesia. Saat ini, potensi terbesar untuk penerapan ESS terletak pada adopsi di sistem yang lebih kecil atau terisolasi. Selain itu, meningkatkan akses terhadap teknologi ESS yang terjangkau, terutama baterai, dan membangun keahlian para pemangku kepentingan di sektor ini akan sangat penting untuk meletakkan dasar bagi implementasi yang lebih luas dan berskala besar di masa depan.

    2. **Memperkuat kerangka regulasi dan kepastian hukum** untuk memberikan kompensasi yang memadai bagi ESS atas nilai tambahnya, sehingga mengurangi risiko pengembangan serta meningkatkan kepercayaan investor terhadap inisiatif ESS. Perencanaan ESS harus diintegrasikan ke dalam perencanaan transmisi, distribusi, dan pembangkit listrik di Indonesia, sejalan dengan peningkatan instalasi VRE. Selain menetapkan target kapasitas, dokumen perencanaan harus mendefinisikan seluruh potensi fungsi ESS. Saat ini, fokus utama masih pada fungsi *smoothing* dan *capacity firming* serta belum membuka peluang teknologi di luar *Battery Energy Storage Systems* (BESS) dan *Pumped Hydro Storage* (PHS). Setelah dokumen perencanaan diperbarui, regulasi tambahan akan diperlukan, termasuk penyesuaian *grid code* untuk mencerminkan kemampuan dan perkembangan teknis terbaru. Selain itu, kebijakan pendukung untuk *long-duration* ESS juga perlu dieksplorasi lebih lanjut.

    3. **Mengadopsi praktik terbaik dari negara lain.** Negara-negara seperti Amerika Serikat, Inggris, dan Australia, yang telah melakukan penerapan ESS yang signifikan, mengikuti strategi serupa: kebijakan yang mendukung dengan fokus pada tiga area utama—sinyal pasar yang kuat, mekanisme pendapatan inovatif, dan regulasi yang memfasilitasi dukungan industri serta investasi R&D. Negara-negara ini telah menetapkan target kapasitas spesifik untuk ESS dan *variable renewable energy* (VRE), serta memperkenalkan harga karbon, jadwal tender, dan kerangka pengadaan. Berbagai peran ESS juga telah dikembangkan menjadi skema penumpukan nilai, yang meningkatkan kelayakan ekonomi kepemilikan ESS.

    4. **Meningkatkan keekonomian proyek ESS** yang dapat dicapai dengan menyesuaikan tarif listrik untuk aset ESS, memberikan insentif kepada pemasang, dan secara jelas mendefinisikan peran ESS dalam sistem kelistrikan untuk memungkinkan skema *value-stacking*. Selain itu, penghapusan subsidi bahan bakar fosil bagi utilitas akan menciptakan lapangan yang lebih setara (*level of playing field*) untuk pengembangan VRE dan ESS, memungkinkan kombinasi keduanya menyediakan listrik andal dengan biaya kompetitif dan menjadi alternatif pembangkit listrik berbahan bakar gas dan batu bara.

5. **Menginisasi proyek pilot untuk menguji berbagai opsi teknologi ESS.** Pengalaman dalam mengembangkan proyek ESS di Indonesia masih sangat terbatas, dan keahlian lokal perlu diperkuat. Melalui perencanaan, pemerintah harus mendorong utilitas untuk menguji berbagai teknologi penyimpanan energi yang baru muncul guna lebih memahami karakteristik, kinerja, dan interoperabilitasnya dalam sistem kelistrikan. Dukungan finansial atau hibah harus disediakan untuk proyek-proyek pilot ini, dengan pendanaan tidak hanya untuk utilitas tetapi juga untuk lembaga penelitian dan universitas.

6. **Menerapkan pendekatan inovatif dengan integrasi sektor (*sector coupling*).** Contoh skema *Vehicle-to-Grid* (V2G) menunjukkan bagaimana upaya dekarbonisasi di sektor transportasi dapat menguntungkan sektor ketenagalistrikan dengan mengurangi kebutuhan investasi mahal untuk baterai baru. Namun, perbaikan teknis pada jaringan listrik diperlukan untuk mendukung V2G. Selain itu, kebijakan dan model bisnis yang jelas harus ditetapkan agar V2G menjadi layak dan menarik. Selain V2G, konsep *power-to-x*, khususnya menggunakan hidrogen sebagai *feedstock* energi yang serbaguna, juga perlu dikembangkan lebih lanjut.

7. **Membangun Ekosistem Teknologi Penyimpanan dan Rencana R&D.** Variasi biaya instalasi ESS di berbagai negara dipengaruhi oleh berbagai faktor, seperti skala proyek, biaya tenaga kerja, dan ketersediaan rantai pasokan teknologi yang kuat. Saat ini, China memimpin dalam hal ini berkat *soft costs* yang relatif rendah dan kapasitas produksi perangkat keras yang maju, terutama dalam sel baterai lithium iron phosphate (LFP). Ketika Indonesia mulai mengembangkan ekosistem baterainya, negara ini harus mengantisipasi pergeseran pasar, seperti munculnya teknologi baterai natrium-ion (SIB) yang diperkirakan dapat merebut pangsa pasar dari baterai berbasis LFP. Agar tetap kompetitif, strategi pengembangan industri domestik Indonesia harus sejalan dengan upaya R&D yang mengikuti kemajuan teknologi global.

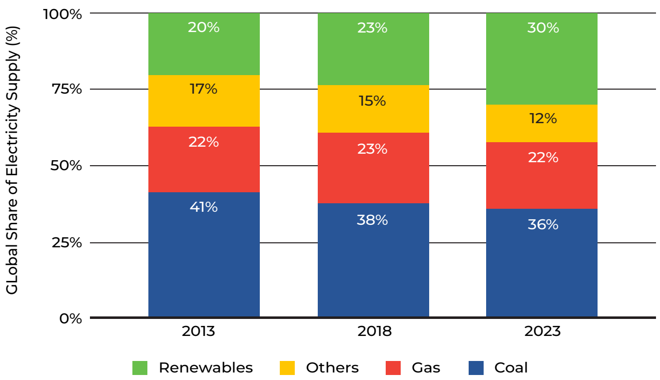
8. **Memastikan praktik penambangan yang bertanggung jawab dan mempersiapkan skema daur ulang (*repurposing*) serta *urban mining* di masa depan,** Indonesia harus menerapkan standar ESG (Lingkungan, Sosial, dan Tata Kelola) yang kuat, terutama dalam aktivitas hulu, untuk mengamankan akses pasar internasional dan mendukung ambisi menjadi pusat baterai regional. Peraturan nasional harus mengadopsi kerangka kerja seperti *Responsible Mining Assurance* (IRMA). Selain itu, penambangan kota (*urban mining*), yang melibatkan pemulihan bahan dari baterai bekas, perlu dikembangkan, terutama karena cadangan nikel diperkirakan akan habis dalam waktu 6-34 tahun. Ini akan membantu Indonesia mempertahankan posisinya yang strategis sebagai pusat regional. Sementara itu, sambil menunggu cukupnya limbah baterai dan kemajuan dalam teknologi daur ulang, pemanfaatan ulang *(repurposing)* baterai EV bekas menjadi *Battery Energy Storage Systems* (BESS) menawarkan model bisnis yang menjanjikan bagi Indonesia.

The Energy Storage Roles in Power System

- The recent surge in solar and wind energy use in power systems
- Challenges in integrating variable renewable energy
- The growing role of energy storage in power systems

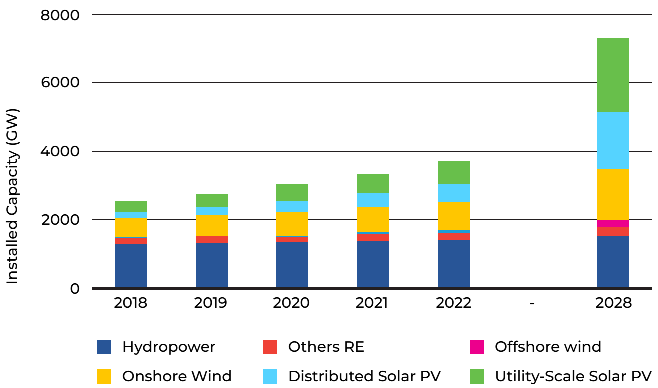
Solar PV and wind currently account for over 13% of global electricity production and are projected to exceed the share of hydropower within the next two years

The shift of global electricty supply mix 2013-2023



Source : IEA, 2023d

The historical capacity growth of renewable power (2018-2022) and the forecasted capacity in 2028



Source : IEA, 2024f

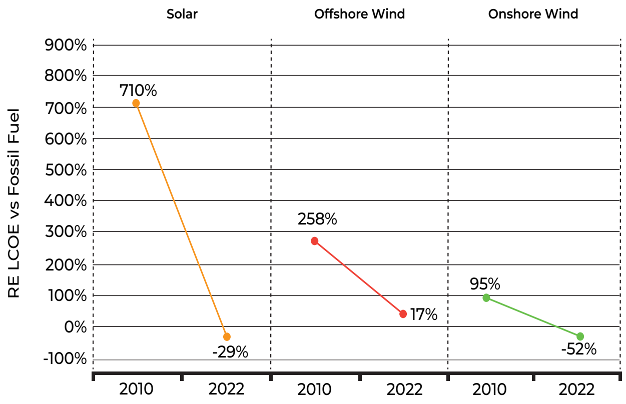
- As of 2023, renewable energy (RE) comprises 30% of the global electricity mix, with solar PV and wind showing remarkable growth. These sources have expanded nearly fivefold (around 17% CAGR) over the past decade, now constituting 13% of the mix (IEA, 2023d). Before the COVID-19 pandemic, there was a significant increase in net additions of solar PV and wind capacity, but growth slowed during the pandemic, rebounding by 2022. Notably, offshore wind installations have seen substantial growth, and recent additions in distributed photovoltaic (PV) capacity nearly matched new utility-scale installations (IEA, 2024f).

- Hydropower remains the largest contributor to clean electricity, accounting for 48%, while solar PV and wind together make up 44%. Despite having lower installed capacity, hydropower's predictability and higher availability result in greater electricity generation. However, with the projected increase in solar PV and wind installations, their combined share is expected to surpass hydropower by 2025, making up nearly two-thirds of all renewable energy by 2028. By 2050, solar PV and wind are expected to contribute nearly 70% of electricity generation (IEA, 2021). In addition to the growing number of projects, advancements in energy storage capacity are enabling variable renewable energy (VRE) to operate more efficiently.

- New VRE installations are projected to meet rising electricity demand and replace fossil fuel generators, leading to reduced reliance on coal-fired power plants (CFPPs). Despite global CFPP capacity growing by around 9% since the Paris Agreement, plant retirements and project cancellations have occurred (Cui et al., 2023). Additionally, some fossil fuel plants have reduced their operating levels, replacing generation with cheaper renewable sources, thereby lowering fuel cost-sensitive operational expenses.

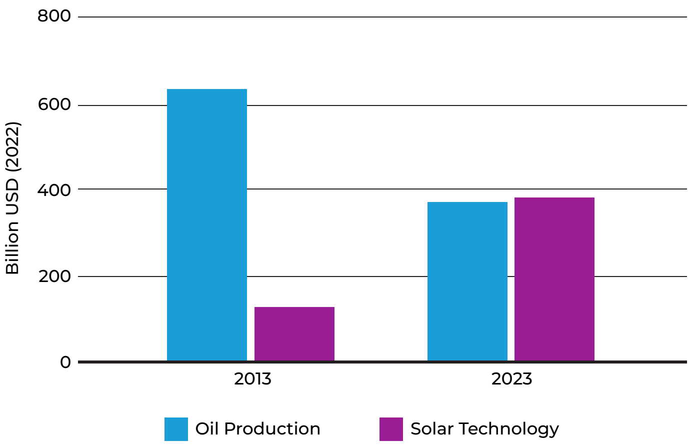
Investment in VRE continues to rise as technology costs decline

The change of VRE electricity costs competitiveness



Source : IRENA, 2023b

The comparison of solar investment against oil production investment in 2013 and 2023



Source : IEA, 2023h

- The reduction in technology costs has been the primary driver of VRE (Variable Renewable Energy) growth, further supported by governments worldwide committing to emission reductions and implementing supportive policies. Over the past seven years, key VRE components have experienced significant price drops. PV module prices, for instance, have fallen by more than 50%, now costing approximately 300 USD/kW. Inverters and energy storage systems (ESS) for solar PV have also become more affordable, with battery-based ESS prices dropping from 2,500 USD/kW to under 1,000 USD (Ramasamy et al., 2023).

- Today, VRE ranks among the cheapest power generation options, with solar PV and onshore wind having a global weighted-average levelized cost of electricity (LCOE) below USDc5/kWh in 2022, 29% and 52% lower than the cheapest fossil fuel generators, respectively (IRENA, 2023b). Their reduced environmental impact, including lower greenhouse gas (GHG) emissions, has boosted public trust and preference. Intermittency issues have been effectively addressed through advanced energy storage and smart grid technologies. Recent reports suggest that VRE remains economically competitive with conventional fossil fuel generators, even when accounting for additional energy storage costs under specific circumstances (Lazard, 2023).

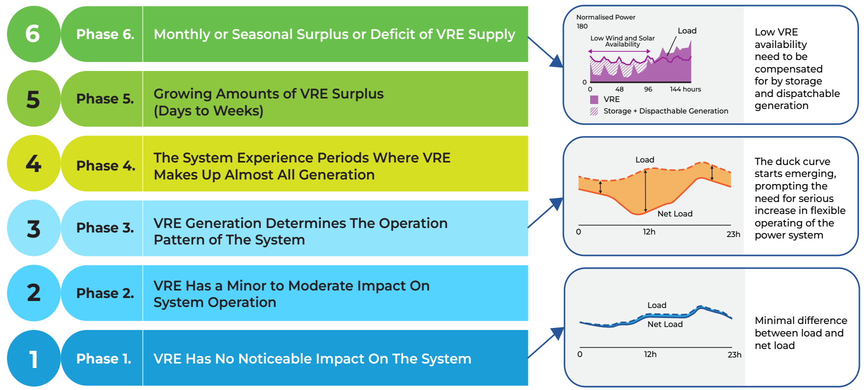
- The recent development of VRE has attracted significant investment, with solar PV leading the way and surpassing fossil fuel generation investment threefold in 2022 (IEA, 2023g). Additionally, solar investments are expected to exceed spending on upstream oil in 2023, reaching USD 382 billion for the year (IEA, 2023h). It is worth noting that investment is critical not only for project development but also for scaling up manufacturing and research and development of low-cost advanced technologies to accelerate deployment levels.

High VRE penetration will require enabling infrastructure to maintain power system stability

- When VRE penetration reaches approximately 6%*, further integration will require support from aggregators or enablers. Some early-transition countries (those in Phase 1, where VRE has no noticeable impact) can initially incorporate VRE with ease. However, if their systems are dominated by inflexible power plants, this may limit further expansion. In Phase 2, VRE begins to affect system stability, prompting the need for grid asset adjustments. In later phases, VRE will dictate the system's operation, necessitating a comprehensive overhaul and reinforcement of the entire system.

- To address stability issues, flexibility solutions have been developed, with energy storage systems (ESS) being among the most popular enablers. Since each solar and wind source has unique intermittent characteristics, ranging from seconds to days, ESS can be valuable in different phases of VRE integration. From early Phase 2, ESS can smooth VRE output and continue to be useful through Phase 6 as a form of seasonal energy reserve.

The phases of VRE integration and their respective impact



Source: Adapted from IEA's Six phases of Variable Renewables Integration Infographic

Note:

*depends on several condition of specifi c power grid. This value is based on study report assessing power grid in Indonesia (EBTKE & DEA, 2021).

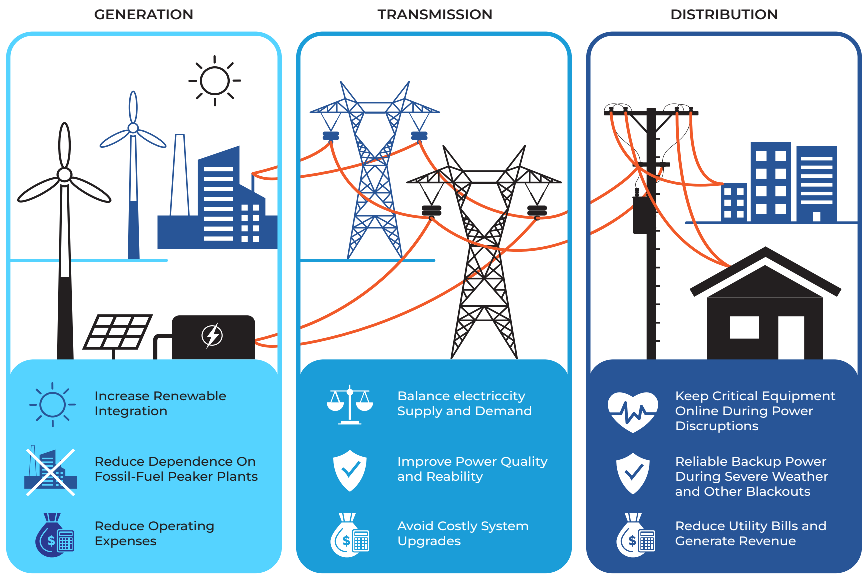
- ESS is not a singular flexibility solution, but its versatility is crucial for VRE integration, especially in less flexible systems or those with limited generation sources. For instance, solar PV projects in areas with high solar potential often incorporate large-capacity energy storage to maximize the availability of daily sunlight. On the other hand, studies indicate that in some regions, VRE penetration can reach 72% without the need for energy storage (Tong et al., 2021), depending on the electricity demand profile and the overall strength of the power grid. In several European countries with abundant wind resources, high VRE shares have been integrated without extensive ESS, thanks to wind's ability to generate electricity around the clock. Nonetheless, these countries continue to invest in the development of seasonal energy storage.

As costs drop, ESS utilization is not limited to supporting VRE alone. ESS is widely used as a fast-response grid asset, competing with gas power plants

- ESS not only helps integrate VRE by smoothing or time-shifting electricity output, but also serves vital roles for electricity producers, grid operators, and consumers. Traditionally, these roles were filled by fast-response fossil-fuel generators, such as grid peaker gas plants or consumer-sited diesel generators. As technology costs decrease, ESS is becoming a more practical and widely adopted solution.

- For power producers and grid operators, ESS improves electricity quality, enhances system reliability, and reduces operational costs. Even without VRE, grid fluctuations make ESS useful for frequency regulation and supporting slow-ramping generators, helping to avoid inefficient ramping, which shortens lifespan and increases maintenance costs (Palacio et al., 2014). During electricity demand surges, ESS discharge can be more cost-effective than operating a peaker gas plant, which can be 30% more expensive (Clean Energy Council, 2021). Moreover, large-capacity ESS can defer grid expansion and maintain power during blackouts caused by generator or transmission failures.

Energy storage value for electricity producer, grid operator, and consumers



Source : Adapted from Global X ETFs, 2022

- For consumers, ESS is frequently deployed as a backup power source, particularly for solar PV users. This is crucial for facilities like hospitals or industries that require uninterrupted power. Additionally, ESS can help reduce electricity bills in areas that implement 'time-of-use' tariffs or demand charges.

Various ESS roles have minimum technological characteristic criteria, and their implementation is influenced by local regulations

- Among ESS options, electrochemical batteries are generally best suited for medium-duration roles, while mechanical storage technologies such as pumped hydro storage (PHS) and compressed air energy storage (CAES) are more suitable for longer-duration applications. Each ESS type possesses distinct characteristics, such as cyclability and response time, which are critical for specific roles. For instance, primary response roles like frequency and voltage regulation require response times within seconds, rendering them unsuitable for conventional PHS, which typically takes minutes to respond. Conversely, for roles where rapid response is less critical, technologies like PHS and CAES, with their extended lifespans and high cyclability, offer cost-effective solutions.

Diagram of several energy storage roles in power systems with applicable technologies and their respective requirements

Application	Size (MW)	Duration (Hours)	Cycles (Per Year)	Response Time (Seconds)	PHES and CAES	Flywheel and Supercaps	Li-ion, Na-ion, Lead-acid, and Na-S Batteries	VRFB and Hydrogen
	Typical Technical Specification				**Suitable Technologies**			
1. Energy Arbitrage	<1 to 2000	1 to 24	50 to 400	>10	✓	X	✓	✓
2. Primary Response	1 to 2000	<1 to 1	250 to 15000	<10	X	✓	✓	✓
3. Secondary Response	10 to 2000	<1 to 24	20 to 10,500	>10	✓	✓	✓	✓
4. Tertiary Response	5 to 1000	>1.5	20 to 50	>10	✓	X	✓	✓
5. Peaker Replacement	1 to 500	2 to 6	5 to 100	>10	✓	X	✓	✓
6. Black Start	<1 to 500	<1 to 46	1 to 20	>10	✓	✓	✓	✓
7. Seasonal Storage	500 to 2000	24 to 2000	1 to 5	>10	✓	X	X	✓
8. T&D Deferral	1 to 500	2 to 8	10 to 500	>10	✓	X	✓	✓
9. Congestion Management	1 to 500	1 to 4	50 to 500	>10	✓	X	✓	✓
10. Bill Management	<1 to 10	1 to 6	50 to 500	>10	X	X	✓	✓
11. Power Quality	<1 to 10	<1	10 to 200	<10	X	✓	✓	✓
12. Power Reliability	<1 to 10	2 to 10	50 to 400	>10	X	X	✓	✓

Source : Adapted from Schmidt et al., 2019

- The deployment of ESS is shaped by local electricity market designs and regulations, which have driven rapid growth in certain countries. In competitive electricity markets, ESS can assist in bill management and provide financial benefits to owners, resulting in widespread consumer-sited ESS installations in several European countries, including Germany and Italy. Moreover, roles such as primary to tertiary response can attract investment in regions with ancillary services or capacity markets, as seen in countries like the UK and Australia. In contrast, in countries such as Indonesia, the potential of ESS remains largely untapped. To fully realize its value, it is essential to define ESS roles within regulatory frameworks and development plans, allowing ESS to play a more prominent role in the power system.

Energy Storage System (ESS) Deployment Trends

- Global energy storage capacity growth and rising deployment targets
- Investment trends and shifting roles driven by global decarbonization ambitions
- Increasing interest in coupling power and transport sectors and utilizing hydrogen
- Supportive policies implemented by early adopter nations

The global installed capacity of ESS has grown significantly, and it is projected to increase twentyfold by 2030

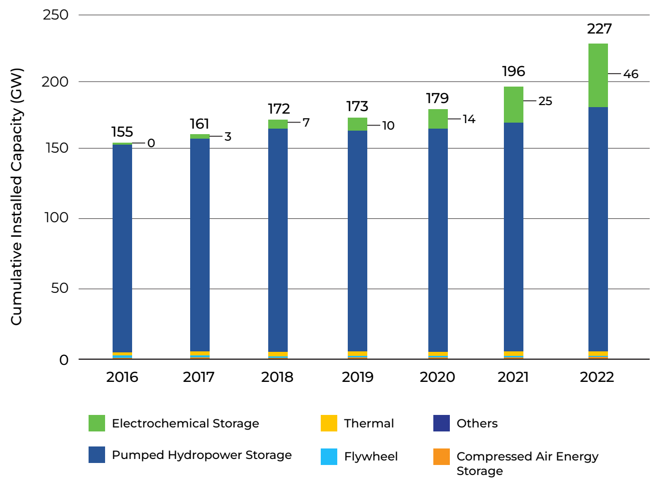
- It is estimated that by the end of 2022, more than 200 GW of energy storage capacity had been installed globally, representing about 41% growth over the past six years. Among these technologies, mechanical-type PHS is one of the most mature, implemented in many regions worldwide and dominating in terms of installed capacity.

- BESS is the fastest-growing technology, with installed capacity increasing more than tenfold between 2018 and 2023, reaching an estimated 86 GW. In 2023 alone, over 40 GW was added. Significant VRE integration has prompted countries to mandate power grid stability improvements through storage solutions. The rapid expansion of BESS is further driven by decreasing technology costs and enhanced performance through extensive research.

- Grid-scale ESS (in-front of meter) capacity installations, typically at the megawatt scale and connected to large power grids, have recently outpaced customer-sited (behind-the-meter) ones. Among the three largest regions for global installations (China, the USA, and the EU), only the EU has a dominant share of behind-the-meter installations of newly installed energy storage, accounting for approximately 90% (IEA, 2024c). Factors contributing to this include high electricity rates and incentives for pairing rooftop solar PV with storage, as observed in countries like Germany and Italy.

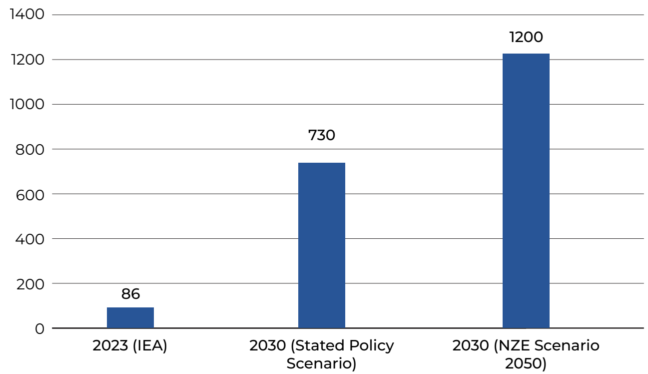
- The growth rate of ESS installations is expected to continue and accelerate if countries strengthen their commitment to achieving net-zero emissions by 2050. The IEA indicates that to meet the COP28 target of tripling renewable energy capacity by 2030, 1,500 GW of ESS installed capacity (excluding hydrogen storage) will be required. Approximately 80% of this capacity is expected to come from BESS. However, other technologies such as PHS are also projected to expand, with targets in countries like China (120 GW) and Indonesia (4 GW).

Global energy storage systems capacity growth



Source : IESR analysis from several reports

The projected capacity growth of BESS



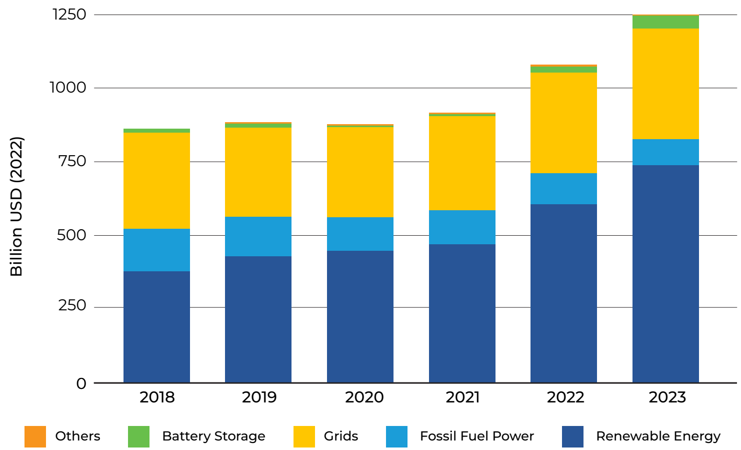
Source : IEA, 2024c

China, the United States, and the EU are the largest investors in BESS development, each supported by national-level policies

- Investment in ESS, particularly batteries, remains relatively small compared to other areas of the power sector. In 2023, global investment in battery energy storage systems (BESS) surpassed USD 40 billion, doubling from the previous year, with approximately 60% directed toward grid-scale systems. Despite this growth, BESS investment constitutes only 3% of total power sector investment. However, this share is expected to rise in the coming years, as meeting the target of tripling renewable energy capacity by 2030 will require annual BESS investment to grow by 25% per year. In comparison, investments in renewable power and grids will need to increase by 10% and 11% annually, respectively (IEA, 2024h).

- Over the past two years, BESS spending has been dominated by the United States, China, and Europe, which together account for approximately 90% of global expenditure. In 2023, both China and the U.S. each invested USD 11 billion in BESS, while the EU's investment reached USD 15 billion. This was largely driven by recent power price volatility, which has encouraged behind-the-meter BESS installations in the residential sector across several countries. Additionally, the auction scheme in the UK has reportedly attracted substantial investment in grid-scale energy storage development.

The global annual clean energy investment



Source : IEA, 2024c

- National-level support is expected to further boost storage investments in the coming years. China and the USA, projected to account for more than half of global storage deployments by 2030, are driving this growth through the 14th Five-Year Plan (FYP) and the Inflation Reduction Act (IRA), respectively. The FYP targets 40 GW of BESS by 2025, while the IRA aims to reduce battery storage capital costs by nearly 15%, stimulating investment. Significant expansion is also anticipated from the Asia-Pacific region, particularly India, which has set ambitious goals for battery storage and domestic technology development. This is supported by the National Electricity Plan draft (which targets 51 GWh of BESS by 2031-2032), more than USD 2 billion through the National Programme on Advanced Chemistry Cell (ACC) Battery Storage, and innovative "round-the-clock" tenders.

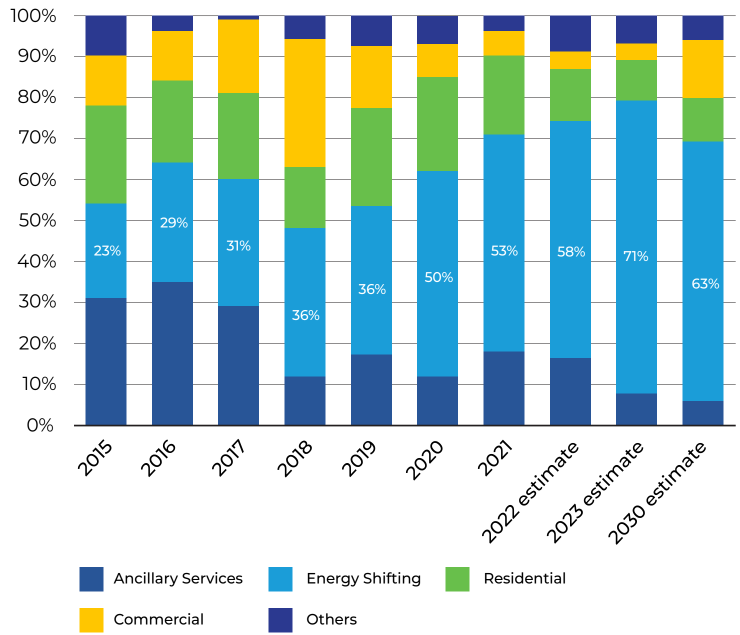
Longer-duration ESS for energy-shifting applications are expected to continue dominating, with the grid-scale segment being the largest

- In 2015, the ESS application mix was primarily dominated by ancillary services, followed by residential uses. Short-duration, grid-scale storage systems were mainly deployed for grid services such as operating reserves and frequency/voltage regulation (BNEF, 2022b). Residential ESS adoption was notably high, especially in the EU, where by 2021, customer-sited residential ESS accounted for 46% of the market—approximately 4-7 times higher than in China or the USA (Wood Mackenzie, 2022).

- In recent years, there has been a clear shift toward utilizing long-duration storage for energy-shifting applications. The ancillary services ESS market has reached saturation, while energy-shifting ESS capacity has grown to occupy more than half of the application mix. This trend is closely linked to the substantial increase in renewable energy deployment, which has doubled in capacity, thus driving the demand for longer-duration ESS deployments that are typically required for energy shifting.

- Grid-scale ESS with longer durations is expected to dominate the market. For example, 83% of the projected 600 GWh energy storage capacity in the USA—the global leader in ESS capacity—by 2031 is expected to be grid-scale (Wood Mackenzie, 2022). Energy-shifting applications are predicted to retain a strong market share as ESS capacity increases, while the use of ESS for ancillary services is forecasted to decline to just 6%. The combined share of residential and commercial ESS usage is projected to remain stable, with residential ESS making up 11% and commercial ESS 13% of the market by 2030. However, this trend may vary across countries, especially in those with low renewable energy penetration, which may lag behind in adopting these systems.

Application mix of energy storage projects (power output base)



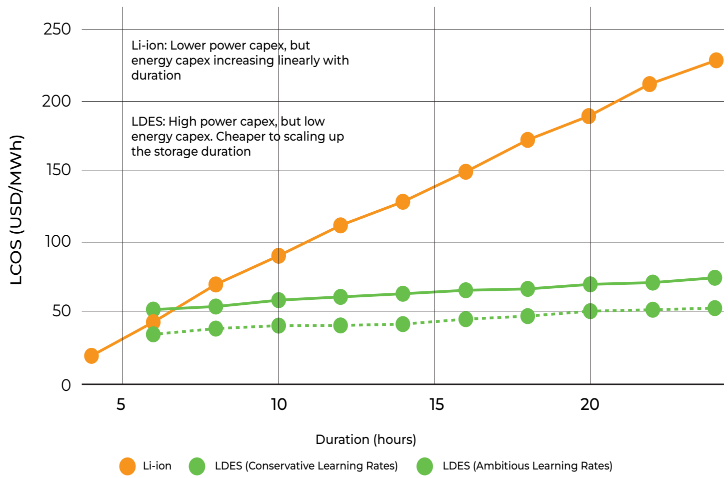
Source: BNEF, 2022b

Note: excluding mechanical energy storage

The value of long-duration energy storage (LDES) in long-term decarbonization efforts needs to be critically assessed to address its current challenges

- The increasing utilization of energy storage systems (ESS) for energy shifting, along with their expanding role in large-scale grid applications, has created strong demand for low-cost LDES technologies. Advancements in promoting LDES initiatives could accelerate performance improvements and cost reductions, particularly through the efforts of the LDES Council, which was launched at COP26 and actively advises governments and industry. The council projects that LDES installations will need to scale up to approximately 1.5–2.5 TW (85–140 TWh) by 2040 to achieve a cost-optimal net-zero energy system (LDES Council, 2021).

Projected energy storage LCOS competitiveness by duration for LIB and LDES in 2030



Source : LDES Council, 2021

- LDES includes a variety of technologies, such as mechanical, thermal, electrochemical, and chemical energy storage systems. In addition to lithium-ion batteries (LIB) and conventional pumped hydro storage (PHS), some LDES technologies offer potential advantages, such as lower costs, shorter lead times, and reduced environmental impact. The LDES Council estimates that there is currently over 5 GW and 65 GWh of cumulative LDES capacity, predominantly composed of thermal molten salt and compressed air energy storage (CAES). Thermal storage is particularly attractive because it can discharge both heat and power, contributing to the decarbonization of the heat sector, which accounts for nearly half of global final energy consumption. Nonetheless, electrochemical storage is expected to lead in terms of project numbers due to its modularity, particularly at capacities below 10 MW.

- The primary challenges for LDES are high installation costs, limited technology maturity, and restricted market availability. However, LDES is expected to become cost-competitive with LIBs for durations over six hours, and even more advantageous for longer durations (over nine hours) by 2030, with a levelized cost of storage (LCOS) projected to fall below 10 USDc/kWh. The increasing deployment of variable renewable energy (VRE) will drive industry-wide advancements in manufacturing, further reducing LDES costs. To fully capture the value of LDES and enhance its competitiveness, enabling factors such as market mechanisms and regulatory incentives are essential. This includes optimizing remote/off-grid and island grids, which is critical for decarbonizing island energy systems, particularly in Indonesia, where LDES could facilitate low-cost, 24/7 clean energy grids.

Batteries have seen a significant price decline compared to other ESS technologies but are currently experiencing fluctuations influenced by regional factors and their chemistry

- Globally, LIB-based BESS has the lowest LCOS among commercially available ESS technologies for medium-scale applications (10 MW), at approximately 20 USDc/kWh. On a larger scale, with storage durations of less than 10 hours, the LCOS of BESS is also competitive with established technologies like PHS and CAES. While LCOS values, representing the cost of electricity supplied from an ESS, can vary depending on the type of operation, reducing capital costs for installation directly lowers LCOS. This cost reduction is primarily driven by advancements in research and manufacturing efficiency, which make cheaper technology available. Additionally, the design and configuration of the ESS integration play a significant role, with reports indicating that LCOS can be significantly lower when hybridized with solar PV or wind generators (Lazard, 2023).

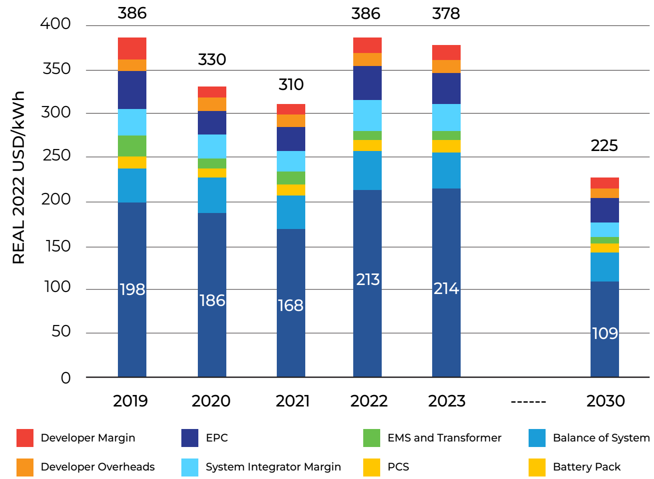
- Compared to other technologies, BESS has seen the most significant drop in installation costs, although there have been recent fluctuations. According to a 2023 BNEF survey, the average cost of a 4-hour BESS has resumed its downward trend, reaching 263 USD/kWh, and is expected to fall further to 175 USD/kWh by 2030 (BNEF, 2024). This marks a turnaround after costs had previously risen to 2019 levels (BNEF, 2022a). The earlier increase was partly driven by limited battery availability due to competition with EV manufacturers and rising costs for components like PCS. However, the recent accelerated decline in costs is attributed to an oversupply of battery cells and market competition across the entire value chain.

The global BESS LCOS in different configuration by 2024

BESS	Configuration	Scale	LCOS Range
In-Front-of-the-Meter	Standalone ESS	100 MW - 1 hour	24.9 - 32.3
	Standalone ESS	100 MW - 4 hour	20.0 - 25.7
	100 MW Utility Scale PV +	50 MW - 4 hour	11.0 - 25.7
	100 MW Utility Scale Wind +	50 MW - 4 hour	6.9 - 7.9
Behind-the-meter	Residential Standalone	6 kW - 4 hour	121.5 - 134.8
	10 kW Residential PV + ESS	6 kW - 4 hour	66.3 - 73.0

Source : Lazard, 2023

BNEF's survey for large 4-hour ESS capital costs



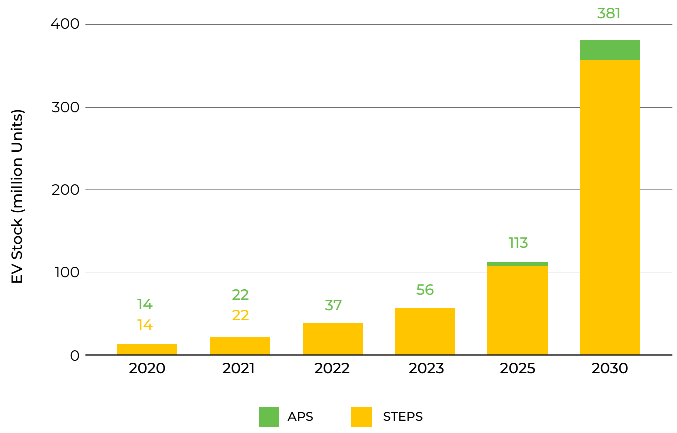
Source : BNEF, 2022a

- BESS costs are heavily influenced by installation location and battery chemistry. In China, for example, costs are generally lower than the global average due to more affordable component supply chains and lower non-battery expenses. Additionally, BESS systems that utilize batteries made from abundant materials, such as iron phosphates (e.g., LFP-LIB), tend to be cheaper than those using nickel-based LIBs.

The potential to strengthen the grid and reduce GHG emissions lies in the vehicle-to-grid (V2G) concept

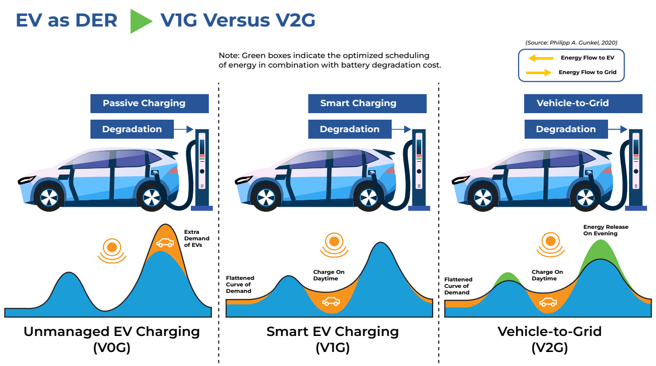
- Implementing the vehicle-to-grid (V2G) concept has emerged as a promising solution for reducing greenhouse gas (GHG) emissions by facilitating power exchange between electric vehicles (EVs) and the grid. According to the International Energy Agency (IEA), there were 28.2 million electric cars in 2023, and this number is projected to reach at least 180 million globally by 2030 (IEA, 2024e). This surge in EV adoption not only reflects their growing popularity but also signals a substantial increase in battery demand, expected to rise from 772 GWh/year in 2023 to at least 3,500 GWh/year by 2030 (IEA, 2024e). While the widespread adoption of EVs may disrupt grid operations and increase costs due to the additional load, the potential of EV batteries to support the grid and reduce battery demand in the power sector is a crucial factor in the energy transition.
- V2G has already been tested in several pilot projects worldwide in various regions. In Norway, for example, 4,500 EV batteries provided electricity to 20,000 households during a power plant failure in June 2023. Additionally, numerous studies have shown that implementing an intelligent V2G algorithm can reduce operational costs and result in lower emissions compared to uncoordinated systems (The Mobility House Team, 2024).
- Despite the benefits of the V2G system, several challenges hinder its widespread adoption. V2G requires more complex systems, and bidirectional chargers are more expensive than conventional ones, creating a high upfront cost barrier. Another challenge is interoperability—ensuring that EVs can seamlessly use any charging station, regardless of the owning company. Drawing from the experience with electric motorcycle batteries, interoperability can be difficult to achieve when there are no commonly agreed-upon standards among service providers. Moreover, the electrical grid needs to be upgraded and prepared to support V2G operations. Regulations enabling power exchange between the grid and vehicles also need to be developed. Other challenges include data protection and cybersecurity concerns, evaluating the benefits of V2G systems, grid overloading, and more. Given these obstacles, an alternative solution is the implementation of smart EV charging systems, which shift charging demand from peak to off-peak hours through policies such as charging incentives in specific areas and times.

The global EV stock projection



Source : IEA, 2024e

EV grid connection types



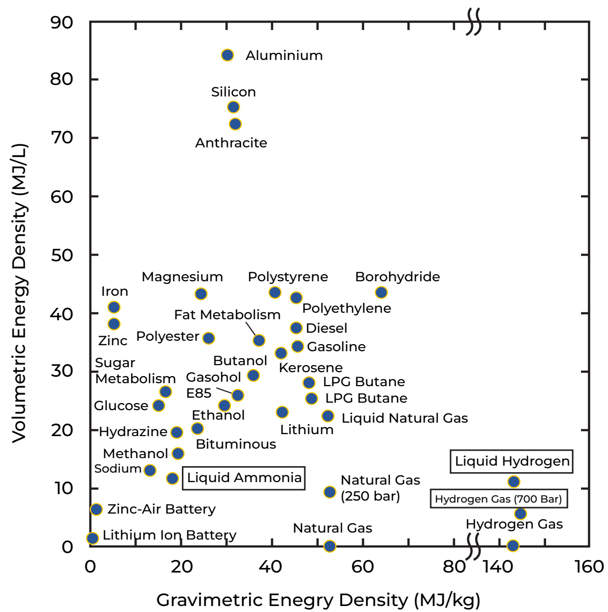
Source : Chulalongkorn University, 2024

Hydrogen as energy storage: a critical key to decarbonization efforts to achieving NZE

- The demand for low-emission hydrogen continues to grow in Japan, South Korea, the USA, the EU, Australia, China, and globally. By the end of 2023, nearly 50 countries had published their National Hydrogen Strategies, following Japan's lead in 2017 (Weltenergierat, 2023). Along with these strategies, many countries have introduced incentives to encourage investment and promote the development of a low-cost, low-emission hydrogen supply chain (KWM, 2023). Several factors contribute to hydrogen's adoption, including its critical role as a fossil fuel alternative to achieve NZE, ensure energy diversity and security beyond the use of electricity, function as a stationary energy storage system, and foster renewable energy technologies. Hydrogen also helps rebalance the geopolitical landscape by introducing new technology and markets, offering economic benefits to hydrogen producers, and promoting the establishment of hydrogen technology hubs and investment partnerships (UK Parliament, 2022; IRENA, 2022; WEF, 2024).

- Initially, hydrogen was a carbon-free chemical used as an energy source and a raw material derived from fossil fuels. Today, hydrogen's role has evolved into an "energy storage" medium for clean electricity generated from renewable sources. To achieve NZE, the ideal "clean electricity" must have a low lifecycle carbon emission (LCE) footprint, achieved through electrification. Clean electricity is the preferred choice for energy use because it is almost entirely pollution-free, though it is still limited in practicality and power density (CAS, 2022; CG, 2022; Hossain, Md. A. et. al., 2023). For this reason, hydrogen's value comes second, as it can store clean electricity.

Comparative analysis of the gravimetric and volumetric energy densities of various energy storage materials and technologies



Source: Kobayashi, H. et al., 2019

- Hydrogen has roughly three times the energy content of gasoline by weight, though volumetrically it contains only about 10–30% of the energy of gasoline. However, it remains competitive compared to batteries and natural gas (DOE, 2023; Kobayashi, H. et al., 2019). The key feature of hydrogen is not only its energy density but also its efficiency in practical systems. This potential was demonstrated by Delft University of Technology in 2023, where a three-wheeled, 72 kg prototype hydrogen car covered 2,488 km using just 1 kg of hydrogen at 300 bar (GWR, 2023; NewAtlas, 2023). Similarly, the sedan-type Toyota Mirai, with a full tank of 5.65 kg of hydrogen at 700 bar, achieved a range of 1,360 km, primarily driven in rush-hour traffic (GWR, 2021; Toyoda, 2024).

As energy storage and feedstock, hydrogen may change the global energy landscape

- Technological innovations have advanced the adoption of hydrogen technology, offering several advantages. Ideally, hydrogen could become one of the greenest energy sources, with a low life-cycle emissions (LCE) footprint comparable to clean electricity and can serve as short- to long-term energy storage (Yan et. al., 2023; Hassan et. al., 2021), a challenge that is difficult to meet with batteries and other energy storage solutions.

- Hydrogen has similar practicality as gasoline, can be transported over long distances via pipelines or logistics networks. As an energy storage option, hydrogen may replace fossil fuels, including gasoline, for transportation. Additionally, hydrogen can act as a feedstock for renewable synthetic chemicals such as ammonia, methane, alcohols and more complex synthetic chemicals and may be used for fuel purposes (Linde, 2024; Eneos, 2024). These synthetic chemicals can be produced while maintaining a low LCE when integrated into the appropriate system. In this context, the International Renewable Energy Agency (IRENA) projects that by 2050, hydrogen will account for nearly 10%, methanol for around 4%, and ammonia for approximately 10% of the total energy trade, valued at USD 1.6 trillion, in alignment with the net-zero emissions (NZE) target (IRENA, 2022; IEA, 2023b; World Economic Forum, 2022). The concept is that hydrogen can be used to recycle captured carbon dioxide, obtained via direct air capture (DAC) or carbon capture, utilization, and storage (CCUS), to produce synthetic chemicals and fuels.

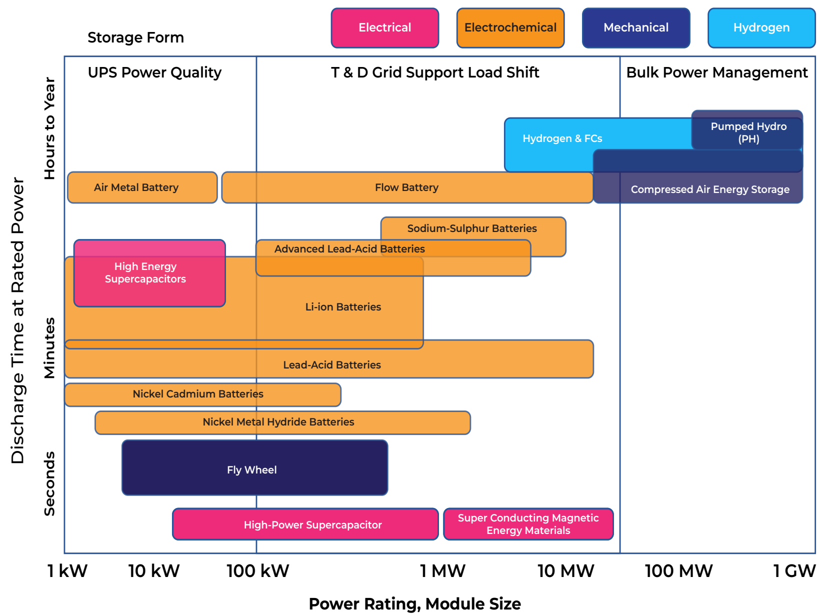
Advantages and Disadvantages of Hydrogen as Energy Storage

No	Advantages	Disadvantages
1	Ideal state are one of the greenest forms of energy with practicality similiar to gasoline	Low energy density by volume
2	Using renewable and sustainable resources, scalability	Hydrogen power is still in infancy and infrastructure is lacking
3	High efficiency, high energy density by mass and suitable for quick charging	Fuel-cells, material for hydrogen utilization and hydrogen-powered transportation are expensive
4	Does not discharge like batteries, can be stored for long time	Renewable energy power production and hydrogen production cost still remains quite expesive
5	If connected, may support grid stability	High capital costs and higher safety risk than gasoline
6	There is no noise or visual pollution	Hydrogen devices have low durability and limited performance and lifetime
7	Cost-effective and low-effort maintenance	Temperature changes might cause a problem
8	Long-term operation of fuel cells is possible	The costs of transporting hydrogen is quite high
9	In-remote areas, hydrogen power may be the perfect solution	There is a possibility of accidents getting out of hand

Source: Authors analysis adapted from many sources

- Other potential applications for hydrogen include power plants (both on-grid and off-grid), buildings, everyday activities, and, crucially, backup power in the emerging technology presence of portable hydrogen fuel cell generators, portable electricity generators, and up to MW power plant capabilities (Skoon, 2024; Hitachi energy, 2024). By the end of 2023, South Korea became the first country to achieve 1 GW of installed hydrogen fuel cell power plant capacity (Hydrogen Insight, 2024). In this regard, hydrogen has the potential to revolutionize the global energy landscape, providing clean, abundant energy and enabling the sustainable distribution of renewable energy necessary to meet the NZE target.

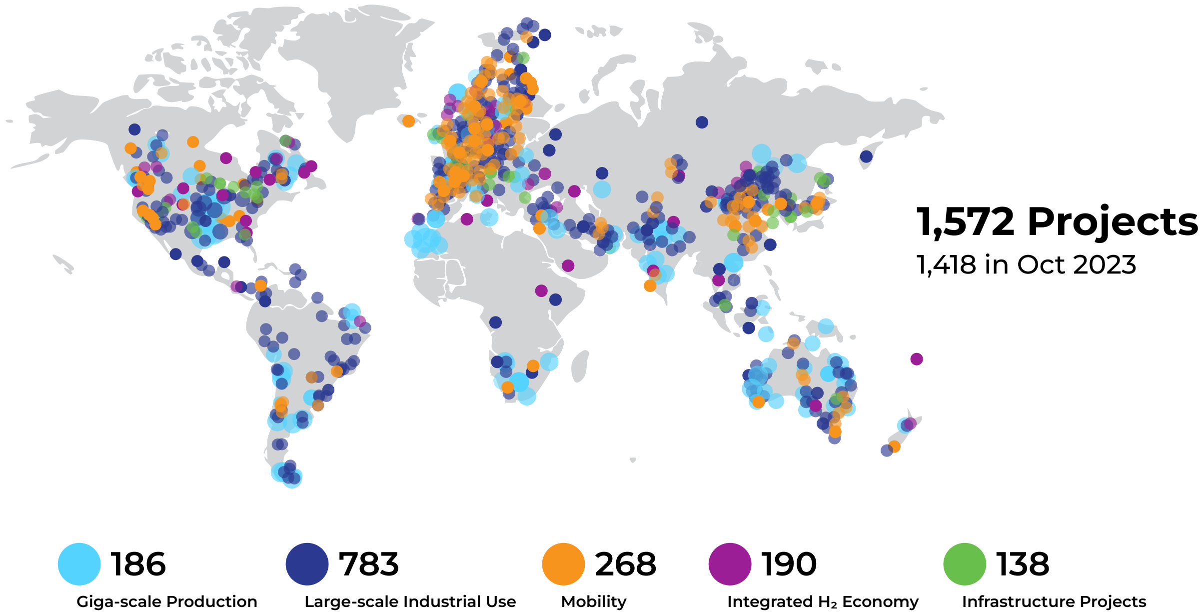
Hydrogen Energy Roles in Power System



Source: Hassan et. al., 2021

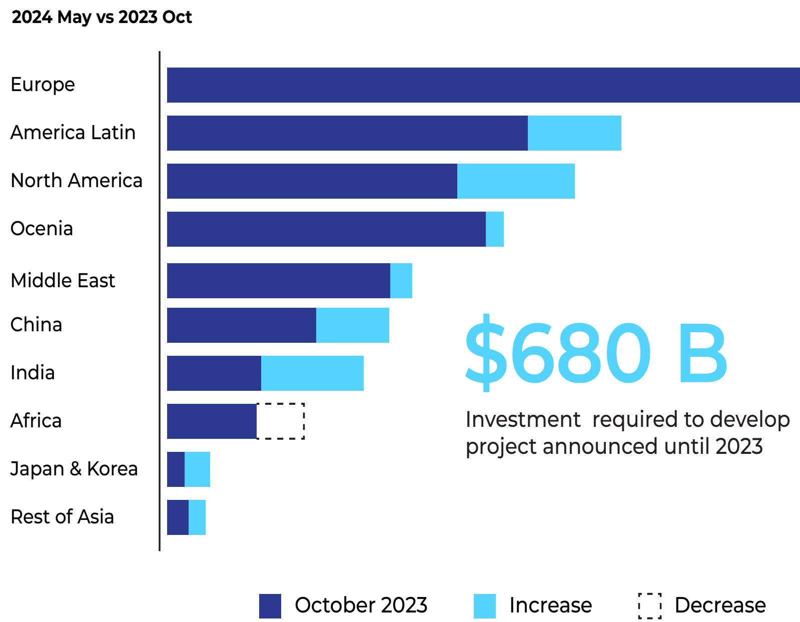
The global hydrogen investment market continues to grow, surpassing half a trillion dollars by mid-2024

Global hydrogen value chain projects



Source: Hydrogen Council, 2024

- Many countries are actively promoting the hydrogen ecosystem by addressing barriers in the supply and value chains that hinder hydrogen adoption. This has led to increased investment in projects that support the transition of hydrogen from the lab to commercial applications. These efforts also include establishing cooperative partnerships for research, development, and trading, as well as developing national hydrogen strategies to encourage domestic investment and adoption.



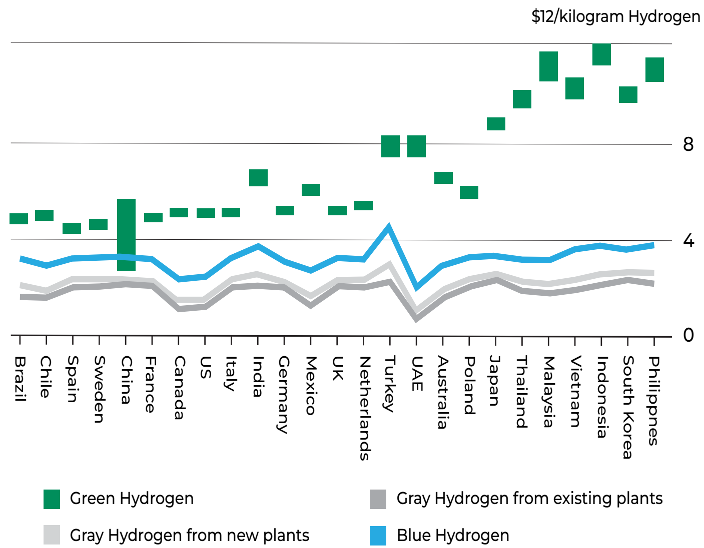
Source: Hydrogen Council, 2024

- As of mid-2024, the global hydrogen economy had accumulated 1,572 projects, with a total investment value of USD 680 billion. Europe leads with the highest number of projects, accounting for nearly 43% of the total. Of these, 434 projects have passed the Final Investment Decision (FID) stage, representing a committed investment of USD 75 billion and a projected cumulative production capacity of 48 million metric tons (MMT) per year by 2030 (Hydrogen Council, 2024). Global hydrogen demand is expected to increase six- to eight-fold, from 90 MMT per year in 2020 to between 530 and 650 MMT per year by 2050, with half of this demand driven by industrial and transportation applications (WHA, 2023; IEA, 2023b). However, the current hydrogen production ecosystem appears insufficient to meet these 2050 projections. Moreover, the technology and infrastructure required for its utilization are still under development, limiting its scope and application.
- The adoption of low-emission hydrogen as a global energy commodity is forecasted to result in cumulative emissions reductions of at least 80 gigatons of CO_2e (World Economic Forum, 2022; Hydrogen Councils, 2021). This reduction is significant, representing nearly 19% of global GHG emissions annually, based on 2023 IEA data (IEA, 2024d), and approximately 17% of cumulative GHG emissions by 2050, according to IRENA (IRENA, 2018). With such substantial environmental benefits, hydrogen projects will likely continue to expand, playing a critical role in reducing fossil fuel dependence—unless a more promising alternative technology or energy source emerges to drive global GHG emissions reduction.

Hydrogen as energy storage is still expensive, and efforts are required to make it cheaper

- Hydrogen color is determined by its energy source, raw material, process, and resulting product. In 2023, over 92–98% of the global hydrogen supply was produced from fossil fuels, primarily as grey hydrogen, which accounts for about 3% of total annual global CO_2 emissions (Forbes, 2022; IFRF, 2019; IRENA 2023a; WoodMac, 2023). Grey hydrogen is fossil fuel-based, with carbon emissions released into the atmosphere during production. Blue hydrogen is produced from grey hydrogen, but with carbon emissions captured using CCS/CCUS, preventing them from being released into the atmosphere. Meanwhile, green or renewable hydrogen is low-emission hydrogen produced from renewable energy sources.
- In some countries, the levelized production cost of green hydrogen can still reach up to USD 12 per kg, while blue hydrogen can cost almost USD 5 per kg, and grey hydrogen is below USD 3 per kg. The global average production costs are estimated at USD 6.4 per kg for green hydrogen, USD 3.1 per kg for blue, and USD 2.1 per kg for grey (BNEF, 2023a). The high cost of blue and green hydrogen is attributed to the fact that they are still classified as emerging technologies. Green hydrogen's production cost is heavily influenced by the technological costs of water electrolysis powered by renewable energy, while blue hydrogen is affected by the cost of CCS/CCUS used to remove CO_2 from grey hydrogen production to classify it as blue hydrogen.

Global hydrogen levelized production cost



Source: BNEF, 2023a

- The wide range of green hydrogen levelized production costs reflects variations in renewable electricity generation, electrolyzers, locations, investments, and operating costs. Two factors are key to reducing these costs: economies of scale and supportive policies for adoption. Global efforts to promote low-emission hydrogen are expected to bring the cost of green hydrogen closer to USD 2 per kg by 2035, and under USD 2 per kg by 2040 (BNEF, 2023b). However, the actual rate of cost reduction will depend on market developments and the adoption of global policies.
- Hydrogen's potential is driving positive sentiment in the global hydrogen market, which is expected to grow rapidly. In 2023, the green hydrogen market was valued at USD 6.3 billion, with projections of growth to USD 143–166 billion by 2033 (GlobeNewsWire, 2024; Precedence Research, 2024). Meanwhile, the blue hydrogen market, valued at USD 18.8 billion, is expected to reach USD 34 billion within the same period (API, 2022; IDTechEx, 2023). Overall, the global hydrogen market is forecast to grow from USD 156 billion in 2022 to between USD 292–410 billion by 2030 (Bloomberg, 2023; GlobeNewsWire, 2023).

Several countries already have support policies with the potential to promote ESS development

- Long-term market signals, revenue mechanisms, and enabling measures, such as research funding, are common types of policies introduced in various countries to support the deployment of energy storage systems (ESS). Market signals are crucial for inspiring confidence among technology developers and producers, encouraging investment in storage development. The presence of direct deployment targets suggests that local stakeholders have assessed the role and added value of ESS for the grid, thereby increasing the likelihood of developing incentives for storage. Revenue mechanisms, such as the creation of capacity markets, can enhance the economics of ESS project development, serving as an initial stimulus. The UK exemplifies this, with operational battery storage capacity reaching 3.5 GW by the end of 2023 and an additional 24.5 GW consented (RenewableUK, 2023). Moreover, funding research and the development of domestic manufacturing can lead to cheaper technologies and production methods, lowering decarbonization costs and positioning the country as a global leader for economic gain.

Support mechanism of energy storage development in several countries

Country	Policy type		
	Long-term market signals	Revenue mechanism	Direct technology support and enabling measure
UK	1. **Emission target**: 78% carbon emission reduction by 2035 2. **Carbon pricing**: National carbon pricing (~80 GPB/ton) 3. **RE target**: Offshore wind 40 GW by 2030, coal-free power system 2024, 100% electricity decarbonization 2035	1. **Capacity market**: ~30-35 GBP/kW-y long term contracts 2. **Balancing market** 3. **Hourly energy attribute certificates (EACs)**: hourly Renewable Energy Certificates piloted in 2022 4. **Grid services**: Stability pathfinder, obligatory reactive power services (ORPS), etc	1. **Ten Point Plan**: £100M funding support storage 2. **BEIS**: £20M for large-scale storage, £9M on storage cost reduction 3. **UK Research institute**: £330M 4. **Single grid tariff charge**
USA (California)	1. **AB2514**: procurement taget for 1.5 GW additional storage by 2024 2. **Long-duration energy storage target**: 1 GW (8+hours) by 2026 3. **Carbon pricing**: (~30 USD/ton)	1. **Nodal LMPs**: enchanced energy arbitrage opportunities 2. **Resource a dequancy**: peak capacity 3-year contract 3. **Grind services**: up/down regulation, non-spinning reserve, flex ramping products	1. **State funding**: $380M in 2022-23 budget for LDES as part of the state's $2B Clean Energy Investment Program 2. **DOE Energy Storage Grant Challenge**: reduce LDES cost by 90% by 2030 (10+ hours)
Australia	1. **Emission target**: Net-zero economy 2050 2. **RE target**: RE power system by 2030 3. **Storage capacity target**: NSW 2 GW LDS ESS taget by 2030	1. **Western Australia Reserve Capacity Mechanism (RCM)** 2. **Grid services**: Frequency control ancillary services (FCAS), Network support and control ancillary services (NSCAS), System restart Ancillary services (SRAS), etc	1. **The Australian Renewable Energy Agency (ARENA) projects**: partial project cost support, with reporting requirements 2. **Clean Energy Finance Corporation**: AUD 6.4B for projects supporting low emission economy
India	1. **Emission target**: Net-zero economy by 2027 and emission intensity reduction of 33%-35% by 2030 from 2005 levels 2. **RE target**: 175 GW by 2022 and 500 GW by 2030 3. **Storage tenders**: four 1 GWh tenders	1. **"Round-the-clock" PPAs**: PPA by solar energy corporation of India for firmed RE 2. **Grid services**: draft regulation allowing participation in fequency control and reserve services	1. **Targeted tenders**: Announced initial 4 GWh tender for ESS

Source : LDES Council, 2021

Energy Storage Technology Options and Their Development Status

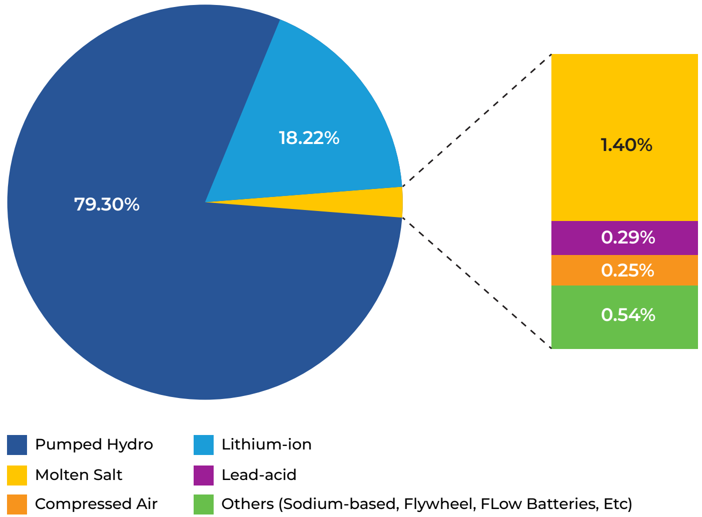
- Trends in the development of various energy storage technologies:
  - Electrochemical batteries
  - Hydrogen conversion technologies
  - Pumped-hydropower storage
  - Flywheel energy storage
  - Compressed air storage
  - Thermal energy storage

Mechanical energy storage dominates the power sector, while electrochemical storage has revolutionized the transportation and consumer electronics segments

- Energy storage technologies are essential across the power, transport, and consumer electronics sectors, providing stored energy for use when needed. In the power sector, energy storage is particularly valuable, as it helps maintain grid balance by managing supply and demand, assisting the power generators ramping, and smoothing the variable renewable energy (VRE) output. The transportation sector remains the largest market for energy storage today, using over 2 TWh batteries to power electric vehicles (IEA, 2024c). The consumer electronics sector, particularly portable devices, continues to require energy storage, although on a much smaller scale. Emerging consumer technologies, such as medium- to small-sized drones, present a potential market for storage technologies like batteries and hydrogen fuel cells.

- Energy storage technologies are categorized into mechanical, electrochemical, and thermal types, based on their working principles, which influence their technical capabilities. While most systems store electricity, thermal energy storage can directly capture and reuse heat, making it especially valuable in industrial applications. This process prevents waste by repurposing excess heat from industrial processes. A diagram of various energy storage types and their applications is available on the next page.

Global energy storage market in power sector by 2023



Source: CNESA, 2023

- In 2023, mechanical energy storage dominated the power sector, accounting for around 80% of global energy storage systems (ESS) capacity, primarily due to pumped hydro storage (PHS). Other mechanical types, such as compressed air energy storage (CAES) and flywheels, held less than 1% of the market. While lithium-ion batteries (LIBs) lead electrochemical ESS, alternatives like sodium-ion and flow batteries are gaining attention and could challenge the dominance of LIBs. Hydrogen energy, though less common at present, shows promise as a future option for seasonal energy storage.

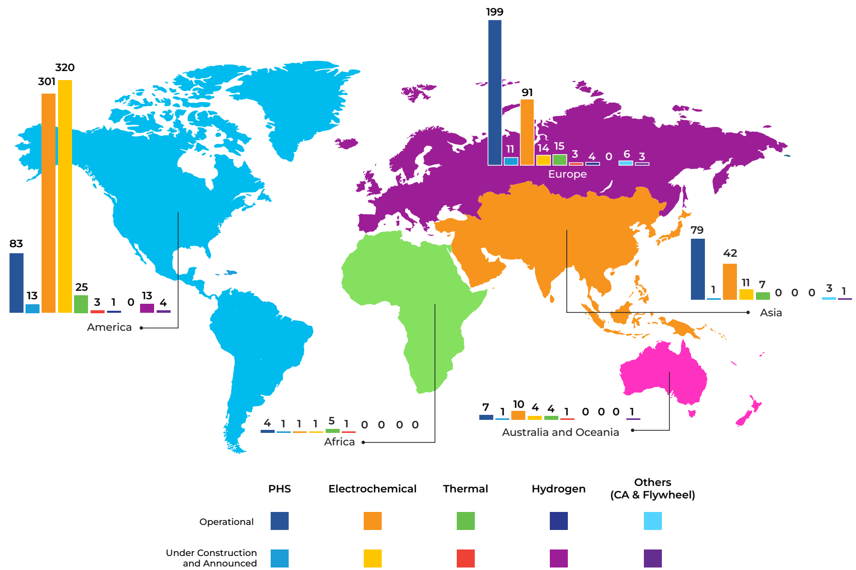
The EU, primarily driven by PHS technology, currently holds the largest total operating ESS capacity. However, its growth is expected to be surpassed by the increasing number of projects in the pipeline across the Americas

- According to the U.S. Department of Energy (DOE) database, the Americas have the highest number of ESS projects with capacities exceeding 1 MW, predominantly using electrochemical technologies, with the USA as the leading installer. Europe, on the other hand, leads in total installed capacity, with most of its projects utilizing PHS technology. Interestingly, despite having less than half the number of ESS projects compared to Europe, Asia has a similar total capacity, indicating that ESS projects in Asia are generally developed on a larger scale.

- While PHS and electrochemical storage are the most widely developed technologies, some countries have also implemented other technologies such as thermal energy storage, compressed air energy storage (CAES), and flywheels, with the Americas having the highest number of such projects. Meanwhile, Europe leads in hydrogen storage deployment, with four operational locations.

- Globally, ESS projects totaling approximately 88 GW are reported to be under construction, with an additional 64 GW announced across five continents. Notably, 89% of these projects in the pipeline utilize electrochemical storage technology. The Americas have emerged as the most ambitious region in the development of ESS to date.

The map of global energy storage project locations

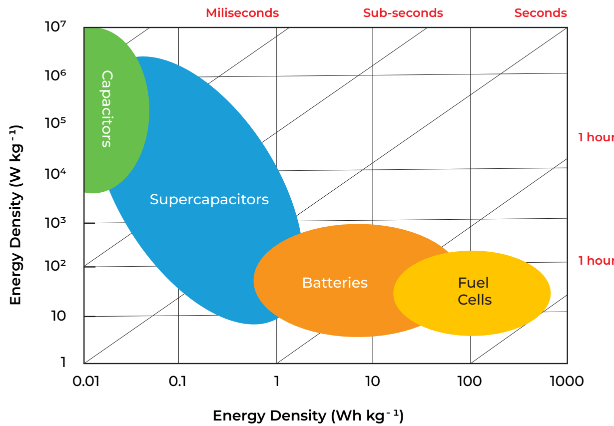


Source : DOE global energy storage database, 2024

While lithium-ion batteries dominate, emerging niche electrochemical storage technologies offer promising advancements in the diverse role of the power system

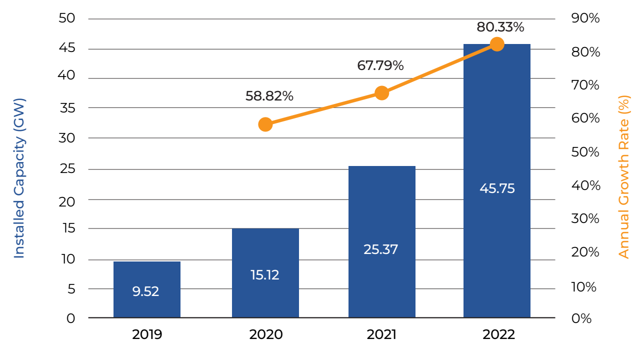
- Electrochemical energy storage (EES) is the fastest-growing technology group due to increases in both technological and manufacturing readiness levels, which enhance the economics of implementation. This growth is driven by the expanding roles of energy storage in the power sector. EES converts chemical energy into electrical energy, or vice versa. EES encompasses sub-technologies with variations in constituent materials, designs, and specific working mechanisms, reflected in their energy storage capabilities. Some, like supercapacitors, can release large amounts of power in a short time (high power density storage), while others, like hydrogen fuel cells, offer high energy density for longer durations but with lower power output. LIBs, with a balance of power and energy density, are currently the most widely used.
- In the last five years, the installed capacity of EES has nearly doubled annually, with LIBs now accounting for over 94% of total capacity (IEA, 2024c; CNESA, 2023). Although the demand for batteries in the power sector is growing, electric vehicles remain the primary end-users of newly produced LIBs. As a result, lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) types of LIBs are the main options for ESS, benefiting from established EV industry production lines. Recently, research institutions and industry players have been developing batteries with different chemistries that could offer cheaper alternatives. For example, sodium-ion batteries (SIB) are promising candidates due to the greater natural abundance of sodium compared to lithium.
- The diverse roles of energy storage in power systems present opportunities for niche EES technologies. Short-duration supercapacitors, for instance, could play a crucial role in providing instant power injection to the grid. They share qualities with flywheels and are commonly used in electric powertrains (Khodaparastan & Mohamed, 2019). Notably, ongoing research aims to enhance supercapacitor energy density, including combining them with batteries in hybrid ESS configurations for superior performance. Additionally, many countries, particularly those with four seasons, expect to use hydrogen fuel cells for long-duration storage to ensure energy supply resilience.

Ragone plot of electrochemical technology



Source : Islam et al., 2022

Global electrochemical storage cumulative installed capacity



Source: CNESA, 2023

There is no perfect battery technology; the best choice depends on where and how the battery is used

- Battery energy storage systems (BESS) are typically employed for residential storage, grid load balancing, and frequency regulation in power system applications. Since 2013, LIBs have surpassed lead-acid batteries as the most widely deployed grid-scale ESS (IRENA, 2019), and this trend is expected to continue. The discussion around preferred cathode chemistries, particularly LFP versus NMC, is ongoing. LFP batteries are increasingly favored for their lower costs—historically around 20% lower due to the absence of cobalt and nickel—along with longer cycle lives and a higher degree of safety. By 2023, LFP batteries accounted for approximately 80% of the total BESS market (IEA, 2024c), a shift that occurred more quickly than anticipated, as LFP dominance in the ESS segment was originally projected for 2030 (Wood Mackenzie, 2020).

Electrochemical storage technologies performance suitability with various industry applications

Applications In Different Indurty (Preferred Performance Matrics)	Batteries Chemistries Performance Match					
	Li-ion (NMC811)	Li-ion (NCA)	Li-ion (LFP)	Li-ion (LCO)	Sodium Li-ion (NaMOx)	Li-Sulfur
Grid - Grid Balancing (Cost/kWh/Cyle > Safety - Reliability > Cycle Life)	Bad	Bad	Bad	Bad	Good	Poor
Grid - Residential Storage or Smart Grid (Safety - Reliability > Cost/kWh/Cycle > Cycle Life)	Bad	Bad	Poor	Bad	Great	Bad
Automotive - Sport Car (Wh/L Energy Density > Rate CApability > Cycle Life)	Good	Good	Average	Average	Bad	Bad
Cunsumer Electronics - Computers or Smartphone (Wh/L Energy Density > Cost > Safety - Reliability)	Average	Poor	Average	Poor	Poor	Bad

Source: Volta Foundation, 2023

- Stationary energy storage applications do not require the high energy density that EVs need for long-distance capabilities. Instead, these applications prioritize batteries that are low-cost, safe, and reliable (Volta Foundation, 2023). Energy density, which relates to space requirements, is less critical, making NMC batteries less common for new BESS projects. However, even the more affordable LFP batteries are still considered insufficient due to the need for BESS integration to be economically competitive (e.g., compared to backup power plant generation costs). As a result, pre-commercialized technologies such as sodium-ion batteries (SIBs) are gaining attention as potential ESS solutions. With a design similar to LIBs, SIBs' constituent materials make them potentially cheaper.

- Commercially available batteries with distinct chemistries and designs, such as redox flow batteries (RFBs) and high-temperature batteries (e.g., beta-alumina Na-S), offer advantages over popular LIBs, particularly for long-duration applications. For instance, RFBs provide flexible capacity expansion and greater cyclability than both LIBs and SIBs (IESR, 2023). However, challenges such as technology maturity, supply chain constraints, and limited demand for long-duration applications currently hinder their widespread adoption.

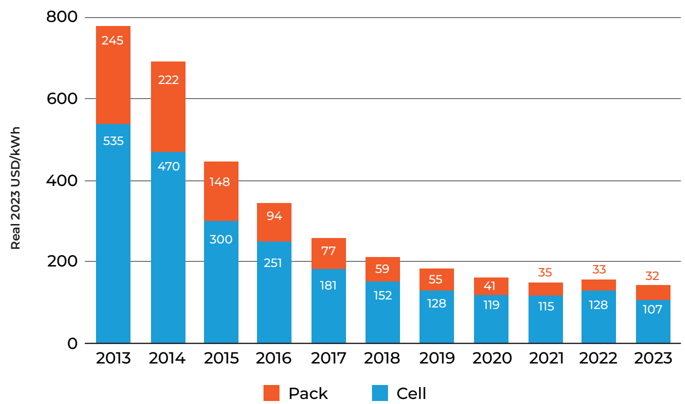
Battery pack prices are expected to return to their downward trend after a spike in 2022, as will other components of BESS installation costs, but at a slower pace

- Last year, lithium-ion battery pack prices resumed their declining trend after a 7% increase in 2022, which was caused by supply chain issues. In 2023, the average price fell to a record low of 139 USD/kWh, with a cell-to-pack cost ratio of 77:23, driven by significant growth in the production capacity of key battery metals (Evelina Stoikou, 2023).

- Battery pack prices, particularly the cost of cell materials, significantly influence the overall BESS installation costs. Therefore, supply chain availability is a critical concern for countries adopting BESS. The 2022 phenomenon highlighted the potential for demand for key materials to outpace supply, causing cost volatility that could affect future BESS costs. Notably, with the growing use of LFP batteries in both BESS and the EV industry, the surge in lithium carbonate prices is particularly concerning. In early 2023, the price of lithium carbonate surged to six times its 2015–2020 average (IEA, 2023e). This spike is significant, as lithium costs play a larger role in determining the final LFP cell price, which contains neither nickel nor cobalt.

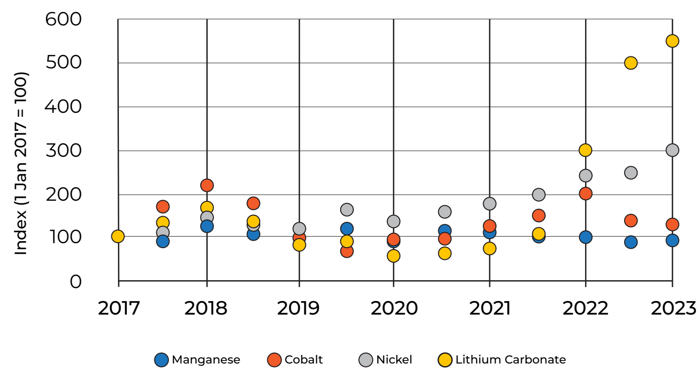
- The contribution of non-battery components to BESS installation costs, currently around 40%, is projected to increase (BNEF, 2022a; PNNL, 2022). While battery pack prices are expected to continue dropping significantly, predicted to fall below 100 USD/kWh by 2025 (Cameron Murray, 2023), the costs of other hardware components (e.g., balance of system (BoS) and power conversion system (PCS)) and system integration will decline more slowly. Notably, BESS requires BoS components, such as electrical components, containers, and thermal management systems, which differ from those used in EVs. According to BNEF projections (2022), non-battery components will account for more than half of the installation costs of 4-hour BESS by 2030.

The global LIB price changes (2013-1023)



Source: Evelina Stoikou, 2023

LIBs' materials price volatility (2015-2023)

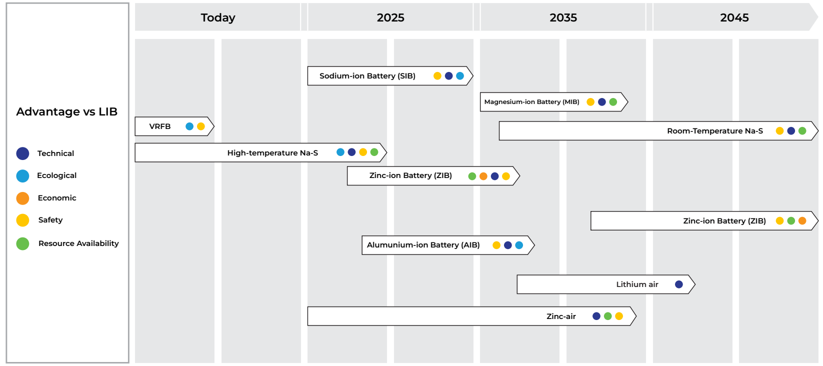


Source: IEA, 2023e

Despite LIBs' continued dominance, R&D and market studies suggest potential for lithium-free alternative battery technologies

- In the coming years, advancements in BESS technology will still be influenced by the specifications required for mobile applications, particularly EVs, due to the lower maturity of alternative technologies and the absence of large-scale applications and markets comparable to LIBs. By 2035, commercial LIBs are expected to reach an energy density of 360 Wh/kg (up from less than 300 Wh/kg) at half the current price. Potentially disruptive technologies remain mostly in the pre-commercial or research stages. Meanwhile, available alternatives like VRFB and Na-S HT need increased demand from the long-duration ESS market to become competitive through high-volume, low-cost production.

The roadmap of electrochemical energy technology development in power system



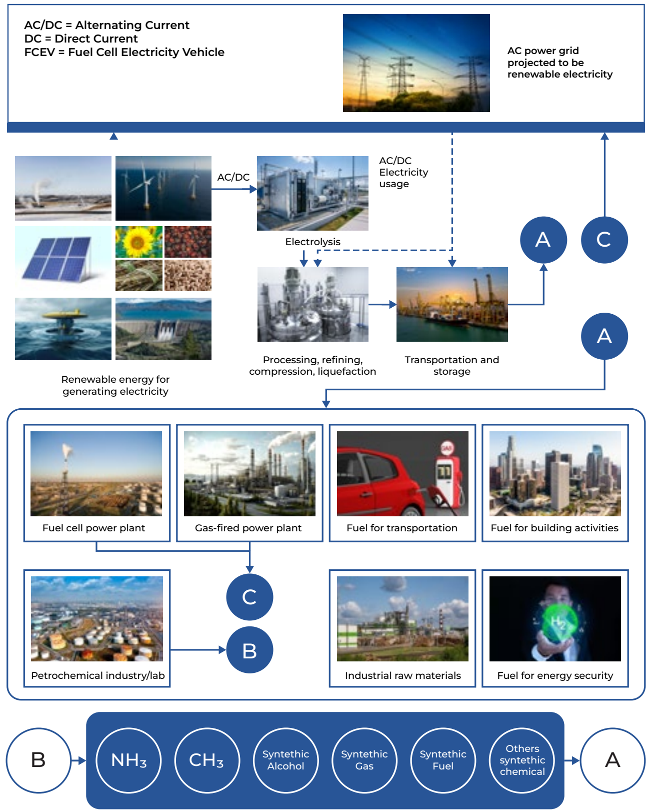
Source: Adapted from Stephan et al., 2023

- With the cost and performance of LIBs often serving as benchmarks, metal-ion batteries that replace lithium with sodium are expected to enter the ESS market first, capturing market share from LIBs before magnesium, zinc, and other metal-ion batteries follow. Novel long-duration batteries, such as zinc-air and iron-air RFBs, are projected to enter the market in 2025, but they will face similar challenges to VRFB and competition from LDES technologies like PHS and CAES.
- Non-lithium chemistries are projected to account for more than 10% of the stationary market by 2025, up from less than 5% in 2021. This shift is driven by improvements in the performance of alternative battery technologies, the cost disadvantages of LIBs in the growing long-duration segment, and the scarcity of critical minerals. Non-lithium metal-ion batteries, especially SIBs, have production processes closely aligned with those of LIBs, making their development for ESS advantageous, as existing production technologies can be adapted.
- Efforts to optimize cell design and explore low-cost material combinations are ongoing in sub-technologies outside of metal-ion batteries. While room-temperature Na-S batteries are not expected to enter the market until the mid-2030s, an iron-air RFB development company began constructing a USD 760 million battery plant in mid-2023. Notably, iron-air RFBs, along with zinc-air and polymer RFBs, are potential cheaper alternatives to vanadium-based RFBs (i.e., VRFB).

The potential for hydrogen adoption continues to grow, encouraging its sustainable integration

- There are over 35 applications for hydrogen, categorized into five key sectors: electric generators and power plants (for an alternative to fossil fuels, hydrogen or co-fired, fuel cell power plants), transportation (for all types of long- and short-distance transportation), industrial processes (for steel, cement production), petrochemicals (for ammonia, alcohol, fertilizers, synthetic chemicals), and residential or everyday use (for heating, cooking, mini power generation) (EIA, 2023; Hydrogen Council, 2020; NHI, 2023; WNA, 2021). As a result, sustainable, low-emission hydrogen plays a critical role in energy storage and is being actively promoted for adoption across various sectors to replace fossil fuels.
- Hydrogen technology utilization in energy storage focuses heavily on innovations in fuel cells, hydrogen combustion turbines, and their hybrid systems. By the end of 2023, it is estimated that 15 GW of global fuel cell manufacturing capacity is available (Hydrogen Council, 2023), a number expected to rise further to meet the increasing demand. The USA is building a 14 GW fuel cell manufacturing facility to meet domestic demand (DOE, 2024). South Korea aims to generate 15 GW of power from hydrogen fuel cells by 2040 (IEA, 2024b). Additionally, 100,000 fuel cell electric vehicles (FCEVs) are expected to be deployed in the EU by 2030 and 50,000 in China by 2025 (IRENA, 2022; PP, 2023). Global demand for FCEVs is predicted to reach 13 million by 2030 (CC, 2024).
- Currently, the global potential for hydrogen utilization in gas turbines exceeds 70 GW (IEA, 2023b). This figure is not limited to gas turbines alone but also includes integrated systems combining fuel cells, energy storage technologies like batteries, and electricity grids. Hydrogen technology is becoming an increasingly integral part of energy solutions across a wide range of applications.

The potential of sustainable, low-emission hydrogen in various applications



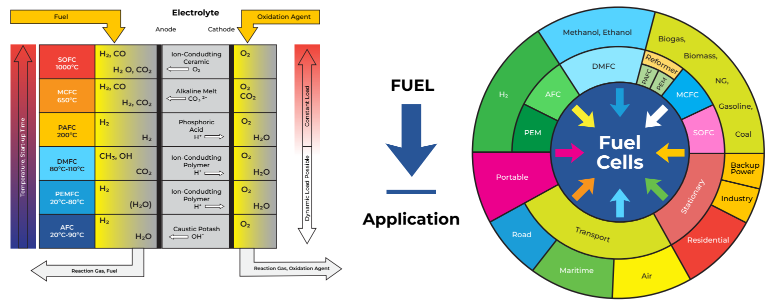
Source: Author analysis, adapted from many sources

Fuel cells are becoming a crucial short- and long-term technology until sufficient availability of low-emission hydrogen.

- Global fuel cell manufacturing capacity reached 16 GW by mid-2024, with South Korea, China, and Japan being the largest supply markets (Hydrogen Councils, 2024). This growth is primarily due to the current reliance on hydrogen fuel cells for utilizing hydrogen. Fuel cell technology can operate on a variety of fuels, including hydrogen, alcohol, methane, ammonia, and even fossil fuels, with or without additional reformers (NAM, 2020; Ebrahimi, M., et. al., 2021; Britannica, 2024; Kobzar et al., 2021). The global hydrogen fuel cell market is expected to grow from USD 2.97 billion in 2023 to USD 18.9 billion in 2033, with the USA market expanding from USD 0.79 billion to USD 7.89 billion over the same period (PR,2023; GNW, 2024). This growing interest in fuel cell technology stems from its ability to produce near-zero-emission energy when utilizing low-emission hydrogen, which is expected to be produced at affordable prices and in sufficient quantities.
- Each fuel cell technology has unique properties in terms of materials, design, fuel type, and application. Molten Carbonate Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC) operate at high temperatures above 600°C and use ceramics as a key material. One of the largest MCFC platforms, with a capacity of 58.8 MW, has been in operation since 2013 (FCE, 2024). , and one of the largest MCFC projects is expected to reach 8 GW by 2040 (IFC, 2023). Similarly, one of the largest SOFC plants has a capacity of 50 MW (OE, 2024), and the U.S. leads the SOFC market with over 500 MW of installed capacity (AEA, 2023). Another type, Phosphoric Acid Fuel Cells (PAFC), uses weak phosphoric acid as an electrolyte, with the largest plants having capacities of 50 MW and more than 200 MW globally (Kobzar et al., 2021; Hyaxiom, 2024; JRC, 2019). These high-temperature fuel cells, typically used for stationary power generation, operate above 200°C and are susceptible to safety and durability challenges, including high-temperature corrosion, shocks, and impacts on materials.

Type of Fuel cell technology

The Fuel cell technology's fuel and its applications



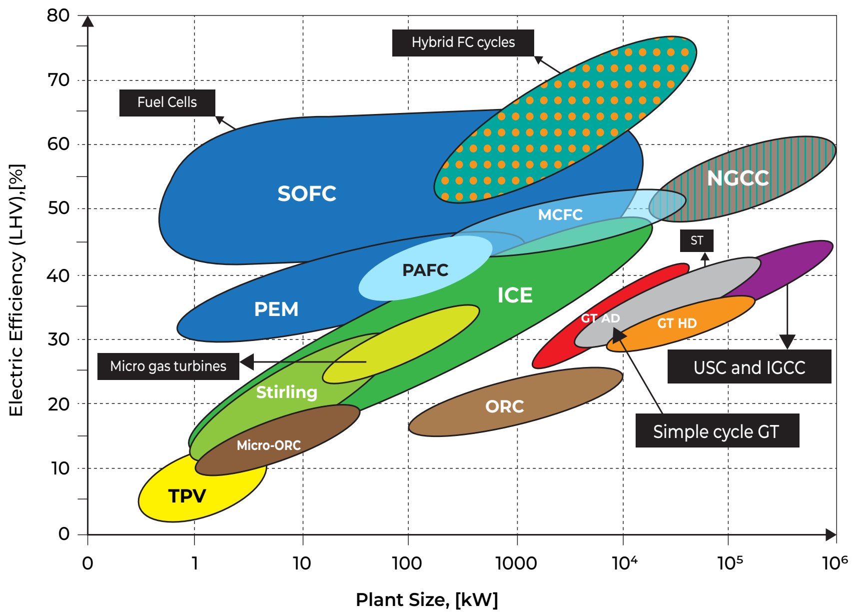
Source: Sauer, 2003; Kobzar et al., 2021

- Alkaline Fuel Cells (AFC), Anion Exchange Membrane Fuel Cells (AEMFC), and Proton Exchange Membrane Fuel Cells (PEMFC) offer greater flexibility and a wider range of applications. AFC and AEMFC use a base electrolyte at operating temperatures of up to 220°C and 70°C, respectively. Meanwhile, PEMFC does not directly use acid as an electrolyte, though it may release a small amount of acid from its electrolyte membrane and binder. AFC, AEMFC, and PEMFC are used not only for stationary power generation but also for mobile and portable applications, including gadgets and transportation (Ebrahimi, M., et. al., 2021; Kobzar et al., 2021.). PEMFCs dominate more than 50% of the global market share for fuel cell technology and are used in almost all fuel cell electric vehicles (FCEVs) globally (Aminudin, M.A., et. al., 2023; AEA, 2023; GVR, 2024). The variety of fuel cell types makes this technology adaptable across various sectors, depending on specific benefits, values, and usage requirements. Additionally, fuel cells can serve as a crucial interim technology if low-carbon hydrogen is not produced in sufficient quantities, given their ability to use flexible fuel sources, including fossil fuels.

The hydrogen combustion system as an alternative for electricity generation

- In addition to fuel cells, hydrogen combustion using hydrogen-compatible gas turbines is another promising technology for generating electricity. In terms of efficiency, fuel cells (FC) have an average efficiency of 50-60%, which can increase to 80-90% when waste heat is recycled through an Organic Rankine Cycle (ORC) or Waste Heat Recovery Systems (WHRS) (Yang, J., et. al., 2023). Meanwhile, combustion using gas turbines (GT) averages 20-40% efficiency, which can increase to 63-74% in combined cycle (CC) systems using WHRS (Rogalev, A., et. al., 2022; Zhang., X., et. al., 2022). Further efficiency increases, up to 95%, can be achieved when integrating fuel cells in a hybrid system, with the fuel cell type adjusted to the system's operating temperature. The growing adoption of hybrid systems in high-temperature power plants aims to maximize energy recovery efficiency.

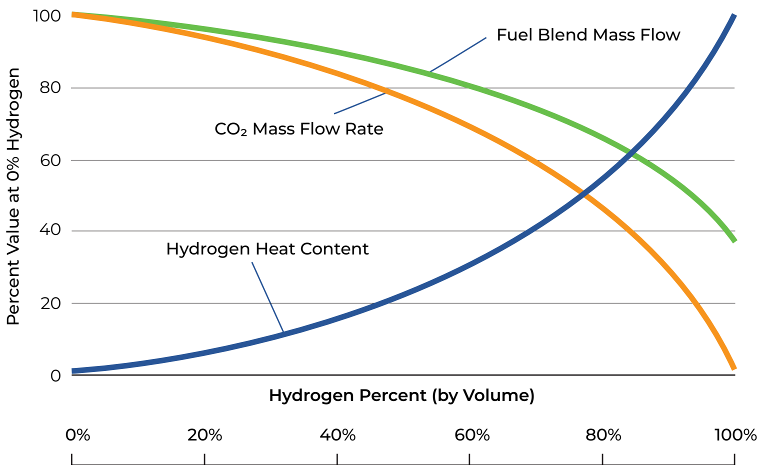
Electric efficiency from various power generation technology



Source: Polimi, 2022

- The working mechanism of gas turbine combustion begins with air being drawn in and compressed by a compressor stage. Then, fuel is introduced and ignited in the combustion chamber with the compressed air, producing high temperatures that can be harnessed for energy extraction (Breeze, et. al., 2014; Sarkar, et. al., 2015; Britannica, 2023). It is important to note that the combustion properties of hydrogen differ significantly from those of natural gas. Conventional gas turbines cannot burn pure hydrogen because it can cause catastrophic fuel nozzle damage. Hydrogen has an air flame speed of 1.7-3.25 m/s and an adiabatic flame temperature of 2,127-2,250°C, much higher than natural gas, which has a flame speed of 0.4-0.45 m/s and an adiabatic flame temperature of 1,937-1,957°C in air (CEA, 2023; Gkantonas, 2023; Michler, et. al., 2021; Shchepakina, 2023). Additionally, hydrogen embrittlement can occur due to hydrogen diffusion and dissolution, affecting material durability (Demaco, 2024). The safe use of hydrogen requires strict. Specifications for materials, design, and operation. While pure hydrogen necessitates these specifications, blends of hydrogen and fossil fuels may be feasible with appropriate mixing ratios, modifications, and risk monitoring (Banihabib, at. al., 2023; Cecere, 2023; NETL, 2022; Shchepakina, et. al., 2023). For instance, a 753 MW combined-cycle gas turbine power plant in Alabama can achieve only 38% hydrogen blending, even with modifications (CE, 2023).

Illustration of gas turbine and Hydrogen blend CO_2 emission effect in gas turbine



Source: GTW, 2022

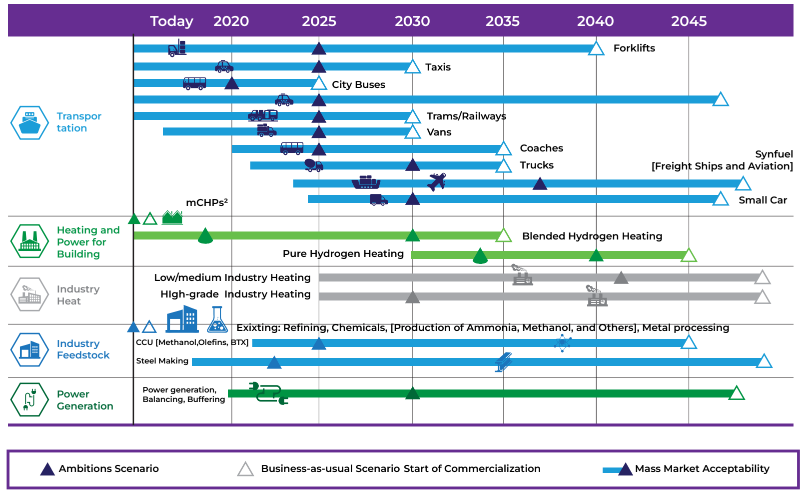
- Hydrogen blending can increase gas turbine efficiency by around 5-20%, or even higher, depending on system optimization (Rogalev., A., et. al., 2022). However, pure hydrogen is required to significantly reduce CO_2 emissions. Hydrogen blending systems still require the adoption of CCS/CCUS technologies (Cameretti et. al., 2020; Davis, et. al., 2023; Simon, N., 2022). The world's largest claimed 200 MW 100% renewable hydrogen gas turbine power plant is set to begin operation by 2026 in Australia (TEIT, 2024). As of now, hydrogen cannot be fully used in gas turbines due to limitations and the additional investments required, making hydrogen blending more appealing than pure hydrogen in some cases.

Snapshot of global hydrogen technology adoption scenario and realization

- Amid rapid global changes, the adoption of hydrogen technology is becoming increasingly significant, driven either by clear strategic motivations or a fear of missing out (FOMO). The global adoption of hydrogen technology for energy storage is dependent on the Technology Readiness Level (TRL) of each technology. From various perspectives, hydrogen technology could become mainstream after 2030, particularly in transportation, with projections indicating up to 13 million hydrogen cars globally (Inci et. al., 2022; Jennifer L., 2023). Many major automotive companies are promoting the growth of hydrogen vehicles to capture market share by 2030.

- Projections suggest that hydrogen will be widely used by 2030 in building heating, industrial heating, and power generation, and it may become a mainstream technology after 2035. The adoption in each sector is heavily influenced by market penetration from hydrogen technology manufacturers, sector-specific initiatives, and hydrogen product and service providers.

Hydrogen Technology adoption Scenario



Source: Inci et. al., 2022

- By early 2024, more than 84,000 hydrogen fuel cell electric vehicles (FCEVs) had been registered worldwide since the first FCEV in 2014. Approximately 80% of these are passenger cars, while 10% are buses, and another 10% are trucks (Hydrogen Insight, 2023a; ICCT, 2023; SNE Research, 2024). In Germany, 14 hydrogen fuel-cell trains began operating in August 2022 but have since faced economic difficulties, with plans announced in August 2023 to transition to battery power (Hydrogen Insight, 2023b). In response to this issue, hydrogen combustion locomotives retrofitted from diesel engines are being piloted in Ireland as of late 2023, which have lower upfront costs compared to fuel cells but are less efficient (Hydrogen Insight, 2023c). Additionally, in early 2024, China converted a pilot diesel locomotive to run exclusively on hydrogen fuel cells (Hydrogen Insight, 2023d). Innovations aimed at reducing CAPEX and OPEX in hydrogen utilization continue globally in the transportation sector, as alternatives for decarbonizing transportation remain limited, particularly regarding electric vehicle performance.

- Moreover, over 50,000 hydrogen FCEV forklifts were in operation in the USA by the end of 2022, running on either pure or mixed hydrogen (USA EPA, 2023). Three hydrogen ferries are also scheduled to begin operations in 2023 or 2024: 'Sea Change' in San Francisco, 'Hydra' on Norway's west coast, and 'Hydro BINGO' in Tokyo, Japan (Hydrogen Insight, 2023e). Lastly, in the aviation sector, a new EU regulation will require aircraft to fly on 35% hydrogen-based fuels (synthetic fuel) by 2050 (Hydrogen Insight, 2023f). These developments demonstrate global enthusiasm for hydrogen storage as part of the energy transition and decarbonization efforts towards Net Zero Emissions (NZE), as well as the growing push to establish a robust hydrogen ecosystem.

The key parameter of hydrogen production technology for future energy storage is limited heavily on LCE footprint

- The hydrogen production process for future energy storage is heavily constrained by its Life Cycle Emissions (LCE) footprint. There are several methods of producing hydrogen, each varying in its LCE impact, and hydrogen can be classified according to its “colour.”. The world is currently transitioning towards low-emission hydrogen and sustainable energy, with clean hydrogen projected to have less than 1 kg of CO_2 equivalent per kg of hydrogen to meet Net Zero Emissions (NZE) targets.

- Hydrogen efficiency depends not only on the technology that uses hydrogen for energy storage but also on the production method. Green hydrogen is produced through electrolysis using renewable energy. However, energy is lost during various stages: 0-35% during production, 5-25% during compression and storage, and 5-12% during transit as fuel, resulting in a final efficiency of 28–90% (Hydrogen Europe, 2022; Guo, J., 2023; AlZohbi., G. 2022). Green hydrogen’s efficiency remains low due to these conversion losses, which also drive up production costs. Despite these challenges, electrolyzer manufacturing capacity has reached nearly 17 GW globally, with 1.75 GW of installed electrolysis capacity, 66% of which is in China (Hydrogen Councils, 2024).

- In summary, the inefficiencies in the hydrogen production value chain, high costs of renewable energy, and significant investment requirements, as green hydrogen is still considered emerging technology, contribute to its high production costs. In comparison, fossil fuel-based hydrogen (blue hydrogen) has a production efficiency of 74–85% (Younas et. al., 2022), while turquoise hydrogen achieves around 58–90% efficiency (Bastardo et. al., 2020; Hydrogen Europe, 2022). In an effort to reduce costs and increase efficiency, hydrogen production technologies continue to be developed as alternative options. These developments create hydrogen with varying LCE footprints, which can be utilized for decarbonization towards achieving NZE. However, regardless of preferences, the LCE footprint of hydrogen production must be minimized as much as possible to compete effectively in the global market.

Hydrogen production technology and its key parameter

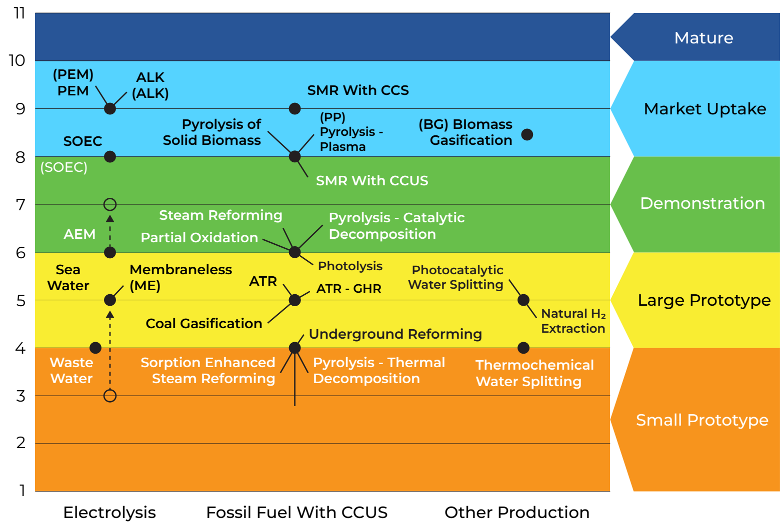
Color	Source	Process	Product	Carbon footprint	Cost (USD/kg Hydrogen)
Black	Black coal (Bituminous)	Coal gasification	$H_2 + CO_2$	Very High up to 27 kg CO_2e/kg Hydrogen	1.20 - 2.10
Brown	Brown coal (Lignite)				
Gray	Coal or Natural Gas	SMR or Gasification		9.3 to 13.7 kg CO_2e/kg Hydrogen	0.50 - 1.70 = (Natural gas) 1.20 - 2.10 (Coal)
Blue		SMR or Gasification + CCUS	$H_2 + CO_2$ (85-90% CO_2 captured)	1 to 5 kg CO_2e/kg Hydrogen	1.00 - 2.50 = (Natural gas) 1.50 - 4.20 (coal)
Turquoise	Natural Gas	Methane Pyrolysis	H_2 + Solid carbon	0.03 to 0.91 kg CO_2e/kg Hydrogen	1.6 - 3.80
Pink	Water (H_2O) + Nuclear	Electrolysis	$H_2 + O_2$ + Nuclear waste	Carbon neutral, considered to have no carbon emissions, 0 to 0.6 kg CO_2e/kg Hydrogen	2.75 - 5.29
Yellow	Water (H_2O) + Renewable Energy specific to solar	Electrolysis	$H_2 + O_2$	Carbon neutral, considered to have no carbon emissions, 0 to 0.6 kg CO_2e/kg Hydrogen	2.70 - 12.84
	Water (H_2O) + Renewable Energy specific to solar + PEC materials	Photoelectrochemical water separation (PEC)		European Union requirements, requiring projects to operate at ≤ 1 kg CO_2e/kg Hydrogen as green hydrogen by 2050	
Green	Water (H_2O) + Renewable Energy	Electrolysis			
Bio-hydrogen	Biomass + Renewable Energy	Biomass gasification without and with BECCS	$H_2 + CO_2$	Carbon neutral, considered to have no carbon emissions, 6-11 kg CO_2e/kg Hydrogen Emissions are considered negative when using BECCS	1.20 - 10.40

Source: Author analysis, sourced from BNEF, 2023; BRIN, 2022; Buffi et. al., 2022; Prabhu., A., et. al., 2023.; Cheng, W., & Lee, S., 2022; EBA, 2023; Giovanni, S.,, 2020; Moberg, J., and Bartlett, S., 2022; Esteves, R. G., , 2023; Hydrogen Insight, 2023g; IEA, 2023; IEA-BECCS, 2023; Webley, P., 2022; Pembina Institute, 2020; Polytechnique insights, 2022; Sodaba Rogh, 2023; Wood Mackenzie, 2023.

Electrolysis and CCS technologies for hydrogen production have matured sufficiently to drive the adoption of low-emission hydrogen as an energy storage solution

- Technology Readiness Level (TRL) 9 has been achieved for hydrogen production using Steam Methane Reforming (SMR) and Carbon Capture and Storage (CCS), as well as electrolysis using Proton Exchange Membrane (PEM) and Alkaline (ALK) technologies. Meanwhile, Solid Oxide Electrolysis Cells (SOEC), Pyrolysis Plasma (PP), and Biomass Gasification (BG) have reached a TRL of 8, while Anion Exchange Membrane (AEM) electrolysis and SMR with CCS have a TRL of 6 (Hobcraft, P., 2020; IEA, 2024a). Thus, hydrogen generation technology is on the verge of maturity, providing several possibilities for sustainability and commercial demand. Meanwhile, recycling technology still requires further development to become commercially viable.

Hydrogen production cost (USD/kg) by ALK and PEM, powered with Solar PV in Southeast Asia Country



Source: Authors adapted from IEA, 2023b; Hobcraft, P., 2020, UNS, 2023

- The primary costs of hydrogen production arise from renewable energy and the capital expenditure for electrolyzer systems. The ALK electrolyzer system ranges from USD 500 to 1,400 per kWe hydrogen, while PEM systems cost between USD 400 and 1,800 per kWe hydrogen, and SOEC systems range from USD 1,850 to 6,667 per kWe hydrogen (Corbeau, A.-S. & Merx, A.-K., 2023; IRENA, 2020; IEA, 2024a). These three types of electrolyzers are widely used by hydrogen producers worldwide, with a market share of 45% for ALK and 15% for PEM, while the remaining 40% is unknown (Hydrogen Councils, 2024). ALK is superior because its components and maintenance are cheaper and more affordable, utilizing alkaline electrolyte solutions. In contrast, PEM relies on a costly membrane with a limited lifespan, and SOEC pricing remains uncompetitive.

- Blue low-carbon hydrogen, produced from fossil fuels using SMR and CCS, has a capital cost of USD 1,583 to 1,753 per kWe hydrogen, which is almost double the capital cost of conventional gray hydrogen produced via SMR alone, priced at USD 710 to 973 per kWe hydrogen (S&P Global, 2023; IEA, 2023a, ERIA, 2023). This type of hydrogen will continue to compete with green hydrogen as CCS, Carbon Capture, Utilization, and Storage (CCUS), Bioenergy with CCS (BECCS), and other technologies develop rapidly, potentially producing negative greenhouse gas emissions or absorbing more CO_2 than they emit (Haszeldine, R. S., et. al.,2018; Walker, C., 2023). Thus, this hydrogen will remain a consideration for fossil fuel-rich nations, allowing them to retain their fossil fuel economic value.

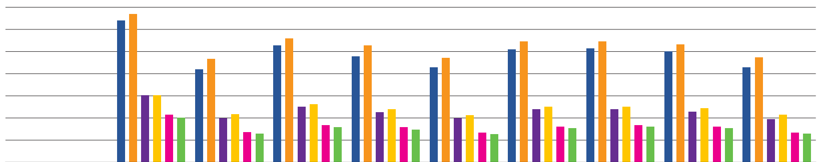
Alkaline and PEM are the dominant green hydrogen production technologies in Southeast Asia, but they may not be competitive enough without intervention

- Focusing on the conditions in Southeast Asia, the electricity costs across the region vary significantly. However, the levelized production cost of grid electricity ranges from USD 0.063 to 0.202 per kWh. In comparison, the cost of electricity generated from solar PV is quite competitive, ranging from approximately USD 0.079 to 0.165 per kWh. However, these costs are still much higher than those associated with hydropower and woody biomass, which are estimated to be between USD 0.02 and 0.058 per kWh (ERIA, 2023).

- According to ERIA data, solar PV is Southeast Asia's primary source of renewable energy for green hydrogen production. Meanwhile, ALK and PEM are considered the main technologies from the perspectives of practicality and CAPEX cost. Based on a comparison of nine countries in Southeast Asia, it is estimated that the levelized production cost for hydrogen produced using solar PV with PEM and AEM will range from USD 8.53 to 13.28 per kg in 2023. These production costs are expected to fall to between USD 3.97 and 6.21 per kg by 2030. Furthermore, these costs are projected to continue declining, reaching USD 2.67 to 4.33 per kg by 2050 (ERIA, 2023).

- The levelized production cost of green hydrogen remain relatively high compared to the global target of USD 2 per kg by 2035 and below USD 2 per kg by 2040 (BNEF, 2023). This implies that, without intervention, the price of domestic production of hydrogen in Southeast Asian countries will lose its competitive edge due to Southeast Asia's high CAPEX cost requirements, coupled with an additional 20% to 30% in regional cost buffers (ERIA, 2023). Possible interventions include building a value chain technology ecosystem for renewable energy and electrolyzers, mass production of renewable energy electricity and green hydrogen, and providing fiscal and non-fiscal incentives for Southeast Asian countries.

Hydrogen production cost by ALK and PEM, powered with Solar PV in Southeast Asia Country



	Indonesia	Thailand	Singapore	Malaysia	Vietnam	Philippines	Brunei	Myanmar	Cambodia
ALK (today)	12.85	8.42	10.52	9.69	8.53	10.19	10.24	9.86	8.53
PEM (today)	13.28	9.41	11.25	10.52	9.50	10.96	11.00	10.67	9.50
ALK (2030E)	6.11	3.97	4.99	4.58	4.02	4.82	4.85	4.66	4.02
PEM (2030E)	6.21	4.34	5.23	4.88	4.38	5.09	5.11	4.95	4.38
ALK (2050E)	4.33	2.72	3.49	3.18	2.76	3.37	3.39	3.25	2.76
PEM (2050E)	4.07	2.67	3.34	3.07	2.70	3.23	3.25	3.12	2.70

ALK (today) PEM (today) ALK (2030E) PEM (2030E) ALK (2050E) PEM (2050E)

Southest Asia	Electrolyser CAPEX (USD/kW)	Electrolyser Annual OPEX (% CAPEX)	Electrolyser Energy Consumption (kWh/Nm³)	Electricity
Today	ALK 1.102	4.7%	3.98	Li et al. (2023)
	PEM 1.808	4.6%	3.48	
2030E	ALK 400	4.7%	3.98	0.60-0.10
	PEM 650	4.6%	3.48	
2050E	ALK 200	4.7%	3.98	0.04-0.08
	PEM 300	4.6%	3.48	

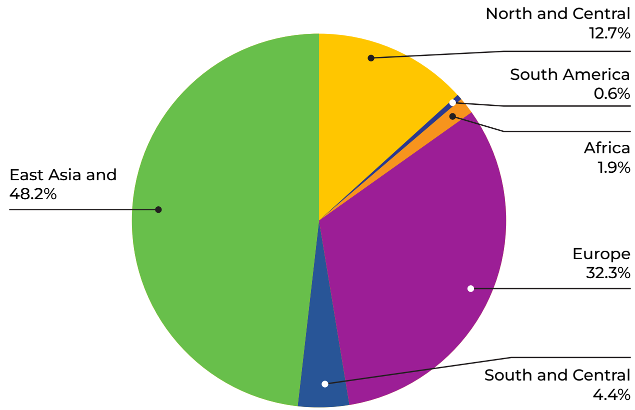
CAPEX = CApital expenditure, E=estimate, kW=kilowatt hour, Nm^3= normal cubic metre, OPEX=operating expense, PEM= proton exchange membrane

Source:: ERIA, 2023

In PHS deployment, East Asia and the Pacific dominate, accounting for nearly 50% of the global share, leaving other regions behind

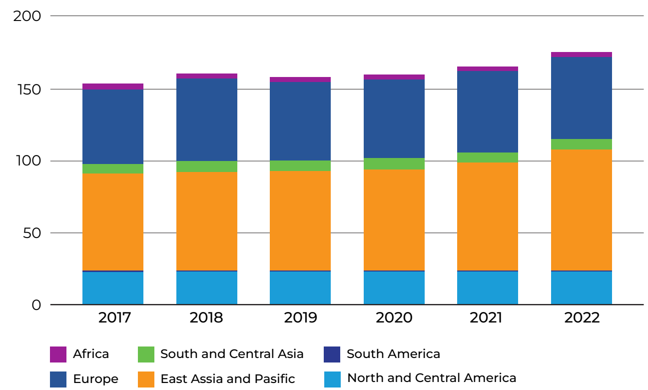
- In 2022, the installed capacity of pumped hydro storage (PHS) grew by 14% compared to five years ago and remains the largest energy storage system (ESS) technology by capacity, despite slower growth than emerging electrochemical technologies. Nearly half of the total 175 GW capacity is in the East Asia and Pacific region, with China and Japan as the main installers. In the EU and Americas, Italy and the United States lead, respectively. The increasing number of variable renewable energy (VRE) power plants drives PHS growth; for example, China's near-term goal to exceed 1 TW of solar PV will require PHS for long-duration energy shifting and to provide grid stability. Notably, the USA and Japan also use PHS to manage the high inertia of nuclear power plants and serve as fast-response peaking plants.
- Although PHS construction requires high upfront capital costs, its long lifespan makes it the least expensive storage option for some power system use cases, particularly long-duration applications. However, PHS development demands specific site conditions and tailored system designs. Its large space requirements can lead to land acquisition complexities, resulting in long construction timelines and social impacts, such as the relocation of local communities and disruptions to traditional livelihoods.
- PHS project development also necessitates a comprehensive environmental impact assessment due to significant land use alterations during construction. Potential impacts include deforestation, soil erosion, landslides, habitat disruption, and water quality degradation, influenced by changes in temperature, oxygen levels, and nutrient concentrations.

Installed capacity share of PHS in 2022 by region (%)



Source : International Hydropower Association (IHA), 2023

PHS Installed capacity growth (GW)

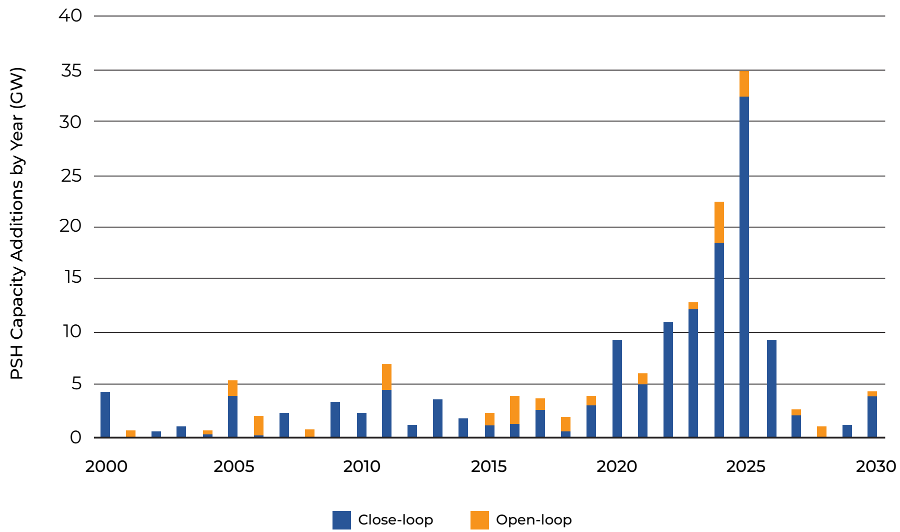


Source : Compiled from IHA reports

Cost reductions from technological advancements, mainly through land-use efficiency, boost the attractiveness of PHS technology

- PHS stores energy by retaining water in higher-level reservoirs, typically charging by pumping water from a lower reservoir when electricity demand is low or by collecting natural rainwater. During peak demand, the stored water is released to generate electricity (discharge). Using mature technologies such as turbines and generators, PHS systems operate similarly to conventional hydropower plants. They are often designed for long-duration discharge capacities exceeding six hours, providing bulk electricity supply. The power and energy storage elements in PHS are decoupled, allowing scalable storage durations.

Annual PHS capacity additions by year



Source : LDES Council, 2021

- PHS systems can be installed in two configurations: open-loop and closed-loop. Open-loop systems connect the lower reservoir to a natural water source, while closed-loop systems isolate the lower reservoir. Closed-loop systems, which are gaining interest due to their reduced environmental impact, use two artificial reservoirs. In contrast, open-loop systems rely on existing natural bodies of water, limiting their availability. Globally, closed-loop PHS has an energy storage potential of around 23 million GW (Stocks et al., 2021), and about 70% of the planned or under-construction PHS projects, totaling over 100 GW by the end of 2021, are associated with closed-loop designs (LDES Council, 2021).

- Despite being over 100 years old, PHS technology has recently regained interest. Various promising advancements, such as submersible pump-turbines and motor-generators, open-pit mine PSH, and wind-hydro hybrid systems, aim to enhance PHS performance and address land-use challenges. Submersible pump-turbines and motor-generators reduce construction costs by eliminating the need for a power house, as they are submerged along with the pump turbine. Open-pit mine PSH repurposes decommissioned open-pit mines as reservoirs, as demonstrated by the Dinorwig PSH plant in the UK. Lastly, wind-hydro hybrid systems link wind power plants with PHS to mitigate wind power intermittency and fluctuations. The first experimental implementation of this concept took place in the late 1970s at the Wreck Cove Hydro Electric system in Canada.

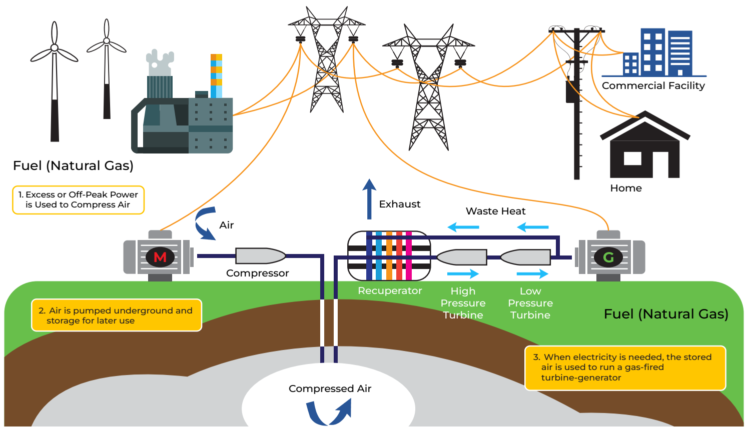
Low efficiency and specific geological requirements hinder CAES growth

- In addition to pumped hydropower and electrochemical energy storage systems, there are other storage technologies such as compressed air energy storage (CAES), flywheel energy storage systems (FESS), and thermal energy storage systems (TESS). CAES can provide a rated capacity of over 100 MW from a single plant and has an efficiency of around 70%, only slightly lower than that of pumped hydro storage (PHS). CAES systems fall into three categories: diabatic CAES, adiabatic CAES, and isothermal CAES.

- CAES operates in two main phases. In the charging phase, ambient air is compressed using cheaper off-peak electricity and stored in a dedicated pressurized reservoir, such as an underground cavern or an aboveground tank, maintaining a pressure of 40-80 bar. The elastic potential energy stored in the compressed air is utilized during the discharging phase. Electricity is generated by extracting the compressed air from the reservoir, heating it, and expanding it through a turbine at high pressure and temperature.

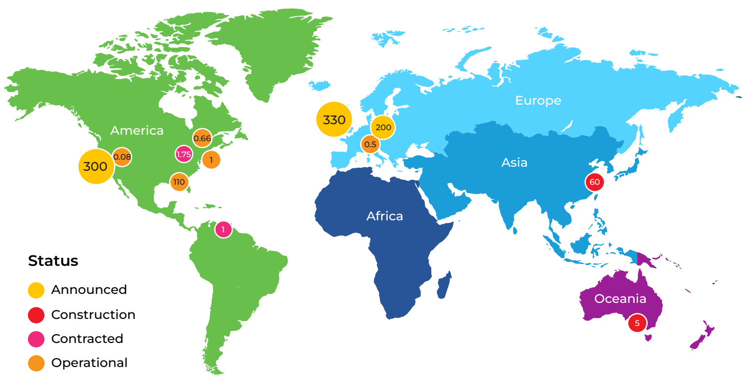
- Currently, there are 12 CAES projects worldwide, with six in operation (DOE Global Energy Storage Database, 2024). The United States hosts some of the largest CAES projects, with a power rating of 110 MW, capable of supplying electricity to 11,000 homes for 26 hours (Baldwin EMC, 2021). CAES growth has been slow due to the requirement for specific geological conditions. Additionally, the system's efficiency is hindered by the energy needed to compress the air during the charging process, which also generates heat.

CAES system overview



Source : Rabi et al., 2023

Global CAES project



Source : DOE global energy storage database, 2024

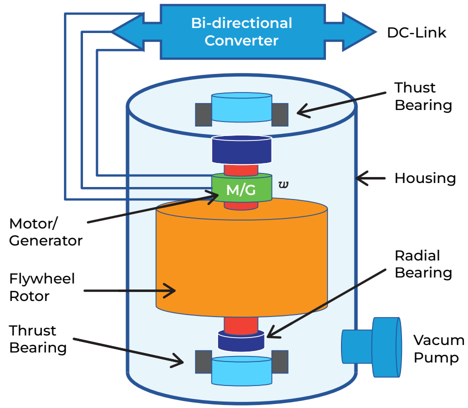
FESS Stores Kinetic Energy and Offers a Longer Lifetime Than Batteries

- Flywheel energy storage systems (FESS) utilize kinetic energy stored in a high-speed rotating disk connected to the shaft of an electric machine. This energy is then released into the network when needed. FESS is known for its superior longevity and power density compared to lithium-ion batteries. Its quick response capabilities make it ideal for applications requiring frequent charge and discharge cycles, such as frequency regulation and power quality management. For instance, a 20 MW FESS has been operating in Pennsylvania since 2014, providing frequency regulation services in the PJM market (Luke, 2020).

- Beyond power grid stabilization, FESS has several other applications, including attitude control in spacecraft, uninterruptible power supply (UPS) systems, load leveling, and hybrid and electric vehicles. The world's largest FESS installation is in Stephentown, New York, with a capacity of 20 MW, capable of supplying 1 MW of electricity continuously for 15 minutes.

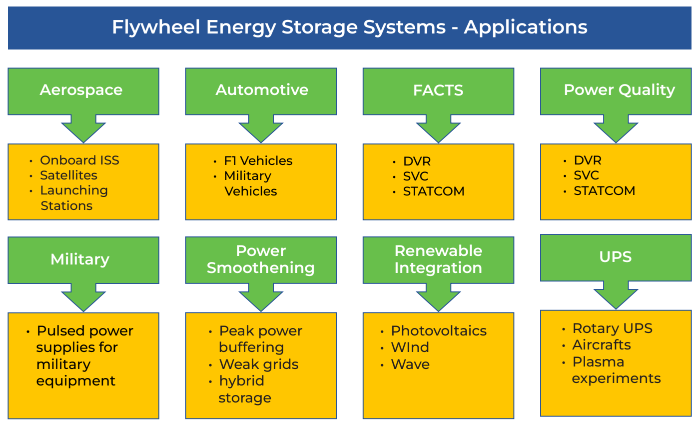
- FESS systems can achieve energy efficiency levels of 80% to 90%. However, they also suffer from energy losses due to mechanical, electrical, and power conversion inefficiencies. FESS is relatively expensive and is subject to mechanical stress, material speed limits, and short discharge times. Additionally, system failures can result in catastrophic events, such as the incident involving Beacon Power in 2011 (Luke, 2020).

Flywheel system and components



Source : Choudhury, 2021

FESS applications

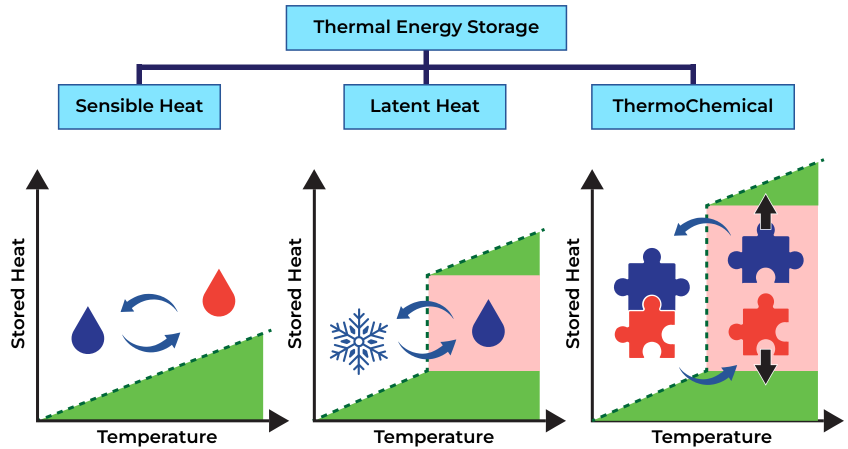


Source : Rojas-Delgado et al., 2019

Ability to Cross-Sector Integration Increases TES Deployment Opportunities

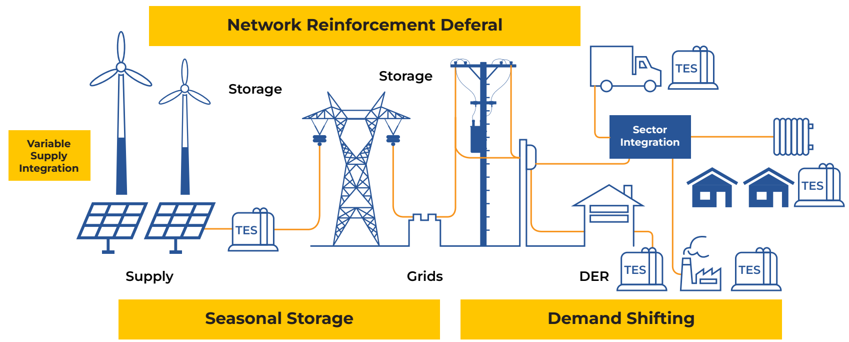
- Thermal energy storage (TES) can be categorized into sensible, latent, and thermochemical storage. Sensible TES involves raising or lowering the temperature of a material, such as water or rock. Latent storage occurs when a material undergoes a phase change, for example, from solid to liquid (like water and ice) or from liquid to vapor (such as salt hydrates). Thermochemical storage, on the other hand, utilizes chemical reactions or sorption processes to store and release heat.
- Currently, TES is used in buildings, district heating, and industrial sectors. By 2030, the demand for TES in space cooling is projected to reach 26 GWh, while molten salts storage is expected to increase from 491 GWh to 631 GWh, according to IRENA's Paris Agreement-aligned scenario. The largest thermal storage facilities are located in Spain (7 GWh), followed by the U.S. and South Africa, each with 4 GWh. TES is attractive due to its flexibility in delivering both heat and cold, its ability to integrate with variable power supplies, and its potential for cross-sector integration between power, industry, and building sectors. It can also meet both winter heating and summer cooling demands through stored energy.
- While TES is relatively inexpensive, has a long discharge duration, and a long lifetime, it also has some limitations. These include low energy density, a decrease in output temperature over time during discharge, and the need for large volumes and space, making it challenging to install in certain applications or locations.

Types of TES system



Source : Beceiro, 2023

Applications of TES in energy sector



Source : IRENA, 2020b

Current status of energy storage adoption in Indonesia

- Energy storage targets in current planning
- Existing and projected capacity of energy storage projects
- Trends in deployment and key adopters
- Case studies

Energy storage is enabler for transforming the power sector toward NZE, but widespread use remains distant due to slow variable renewable energy deployment

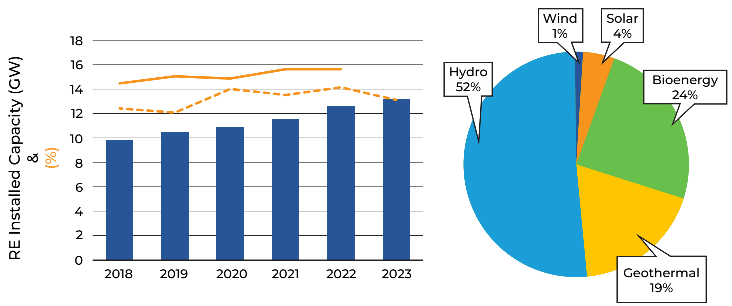
- Indonesia aims to achieve NZE by 2060 or sooner, with variable renewable energy (VRE) projected to dominate 77% of the total installed generating capacity, according to the roadmap by MEMR in late 2022. This includes plans for 421 GW of solar PV and 94 GW of wind power. To support VRE, at least 60.2 GW of energy storage, including pumped hydro storage (PHS) and battery energy storage systems (BESS), will be required (MEMR, 2022).

- By the end of 2023, only 13.15 GW of the projected 708 GW of clean power generation capacity for 2060 had been installed, with no large-scale energy storage systems yet operational. Recent renewable energy development has primarily focused on dispatchable hydro and geothermal sources, with VRE accounting for just 5.5% of the total installed renewable capacity.

- For energy storage planning, only 4.2 GW of PHS is outlined in the PLN RUPTL 2021–2030. BESS adoption is limited to the 225 MW early-stage diesel generator conversion program with a tentative battery capacity. The Upper Cisokan PHS pilot project, currently under construction, is expected to strengthen the grid by 2027. According to MEMR's NZE roadmap, BESS is expected to see greater utilization post-2034 as VRE penetration increases and battery costs decline.

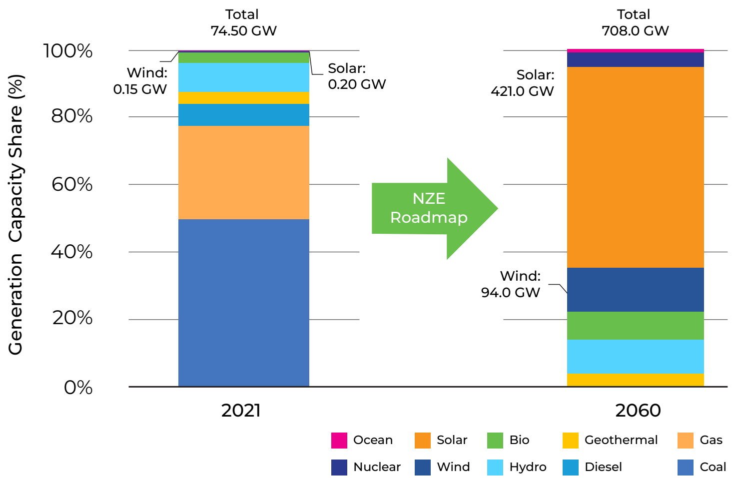
- VRE and energy storage capacity targets may change following the evaluation of the national electricity and energy system. In recent years, the Government of Indonesia (GoI) has been updating decarbonization plans and policies (e.g., KEN, RUEN, RUKN, and the new EBET Bill). Recent discussions indicate that the 2060 electricity demand projection is about 75% of the 2022 roadmap, reducing the need for generating capacity and infrastructure, including energy storage. However, clearer strategies for VRE and energy storage implementation should have been included in these documents.

Renewable energy capacity growth in Indonesia



Source : MEMR, 2024

Projected installed capacity in 2060 (NZE) compared 2021

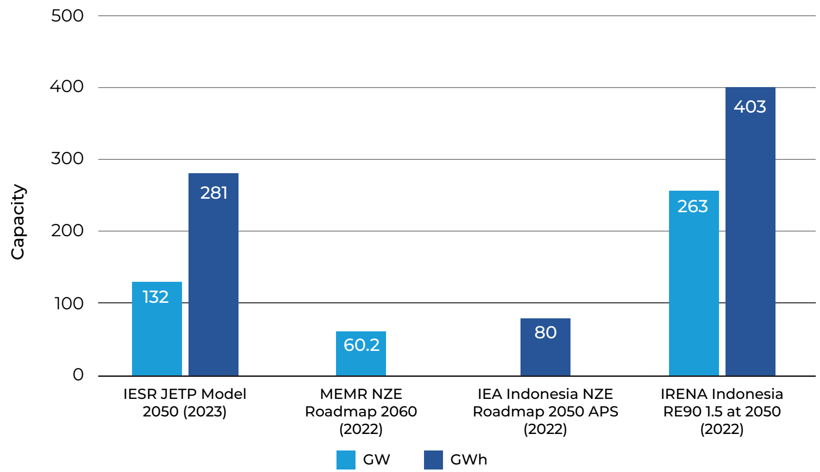


Source : MEMR, 2022

The required capacity and installation targets for ESS to reach NZE are still being assessed, with demand projections, emission constraints, and technology preferences playing major role

- IESR calculations, using more realistic demand projections based on the JETP scenario, estimate the need for energy storage capacity to reach 8.75 GW by 2030 and 132 GW by 2050. This is more than double the 2022 NZE roadmap estimates, despite lower electricity demand. One determining factor is the looser emission targets in the older NZE model, which allowed for competition from gas power plants with lower investment costs as peaker and load follower assets. Currently, in new long-term policy discussions, there is a preference to rely on gas power plants, especially from 2040–2050, with plans to extend their operations through hydrogen fuel switching and the addition of CCS.

Required energy storage capacity in different scenarios



Source: IESR analysis from several documents

- Although flexible power plants may take on some roles traditionally filled by ESS, their ability to shift VRE generation, especially in smaller systems, remains irreplaceable. Notably, the reference generation cost in small systems, per MEMR regulation 169/2021, is nearly three times the national average of 7 cents/kWh. Therefore, hybrid systems integrating solar PV and BESS can be economically competitive for de-dieselization sites. Studies show that diesel generation costs in these areas often exceed 30 cents/kWh due to high fuel transportation costs. Additionally, these small systems have limited energy resources and electricity demand, making other generation options less viable.

- Until mid-2024, discussions suggest that the actual need for energy storage capacity in 2060 is roughly half of the projections in the 2022 NZE roadmap, primarily concentrated in eastern Indonesia. BESS capacity will dominate, with no additional plans for PHS development. BESS, which is currently available in a modular and scalable containerized design, is well-suited for small systems. However, the potential for developing off-river PHS, which could reach 800 TWh and is distributed throughout Indonesia (Silalahi et al., 2021), needs to be revisited. This could potentially become a more economical ESS and peaker asset option than what is currently planned.

The announced projects will boost Indonesia's installed energy storage capacity by 1,000 times

- IESR's tracking shows that, over the past decade, Indonesia's total cumulative installed energy storage capacity has reached around 35 MWh by mid-2024, primarily from BESS installations in distributed, isolated systems supporting solar PV generation. It is worth mentioning that the exact capacity figures, operating status, and performance are currently difficult to monitor, as storage asset ownership is mostly private, and there has been no visible initiative to collect this data, including by government agencies.

- Compared to the use of BESS in hybrid systems with solar PV, current energy storage technology adoption in Indonesia mainly involves government-funded APDAL units or small plug-and-play battery packs for remote area electrification. The MEMR reported the distribution of over 20,000 APDAL units to 305 villages between 2021 and 2023 (MEMR, 2024). This equates to approximately 10 MW of battery capacity, assuming each APDAL unit has a capacity of 0.5 kWh.

ESS installed capacity in Indonesia by 2024 and the projected new capacity addition

Traced installed capacity by private sector and PLN:
>25 MWh
out of 31 traced projects

Government distributed energy storage:
Around 10 MWh
From more than 20,000

PLN pipeline:
>4.5 GWh
including Dedieselization and PHS development plan

Other announced project
Around 29 GWh
electricity export solar PV+battery projects

Potential Installed Capacity by 2030: 33.7 GWh

Source: IESR analysis

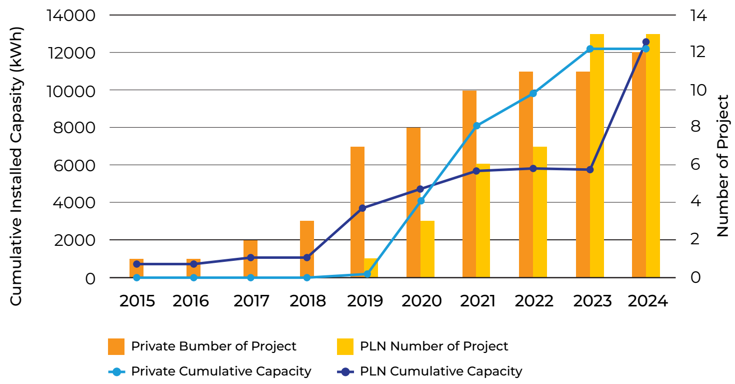
- Recent solar PV projects, especially at the megawatt scale, are increasingly using lithium-ion batteries (LIBs), a popular global choice. Installations on Selayar Island, Nusa Penida, and Bawean solar PV systems exemplify this trend. Some new residential rooftop solar PV users also prefer LIB over lead-acid batteries due to increasingly affordable local prices. However, larger-scale storage is still mainly deployed for smoothing solar PV output, lagging behind the global trend of adopting long-duration energy storage for grid applications. An interesting case is the 1.3 MWh BESS on Bawean Island, paired with a 406 kWp solar PV system, which reportedly functions as a substitute for a peaker gas power plant.

- Indonesia's installed energy storage capacity could exceed 30 GWh by 2030, based on announced projects. In addition to PHS and BESS in the de-dieselization program, planned VRE installations totaling 5.3 GW, as listed in the RUPTL, will integrate energy storage. Projects like IKN Solar PV and Tanah Laut Wind Farm, each including BESS capacities of around 10 MWh, highlight this trend. Additionally, plans for high-capacity clean electricity exports may drive large-scale adoption of long-duration storage. Government efforts to promote electrification through distributed hybrid systems with BESS are also evident in recent MEMR tenders.

Some of ESS technology early adopters are private sectors and remote areas supported by grants for electricity access

- The private sector has been an early adopter of energy storage installations and the latest technology. Of the 25 projects identified that utilize BESS with a capacity of more than 100 kWh (totaling 25.3 MWh), 13 were developed by PLN, while the rest were implemented by private sectors, including industries, commercial entities (hotels and resorts), and conservation areas. The private sector began using medium-scale BESS as early as 2015, well before PLN, which started in 2019. Moreover, the private sector ventured into investing in LIBs in 2017. Since PLN implemented LIB in the hybrid system on Selayar Island, it has installed at least an additional 5.5 MWh of LIB capacity.

The installed BESS capacity (larger than 100 kWh) in Indonesia



Source: IESR analysis

- On the consumer side, most private sector entities willing to invest in solar PV + BESS systems were those previously reliant on costly diesel generators. Besides gaining a green label, these installations, particularly in industries and eco-resorts, offer significant electricity cost savings. Unfortunately, the residential sector connected to the grid has not yet seen satisfactory returns on BESS installation. IESR estimates that incorporating a 2 kWh BESS into a rooftop solar PV system adds about USD 400 for improved reliability, extending the payback period by roughly 18 months.

- In addition to private sector investments, several BESS installations in solar PV systems have been initiated by foreign donors and the government, typically on a small scale, aimed at electrifying remote areas. However, maintenance issues have posed challenges, with many installed BESS units reportedly experiencing damage (Denun, 2018; Mathis & Listyorini, 2022). Unlike privately-owned assets, addressing damage in these cases can take a long time. Notably, several donor-funded projects are handed over to local governments for maintenance, which have strict budgeting systems. In the future, improving the technical capacity of asset operators at the sub-national level will be crucial to ensuring that BESS systems operate according to their expected lifetimes.

Case Study: Nusa Penida Hybrid System

- The Suana isolated hybrid system on Nusa Penida Island, operated by PLN, integrates a 3.5 MWp solar PV plant with a 3 MW/1.84 MWh BESS. Before this renewable integration, approximately 62,000 residents across the three main islands (Nusa Penida, Nusa Lembongan, and Nusa Ceningan) relied on 13 diesel generator units with a total capacity of 12.4 MW. According to IESR calculations, the cost of generating electricity from these diesel generators is 33 cents/kWh, significantly higher than the MEMR regulation 169/2021 reference of 13.3 cents for the Nusa Penida system, and about four times higher than the national average.
- Since being showcased at the G20 summit in 2022, the Suana Solar Plant has reportedly contributed around 30% of daily electricity loads and up to 65% of daytime loads. The BESS plays a crucial role in stabilizing the system and regulating the solar PV output. This integration has increased the renewable energy supply mix, reduced electricity generation emissions by about 10%, and lowered electricity generation costs. The system's LCOE is estimated to decrease by 8.5% due to fuel savings. Despite its limited use, the deployment of BESS in the Nusa Penida system marks a significant milestone as the first megawatt-scale grid-connected storage using LIB technology. This setup could pave the way for greater VRE penetration by unlocking the potential for daily energy shifting.

Estimated Nusa Penida system's characteristics
(top: existing system and pre-RE integration; bottom: in different configurations by 2030)

	Diesel based system	Existing hybrid system
RE fraction (%)		10.5
Fuel (mioL/year)	15.5	13.8
CO_2 (t/year)	~ 40	~ 36
LCOE ($/kWh)	0.326	0.298

@ 210 MWh/day (2030)	100% Solar PV +BESS	Solar PV +100MWh BESS +bioenergy	Solar PV +PHS** +bioenergy
RE fraction (%)	100	95	97.5
Fuel (mioL/year)	-	1.4*	0.6*
CO_2 (t/year)	-	~ 4	~ 2
LCOE ($/kWh)	0.446	0.213	0.151

* from 5% of the 95% biodiesel constraint

** hypothetical availability of 210 MWh capacity

- Renewable energy penetration and energy storage capacity are likely to increase alongside rising electricity demand and PLN's plan to phase out diesel generators by 2030. Since 2023, electricity demand in the Nusa Penida system has returned to pre-COVID levels, with peak loads exceeding 10 MW. Last year, there was even a reported supply deficit, necessitating the use of multiple mobile small diesel generators for backup. Expanding renewable energy capacity should be prioritized, especially for Nusa Penida, which has the potential to become a leader in green tourism.
- A well-planned strategy is essential to optimize renewable resources and energy storage in transforming the Nusa Penida system at minimal cost, including exploring PHS as an alternative to BESS. IESR has assessed various scenarios for Nusa Penida's transition to 100% renewable energy (IESR, 2024). However, unless BESS prices drop to about half of the current estimate, using a 100% Solar PV + BESS setup to meet the 2030 daily electricity demand of 210 MWh/day will result in a higher LCOE than the current level. Meanwhile, incorporating more bioenergy is expected to reduce the LCOE, although supply chain uncertainties and local availability pose challenges. Further studies are also needed to explore other technologies, such as tidal power plants and PHS.

Case Study: BESS utilization by off-grid C&I solar rooftop system

- BESS installed in industrial microgrids currently tends to be of short duration with large output capabilities, as they can be used to provide an instantaneous power source for uninterrupted industrial processes, in addition to optimizing VRE performance. In contrast, BESS in the commercial sector, such as hospitality, generally has a longer duration to maximize the use of energy produced by VRE.

Case 1:

Industrial sector customer-site BESS

Project description:

- The hybrid microgrid system at a remote mining site on Borneo Island comprises 7 MW steam turbines, an 800 kW diesel generator, and 2.4 MW of solar PV power generation.
- In 2019, a 2 MW/2 MWh LIB-based BESS and smart microgrid were installed and began operation a year later.

Reported outcomes:

- In addition to allowing VRE integration by smoothing solar PV output fluctuations, the BESS and smart grid assets improved both night and day system operation through load sharing. The BESS strengthened grid stability and was dispatched around 330 times per month.
- The integration of solar PV, BESS, and smart grid reportedly displaced 846,000 liters of fuel annually and reduced CO_2 emissions by 2,267 tons, supported by 2.7 GWh of annual solar PV production.

Additional remarks:

- A similar scope of BESS deployment has been recently reported, where a 1 MWh storage system is used to support a 2 MW solar PV installation in another location on Borneo Island.

Source: Hitachi ABB, 2021

Case 2:

Private-island customer-site BESS

Project description:

- In 2019, a 110 kWp solar PV system and a 144 kWh LIB-based BESS (with 50% system renewable energy penetration, relying on a diesel generator for the rest of the power generation) were successfully installed in a luxury resort in the Riau Archipelago.

Reported outcomes:

- The addition of the PV+BESS system was expected to reduce diesel consumption by about 45,000 liters annually. According to the resort, this resulted in a cut of the island's diesel fuel usage by approximately 60% (around 6,000 liters, which is estimated to produce 19 tons of CO_2) over a monitoring period of about two months.

Additional remarks:

- A similar hybrid system has been previously installed on other island in the archipelago with 77 kWh LIB-BESS.

Source: Andy Colthorpe, 2019

Case Study: Second-life battery utilization and pilot project of promising ESS technology

- Installing energy storage in the residential sector requires individual initiative and willingness due to the lack of rewards or promising investment schemes. Similarly, testing various types of energy storage through pilot projects involves high costs and uncertain results. However, the trial results can be very helpful in identifying best practices for the future large-scale development of new technologies.

Case 3:

Residential customer-site BESS

Project description:

- Residential rooftop solar PV users with a capacity of 12 kWp integrate a BESS with a total capacity of 40 kWh.
- The electrical system is a hybrid system combining solar PV, BESS, and a grid connection.
- The installed batteries are used lithium-ion, with half specifically being of the LFP type.

Reported outcomes:

- Users report that both the solar PV and batteries operate as expected without any serious issues or maintenance problems, despite using second-hand batteries.
- The supply from the installed capacity sufficiently meets the daily electricity needs of the two occupants. Grid electricity is only required when guests stay for extended periods or during the rainy season.

Additional remarks:

- It is estimated that the installed hybrid configuration saves more than 1 million rupiah per month in electricity costs.
- Estimated investment costs are around 250-300 million rupiah, with battery components contributing one-third.
- Battery costs can more than double with new batteries. Users report that second-hand batteries, especially those from electric buses and telecom base stations, are widely available at around 2 million rupiah per kWh.

Source: Interview with solar PV installer in May 2024

Case 4:

A pilot project with redox flow battery (RFB)

Project description:

- The Sumba Smart Micro Grid (SSMG) demo plant facility, built by BPPT and inaugurated in 2012, is connected to the 20 kV PLN grid. It integrates 500 kWp of solar PV, a 480 kWh vanadium redox flow battery (VRFB), and two 135 kVA diesel generators. Before the integration of solar PV and storage, the Sumba power grid was already supplied by 1.8 MW of micro-hydro and 4.9 MW of diesel generators.
- Conducted over approximately two years, the RFB was expected to increase the solar PV penetration limit to serve a total load between 1.2 MW and 1.5 MW.

Reported outcomes:

- The BPPT report suggested that the VRFB was not utilized optimally from the beginning of the test. The VRFB was mainly used for solar PV smoothing or output correction and was connected to the PLN grid. Meanwhile, when the VRFB was tested in stand-alone supply mode, the system failed. SSMG supplied more than 100 MWh of electricity in a year of testing, which translates to a substitution of 33,000 liters of diesel fuel.
- According to a report published in 2017, the VRFB in SSMG stopped operating due to damage to its components, while the solar PV was still able to supply the PLN grid at a limited low rate of 150 kW (about 30% of maximum capacity) during daytime.
- Valuable experience in operating the VRFB was gained, including knowledge of VRFB system integration, charge-discharge, and self-consumption characteristics.

Additional remarks:

- In 2022, PLN officials mentioned their interest in adopting VRFB technology, particularly for deployment in remote areas due to its potential low cost.

Source: Akhmad et al., 201

Case Study: Production of green hydrogen based on solar and geothermal energy in Muara Karang, Jakarta

Project description:

- Indonesia, at the end of the third quarter of 2023, inaugurated its first green hydrogen plant (GHP) under the auspices of PLN, located in the Muara Karang Steam Gas Power Plant (PLTGU) area in Pluit, North Jakarta.
- The installed electrolyzer capacity is projected to reach 2,795 MWh per year, potentially producing 51 tons of green hydrogen annually, with an energy requirement of 55 kWh per kg of green hydrogen. The current use of green hydrogen is limited to 8 tons per year for cooling generation needs.

Reported outcomes:

- The electrolyzer used is of the alkaline (ALK) type, which employs a base solution, is easy to maintain, and has capacities ranging from 40 kW to 100 kW. Some of these electrolyzer machines have been in operation at PLN since the 2000s, while the newest ones are less than three years old.
- The hydrogen produced is stored as compressed hydrogen at low pressures of 7-9.5 Bar and high pressures of up to 156 Bar; however, PLN typically uses the low-pressure variant. The high-pressure hydrogen must be decompressed prior to use.
- As a renewable energy source, the GHP is supported by solar PV with a capacity of 724 MWh and geothermal energy of 2,077 MWh. It is equipped with a renewable energy certificate (REC), certified by a professional third party, covering the 2,077 MWh per year derived from on-grid geothermal energy. The Solar PV component is currently undergoing the REC certification process.

Additional remarks:

- This green hydrogen plant project is not yet considered strategic, as there is no information regarding further development or production projections for larger-scale operations. Domestic demand has not yet developed sufficiently, and the current production volume is too small for export.
- Furthermore, the GHP is viewed as a pilot project for green hydrogen production and is positioned as a model to demonstrate that hydrogen can be safely produced and used, while also enhancing PLN's portfolio in hydrogen production technology.
- In terms of pricing, without considering CAPEX investment and focusing solely on OPEX related to energy costs and minimum maintenance, the cost of producing green hydrogen is above USD 5. This cost could escalate to USD 7-12 when factoring in CAPEX investment and high maintenance requirements.
- There are challenges in detecting small leaks in the pipelines, as the leak detection system relies on pressure control. In the room where the electrolyzer is located, a combustible gas sensor is used for monitoring. Another challenge is that hydrogen is odorless, colorless, and disperses directly into the air. Additionally, the hydrogen produced must have a high purity of over 99.9%, limiting its ability to be mixed with other chemicals as a leak indicator.
- Currently, this GHP contributes to the largest capacity, accounting for around 25% of the national production capacity of green hydrogen, but it is still far from replacing the demand for grey hydrogen, which stands at 1.8 million tonnes per year.

Source: Interview with in PLN 2024


ENERGY
STORAGE
ENERGY
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Challenges and opportunities for energy storage development in Indonesia

- Technical challenges and opportunities for energy storage deployment in existing power systems
- Readiness for adoption from regulatory and economic feasibility perspectives
- ESG and supply chain challenges, from upstream processes to recycling industries
- The future prospects of green hydrogen development

Maximizing the currently limited deployment opportunities for energy storage systems (ESS) is a crucial first step in expanding their role within Indonesia’s power system

- Developers’ access to increasingly affordable ESS technology, particularly batteries, combined with the growing expertise of stakeholders in the power sector, can provide a solid foundation for broader ESS adoption. At present, the best opportunities for ESS deployment lie in smaller or isolated systems, which will also help to strengthen the domestic technology supply chain. However, large-scale nationwide implementation may still be a decade away and will require ESS to be economically competitive with other flexible grid assets. Demand for ESS could increase significantly if variable renewable energy (VRE) integration targets rise, necessitating greater system flexibility.

The summary of existing characteristics of power system in Indonesia and its influence to energy storage system adoption

Characteristics	Influence on ESS Adoption	Description
Low VRE penetration level and slow growth in the past few years	Demote	- The output variability of VRE at the current penetration level has no significant impact on grid stability, reducing the need for ESS to smooth VRE output. - VRE electricity production levels are still low and can be supplied to the grid. At higher levels, ESS will be needed to reduce VRE curtailment.
Low electricity load and peak load growth	Demote	- The capacity of non-VRE power plants (committed projects) has increased significantly, while the growth in electricity demand has been relatively low in recent years, hampering utilities’ ability to invest in new grid assets. - The system load factor has been high, indicating a low need for ESS development as a peaker asset. - The installed fast-response generating capacity is already quite high.

Source: IESR analysis

Characteristics	Influence on ESS Adoption	Description
High capacity of fast response generators in the pipeline	Demote/ Neutral	- This limits the potential for additional development of ESS as an ancillary services provider. - ESS projects must be economically competitive with generating assets such as gas-fired power plants and conventional hydropower plants.
Several isolated systems with limited energy sources	Promote	- In certain remote areas, particularly those with limited energy resources and no grid connection, access to electricity is often restricted to lighting. - Electricity generation using a solar PV plus storage system can be more cost-effective than fossil fuel generators like diesel generators.
Inferior power system reliability and efficiency in smaller systems	Promote	- There is potential to increase system efficiency based on the low system load factor, particularly in several small systems. - The higher-than-average level of system interruptions in small systems suggests potential for ESS implementation as a backup power source or for deferring transmission and distribution (T&D) upgrades. - Systems with high VRE penetration levels are beginning to be impacted by the variability of VRE output.
Low flexibility in current generation mix to accommodate rapid VRE integration	Promote /Neutral	- The plan to significantly expand VRE capacity to reach the final net zero emissions (NZE) target will require large-scale, versatile energy storage to facilitate rapid VRE integration. - The number of existing grid assets that can be operated with flexibility is limited.

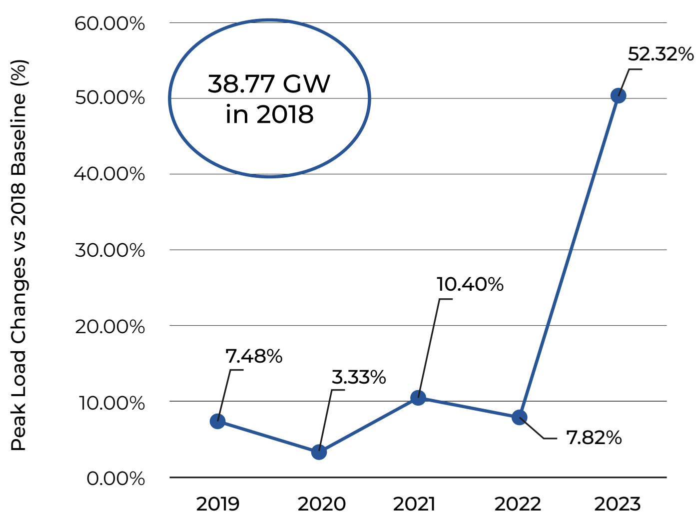
Source: IESR analysis

Some existing technical characteristics of the power system are currently not favorable for energy storage development

- Historically, the growth of VRE capacity has been minimal, and current conditions are unlikely to drive large-scale ESS investments to support VRE (e.g., smoothing output and reducing curtailment). Dispatchable power plants still dominate Indonesia's electricity generation capacity, with VRE contributing just 0.00004% of total utility electricity production (PLN, 2023). Assuming no interconnection issues, the Indonesian power system is currently in Phase 1 of the energy transition, where VRE integration has no significant impact on system stability. The effects of VRE will become noticeable at higher penetration levels, around 6% (EBTKE & DEA, 2021).

- The urgency to deploy ESS as a peaker asset remains low. Recent electricity demand growth has been met by an increase in generating capacity, which appears excessive and dampens the investment appetite for the development of unfamiliar technologies like ESS. Prior to 2023, total installed capacity consistently exceeded the reasonable capacity*. For instance, generating capacity reached 69 GW in 2022, well above the reasonable level of 56.4 GW. Additionally, there is already a significant number of fast-response power plants, accounting for around 17-19% of total installed capacity, while peak load growth between 2018 and 2022 was relatively low, increasing from 39 GW to 42 GW. Last year, a 39% surge in peak load compared to 2022 was reported, which seemed promising for ESS peaker development initiatives. However, with many fast-response power plants still under construction, the prospects for ESS remain highly uncertain.

The peak load changes of PLN's system



Source: IESR analysis from PLN statistic (2019-2023)

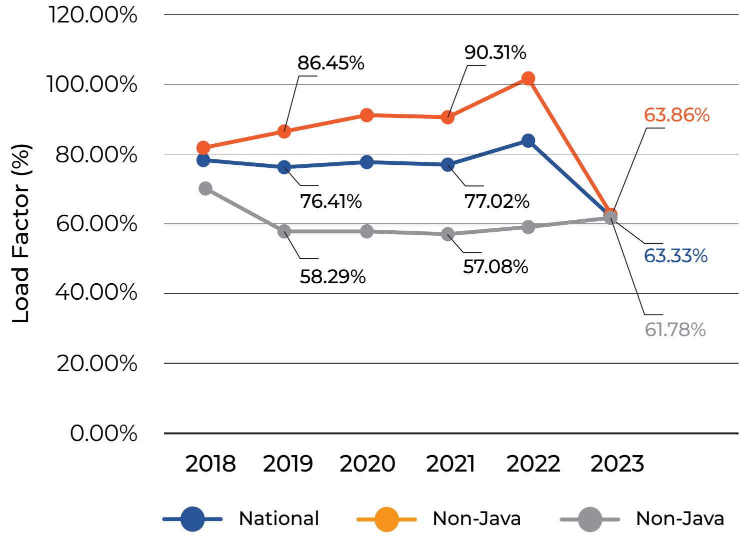
Footnote:
*(1+regulated standard reserve margin of 30-35%)*peak load.

- ESS are unlikely to be prioritized as providers of ancillary services for the grid in the next few years. The government's increasing commitment to boosting VRE during the process of updating power sector planning documents presents an opportunity for ESS to play various roles in grid reinforcement. However, to date, fast-response diesel, gas-fired, and hydropower plants have been used to fulfill a role similar to that of ancillary services in Indonesia, and these technologies remain a priority in medium-term planning. In PLN's RUPTL, approximately 48% of the planned electricity sources (including gas power plants, hydropower plants, and a total of 4.7 GW of pumped hydro storage) until 2030 fall into this fast-response asset category, which may limit opportunities for more ESS to take on this role. In the long term, the future of ESS deployment will largely depend on its cost competitiveness compared to traditional assets and the experience of policymakers and PLN with the benefits of operating ESS.

ESS deployment opportunity in small-scale in near term and large-scale in the long term due to net zero system's flexibility requirement

- The challenge the government faces in providing affordable electricity to remote areas has become an opportunity for significant ESS deployment. As an archipelagic country, Indonesia has many isolated power systems with limited energy resources and is not yet fully electrified. Despite achieving a 99.78% electrification ratio in 2023, about 3% of this still only provides basic lighting through the Energy Saving Solar Light (LTSHE) program, which is classified as Tier-1 electricity access (ESMAP, 2015). Meanwhile, to support economic development, more reliable electricity is needed for devices like TVs and phone chargers, and productive use. Before the availability of affordable VRE options, some systems relied on costly diesel generators that often faced fuel logistics issues. PLN has recognized the benefits of the VRE plus storage system and initiated a diesel generator conversion program at thousands of locations. Moving forward, a similar strategy could be expanded to community microgrids or areas currently dependent on LTSHE by installing sufficient ESS capacity to ensure 24/7 electricity access.

Comparison between the average non-Java system load factor with Java and National average



Source: IESR analysis from PLN statistic (2019-2023)

- The reliability and efficiency of power systems outside the Java-Bali region are significantly lower than those in the Java-Bali area, making ESS a reasonable option for backup, peaker assets, or ancillary services. This lower reliability is reflected in the reported SAIDI and SAIFI values, which averaged 8.17 hours per consumer and 5.93 outages per consumer, respectively, in 2023. Some systems reported SAIDI values more than three times longer than the Java system's 3.92 hours. Notably, there is a PLN system on Sulawesi Island that reportedly can no longer accommodate additional VRE penetration without integrating ESS, as the grid's limited flexibility is already affected by VRE output variability. Moreover, low load factors, particularly for systems outside Java that have persisted in recent years, further underscore the need for efficient peak control assets, with ESS emerging as a practical solution.

- The limited flexibility of Indonesia's current power system underscores the potential need for large-scale ESS deployment to support large scale integration of VRE. An IEA study in 2022 suggests that the Java-Bali and Sumatra grids, which account for 80% of national demand and are relatively resilient to variability, can accommodate up to 10% variable solar electricity by 2025. However, this may fall short of the capacity required for achieving long-term net-zero goals. Several scenarios referenced in the recent JETP CIPP document indicate that national VRE penetration could reach 23% to 48% by 2050 (JETP Indonesia, 2023), necessitating grid assets that can manage minute-by-minute fluctuations and provide fast-response bulk electricity—a role that ESS can fulfill. Concerns have been raised regarding the grid's ability to handle the growing VRE, primarily due to earlier planning decisions that have increased grid stiffness, with many new coal-fired power plants (CFPPs) bound by long-term take-or-pay contracts. While retrofitting CFPPs or restructuring contracts to allow for flexible operations is a potential solution, an IESR study found that retrofitting older CFPPs tends to raise emissions and increase the levelized cost of electricity (IESR, 2022). Building inter-island connections could enhance flexibility and complement the implementation of grid-scale ESS. However, long lead times and high investment costs pose significant challenges. Although the concept of a 'supergrid' has existed for years, it has yet to be realized.

Indonesia's regulatory framework still has significant gaps to fix for enabling widespread ESS adoption in neart term

- While strategy documents and ESS implementation targets are being evaluated for long-term planning aligned with net-zero emissions (NZE) goals, several energy storage regulations will require adjustments to meet these objectives. As ESS technology is still relatively new, many essential policy frameworks have yet to be introduced. Closing the regulatory gap and establishing legal certainty are vital to reducing development risks and boosting investor confidence in ESS initiatives.

- Previous long-term planning documents for the power sector do not fully recognize the unique versatility and value of different types of stationary ESS. The implementation plan generally views ESS as a source of bulk electricity and as a supporting component of VRE. In contrast, other countries have identified and implemented various ESS types as providers of different ancillary services for their power systems. The current narrow definition of ESS and the absence of significant capacity targets in existing planning documents limit the full adoption potential of ESS by sending weak market signals to investors and technology producers. Current plans mainly focus on pumped hydro storage (PHS) and battery energy storage systems (BESS), whereas a technology-agnostic approach would better support cost-competitive storage solutions from emerging technologies. Given that energy storage is one of the fastest-evolving research areas, with market leadership constantly shifting, Indonesia will need rapid adaptation and knowledge transfer capabilities, making a flexible research and development (R&D) roadmap, including pilots essential to keeping pace with global developments.

Several ESS-related existing regulatory frameworks

Document type	Document	Remarks
Planning and/or ESS definition	MEMR's NZE Roadmap 2022	Sizable capacity target, limited ESS definition
	National Electricity Plan (RUKN) Draft 2023-2060	
	PLNs RUPTL (2021-2030)	
	MEMR Reg 9/2023 (RENSTRA 2020-2024)	Storage deployment plan beyond RUPTL
	Government Reg 25/2021	May need an update with detailed terms for ESS
Grid code	MEMR Reg 20/2020	May need adjustment with recent high VRE adoption plan
Others	MEMR Reg 12/2021 (Business certification)	Quite detailed, may need to be evaluated after the introduction of other new or update regulation
	MEMR Reg 22/2021 (APDAL regulation)	

Source: IESR analysis

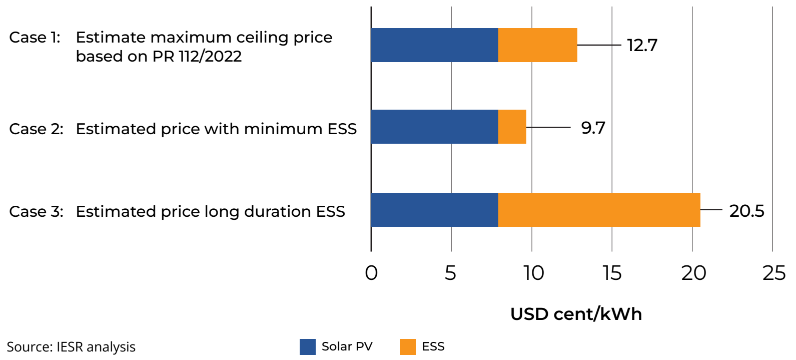
- The current market structure and regulations do not provide a sufficient enabling environment for ESS adoption. For example, the business development scheme for ESS ownership, as outlined in Gov Reg 25/2021, permits the sale of electricity from ESS assets; however, the single-buyer market policy limits revenue stacking opportunities for ESS owners. Additionally, there are no specific regulations outlining the terms for utilities purchasing electricity from ESS owners, which may require adjustments to MEMR Reg 10/2017. The development of customer-sited ESS is also hindered by the absence of innovative schemes like "community BESS," particularly since the flat electricity tariff in Indonesia offers limited economic incentives for customers to invest in ESS.

- A transparent and efficient procurement framework needs to be established to achieve the targeted ESS deployment. In addition to ensuring that projects are completed on time, a well-structured framework can improve cost-effectiveness, such as by bundling multiple ESS projects to achieve economies of scale. Updating the grid code to reflect the expanding role and advanced operational mechanisms of ESS assets will be necessary, as the grid code will guide the procurement criteria. Additionally, installation and technology component standards must be clarified and made consistent for each ESS type and configuration. Although there are existing standards, particularly for BESS technology (e.g., SNI, IEC, IEEE, ISO), past projects—especially those involving PLN as the offtaker—often included additional requirements (such as SPLN) in their tenders.

To increase installations of ESS, adjustments to electricity tariffs for ESS assets will be necessary, along with support for the domestic industry to produce components at competitive prices

- Despite the proven technical maturity of ESS technology in strengthening the electricity system, its high cost requires substantial investments for widespread deployment. Stimulus through supportive policies and schemes is essential, particularly given the electricity market's limited inherent attractiveness, which would lead to a low adoption rate without intervention.
- Regulations governing ESS components and facility pricing need to be developed. Currently, ESS tariffs refer to Presidential Regulation 112/2022, which caps ESS prices at 60% of the Variable Renewable Energy (VRE) ceiling price, or higher with ministerial approval. However, this regulation only applies to ESS bundled with VRE, and pricing for stand-alone ESS has yet to be established. Setting a price for stand-alone ESS is crucial to attract investment for larger-scale systems. For bundled ESS, rather than fixing a maximum price, introducing a ceiling price based on type, capacity, and scale—similar to power plants—would enhance project development transparency and competitiveness. This could help address challenges in developing VRE and ESS for isolated systems, where the required ESS capacity is significantly higher and could cost twice as much as the plant itself. Although current regulations allow for such projects with ministerial approval, the procurement process remains inefficient.

Estimated VRE+ESS price in different cases



Source: IESR analysis

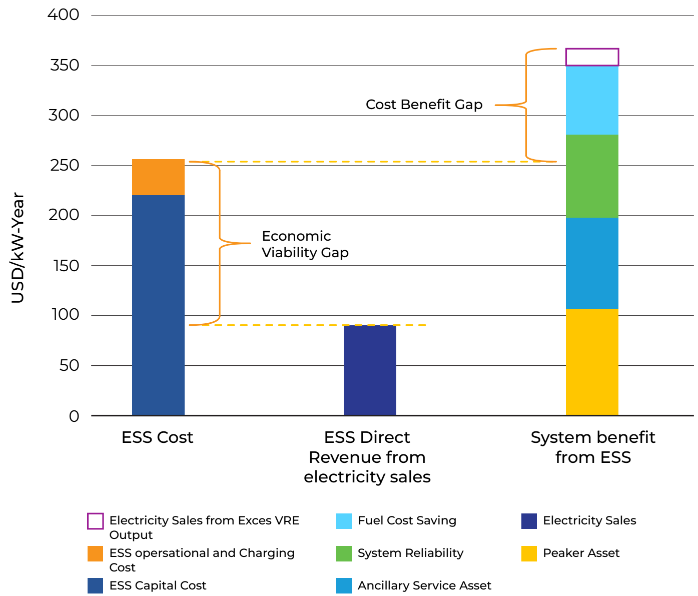
Notes:
1. The assumption for the Solar PV component price is based on a 10 MW scale with an 1 F factor in the first staging of Presidential Regulation 112/2022.
2. The ESS price estimate is based on IESR's analysis for LIB-LFP ESS with a scale of 10 MW-1h (for case 2) and 10 MW-8h (for case B) with 1000 cycles/year.
3. In case 2, Minimum ESS refers to the minimum capacity in the existing grid code, which is 10% of the power plant capacity.
4. In case 3, the price of long-duration ESS is an estimated cost for ESS with 100% of the power plant's capacity, which represent requirement for isolated system cases.

- Several VRE developers have highlighted the high costs associated with ESS development, underscoring the need to strengthen the supply chain to enable broader adoption of more affordable components, which would require strong domestic demand. At present, with most components being imported, an ESS with the same output capacity as a VRE system can cost twice as much. Experts and industry stakeholders believe that local production of components, particularly battery cells, could reduce costs by approximately 20% compared to imports. However, most planned battery production in Indonesia focuses on nickel-based cells, which are typically more expensive than the Lithium Iron Phosphate (LFP) cells commonly used in Battery Energy Storage Systems (BESS). If domestic manufacturers diversify their production to include other cell types, achieving economies of scale will be crucial. Recent reports suggest that a viable production plant would require a minimum capacity of 0.9 GWh per year.

In addition to incentives, the potential value stacking of ESS needs to be evaluated to enhance its economic feasibility

- Currently, there are no specific incentives or subsidies to encourage the expansion of ESS projects and reward early adopters. Government-led initiatives, such as investment cost subsidies and tax credits, have proven effective in countries where ESS deployment is progressing rapidly. Subsidies could also facilitate smaller-scale customer-sited ESS installations, especially in the commercial and industrial (C&I) sector. Additionally, incentives for technology producers, including research and development (R&D) funding, are essential to building a supply chain ecosystem and reducing future project costs.
- The total system cost benefits of integrating ESS should be considered when evaluating its economic viability, particularly at the utility scale in Indonesia. When ESS costs are viewed as generation component costs, the potential revenue from electricity sales—often used as an economic benchmark—does not favour ESS integration options, especially due to relatively low electricity tariffs. The same applies when comparing ESS to fast-response power plants for dedicated roles, such as peaker assets.
- Moreover, ESS offers valuable functions beyond those of traditional power plants, including the ability to reduce variability and store excess generation. Unfortunately, research on potential value stacking and revenue mechanisms for ESS in Indonesia is still limited. For grid-scale deployment, collaboration between the government, PLN (Perusahaan Listrik Negara), and academic institutions is necessary. PLN's transparency regarding system conditions will assist policymakers in understanding the value of ESS and developing supportive schemes for its deployment.

Estimated system benefit of utility scale ESS compared to its costs



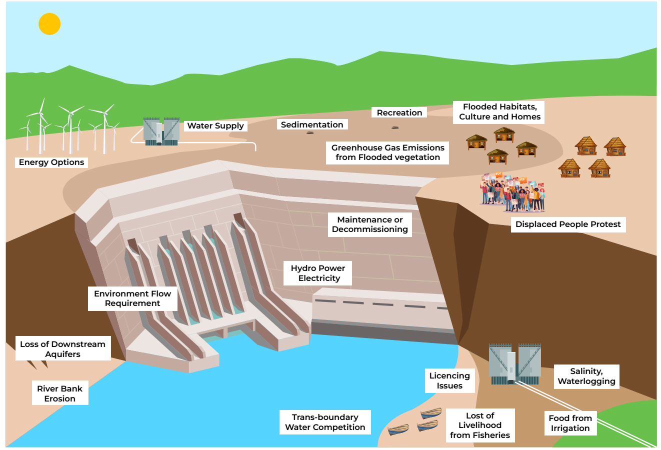
Source: IESR analysis

Notes:
1. The estimated ESS cost is for a 100 MW-4h LIB-LFP with 350 annual cycles and a charging cost of 3 USD cents/kWh.
2. The estimated direct revenue is calculated based on electricity sales from ESS output over a year, priced at 9.3 USD /MWh.
3. The estimated peaker and ancillary asset cost is based on the cost of building a gas power plants.
4. The estimated reliability cost is based on potential revenue lost due to system interruptions.
5. The estimated fuel cost savings are based on the cost of gas fuel for generating the same amount of electricity as the ESS output.

ESG issues haunt construction of ESS and EV downstreaming projects

- The development of the Energy Storage System (ESS) project faces significant challenges in the Environmental, Social, and Governance (ESG) field. Hydropower plants, in particular, encounter various environmental issues, including land-use changes, biodiversity decline, reservoir sedimentation, and social impacts during and after development (Media Tata Ruang, 2023). Potential conflicts may also arise, as local laborers may feel marginalized due to the project's preference for foreign workers, along with the relocation of endemic forest animals. Notably, the World Bank withdrew its funding from one hydropower project due to on-the-ground conflicts (Sidjabat, 2020). The Upper Cisokan project, a critical component of the ESS initiative with its 1,040 MW pumped storage facility (World Bank, 2011), is grappling with severe environmental issues. Originally announced in 2010 (MEMR, 2010), construction was delayed until 2022 (Citarum Harum Juara, 2022), and operations are now set to commence in 2027 (Aristi, 2022). The Cirata and Saguling hydroelectric power plants, which are already in operation, also face ongoing environmental issues stemming from the permanent impacts of land conversion.

Illustration of environmental Impact of Hydropower Plants



Source : Globevnik et al., 2014

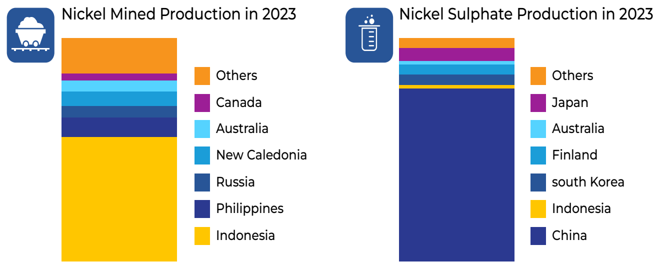
- ESG concerns are similarly significant in the development of electrochemical energy storage systems. For example, the sulfuric acid used in lead-acid batteries is highly corrosive, and improper disposal can contaminate soil and water sources. Lead, the primary component of lead-acid batteries, is a toxic metal that poses serious health risks to humans and the environment. Communities living near used battery smelting facilities have been found to have blood lead levels four times above the limit (Arah Environmental, 2022). Additionally, lead-acid batteries can release harmful chemical compounds, contaminating the soil and water when exposed to sunlight. Health effects related to lead exposure include neurological issues, delayed brain development in young children, decreased fertility in animals, stunted plant growth, behavioral abnormalities in humans, hearing problems, anemia, and more. Unfortunately, these effects often manifest after ten years, and certain regions in Indonesia, such as Riau in 2004 and Bogor in 2015, have already exceeded safety thresholds.

- Indonesia's ambition to become a global hub for electric vehicles (EVs) also faces ESG challenges. Indonesia Weda Bay Industrial Park (IWIP) has been reported to violate human rights (Aranditio, 2024), cause deforestation, and contribute to water and air pollution. The local community's involvement in the environmental planning and analysis was limited, and some had their land taken without consent or compensation. Additionally, the coal-fired power plants, with a combined capacity of 3.78 GW, used to support the nickel industry exacerbate air pollution. Deforestation has further worsened air quality, as the project has cleared 5,331 hectares of tropical forest (Belseran, 2024). Moreover, the local community's livelihoods have been disrupted due to inadequate waste management practices. Similar issues have occurred during the construction of the Indonesia Konawe Industrial Park (IKIP), where 3,500 hectares of forest were cleared. In total, nickel mining along Sulawesi and North Maluku has cleared 76,000 hectares of forest (Project Multatuli, n.d.)..

Small production of battery materials and environmental issues obstructing Indonesia's aspirations to become a global EV hub

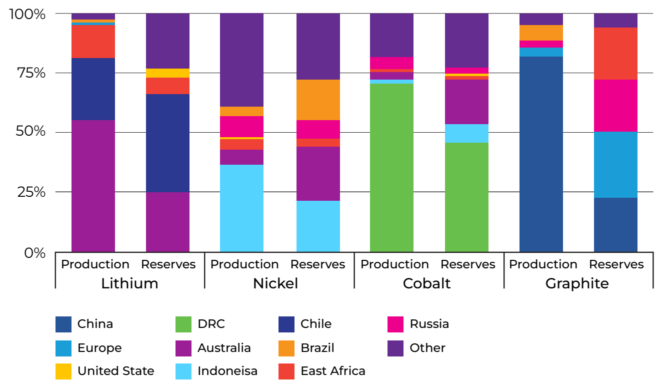
- Indonesia's abundant reserves of critical minerals for battery production, such as bauxite, tin, and cobalt, along with low-cost nickel, strategically position the country as a key player in the global battery supply chain. With major investments and partnerships involving automakers and battery producers, Indonesia is well-placed to dominate the EV and renewable energy markets, boosting its global competitiveness.
- Despite these opportunities, several challenges hinder Indonesia's battery production. While Indonesia is the world's largest nickel producer, only a small portion of its mined nickel is currently processed into nickel sulfate for battery production. This is largely due to the dominance of smelters using RKEF (Rotary Kiln-Electric Furnace) technology, with 49 RKEF smelters compared to just 5 HPAL (High-Pressure Acid Leaching) smelters (Hasiana, 2024). As a result, most of the nickel is diverted to the stainless steel industry rather than being used for EV batteries. Additionally, high carbon emissions, deforestation, and poor tailings management have led to Indonesia's nickel being labeled as "dirty mining," making it challenging to access the global market. Moreover, the lack of domestic lithium reserves further limits Indonesia's ability to fully support battery production.
- To overcome these challenges and fully leverage its mining potential, Indonesia must invest in cleaner mining technologies and enforce stricter environmental regulations. One approach is to adopt responsible mining practices, which include respecting human rights and the aspirations of affected communities, providing safe, healthy, and supportive workplaces, minimizing environmental harm, and leaving positive legacies (IRMA, 2024). By transitioning to lower-carbon extraction methods and improving tailings management, Indonesia can enhance its appeal in the global market. Additionally, research and development to identify substitute materials not currently available in Indonesia, as well as preparing for urban mining (recycling from used batteries), will be essential to ensure the longevity and sustainability of Indonesia's EV battery industry. Establishing joint ventures with market leaders and focusing on technology transfer for the midstream industry will also help Indonesia meet future battery demand and achieve its net-zero emissions (NZE) goals, whether through electric vehicles (EVs) or energy storage systems (ESS).

Nickel mined production and nickel sulphate production in 2023



Source : Volta Foundation, 2024

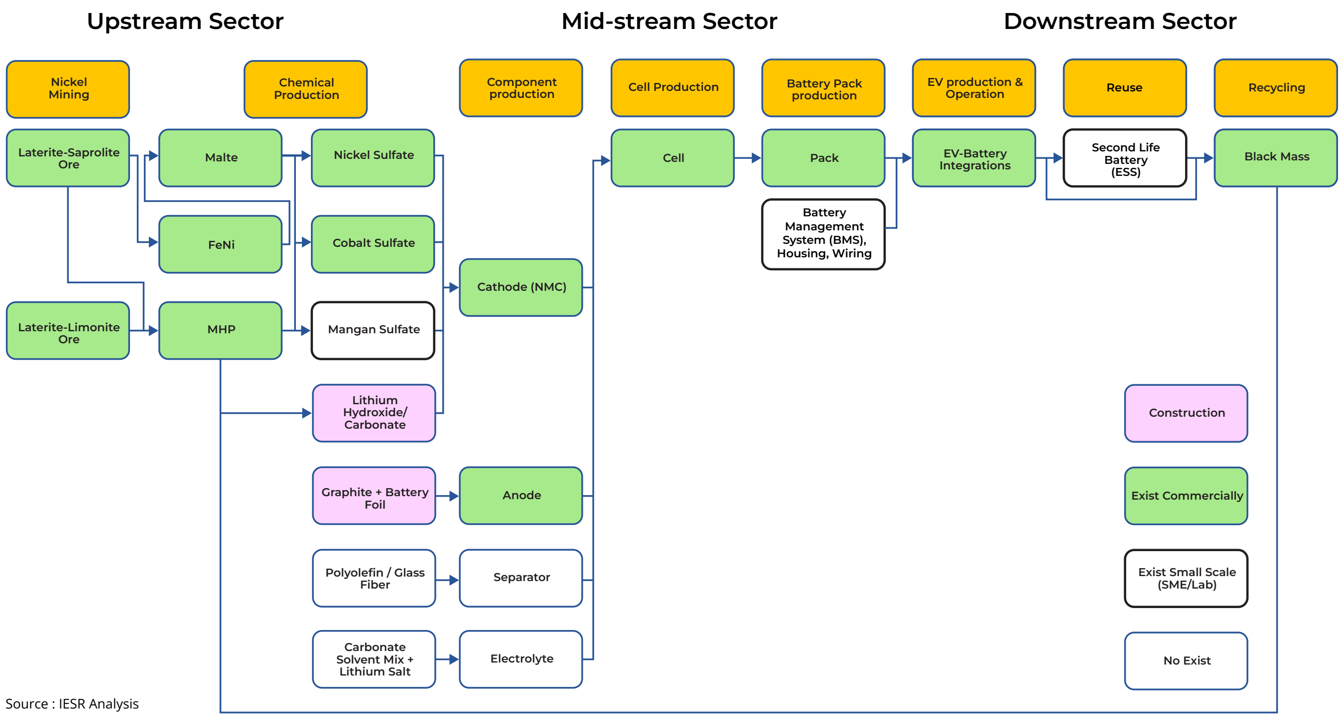
Current battery minerals mining production vs reserves



Source : IEA, 2022

EV adoption obstructs middle-stream EV battery investment

The EV Battery Supply Chain in Indonesia



Source : IESR Analysis

- Indonesia has been focusing on electric vehicle (EV) battery supply chain investments in recent years. Recently, the world's second-largest anode battery lithium manufacturer invested IDR 3.2 trillion in the Kendal Special Economic Zone (KEK), creating 7,800 job vacancies. The industry will have a production capacity of 80,000 tonnes per year, consisting of 30,000 tonnes of artificial graphite anode and 50,000 tonnes of natural graphite anode, and is expected to grow to 160,000 tonnes per year by 2025 (Wijanarko, 2024). The company is known to supply EV batteries to Tesla and other major players such as LG, SK Group, Samsung, Panasonic, and other prominent names.

- Despite the Indonesian government's efforts over the past five years to localize the nickel industry for EV batteries, a significant gap remains in the midstream sector, with many battery energy storage system (BESS) facilities focusing solely on battery packaging. To address this, the government plans to close the gap in the battery industry supply chain by gradually increasing the local content requirements (LCR) threshold for EVs to qualify for incentives. Additionally, the government must prepare for technological shifts, as several NMC (Nickel Manganese Cobalt) projects globally have been canceled in favor of LFP (Lithium Iron Phosphate) technology. This transition underscores the need for Indonesia to adapt its strategies to align with global trends and ensure the local battery industry remains competitive in a rapidly evolving market.
- On the other hand, the local battery industry's production capacity is currently limited to 100 kWh, restricting its application to residential, commercial, and industrial segments. This limitation makes it difficult to compete with global battery producers, who can supply larger projects requiring over 10 MWh, with production capacities exceeding 1,000 kWh per module. To strengthen its position, Indonesia must enhance its production capabilities and diversify its offerings to meet the growing demands of the international market.

Huge potential within used EV batteries in near term, but battery waste collection, transport, and pricing issues remain challenging

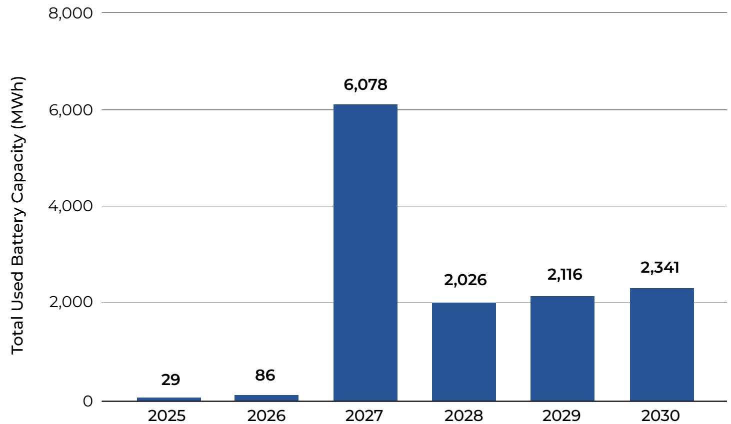
- Repurposing degraded battery cells from EV fleets could offer a cost-effective solution for developing battery energy storage systems (BESS). When an EV battery's capacity degrades to around 80% after multiple charging cycles, it can no longer perform effectively in vehicles and needs replacement. However, these used batteries can still be repurposed for applications like BESS to support variable renewable energy (VRE) or as backup power units. Since battery cells account for about 30% of residential BESS costs and over half of the costs for commercial and grid-scale systems (NREL, 2024), using spent EV batteries could significantly lower overall expenses.

- Even battery cells that are no longer suitable for reuse after serving as BESS still hold potential value through recycling. Metals extracted from recycled battery cells can be sold or reused to produce new cells. Although the profitability of recycling is uncertain, recycling nickel-based EV batteries with a capacity of 60 kWh is expected to yield a profit of around USD 727. However, the current cost of recycling LFP-type cells is estimated to exceed the value of the recovered materials (Cho, 2022). Ongoing research aims to improve the efficiency and economics of the recycling process, and future breakthroughs could enhance the profitability of battery recycling.

- Indonesia needs to develop schemes and business models for managing spent EV batteries. Effective management of these batteries through reuse and recycling can optimize their remaining value while minimizing environmental impacts and the costs associated with hazardous waste. From private EV adoption alone, an estimated 86 MWh of spent battery cells will be available by 2026, and at least 2 GWh of spent batteries will become available annually from 2027 if the NDC target for EV adoption is met. However, no companies currently specialize in collecting or recycling these batteries on a large scale due to the limited availability of end-of-life cells. Trials on dismantling, repurposing, and recycling degraded EV battery cells have only been conducted on a small scale, mostly in research laboratories.

- Investing in the end-of-life battery industry and research will be crucial to enhancing Indonesia's position as a regional manufacturing hub. ASEAN countries, rich in critical minerals needed for battery production, have attracted global interest. By 2030, Indonesia is expected to contribute half of ASEAN's cell production capacity and has already established its first large-scale EV battery cell plant. However, in the long term, domestic production of critical minerals will be depleted, and fluctuating prices of imported materials like lithium could affect the competitiveness of the domestic industry.

The estimated waste battery potential per year



Source : IESR Analysis

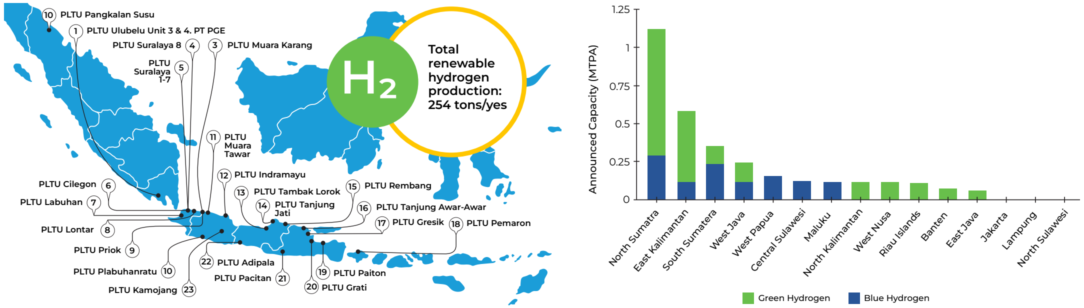
Battery cell recycling economic value comparison

	NCM811	LFP	Difference
Gains from recycling (value - cost)	**$727**	**-$410**	**$1,137**
Recycling value	$1,668	$930	
Recycling cost	$942	$1,341	
Battery price (in 2021)	**$8,408**	**$7,942**	**$466**

Source : Cho, 2022

Pursuing a green hydrogen production on-site to reach a competitive cost below USD 4/kg

Location mapping of renewable hydrogen production



Source: IESR adapted from GoI, 2024; IESR, 2023, AntaraNews, 2023; Petromindo, 2023

Potential hydrogen production cost (on-site)

No	Regional	Renewable potential	Hydrogen cost production potensial
1	Jawa Barat	Geothermal Solar	USD 2.9/kg USD 2.9/kg
2	Gresik	Solar	USD 2.5-2.7/kg
3	Balikpapan dan Bontang	Solar	USD 2.5-2.7/kg
4	NTT dan NTB	Solar	USD 1.9/kg
5	Batam dan Bintan	Floating solar	USD 2.3/kg
6	Sulawesi Utara	Geothermal Solar	USD 2.8/kg USD 2.3/kg
7	Sumatera Selatan	Geothermal	USD 2.8/kg
8		Solar	USD 2.5-2.9/kg
9	Cilegon	Geothermal Solar	USD 2.8/kg USD 2.9/kg
10	Kendari	Hydropower Solar	USD 3.1-3.1/kg USD 2.3/kg
11	Semarang	Solar	USD 2.5-2.7/kg
12	Aceh	Hydropower Solar	USD 2.9/kg USD 2.9/kg
13	Dumai	Geothermal Solar	USD 2.8/kg USD 2.9/kg
14	Papua Barat Daya	Hydropower Solar	USD 2.3-2.9/kg USD 2.9/kg
15	Kalimantan Utara	Hydropower Solar	USD 2.9/kg USD 2.9/kg
16	Kalimantan Tengah dan Kalimantan Selatan	Offshore wind Solar	USD 3.9/kg USD 2.9/kg
17	Papua Selatan	Hydropower Solar	USD 3.9/kg USD 2.9/kg

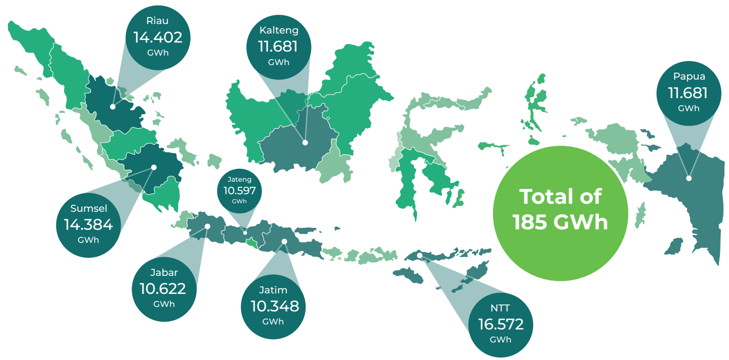
Source: Adapted from MEMR, 2023; Kompas, 2024

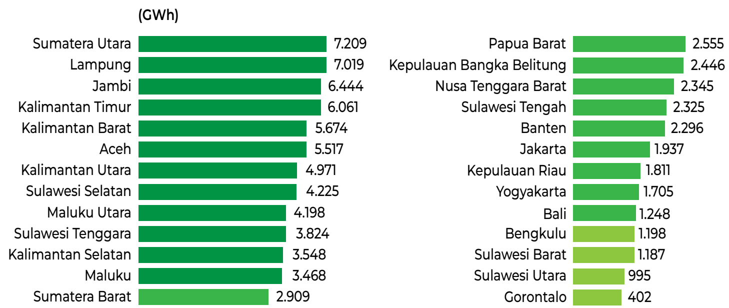
- Indonesia has begun developing a hydrogen fuel ecosystem. Currently, the country produces renewable hydrogen from 23 green hydrogen plants (GHPs), with 1 GHP owned by Pertamina and 22 GHP by PLN, supplying 254 tons of renewable hydrogen per year (GoI, 2024; IESR, 2023). The total renewable hydrogen production capacity is projected to reach 2 million tonnes (Petromindo, 2023). To support hydrogen supply, Pertamina has mapped and plans to develop at least 17 locations across Indonesia that could provide green hydrogen at low production costs, ranging between USD 1.9 and 3.9 per kg green hydrogen, with commercialization projected by 2040 (Kompas, 2024). This is quite competitive, as the current global production cost range is between USD 2.7 and 12.8 per kg. If these costs can be achieved, it is possible that Indonesia could become one of the world's major hydrogen production hubs.
- To support the supply chain, Indonesia is conducting pilot trials of a hydrogen refueling station (HRS) from 2024 to 2027, led by PLN (Bisnis, 2024). The HRS is planned to be tested for hydrogen refueling of buses and passenger vehicles in August and September 2024 (Bisnis, 2024). The cost of using hydrogen as a transportation fuel is estimated to be IDR 276-300 per km, which is cheaper than petrol at IDR 1,300-1,500 per km, electric cars at IDR 350-555 per km, and CNG at IDR 343-468 per km (Bisnis, 2024; CNBC Indonesia; 2024). The future use of hydrogen fuel has the potential to reduce fuel consumption by 1.59 million liters per year and cut emissions by 4.15 million kilograms of CO_2 per year (Bisnis, 2024; Kumparan, 2024). This brief illustration highlights the current potential of hydrogen adoption in Indonesia and provides a projection that Indonesia is serious about developing a hydrogen car ecosystem as an alternative for decarbonizing the transportation and logistics sector towards net-zero emissions

Maximizing renewable energy potential for green hydrogen production of 185 GW by 2060

- MEMR data indicates that Nusa Tenggara has the highest potential for renewable energy due to its abundance of available sources. Several provinces in Indonesia, including West Java, Central Java, East Java, Papua, Riau, and South Sumatra, are also expected to produce green hydrogen at levels far above the national average. Indonesia has outlined plans to harness 185 GWh of renewable energy for green hydrogen production by 2060 (MEMR, 2023). While this represents a significant amount of energy, it remains relatively small in proportion to the country's total renewable energy potential of 3,698 GW, accounting for less than 1%.
- To realize these plans, the funding and investment components are critical. According to the Ministry of Industry's calculations, achieving a cumulative capacity of 52 GW by 2060 will require at least USD 25.2 billion in funding. Consequently, it is estimated that a minimum of USD 90.1 billion will be needed to utilise 185 GWh of renewable energy for green hydrogen production through 2060. This substantial investment necessitates the creation of an ideal hydrogen ecosystem to accelerate the adoption of hydrogen in Indonesia. Achieving this figure poses a significant challenge, one that may be unattainable if the Government of Indonesia (GoI) does not demonstrate serious commitment to fostering a favourable investment climate for green hydrogen.
- Among the emerging markets for hydrogen in Indonesia, eastern regions have been pioneering hydrogen-powered power generation through a collaboration between MEMR, PLN, and HDF Energy. The Renewstable® technology combines intermittent renewable energy sources with battery storage and hydrogen energy storage. Currently, there are 23 active Renewstable® projects in Eastern Indonesia, with a potential investment value of USD 1.5 billion, supported by a recent Memorandum of Understanding signed in late Q3 2024 (HDF, 2024; SWA, 2024). This marks a new chapter in the use of hydrogen, with the GoI promoting the development of its ecosystem, particularly in distributing electricity to underdeveloped, frontier, and outermost regions. It is hoped that this will spur the creation of a domestic hydrogen trading market.

Distribution map of green hydrogen production potential in the NZE model by 2060





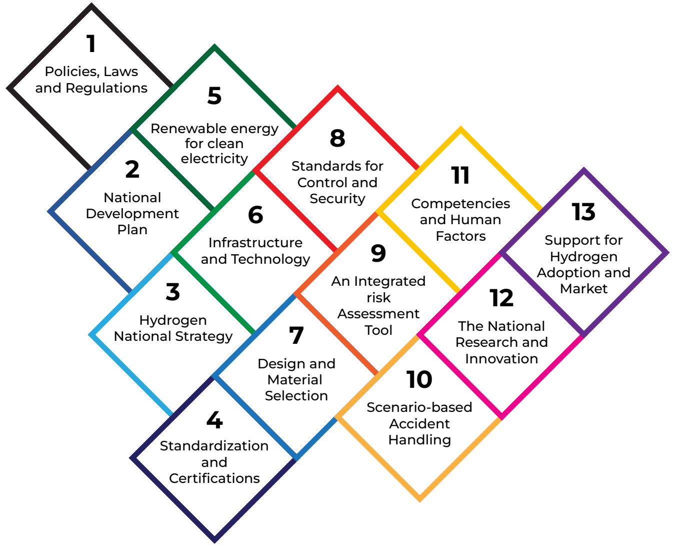
Source: MEMR, 2023

Unlocking hydrogen adoption potential by addressing 13 key factors for an ideal hydrogen ecosystem

- Policy approaches aimed at overcoming challenges, establishing a hydrogen market, and unlocking Indonesia's hydrogen potential involve addressing at least 13 key factors. These factors must be developed and harmonized to enable the safe and sustainable adoption of hydrogen. Factors 1 to 4 serve as key enablers in creating a robust legal framework that ensures investment security for key stakeholders, while aligning with a clear national vision.

- By the end of 2023, a minimum of ten laws, government regulations, presidential regulations, and MEMR regulations can be leveraged to support hydrogen adoption in Indonesia. However, further review is necessary to establish the ideal legal foundation. National development plans, such as the National Energy Plan (RUEN), National Long-Term Development Plan (RPJPN), National Medium-Term Development Plan (RPJMN), and the Masterplan for the Acceleration and Expansion of Indonesia's Economic Development (MP3EI), should be aligned to support each other and provide a clear framework for hydrogen adoption. This includes setting targets, defining roadmaps, and outlining key information on investment opportunities and government project funding.

The 13 key factors that need to prepared for ideal hydrogen ecosystem



Source: Authors analysis

- Regarding hydrogen strategies, Indonesia officially published its strategy under MEMR at the end of Q4 2023, making it one of 50 countries globally with a formal hydrogen strategy. Additionally, Indonesia has developed a roadmap under MEMR to establish approximately 26 Indonesian National Standards (SNI), based on international standards, over a five-year period from 2024 to 2028 across various segments of the hydrogen supply value chain (MEMR, 2023). This initiative will positively contribute to ensuring the standardized and safe use of hydrogen.

- As a final note, other factors that serve as key enablers include the hydrogen roadmap and the standard classification of Indonesian business fields for hydrogen utilization. Additionally, standards related to hydrogen technology, quality, and human resources are crucial, particularly regarding key safety indicators. All these elements are currently under development by the government in collaboration with various key stakeholders and will be made public at a later date. It is imperative to thoroughly consider the accelerated preparation of these 13 key factors to fast-track the establishment of an ideal hydrogen ecosystem in Indonesia.

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