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International study on

Financing Needs for New Age Critical Clean Energy Technologies: Battery Energy Storage (BES)

IIM AHMEDABAD

NTPC NETRA

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International study on financing needs for new age critical clean energy technologies: Battery Energy Storage (BES)

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Preface

Energy storage is important for large-scale deployment and grid integration of variable renewable energy sources such as solar and wind. Although pumped hydro storage is the dominant technology for energy storage right now, battery energy storage (BES) is catching up due to falling costs, suitable characteristics, and scalability of battery technologies. In the past decade, the cost of battery storage, particularly Li-ion batteries (LIBs), has gone down by over 90% and most of the new investments have also come up in BES.

The battery storage capacities are projected to reach up to 3000 GW by 2030 and further rise to 6000 GW by 2050 in the ambitious mitigation scenarios that meet the Paris Agreement goals. There are, however, supply concerns like the environmental and energy-use impacts of increased extraction of mineral resources, and the relative vulnerability of developing countries to the supply of critical elements required for manufacturing BES. With increasing demand for energy storage for clean transitions, technology development on reuse, recovery, and recycling of the critical minerals would be important and play a vital role in limiting and meeting future mineral demands.

The number, size, and geographical diversity of BES projects (size ranging from 2MW to 21GW, investment ranging from 1.8 to 3160 million USD), are expanding every year. The levelized cost of storage for Li-ion Phosphate batteries and Li-ion Nickel Manganese Cobalt batteries were comparatively lower as compared to other technologies. Traditional lead acid batteries (LABs) may require further R&D for cost improvement, while in case of Sodium batteries, the cost estimates vary widely, and the available data is limited. While considering capacity and time degradation which affects battery performance in the long run, LIBs, Vanadium Redox flow batteries or Zinc batteries exhibit lower levelized cost over LABs.

This study suggests following recommendations which are encouraged for discussion and adaption by G20 countries to support BES projects.

- Invest in research and development - as the demand for BES increases in the future, G20 countries could build an international consortium to research, develop and finance alternatives technologies like flow batteries and sodium sulphur batteries.
- Since the technology landscape is changing rapidly, efforts to update the future BES projections under different scenarios and the underlying demand for critical minerals could be supported for G20 countries through collaborations like the Network for Greening the Financial System
- Critical minerals are important to fulfil the future demand for BES. Given their limited availability and concentration in few geographic locations, international co-operation to share these resources is recommended. Further, refurbishing, recycling, and mineral recovery would play a vital role in sustainable use of mineral resources. G20 countries could invest in technology development and build international cooperation in these areas.

- Since there are multiple technologies at the development stage, the scalability of BES technologies at a commercial scale in various countries poses a significant risk to the project developers. This could also pose uncertainties in terms of cost of storage and, in turn, the cost of electricity. Financing mechanisms and regulatory support to address such concerns by project developers would help in future development of these technologies. Non-monetary or regulatory instruments like subsidies on clean energy technologies and public programs to promote energy storage infrastructure could also be deployed to promote BES technologies.
- Governments could consider grid-scale battery storage as part of their long-term energy transitions to promote flexibility in power planning and renewable energy integration.
- With regard to low-cost financing of BES, it is recommended that-
    - A dedicated fund supported by Multilateral Development Banks (MDBs) could be created to finance BES projects globally, especially in the emerging markets and developing countries (EMDCs)
    - Capital resources of MDBs and other funds should be increased substantially to scale up funding for BES projects globally. Paid-in capital and callable capital of MDBs should be increased periodically to enhance financing capabilities of MDBs to fund BES projects in EMDCs
    - International financing instruments such as green bonds (also loans), outcome-based sustainability debts, Structured equity funds, Co-financing, Guarantees, BES Investment Trusts, Leasing of Batteries and Credit Default Swaps may be adopted to de-risk investment in BES projects and crowd-in private investments

I complement my researcher team members at the Indian Institute of Management Ahmedabad for writing this international study report and Ministry experts namely NTPC, NETRA and PFC for commissioning and supervising this study. I hope that it will catalyse interesting and engaging interactions amongst G20 members, researchers, business community and financial institutions.

January, 2023

Amit Garg
Professor, Public Systems Group, IIM Ahmedabad
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Abbreviations and Acronyms

ADB	Asian Development Bank
AfDB	African Development Bank
AIIB	Asian Infrastructure Investment Bank
APS	Advanced Pledges Scenario
AR6	Sixth Assessment Report
BES	Battery Energy Storage
BNEF	Bloomberg New Energy Finance
C&C	Control & Communication
CBD	Convention on Biological Diversity
CBI	Climate Bond Initiative
CDS	Credit Default Swaps
CIF	Climate Investment fund
CO_2	Carbon Dioxide
DFI	Development Finance Institutions
EBRD	European Bank for Reconstruction and Development
EIB	European Investment Bank
EMDCs	Emerging Markets and Developing Countries
EPC	Engineering, Procurement, and Construction
ES	Energy Storage
ESG	Environmental, Social, and Governance
ESS	Energy Storage Systems
EU	European Union
EVs	Electric Vehicles
FITs	Feed in Tariffs
GCF	Green Climate Fund
GEF	Global Environment Facility
GFANZ	Glasgow Financial Alliance for Net Zero
GHG	Greenhouse Gas
GW	Giga Watt
GWh	Giga Watt hour
IDBG	Inter-American Development Bank Group
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IsDB	Islamic Development Bank
kW	kilo Watt
kWh	kilo Watt hour
LAB	Lead Acid Batteries
LCOS	Levelized Cost of Storage
LDCs	Least Developed Countries

LFP	Li-ion Phosphate
LIBs	Li-ion Batteries
Li-NMC	Li-ion Nickel Manganese Cobalt
MDBs	Multilateral Development Banks
MIGA	Multilateral Investment Guarantee Agency
MIT	Massachusetts Institute of Technology
MW	Mega Watt
MWh	Mega Watt hour
NaS	Sodium Sulphur
NDCs	Nationally Determined Contributions
NGFS	Network for Greening the Financial System
Ni-Cd	Nickel Cadmium
Ni-MH	Nickel Metal Hydride
NZE2050	Net-Zero by 2050 Scenario
O&M	Operating and Maintenance
OECD	Organisation for Economic Co-operation and Development
PHS	Pumped Hydro Storage
PNNL	Pacific Northwest National Laboratory
PPA	Power Purchase Agreement
PPP	Public Private Partnerships
PV	Photovoltaic
REDD	Reducing Emissions from Deforestation and Forest Degradation
RTE	Round Trip Efficiency
SB	Storage Block
SBOS	Storage Balance of System
SCES	Super Capacitor Energy Storage
SIDS	Small Island Developing States
SMES	Superconductive Magnetic Energy Storage
STEPS	Stated Policy Scenario
T & D	Transmission and Distribution
ToD	Time of Day
UNCCD	United Nations Convention to Combat Desertification
UNFCCC	United Nations Framework Convention on Climate Change
USD	United States Dollar
V_2O_5	Vanadium Pentoxide
VRE	Variable Renewable Energy
VRFB	Vanadium Redox Flow Batteries
WACC	Weighted Average Cost of Capital
WBG	World Bank Group
WG	Working Group
Zn Br	Zinc Bromine

Executive Summary

Energy storage is important for large-scale deployment and grid integration of variable renewable energy (VRE) sources like solar and wind. Although pumped hydro storage (PHS) is the dominant technology for energy storage right now, battery energy storage (BES) is catching up due to falling costs, suitable characteristics, and scalability of battery technologies. In the past decade, the cost of battery storage, particularly Li-ion batteries (LIBs), has gone down by over 90% and most of the new investments have also come up in BES. In this report, we first discuss the technology options available for grid scale energy storage with focus on commercially available and upcoming battery technologies. We then discuss future electricity and energy storage demand projections from leading global integrated assessment models under different scenarios like current policies, nationally determined contributions (NDCs) and stringent climate mitigation targets to meet the Paris Climate Agreement. The future energy storage projections are then used to determine the investment needs and storage costs under different scenarios and BES technology options. We also discuss the risks arising from availability of critical minerals under these scenarios. Further, we delve into the financing mechanisms and investment risks associated with BES projects and propose various regulatory, economic, and other types of policy interventions to meet the future deployment of BES technologies.

Energy Storage Technologies

There are five types of energy storage technologies: 1) Electrochemical, 2) Mechanical, 3) Electrical, 4) Chemical, and 5) Thermal with four major applications in the electric grid: 1) RE integration, 2) Bulk Energy Storage, 3) Ancillary Services, and 4) Energy Management.

Among the commercially mature technologies in 2022, LIBs were best suited for the a variety of energy storage applications. The high power (150-315 W/kg) and energy (75-200 Wh/kg) densities of LIBs make them suitable for stationary energy storage applications. These are also suitable for mitigating power fluctuations. So far, LIBs are also considered suitable for grid integration of renewable energy sources and for ancillary services. Further, due to their very small daily self-discharge rates, they are also found suitable for prolonged duration storage applications. However, LIBs also face risks arising from the scarcity of critical minerals and thermal runaways. These risks have prompted the development in other alternatives like flow and sodium sulphur battery technologies.

Among the other commercially available BES technologies, Lead Acid batteries (LABs) are also considered suitable for stationary grid storage but face technological limitations like low-energy density, restricted cycling ability, and high environmental impact.

Electrochemical flow battery technologies such as Vanadium Redox flow batteries (VRFB), Polysulphide Bromine flow batteries (PSB) and Zinc Bromine flow batteries (Zn Br) are suitable for RE integration and ancillary service like frequency balancing but are not commercially mature as of date.

Other electrochemical technologies like Sodium sulphur (NaS), Sodium nickel chloride ($NaNiCl_2$), Nickel-metal hydride (Ni-MH) and Nickel cadmium (Ni-Cd) need further research and development to evaluate their suitability for grid storage at commercial scales.

Electrical storage technologies like Super capacitor energy storage (SCES) and Superconductive magnetic energy storage (SMES) are only suitable for short-time duration energy management applications involving power quality and regulation applications due to their high self-discharge rate.

Mechanical storage technologies like Pumped Hydro Storage (PHS) are suitable for RE integration and currently accounts for over 90% of total grid storage. However, the locations to deploy large-scale PHS are limited.

Thermochemical storage technologies, owing to their high service life (~35 years) are more suitable for bulk energy applications.

Energy storage is important for large-scale deployment and grid integration of variable renewable energy (VRE) sources like solar and wind. Although pumped hydro storage (PHS) is the dominant technology for energy storage right now, battery energy storage (BES) is catching up due to falling costs, suitable characteristics, and scalability of battery technologies. In the past decade, the cost of battery storage, particularly Li-ion batteries (LIBs), has gone down by over 90% and most of the new investments have also come up in BES. In this report, we first discuss the technology options available for grid scale energy storage with focus on commercially available and upcoming battery technologies. We then discuss future projections from leading global integrated assessment models which estimate the required electricity demands and energy storage under different scenarios like current policies, nationally determined contributions (NDCs) and other stringent climate mitigation targets to meet the Paris Climate Agreement. The future battery projections are then used to determine the investment needs and storage costs under different scenarios and BES technology options. We also discuss the risks arising from availability of critical minerals under these scenarios. Further, we delve into the financing mechanisms and investment risks associated with BES projects and propose various regulatory, economic, and other types of policy interventions to meet the future deployment of BES technologies.

BES demand in future scenarios

In the future, the demand for BES could increase due to large scale deployment of VREs like solar and wind. For our analysis, we use the projections from mitigation scenarios[1] developed by the Network for Greening the Financial System (NGFS) – a voluntary network of Central Banks and Supervisors which aims to develop a system for environment and climate risk management in the financial sector, and to mobilize mainstream finance towards low-carbon

[1] Scenarios are the tools to develop alternative images of an uncertain future and are widely used to evaluate the long-term transitions in energy systems and emissions trajectories in an internally consistent manner (IPCC, 2000; Mietzner & Reger, 2005; O'Neill & Nakicenovic, 2008).

and green technologies. In addition, we assess the scenario projections from other leading agencies like the International Energy Agency (IEA), IPCC's sixth assessment report (AR6) and Bloomberg New Energy Finance (BNEF).

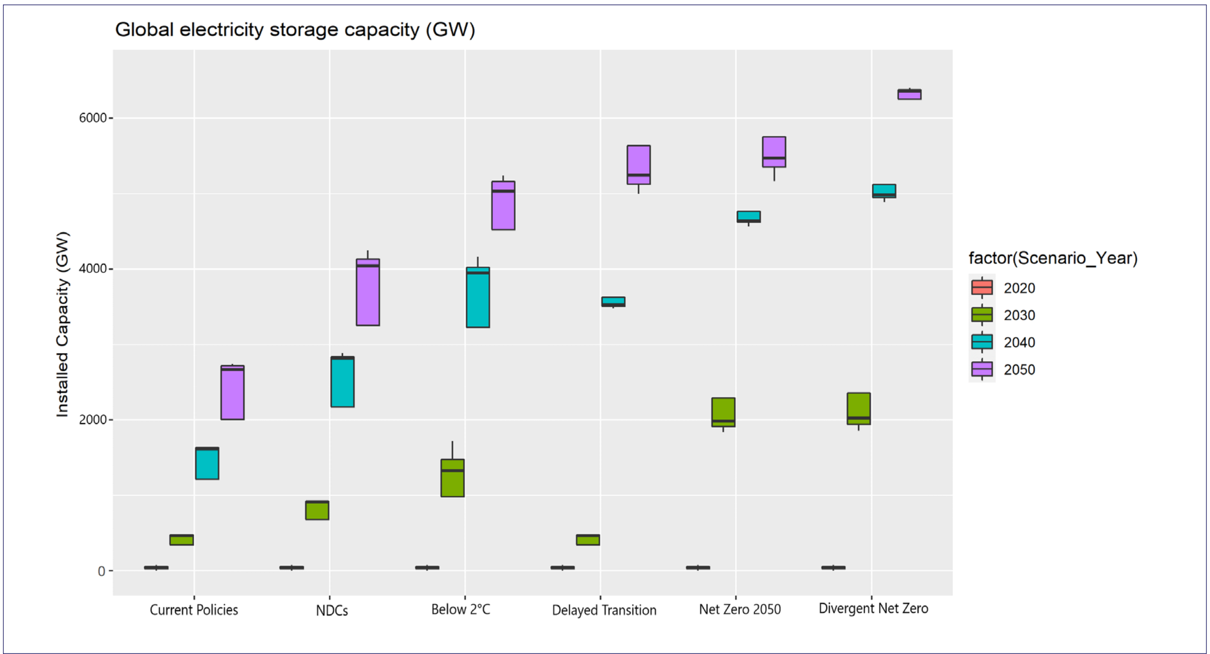

Figure ES1: Future energy storage projections under different NGFS scenarios (in GW)

Based on the NGFS, IEA and IPCC projections, the storage capacities could reach up to 3000 GW by 2030 and further rise to 6000 GW by 2050 in the ambitious mitigation scenarios that meet the Paris agreement goals.

Compared to the Nationally Determined contributions (NDCs) and the Current Policies scenarios (figure ES1), this could mean a 3 to 6 times increase in storage capacity in the near-term (2030) and around 1.5 to 2.5 times increase in the long-term (2050). This would mean massive investments and capacity building in energy storage by 2030 if the world must stay on the path of Net-Zero 2050 scenarios as compared to the current policies and NDCs scenarios.

Risk due to Critical minerals

There are supply concerns like the environmental and energy-use impacts of increased extraction of mineral resources, and the relative vulnerability of developed countries to the supply of critical elements required for manufacturing BES.

Aluminium, Chromium, Cobalt, Copper, Graphite, Iron, Lead, Lithium, Manganese, Nickel, Vanadium and Zinc are few of the majorly used minerals across battery technologies.

Although, the current share of Na-ion batteries is very little as compared to Li-ion, there are efforts to make it commercially feasible globally. With increasing demand for energy storage for clean transitions, technology development on reuse, recovery, and recycling of the critical minerals would also become important. Refurbishing, recycling, and mineral recovery would play a vital role in limiting and meeting future mineral demands. G20 countries could invest in technology development and build international cooperation in these areas.

Investment Outlook and levelized cost of storage

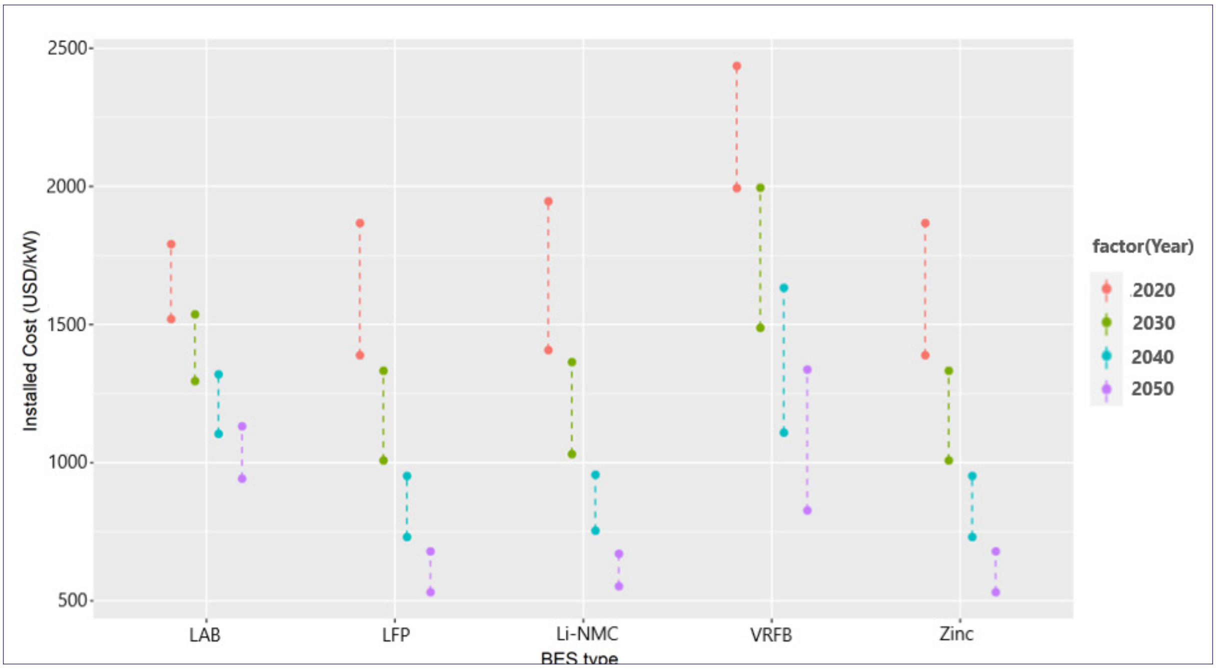

Figure ES2: Total installed cost of 10 MW/4 Hr. grid-scale BES (USD/kW)

Based on the projected capacity additions of energy storage and battery cost estimates from the literature, this study has projected a range of costs for different types of BES systems (Figure ES2). The results indicate a decrease in costs by 2050 but also highlights for need for further research and policy support to bring the down the costs of newer technologies like flow batteries, zinc, and sodium-based technologies.

Further, we have evaluated the investment needs under NGFS scenarios like Current Policies, NDCs and Net Zero 2050 for 4 types of BES technologies: Lead Acid Batteries (LAB), Li-ion Phosphate (LFP), Li-ion Nickel Manganese Cobalt (Li-NMC), and Vanadium redox Flow (VRFB). The results are presented in Table ES1.

Table ES1: Future investment needs for different BES technologies in select NGFS scenarios (in Billion USD)

Period	2020-30				2030-50			
Scenario/Technology	LAB	LFP	Li-NMC	VRFB	LAB	LFP	Li-NMC	VRFB
Current Policies - High	595	505	525	754	2643	1738	1841	3074
Current Policies - Low	0	0	0	0	156	97	105	177
NDC – High	1237	1045	1085	1567	3944	2638	2791	4613
NDC – Low	3	2	2	4	1167	730	777	1335
Net Zero 2050 - High	4296	3616	3756	5435	4039	2727	2882	4738
Net Zero 2050 – Low	2655	2233	2320	3358	4134	2912	3068	4922

At present, some case examples of companies around the world have attracted investments in BES technologies (Table ES2). However, their population, size and geographic coverage is growing with time.

Table ES2: Case examples of companies operating in the BES space and their market capitalizations

Sr. No.	Company Name	Country	Market Cap. (million USD)	Net Worth (million USD)
1	ATON Green Storage SpA	Italy	48.3	15.2
2	Dry Cell and Storage Battery JSC	Vietnam	62.7	36.1
3	Thai Energy Storage Technology PCL	Thailand	140.6M	64.8
4	Thai Storage Battery Ord Shs	United States	167.7	50.3
5	Hitachi Chemical Storage Battery Ord Shs	Thailand	167.7	50.3
6	Tyumenskiy Akkumulyatornyi Zavod AO	Russia	--	57.2
7	Saltbae Capital Ord Shs	Germany	--	14.5

Source: (Refinitive, 2022)

There are number of BES projects (investment ranging from 1.8 to 3160 million USD) around the world (annexure-5). The number of such projects, geographical diversity and size are expanding every year.

In case of levelized cost of storage (LCOS), our analysis shows that Li-ion Phosphate (LFP) batteries and Li-ion Nickel Manganese Cobalt (Li-NMC) batteries have comparatively lower levelized costs compared to other technologies evaluated. Traditional LABs may require further R&D for cost improvement. In case of Sodium batteries, the cost estimates vary widely, and the available data is limited.

Further, if we consider capacity and time degradation which affects battery performance in the long run, Lithium batteries, VRFB or Zinc batteries exhibit lower levelized cost over LABs.

Investment and bankability risks

Since there are multiple technologies at the development stage, the scalability of BES technologies at a commercial scale in various countries poses a significant risk to the project developers.

Although BES systems based on LIBs are generally preferred, the availability of critical minerals to manufacture LIBs may constrain the expansion of new BES projects and the replacement of LIBs after the completion of useful life in existing BES projects.

On the revenue side, the cost of BES projects will have to be subsumed in the cost of electricity to make BES projects viable. Low-cost financing of BES projects is crucial to improve their viability and to limit the escalation in the cost of electricity.

Financing mechanisms and policy instruments

Many Multilateral Development Banks (MDBs) and climate funds have deployed resources through blended financing instruments, grants, and concessional loans to de-risk investments in climate action and to crowd-in private investments. However, the capital resources of existing funds are not enough to fulfil current climate financing requirements to meet the Paris Agreement targets.

MDBs and funds such as Clean Technology Fund are already financing renewable energy projects globally. A dedicated fund supported by MDBs could be created to finance BES projects globally with focus on the emerging markets and developing countries (EMDCs).

A dedicated fund would provide a single window for project application and appraisal, reducing the time and effort required for project documentation. Experience and expertise of MDBs in project appraisal and monitoring could also be leveraged to address adverse risk perceptions about EMDC by bridging information asymmetry.

Non-monetary or regulatory instruments like subsidies on clean energy technologies and public programs to promote energy storage infrastructure could also be deployed to promote BES technologies.

Governments could consider grid-scale battery storage as part of their long-term energy transitions to promote flexibility in power planning and renewable energy integration. In this direction, project tenders from the government agencies that promote the co-location of BES with solar and wind energy projects, with specific annual targets, could be explored.

Co-location of BES systems with VRE sources like solar and wind could also help in managing peak demand to improve system flexibility. BES could therefore reduce the dependence on peak generators with suitable policy interventions in power systems.

In addition, regulatory support to help transmission and distribution companies to use energy storage as an alternative to additional investments in grid infrastructure could be explored.

International cooperation

International cooperation on technology development, especially in upcoming and future technologies like flow batteries and sodium sulphur batteries could be explored.

International mechanisms for sharing of critical minerals to support the development and deployment of BES is required.

The G20 countries could develop mechanisms for making low-cost financial resources available for faster and deeper adoption and penetration of BES.

In general, the G20 could develop an ecosystem to support clean energy transitions. This would involve BES demand estimation for net-zero scenarios for the world, fair share deploying just energy transitions, promoting start-ups, low-cost financing, critical minerals sharing, and national grid stability.

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Chapter 1

Battery Energy Storage (BES) – Future outlook

1.1. Role of BES in energy transitions (mobility, stationary applications etc.)

Energy systems are the single largest source of anthropogenic emissions that are responsible for climate change (IPCC, 2018, 2022). Hence, net-zero emissions from energy systems are essential to meet the Paris climate goals. The global carbon dioxide (CO_2) emissions, mainly from fossil fuel combustion and processes, were responsible for around 75% of the total greenhouse gas (GHG) emissions and were a major driver of emissions growth in the past few years (Crippa et al., 2020; Olivier & Peters, 2020). Over 60% of global power generation is still from fossil fuels. One of major strategies for net-zero energy systems is to increase the electrification of end use services and simultaneous decarbonization of electricity generation (IPCC, 2022).

As alternatives to fossil fuels, renewables like solar and wind energy have seen a rapid growth in capacity in the past decade or so. In comparison, other low carbon technologies like nuclear, hydropower, bioenergy, marine, geothermal, and abatement technologies like carbon capture and storage have experienced low growth as of date (Clarke et al., 2022). The electricity capacity based on renewable sources has more than doubled in the past decade owing to an exponential rise in solar photovoltaic (PV) (IRENA, 2022a). In particular, the solar PV and wind electricity capacities grew at an annual rate of 28% and 11% per year in the last five years (Clarke et al., 2022). Globally, the cost of solar PV modules has decreased by around 22% with each doubling of installed capacity and is expected to reduce further in the coming decade (Creutzig et al., 2017)but it does not identify solar energy as a strategically important technology option. That is surprising given the strong growth, large resource, and low environmental footprint of photovoltaics (PV. However, solar and wind are variable renewable energy (VRE) sources whose output varies with seasons and time of the day. Given the intermittent nature of these renewable sources, they account for less than 10% of the total global electricity generation as of now (Clarke et al., 2022). Hence, these VRE capacities require the support of energy storage systems which could store the electricity when it is generated and make it available 24x7 to completely replace the use of fossil fuels. Reliable and affordable energy storage is important to achieve large scale integration of variable renewables like solar and wind in the electricity grid and substantially reduce the emissions intensity of electricity generation. In addition, energy storage technologies are playing an important role in the electrification passenger vehicles. The rising demand for electric vehicles (EVs) is one of the drivers for the capacity expansion and cost reductions in battery storage technologies.

Going forward, large scale deployment of VREs will depend on the successful roll out of energy storage technologies. Therefore, it is essential to understand their various applications, technology options, near-to-medium term projections, costs, and financing mechanisms. This could be important to inform the future policies on energy storage technologies and to enable the transition towards net-zero energy systems.

1.2. BES technologies: overview and status

Decarbonisation of electricity sector is leading to an increased penetration of renewable energy sources into electricity networks globally. However, replacing conventional baseload generation (centralised coal-fired plant) with decentralised, low-carbon VRE sources (e.g. wind and solar) leads to new threats to secure energy supply due to their intermittency and reduced dispatchability characteristics (Hannan et al., 2021; Jones et al., 2021; Murarka et al., 2022). There has been emergent interest in the research, development, demonstration, and deployment of energy storage technologies which would mitigate the threats to energy security. Energy storage technologies would add buffer capacity and improve the overall use of the available green energy (Jones et al., 2021).

1.2.1 Energy storage technologies: classifications and applications

Storing energy so that it can be used in future, when and where it is most needed, is key for an increased VRE production and for energy security. Energy storage can stabilise fluctuations in electricity demand and supply by allowing excess electricity to be saved in large quantities over different time periods which consists of fast storage in seconds to longer storage over days (EC, 2022). Energy storage technologies can be used for stationary applications including entire electricity supply system such as generation, transmission and, distribution as well as for local applications i.e. for residential, commercial and industrial customers (Kebede et al., 2022; Schmidt et al., 2019). These energy storage technologies can be classified into five main categories, namely, Mechanical, Electrochemical, Thermal, Electrical and Chemical (figure 1) (Kebede et al., 2022).

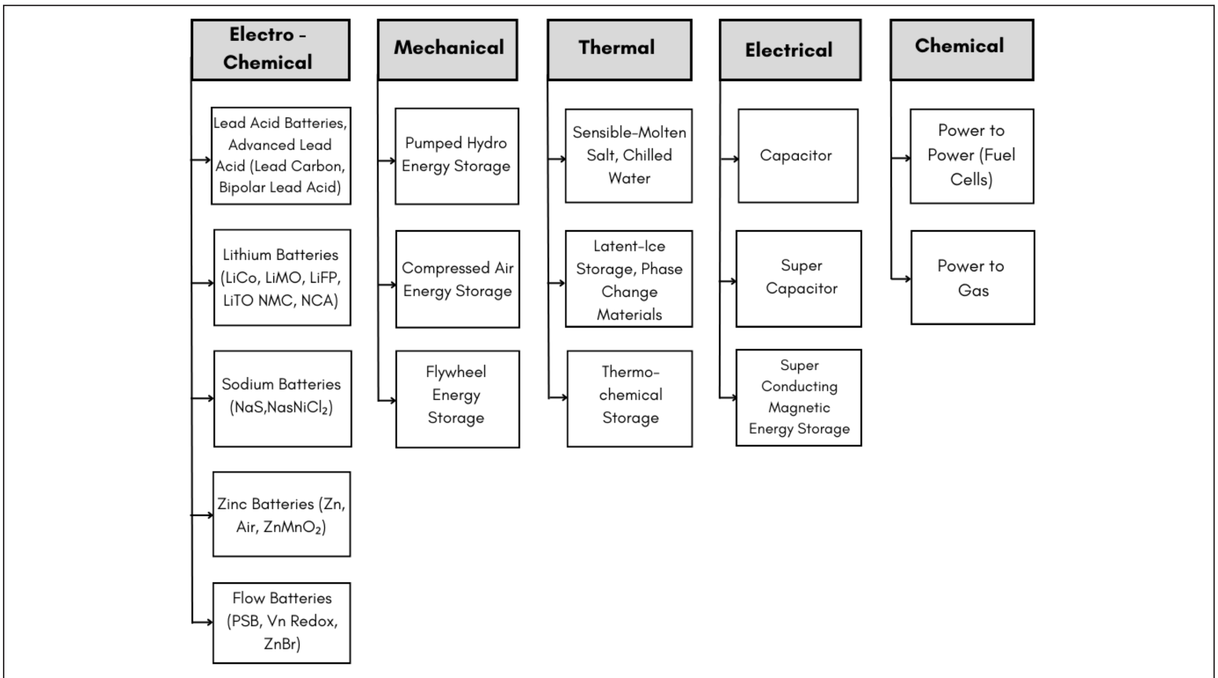


Figure 1. Classification of energy storage technologies

Source: Adopted from (ISGF, 2019; Kebede et al., 2022)

Energy storage technologies can be used in various applications of power system operations, network operations, and power consumption (Kebede et al., 2022; Schmidt et al., 2019). Some of these applications are listed below:

- **Energy arbitrage:** Purchasing power at a lower price and selling it during higher price periods in wholesale or retail market
- **Primary response:** Correcting continuous and sudden frequency and voltage changes across the network
- **Secondary Response:** Correcting anticipated and unexpected imbalances between loads and generation
- **Tertiary response:** Replacing primary and secondary response during prolonged system stress
- **Peak load replacement:** Ensuring availability of enough generation capacity during peak demand periods
- **Black start:** Restoring power plant operations after network outage without external power supply
- **Seasonal storage:** Compensating long-term supply disruptions or seasonal variability in the supply and demand of electricity
- **T&D investment deferral:** Deferring network infrastructure upgrades caused by peak power flow exceeding existing capacity
- **Congestion management:** Avoiding re-dispatch and local price differences due to risk of overloading existing infrastructure
- **Bill management:** Optimising power purchase, minimizing demand charges and maximising self-consumption
- **Power quality:** Protecting on-site load against short duration power loss or variations in voltage or frequency
- **Power reliability:** Covering temporal lack of variable supply and providing power during blackouts
- **Energy efficiency improvement:** Improving productivity in the energy mix with time-shift, storage, and load control for improved performance in distribution system.

1.2.2 Energy storage technologies in low carbon electricity services

Energy storage technologies are key technologies which enable low carbon electricity systems (Clarke et al., 2022; Schmidt et al., 2019). They allow VRE technologies to replace more expensive steady low carbon generation technologies and reduce investment costs in backup generation, interconnection, transmission, and distribution network upgrades (Clarke et al., 2022). Low carbon energy storage technologies can provide a range of grid services depending on their technical features (table 1).

Table 1. Low carbon energy storage technologies with technology suitability for grid services

Technology suitability	PHS	LAB	LIB	RFB	NaS
Upgrade deferral	√	√	√	√	√
Energy Arbitrage	√	√	√	√	√
Capacity firming	√	√	√	√	√
Seasonal storage	√				
Stability	√	√	√	√	√
Frequency regulation	√	√	√	√	√
Voltage support	√	√	√	√	√
Black start	√	√	√	√	√
Short term reserve	√	√	√	√	√
Fast reserve	√	√	√	√	√
Islanding		√	√	√	√
Uninterruptible power supply		√	√	√	√
Opportunity to reduce costs over next decade	Low	NA	High	High	NA

Sources: Adapted from (IPCC, 2022; ISGF, 2019)

Notes: PHS - Pumped Hydroelectric Storage, LAB – Lead Acid Batteries, LIB – Li-ion Batteries, RFB - Redox Flow Batteries, NaS – Sodium Sulfur

Technology suitability for other types of energy storage technologies (mechanical, thermal, electrical, and chemical) based on their grid service applications are listed in annexure 1.

1.2.3 Overview of battery energy storage technologies and their applications

Different types of batteries have unique features and suitability. The most important feature of batteries is their rapid response time, which makes them suitable for enhanced frequency regulation and voltage support, enabling the integration of VRE into electricity grids (Hannan et al., 2021; IPCC, 2022). They have high reliability and low self-discharge rate (Hannan et al., 2021). They can provide almost all electricity services, except seasonal storage. Their main drawbacks include relatively short life time and the use of hazardous or costly materials in some variants (IPCC, 2022). The main technical features (life span, efficiency, specific energy and specific power) of various BES technologies, their technology maturity and environmental impact are presented in table 2.

Table 2. The core technical features, technology maturity and environmental impact of BES technologies

BES technology	Life span (cycles)	Round trip efficiency	Specific energy (Wh/kg)	Specific power (W/kg)	Technology maturity	Environmental impact
LAB	300-800	70-90%	20-50	75-300	Very matured/ Fully commercialized	High
LIB	1000–6000	85-95%	75-200	150-370	Proven/ Commercialized	Medium/Low
Lithium nickel manganese cobalt oxide (Li-NMC)	1000-2000	86%	150–220[2]	NA	Proven/ Commercializing	Medium/ Low
Lithium iron phosphate (LFP)	2000	86%	90–120[1]	NA	Proven/ Commercializing	Medium/Low
Vanadium Redox flow batteries (VRFB)	5000-8000+	70-85%	10-35	80-150	Proven/ Commercializing	Medium
Zink Bromine (Zn Br) flow batteries	5000-8000+	60-85%	20-54	90-110	Proven/ Developing	Medium
NaS	3000-5000	70-90%	100-240	150-230	Proven/ Commercializing	High

Source: *Adapted from (Hannan et al., 2021; Kebede et al., 2022; ISGF, 2019)*

As compared to other electrochemical (battery) energy storage technologies, as of date, Li-ion battery technologies are best suitable for VRE integration to the power grid system because of their higher power and higher energy density, higher round trip efficiency (RTE), relatively higher discharge time (hours) at rated power, low environmental impact, and light weight (Kebede et al., 2022). While the sodium-ion batteries and flow batteries are suitable for RE integration and ancillary service like frequency balancing but are not commercially mature as of date.

[2] https://batteryuniversity.com/article/bu-216-summary-table-of-lithium-based-batteries

- ***Lithium-ion Batteries (LIBs)***

  LIBs can store high energy and power in small volumes and with low weight, making them best suitable in both transportation (EVs) and stationary applications (grid integration) (IPCC, 2022; Kebede et al., 2022). EV batteries are expected to form a distributed storage resource which will impact and support the grid as its market keeps growing. LIBs as battery storage technology have accounted for over 90% of new capacity addition since 2015. About 10 GW of batteries were connected at the grid and consumer level in 2019 as compared to 0.6 GW in 2015 (IPCC, 2022). Globally, the cost of LIBs is decreasing but the risk of thermal runaway, availability of critical minerals, safety issues and environmental impacts are some of the concerns associated with this technology (Hannan et al., 2021; IPCC, 2022; Kebede et al., 2022).

- ***Lead-acid batteries (LABs)***

  Lead-acid batteries are characterized by moderate RTE and low cost. They are found to be comparable with LIBs with respect to service life and self-discharge rate in addition to their low cost. These features make the LABs suitable for stationary applications (Kebede et al., 2022). The main limitation of these batteries include low-energy density, restricted cycling ability, and high environmental impact (Hannan et al., 2021).

- ***Flow batteries***

  Flow batteries are another type of electrochemical technologies used in stationary energy storage applications. The flow batteries used as stationary energy storage technologies include Polysulphide bromine (PSB), Vanadium redox (VRFB), and Zinc bromine (Zn Br) redox flow batteries. Their technical features such as low self-discharge, high service life and fast response characteristics make these batteries suitable in stationary storage applications. However, the major disadvantages of these batteries include high maintenance cost, complex monitoring and control, and the need for extra electrolyte tank. These battery technologies have not commercialized yet. They are still at proven or development stage in terms of technology maturity and would require further research and development to ascertain their viability in the long run (Hannan et al., 2021; Kebede et al., 2022). Due to urbanization and the rapid growth of population, carbon emission is increasing, which leads to climate change and global warming. With an increased level of fossil fuel burning and scarcity of fossil fuel, the power industry is moving to alternative energy resources such as photovoltaic power (PV.

- ***Sodium sulphur (NaS) batteries***

  Flow batteries are another type of electrochemical technologies used in stationary energy storage applications. The flow batteries used as stationary energy storage technologies include Polysulphide bromine (PSB), Vanadium redox (VRFB), and Zinc bromine (Zn Br) redox flow batteries. Their technical features such as low self-discharge, high service life and fast response characteristics make these batteries suitable in stationary storage applications. However, the major disadvantages of these batteries include high maintenance cost, complex monitoring and control, and the need for extra electrolyte tank. These battery technologies have not commercialized yet. They are still at proven or development stage in terms of technology maturity and would require further research and development to ascertain their viability in the long run (Hannan et al., 2021; Kebede et al., 2022).

1.3. Future casting of BES with different scenarios

At present, almost all energy storage is based on pumped hydropower technologies. However, battery energy storage (BES) systems led by Li-ion battery chemistries are catching up due to their rising demand and declining prices. The cost of lithium-ion batteries (LiBs) has declined by 90% in the past decade alone (Clarke et al., 2022; Ziegler & Trancik, 2021). This decline has led to a battery storage capacity of 27 GW in 2021 as compared to less than 1 GW a decade ago (IEA, 2022b). In the future, the demand for energy storage is expected to grow further due to increasing deployment of VREs like solar and wind energy. An assessment by BNEF (2022) projects the energy storage capacity to reach around 410 GW (~1200 GWh) by 2030 in the current policy scenario, a 15-times rise as compared to the capacity in 2021.

Here we discuss the future electricity and energy storage projections based on a wide array of mitigation scenarios developed by the Network for Greening the Financial System (NGFS) – a voluntary network of Central Banks and Supervisors which aims to develop a system for environment and climate risk management in the financial sector, and to mobilize mainstream finance towards low-carbon and green technologies. In addition, we also discuss the scenario projections from the recent reports of the IEA and BNEF which conduct periodic assessments of future energy transitions.

Scenarios are the tools to develop alternative images of an uncertain future and are widely used to evaluate the long-term transitions in energy systems and emissions trajectories in an internally consistent manner (IPCC, 2000; Mietzner & Reger, 2005; O'Neill & Nakicenovic, 2008). Scenarios are not forecasts but a range of plausible (not probable) outcomes for the earth's natural and social systems based on the baseline inputs and assumptions.

The latest NGFS study explores six global scenarios, consistent with the NGFS framework described in figure 2.

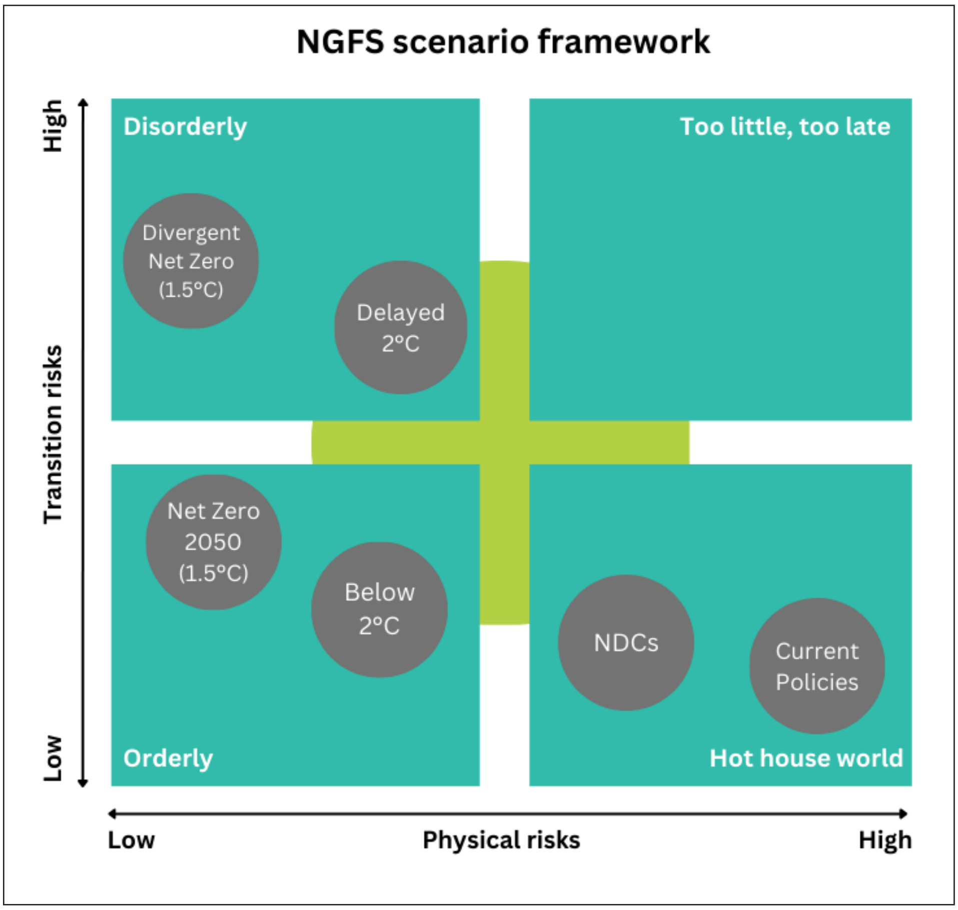
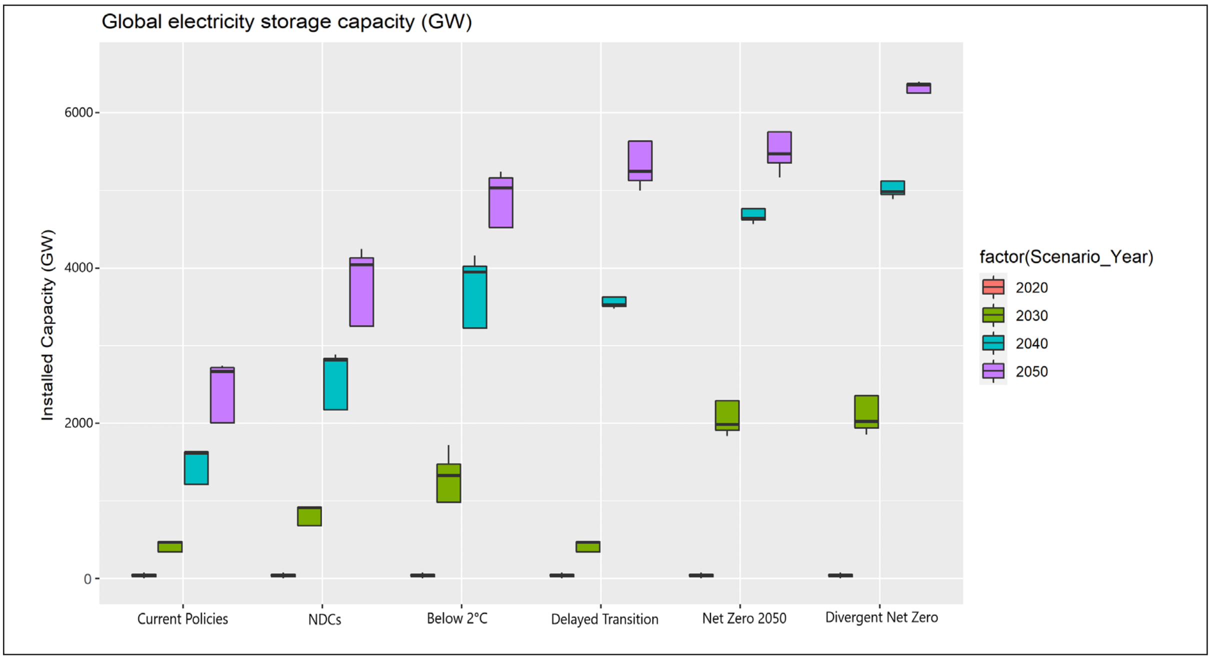


Figure 2. NGFS Scenario framework

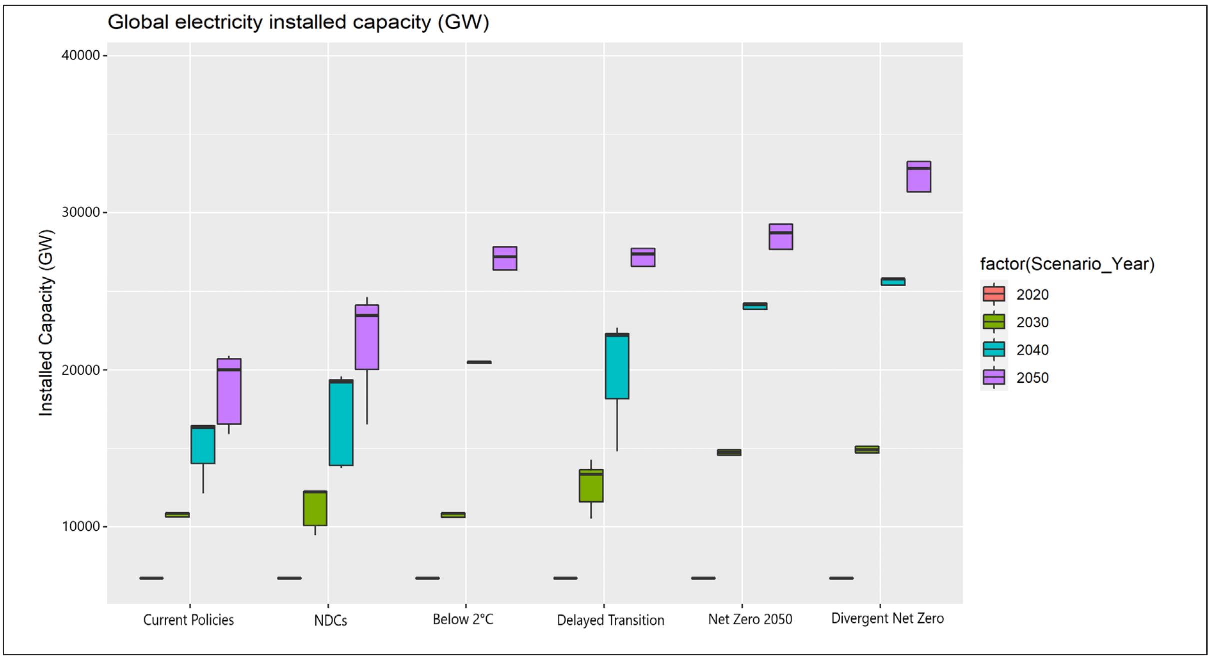
Source: (NGFS, 2022)

The 'Orderly' scenarios (Net-Zero 2050 and Below 2°C) assume an early implementation of climate policies with a gradual implementation of stringent climate mitigation measures to comfortably achieve the Paris climate goals (UNFCCC, 2015). The 'Disorderly' scenarios, on the top left quadrant, assume higher transitions risks due to delayed and divergent climate action across countries. The 'Hot house world' scenarios assume insufficient climate action and implementation of climate policies in few countries which leads to severe risks to natural and social systems. The six scenarios in these three categories cover a spectrum of plausible outcomes which could act as a common starting point for governments, central banks, and financial institutions to develop a plan for sustainable, low-carbon transitions. The six scenarios were implemented in leading integrated assessment models (IAMs) from across the world. In addition, we also discuss the total electricity demand along with solar and wind demand projections to put the energy storage demand in perspective.

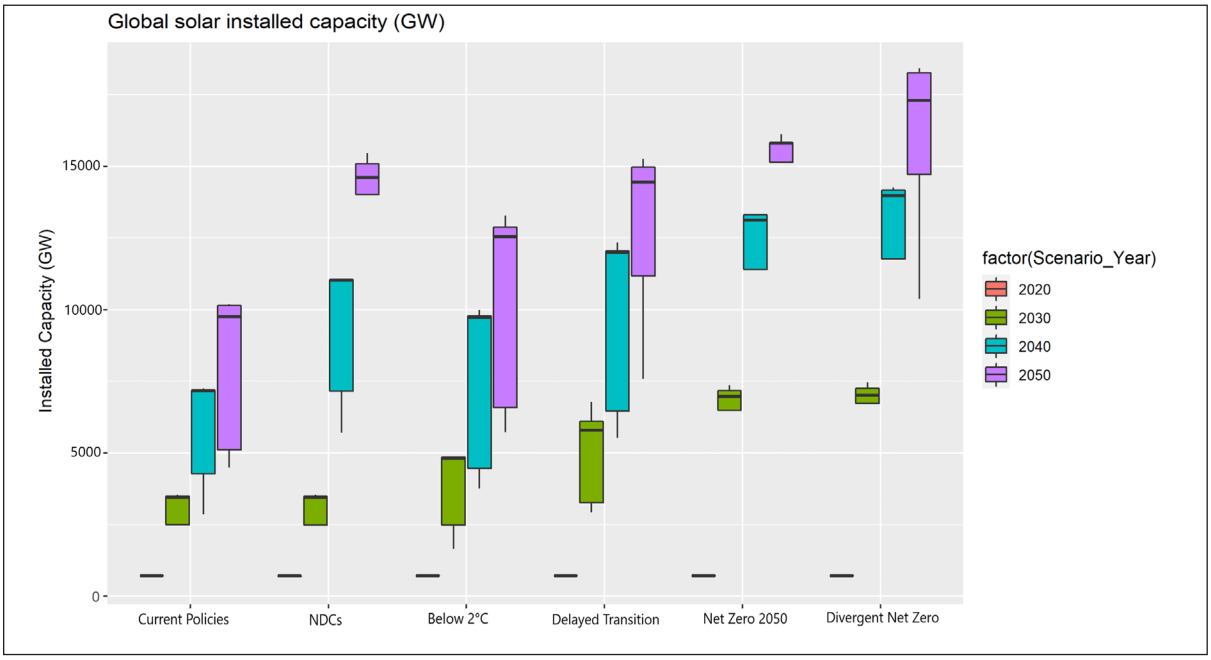
(a)


Global electricity storage capacity (GW)
Installed Capacity (GW)
6000
4000
2000
0
Current Policies
NDCs
Below 2°C
Delayed Transition
Net Zero 2050
Divergent Net Zero
factor(Scenario_Year)
2020
2030
2040
2050

(b)


Global electricity installed capacity (GW)
Installed Capacity (GW)
40000
30000
20000
10000
Current Policies
NDCs
Below 2°C
Delayed Transition
Net Zero 2050
Divergent Net Zero
factor(Scenario_Year)
2020
2030
2040
2050

(c)



(d)

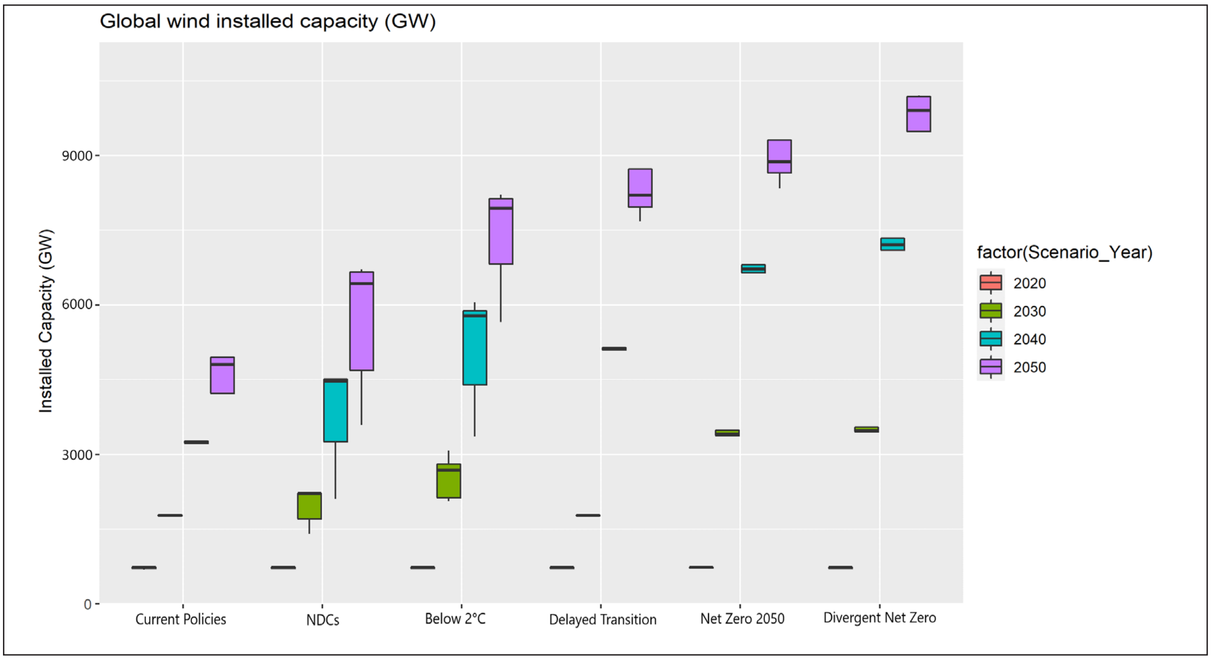


Figure 3. (a) Global electricity storage capacity; (b) Global total electricity capacity; (c) solar capacity; and (d) wind capacity based on the NGFS climate mitigation scenarios

Source: Authors' illustration based on NGFS scenario database (Richters et al., 2022).

As the scenario results indicate, the highest deployment of energy storage is envisaged in the

Net-Zero 2050 scenario due to early and large-scale deployment of solar and wind technologies for electricity generation. In this scenario, the deployment of energy storage ranges between 1800-3050 GW in 2030 and reaches up to 5500-6400 GW by 2050. In the near-term (2030), this means over six times rise in storage capacity as compared to the Current Policies scenario and over three times rise compared to the Nationally Determined Contributions (NDC) scenario. In the long-term (2050), the difference between these scenarios reduces and the projected storage requirement in the Net-Zero 2050 scenario becomes 2.4 times as compared to the Current Policies scenario and 1.5 times the NDCs scenario. This would mean massive investments and capacity building in energy storage by 2030 if the world must stay on the path of Net-Zero 2050 scenario as compared to the current policies and NDCs.

A second set of assessment of energy storage projections is presented by the IEA. IEA's latest world energy outlook is based on three scenarios for future energy systems. The stated policy scenario (STEPS) considers all the current policies in place but does not assume any extra efforts on the part of the government or new announcements to meet the climate goals. The advanced pledges scenario (APS) accounts for the additional pledges announced by countries in addition to the current NDC policies will be met in full within stipulated timeframes. The net-zero by 2050 scenario (NZE2050) shows a pathway where the world reaches net-zero emissions from energy systems by the end of 2050 while also meeting the sustainable development goals like universal energy access for all by 2030. These scenarios give a range of possibilities to consider when planning for the future electricity capacities (IEA, 2022b). According to the latest world energy outlook by the IEA, the total global electricity capacity in 2050 is projected to reach around 20 TW in the STEPS, 26.5 TW under the APS and around 34 TW under the NZE2050. The electricity capacity in the APS and NZE2050 scenarios goes up by 8% and 28% higher than STEPS in 2030 and 34% and 71% higher in 2050. This could be attributed to the higher share of VREs like solar and wind in APS and NZE2050 as compared to the STEPS. As a result, the battery storage in terms of power capacity is projected to reach 425 GW (2030) and 2300 GW (2050) in the APS and 780 GW (2030) and 3860 GW (2050) in the NZE2050 to facilitate the integration of variable renewables into the energy system. In general, battery storage emerges as an important option for grid flexibility in all three scenarios. In NZE2050, it replaces gas as the leading option for grid flexibility by 2035.

Another recent assessment of future electricity growth and energy storage scenarios was conducted by the WGIII (Mitigation) of the IPCC which was published in the AR6 this year (IPCC, 2022). The IPCC assessment considers recent global mitigation scenarios from peer-reviewed integrated assessment models (IAMs) which again consider various plausible futures to project the demand for different energy sources. The results from three types of IPCC scenario pathways, (1) C2 scenarios which considers scenarios with the possibility to restrict the global temperature rise below 1.5 degrees by 2100 as compared to the pre-industrial levels, (2) C4 scenarios which limits the temperature rise to 2 degrees, and (3) C6 scenarios which limit the temperature rise to up to 3 degrees which is in line with the NDCs and current policies. C6 can therefore be compared to the Current Policies or NDCs scenarios whereas C2 and C4 scenarios represent the ambitious climate change pathways to meet the Paris Climate Agreement goals.

These are based on the scenario database for AR6, documented by IIASA (Byers et al., 2022). The IPCC pathways, C2 and C4 also indicate a high share of VREs (solar and wind) in the electricity mix which would require large scale deployment of energy storage technologies. Based on the assessment of these scenarios, the median power storage capacities were found to be 420 GW (C2), 180 GW (C4), and 170 GW (C6) in 2030 and 5500 GW (C2), 1800 GW (C4) and 810 GW (C6) in 2050.

Based on the NGFS, IEA and IPCC projections, the storage capacities could reach up to 3000 GW by 2030 and further rise to 6000 GW by 2050 in the ambitious mitigation scenarios that meet the Paris agreement goals. Further, given the limited locations available for established technologies like pumped storage, most of the projected capacities could be expected in the form of battery energy storage (BES) systems.

In case of material and minerals required for manufacturing BES systems, the demand for lithium is expected to rise exponentially in next few years (IEA, 2022b; IRENA, 2022b). However, the actual material projections are continuously evolving given the changing projections for electric vehicles, grid storage and battery chemistries. According to the IPCC AR6 assessment, the superior characteristics of lithium-ion batteries (LiBs) make them the dominant choice for EVs and grid applications in the medium-term. However, the report also finds that no single technology among the portfolio of mature battery chemistries is suitable for all the grid service applications. The optimum solution lies in a combination of energy storage technologies. So far, several next-generation battery chemistries are showing good results for commercialization. Research on cost reductions and extending the life of the newer technologies could lead to newer battery chemistries becoming available as alternatives the lithium-ion batteries.

1.4. Macroeconomic impacts of BES implementation, worldwide

The deployment of battery energy storage to support large-scale integration of VREs could affect the global economy in various ways. Some of the potential macroeconomic impacts are discussed here.

- In terms of employment and government revenues, BES could facilitate the creation of green jobs which could help in compensating the loss of jobs in traditional fossil fuel sectors. However, the new jobs may not always be created in the same locations where the fossil fuel industries are operational. This may have implications for government revenues and employment opportunities at subnational and local levels. For example, in countries like India, Australia, Germany and the United States of America, the coal mining and power plants are concentrated in a few locations which may not always be suitable for the deployment of solar and wind energy (Diluiso et al., 2021)
- The deployment of BES could allow VRE technologies to replace more expensive clean energy technologies and reduce investment costs in backup generation, interconnection, transmission, and distribution network upgrades (Clarke et al., 2022). Thus, investing in the research and development of newer BES technologies could offer alternatives for grid

flexibility and enhance the resilience of electricity systems to meet rising electricity demands and support robust economic development in the future

- BES deployment in combination with rooftop or solar microgrids could aid in providing electricity access to rural and remote areas of developing countries which lack access to clean energy. The access to reliable electricity could promote local livelihood, education and overall economic development in these regions (Alstone et al., 2015)
- However, many of the current BES technologies depend on critical minerals which are concentrated in a few countries of the world. This could pose energy security risks for some countries which do not have domestic resources of the minerals that are critical to the development of BES systems. The mining of critical minerals may also lead to disruptions for local communities and the environment which may impact the political and economic stability in the mining regions (see section 2.2)
- In terms of BES financing, many developing countries find it difficult to divert funds for expensive mitigation technologies like grid-scale batteries. There are many uncertainties in the current and upcoming technologies such as the Redox Flow (RFBs) batteries. In such a scenario, public funding of BES projects could increase debt and in turn the interest rates. An increase in the interest rate would crowd out private investments which could have an adverse impact on economic growth

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Chapter 2

Global estimation of cost and risk for implementation of BES

2.1 Assessment of cost for BES technologies

As discussed earlier, the cost of battery storage technologies, led by Li-ion battery chemistries has reduced by over 90% in the past decade (Clarke et al., 2022). These declines have accelerated the growth of VRE integration in electricity systems. The BES system has three main cost components: installed capital costs, operating costs, and decommissioning costs. The installed capital costs include the cost of storage block, storage balance of system, storage system, control & communication, system integration, EPC, project development, and grid integration. The operating costs include the costs associated to fixed operations & maintenance (O&M), variable O&M, round trip efficiency (RTE) losses, warranty, and insurance. Further, decommissioning costs include the costs for disconnection, disassembly/removal, site remediation and recycle/ disposal. The detailed description of these cost components for BES systems have explained in annexure 2. These costs are summarized in table 3 for the leading battery chemistries like Lithium-ion Iron Phosphate (LFP) batteries, Lithium-ion Nickel Manganese Cobalt (Li-NMC) batteries, Lead-Acid Batteries (LAB) and Vanadium Redox Flow Batteries (VRFB) with 10 MW (4 hours) capacity. The costs of these batteries for power levels of 1MW (4 hours) and 100 MW (4 hours) are included in annexure 3A and 3B, respectively.

Table 3. Component-wise installed capital cost (2020 & 2030) and operating cost (2020) for various BES technologies (10 MW, 4 hours)

Parameters	Units	LFP batteries	Li- NMC batteries	LAB	VRFB
Storage Systems (2020)					
Storage Block	$/kWh	156 - 191	166 - 203	161 - 181	247 - 302
		174	185	171	275
Storage Balance of System	$/kWh	36 - 44	29 - 43	44 - 50	49 - 60
		40	35	47	55
Energy storage systems (ESS) (2020)					
Power Equipment	$/kW	66 - 80	66 - 80	125 - 141	120 - 146
		73	73	133	133
Controls & Communication	$/kW	[7 - 9]	[7 - 9]	[7 - 8]	[7 - 9]
		8	8	8	8
System Integration	$/kWh	35 - 52	36 - 54	41 - 47	46 - 56
		47	48	44	51
ESS installed cost (2020)					

Parameters	Units	LFP batteries	Li- NMC batteries	LAB	VRFB
Engineering, Procurement, and Construction	$/kWh	44 - 68	45 - 71	46 - 52	53 - 64
		56	58	49	58
Project Development	$/kWh	52 - 83	53 - 87	58 - 65	66 - 81
		67	69	62	73
Grid Integration	$/kW	22 - 27	22 - 27	23 - 26	23 - 28
		25	25	25	25
Total ESS Installed Cost* (2020)	$/kW	1389 - 1868	1408 - 1947	1520 - 1792	1995 - 2438
		1643	1685	1657	2216
	$/kWh	347 - 467	352 - 487	380 - 448	499 - 609
		411	421	414	554
Total ESS Installed Cost (2030)	$/kW	1008 - 1334	1031 - 1365	1296 - 1538	1488 - 1996
		1156	1204	1415	1773
	$/kWh	252 - 333	258 - 341	324 - 384	372 - 499
		289	301	354	443
Operating Cost (2020)					
Fixed O&M	$/kW-yr	3.63 - 4.43	3.72 - 4.55	5.11 - 5.76	5.65 - 6.91
		4.03	4.13	5.43	6.28
Variable O&M	$/MWh	0.5125	0.5125	0.5125	0.5125
System RTE Losses	$/kWh	0.005	0.005	0.008	0.014

Notes: ** indicates that it does not include warranty, insurance, or decommissioning costs*

Source: *Adapted from Pacific Northwest National Laboratory (PNNL) data (Mongird et al., 2020a)*

The total BES installed capital costs for 10 MW, 4 hours systems in case of LIBs were less as compared to LABs and flow batteries. Similarly, fixed operational and maintenance (O&M) costs and costs of system round trip efficiency (RTE) losses were lower for LIBs followed by LABs and VRFBs (refer Table 2.1). The installed capital costs as well as O & M costs for these BES technologies would decrease by around 8-9% and 13-14% if their power capacities are increased from 1MW to 10 MW and 100 MW, respectively for 4 hours durations (refer annex-3). As the technology achieves a sufficient state of maturity and due to economies of scale, the capital cost as well as O & M costs of BES technologies are expected to further reduce in the future.

Although the difference between installed capital costs of LIBs and LABs are not significant, the LABs are not widely used for grid-scale storage applications due to their major limitations such as low-energy density, restricted cycling ability, and high environmental impacts. Moreover, the global trend in lithium-ion battery prices indicate a rapid decline during 2011-20. Projecting this trend in the future, BNEF (2020) expects the cost of Li-ion battery packs to decline further by 58% between 2020-30 (figure 4).

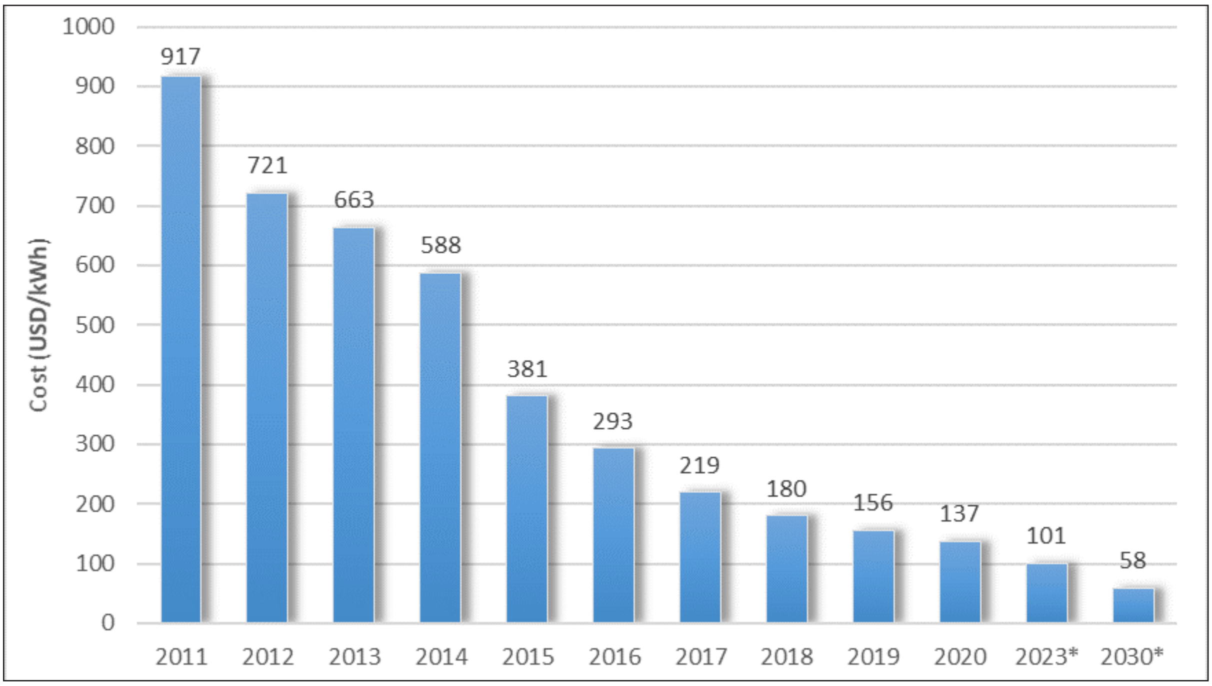


Figure 4. Lithium-ion battery pack costs worldwide since 2011-2020 and projected till 2030

Source: Authors' illustration based on data from Statista (2022); BNEF (2020)

2.2 Critical minerals and the risk for implementation of BES

In terms of the risks, battery technologies have faced challenges in recent times due to fire hazards, technology related concerns, scarcity of critical minerals and supply chain disruption due to recent events like the COVID-19 pandemic and the Russia-Ukraine conflict. In this section, we focus on the risks and challenges to BES implementation due to the availability of critical minerals. Other technological and financing risks associated with BES are covered in section 3.

A major risk to current battery technologies comes from the availability of critical minerals. Low carbon future would require minerals and metals to play a crucial role in the energy transitions. Thus, mining sector would also experience substantial changes. The growth in low carbon technologies for power generation, especially renewables, and EVs imply the increased need for energy storage. This has the potential to profoundly alter the magnitude and composition of minerals and metals demand (IEA, 2022c). Huge amounts of metals and minerals are needed for an adequate supply of raw materials to manufacture clean technologies to tackle climate change (Ali et al., 2017). However, there are supply concerns like the environmental and energy-use impacts of increased extraction of mineral resources, and the relative vulnerability of developed countries to the supply of critical elements required for the clean energy transition (Hund et al., 2020).

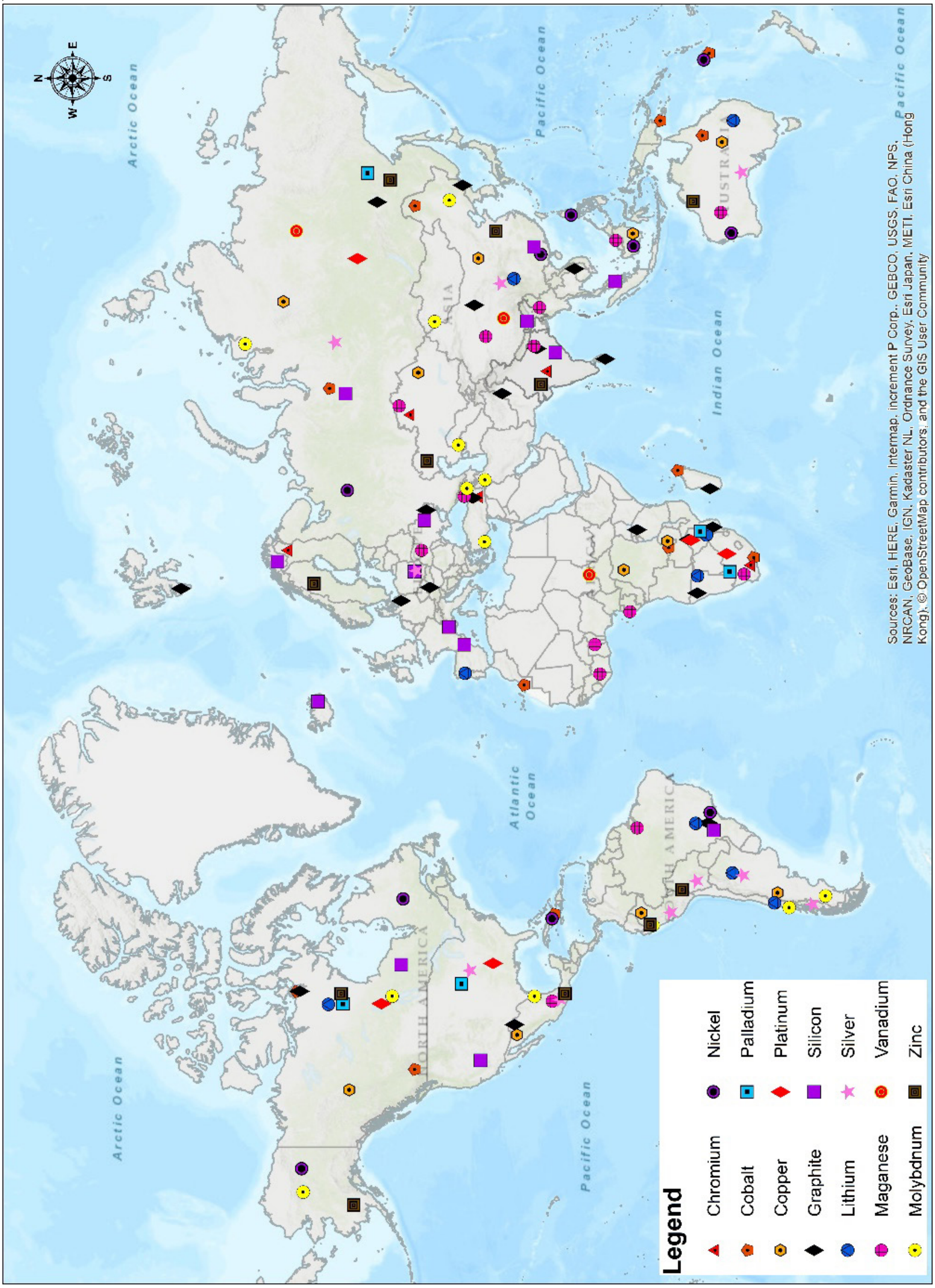
The type and quantum of minerals required for energy storage vary by technology and use. Since LIBs are high power and high energy density, they are useful for stationary and transportation purposes. While the redox/bromine flow batteries are more suitable for renewable energy integration. Aluminium, Chromium, Cobalt, Copper, Graphite, Iron, Lead, Lithium, Manganese, Nickel, Vanadium and Zinc are few of the majorly used minerals across these battery technologies. With current technology landscape, Lithium, Cobalt and Nickel are crucial as they play a central role in giving batteries greater performance, longevity and higher energy density (IEA, 2022c). As some technologies become more prominent and penetrate at a large scale, the minerals used in them could see a heavy increase in demand as compared to the minerals used in other battery technologies.

With increasing demands for critical minerals, the global supply chains for these minerals become of great importance. The supply chain for the raw materials is more geographically concentrated (fig. 5 and fig. 6) as compared to fossil resources- especially oil and natural gas. Minerals critical for battery technologies like Nickel and Cobalt have reserves in very few locations globally making a case for resource nationalization. Demand for Graphite, Lithium and Cobalt is expected to exponentially increase, the supply will also observe constrains since more than 60% of graphite and cobalt production are concentrated in China and the Democratic Republic of Congo, respectively (Tapia-Ruiz et al., 2021)due to their limited availability and consequent expected price increase, have raised awareness of the importance of developing alternative energy-storage candidates that can sustain the ever-growing energy demand. Furthermore, limitations on the availability of the transition metals used in the manufacturing of cathode materials, together with questionable mining practices, are driving development towards more sustainable elements. Given the uniformly high abundance and cost-effectiveness of sodium, as well as its very suitable redox potential (close to that of lithium).

Next generation batteries are expected to be vanadium based redox flow batteries, solid state LIBs and zinc air batteries. Redox flow batteries are an emerging technology in stationary energy storage. They are heavy and large, and thus unsuitable for vehicles, but they can be built with extremely large capacities (up to 200 MW, compared with 100 MW for Li-ion) and have a long-life span. The VRFB are recyclable ad hence further lead to reduced mineral needs. Highest Vanadium deposits are located in China, Russia, Australia, South Africa and Brazil. However, Vanadium occurs in almost 65 minerals. The redox flow batteries use Vanadium Pentoxide (V_2O_5) as the electrolyte. V_2O_5 is extracted from the Titaniferous magnetite ore during steel making. Aluminium processing from Bauxite also allows for Vanadium extraction. Thus, in Iron and steel industries, Aluminium plants as well as crude oil, tar and coal refining and processing ash, slag, spent catalyst or residue is generated which contains Vanadium with is recovered. Hence, Vanadium availability is relatively distributed across the globe.

For solid state batteries- Lithium is used in anode. Lithium-ion batteries are among the dominant technology as more energy can be stored for the weight of the battery. Graphite demand will change in future as it will be replaced by Lithium. However, Lithium resources are limited and experience price increase. Hence, new research investments are coming into developing alternative technologies. Given sodium's abundant resources and cost-effectiveness, along with its very suitable redox potential (similar to that of lithium), sodium-ion battery technology has great potential to be a counterpart to lithium-ion batteries, including stationary energy storage and EVs by 2030 (Tapia-Ruiz et al., 2021)due to their limited availability and consequent expected price increase, have raised awareness of the importance of developing alternative energy-storage candidates that can sustain the ever-growing energy demand. Furthermore, limitations on the availability of the transition metals used in the manufacturing of cathode materials, together with questionable mining practices, are driving development towards more sustainable elements. Given the uniformly high abundance and cost-effectiveness of sodium, as well as its very suitable redox potential (close to that of lithium. Sodium batteries are also expected to be much more cost effective due to global availability of Sodium resources. Although, the current share of Na-ion batteries is very little as compared to Li-ion, there are efforts to make it commercially feasible globally. Hence, the share of Na-ion batteries is expected to increase substantially in the future. There are also uncertainties about electrolyte compound possible minerals- Tin, Aluminium, Silver and Boron.

(a)


Arctic Ocean
Pacific Ocean
Atlantic Ocean
Indian Ocean
Pacific Ocean
Arctic Ocean
Pacific Ocean
Legend
Chromium
Cobalt
Copper
Graphite
Lithium
Maganese
Molybdnum
Nickel
Palladium
Platinum
Silicon
Silver
Vanadium
Zinc
Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), © OpenStreetMap contributors, and the GIS User Community

(b)

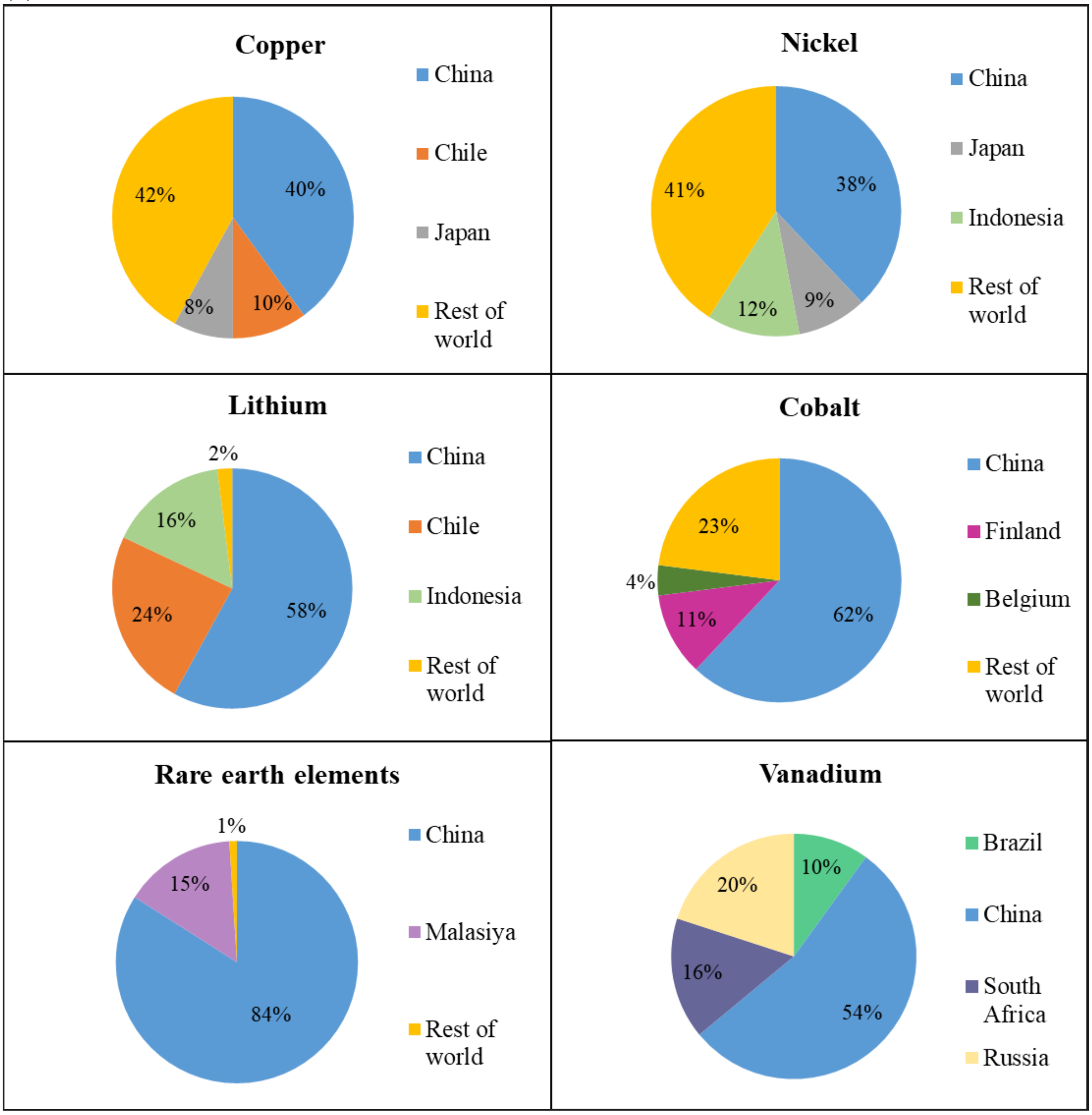


Figure 5. (a) & (b) Global minerals resource deposits

Source: Authors' compilation from (IBM, 2018; IBM, 2019; IBM, 2020; IEA, 2022c)

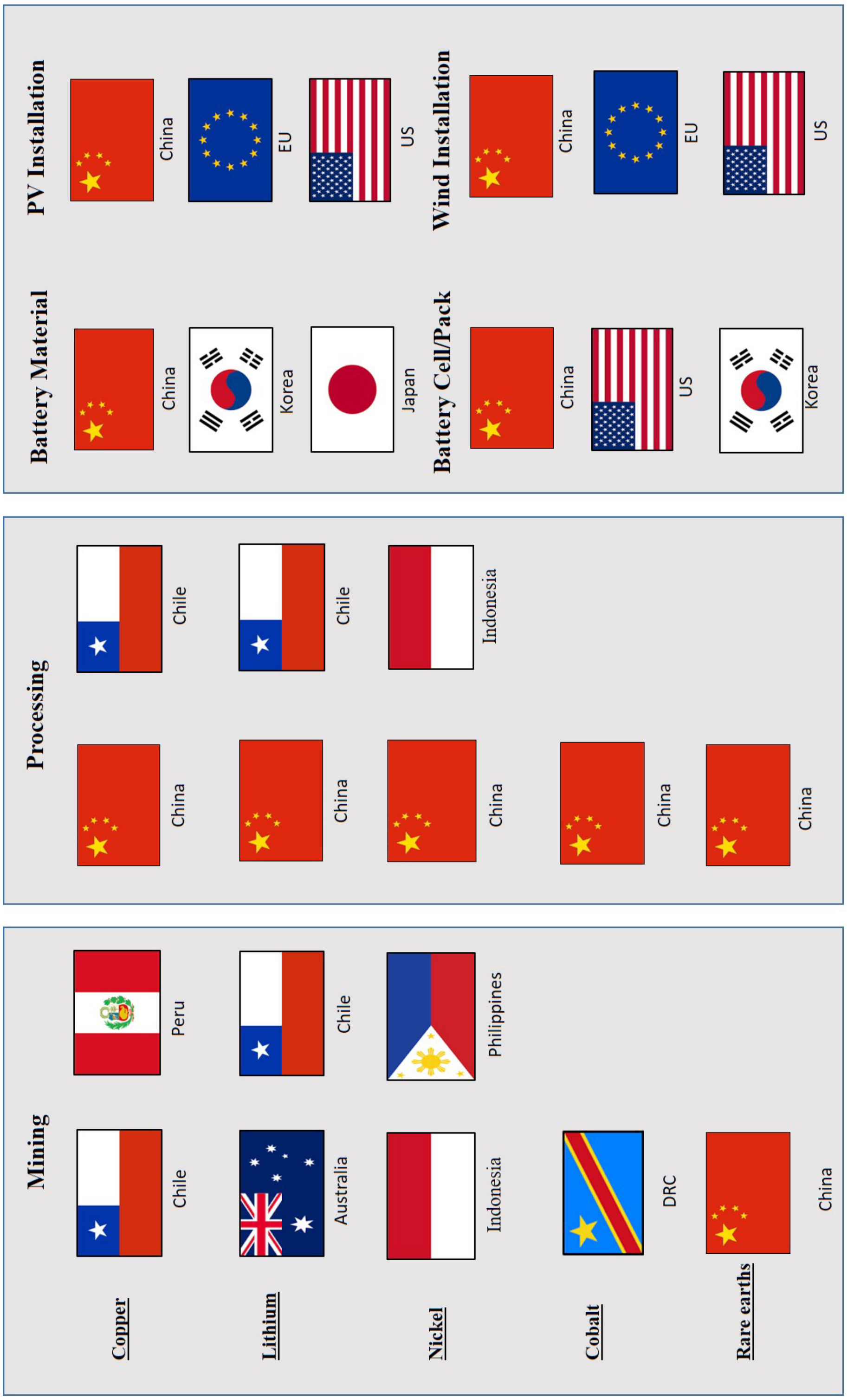


Figure 6. Global mineral supply chain

Source: Authors' compilation based on (IEA, 2022c)

Table 4 describes the total mineral demand in years 2030 and 2050. Here we assume that the entire demand for storage as indicated in the NGFS scenarios is fulfilled by one technology at a time. Thus, for instance the Lithium estimates for 2030 suggest the tonnes of mineral need if the entire storage demand is fulfilled using LIBs. The demand described here is for first time requirement and does not consider the BES replacement needs or the mineral recycling and recovery rates that may have an impact on that total demand of minerals.

Table 4. Total mineral requirement estimates based on NGFS scenarios (tonnes) per GW of BES

2030	Aluminium	Cobalt	Iron	Manganese	Nickel	Lithium	Vanadium (V_2O_5)
Below 2 °C	28.33	254.98	679.95	226.65	226.65	283.31	1511000
Current Policies	8.84	79.59	212.25	70.75	70.75	88.44	471667
Delayed transition	8.84	79.59	212.25	70.75	70.75	88.44	471667
Divergent Net Zero	56.87	511.82	1364.85	454.95	454.95	568.69	3033000
NDCs	17.21	154.86	412.95	137.65	137.65	172.06	917667
Net Zero 2050	55.36	498.26	1328.70	442.90	442.90	553.63	2952667
2050							
Below 2 °C	116.27	1046.42	2790.45	930.15	930.15	1162.69	6201000
Current Policies	51.33	461.93	1231.80	410.60	410.60	513.25	2737333
Delayed transition	137.96	1241.61	3310.95	1103.65	1103.65	1379.56	7357667
Divergent Net Zero	156.86	1411.71	3764.55	1254.85	1254.85	1568.56	8365667
NDCs	83.58	752.18	2005.80	668.60	668.60	835.75	4457333
Net Zero 2050	140.88	1267.93	3381.15	1127.05	1127.05	1408.81	7513667

Source: Authors'compilation based on (Arrobas et al., 2017)

Zinc Air Batteries are also expected to come in a big way in future. They could reduce demand of minerals used in Lithium-ion batteries. Thus, the demand could shift to Nickel, Manganese, Zinc, Lanthanum or Silver. Zinc-based Batteries incorporate zinc with various compounds and are in a more advanced phase of development than some other battery technologies. Previously, zinc batteries could not be recharged, but researchers are overcoming obstacles to create fully rechargeable zinc-based batteries. This technology is well-known for being light, inexpensive, and non-toxic (ISGF, 2019).

With increasing demand for energy storage for clean transitions, technology development on reuse, recovery and recycling of the critical minerals also becomes of prime importance. Refurbishing, recycling, and mineral recovery would play a vital role in limiting and meeting future mineral demands. G20 countries may want to invest in technology development here.

Chapter 3
Investment Outlook

3.1 Investments required for BES in upcoming years

Existing investments for BES have been encouraging with investments picking up sharply amid the discussions for achieving net zero emissions. These investments are broadly focussed in four geographies – North America, Europe, Asia Pacific (excluding China), and China (figure 7). The addition of grid scale storage is required to address the increasing share of VRE to achieve net zero energy systems.

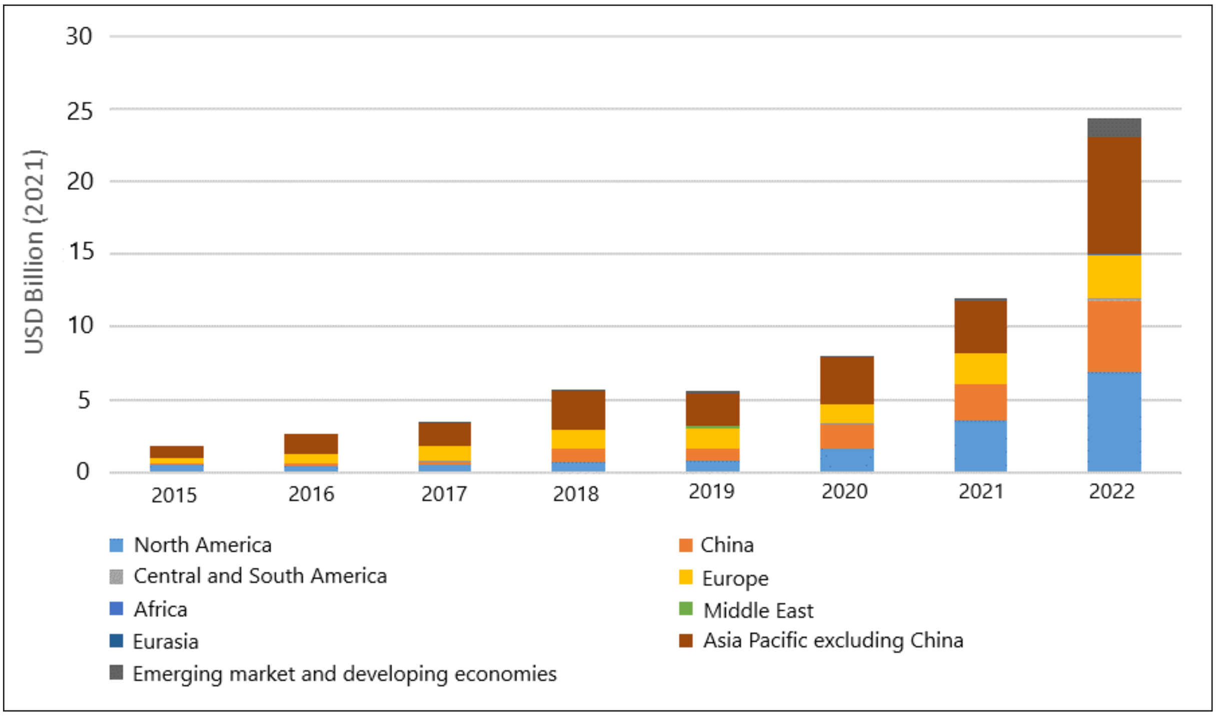


Figure 7. Global investments in electricity storage

Source: IEA World Investment Report 2022 datafile

Few case examples of companies around the world have attracted investments in BES technologies (Table 5). However, their population, size and geographic coverage is growing with time (refer annexure 4).

Table 5. Case examples of companies operating in the BES space and their market capitalizations

Sr. No.	Company Name	Country	Market Capital (USD million)	Net Worth (USD million)
1	ATON Green Storage SpA	Italy	48.3	15.2
2	Dry Cell and Storage Battery JSC	Vietnam	62.7	36.1
3	Thai Energy Storage Technology PCL	Thailand	140.6	64.8
4	Thai Storage Battery Ord Shs	United States	167.7	50.3
5	Hitachi Chemical Storage Battery Ord Shs	Thailand	167.7	50.3
6	Tyumenskiy Akkumulyatornyi Zavod AO	Russia	--	57.2
7	Saltbae Capital Ord Shs	Germany	--	14.5

Source: Authors' compilation from (Refinitive, 2022)

Also, there are number of case examples of BES projects (investment ranging from 1.8 to 3160 million USD) around the world (refer annexure 5). The number of such projects, geographical diversity and size are expanding every year.

For this report, we primarily explore the NGFS scenarios till 2050 to understand BES capacity additions projected by different models across various scenarios. Projections of global electricity storage capacity across various scenarios mentioned in NGFS scenarios have been presented in figure 3 (a).

While existing growth of BES has shown sharp upswings, projected growth till 2030 is expected to be much steeper, increasing from 16 GW in 2021 to 680 GW in 2030. The cumulative capacity additions have been worked out following various NGFS scenarios (table 6).

Table 6. BES cumulative capacities (GW) till 2050

Scenarios	2025	2030	2035	2040	2045	2050
Current Policies - High	132	409	964	1571	2157	2667
Current Policies - Low	0	0	0	46	120	136
NDC - High	244	853	1837	2811	3626	4172
NDC - Low	0	2	167	246	654	1041
Below 2 °C - High	421	1643	3144	4085	4679	5165
Below 2 °C - Low	28	165	459	1140	2327	3296
Delayed transition - High	132	409	1720	3813	5395	6503
Delayed transition - Low	0	0	672	3481	4554	5000
Divergent Net Zero – High	833	3121	4548	5402	5905	6327
Divergent Net Zero - Low	445	1857	3705	4889	5538	5976
Net Zero 2050 - High	730	2974	4154	5047	5825	6349
Net Zero 2050 - Low	445	1838	3585	4569	4976	5168

Source: Authors' estimates for capacity projections adopted from NGFS scenarios

Based on the above projected capacity additions, the study has considered the following batteries as projected in the literature: Li-ion Phosphate (LFP), Li-ion Nickel Manganese Cobalt (Li-NMC), Lead Acid and Vanadium redox Flow (VRFB). Na ion batteries are also projected to be adopted in the mainstream technology. However, cost parameters around Na ion batteries vary widely to be used for any projections. The projected range total installed costs of grid-scale BES systems (10 MW/4 hrs.) are presented in figure 8. The study has considered the total installed cost of these battery types and their projections using the Pacific Northwest National Laboratory (PNNL) data (Mongird et al., 2020b). The cost numbers from PNNL are on the higher side but cost estimations from other studies could also be explored using the same methods to arrive at a range of future cost projections.

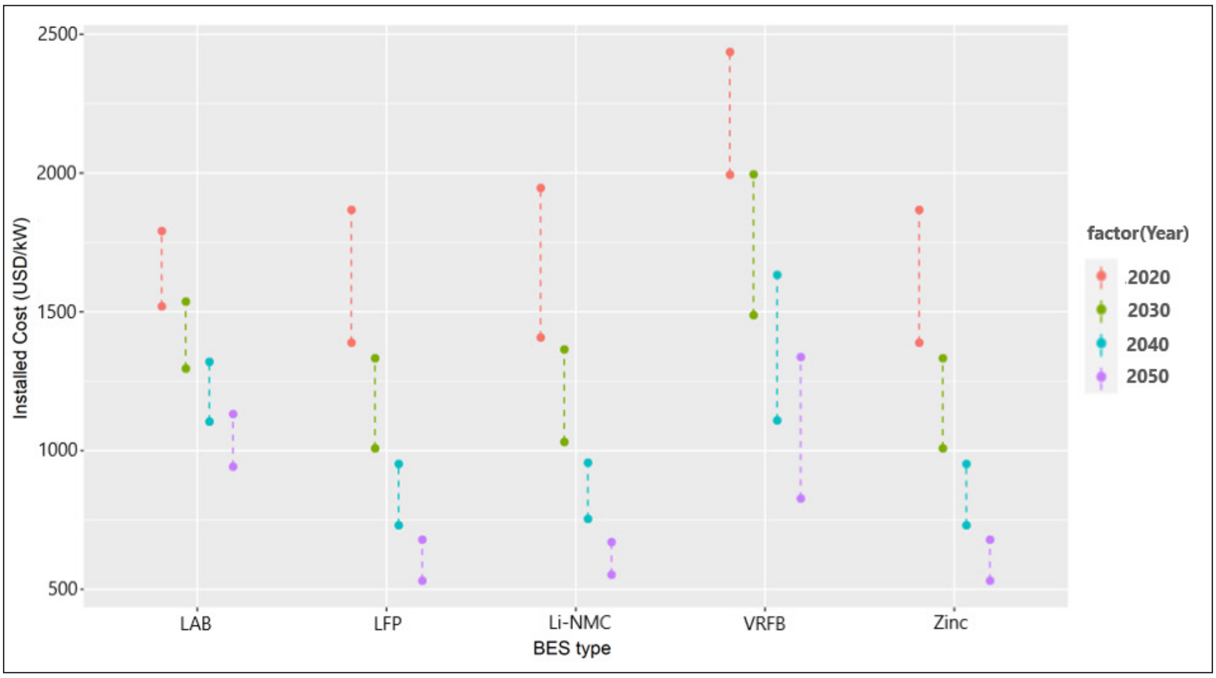


Figure 8. Total installed cost of grid scale BES including all BES types (10 MW/4 hrs)

Source: Estimated based on PNNL 2020 Grid Energy Storage Technology Cost and Performance Assessment (Mongird et al., 2020b)

While LIBs are the most popular choice, supply of minerals seem to be a concern in the long term as pointed out in various studies. Nevertheless, the study has estimated the following investment requirements across battery types assuming the entire capacity to be populated by a single type of battery (refet table 7 to 10).

Table 7. Estimated investment requirement (USD billion) for all systems adopting LFP (excluding other batteries)

Scenarios	2020-25	2025-30	2030-35	2035-40	2040-45	2045-50
Current Policies – High	185	320	546	494	406	292
Current Policies – Low	0	0	0	37	51	9
NDC – High	341	704	969	792	565	312
NDC - Low	0	2	162	64	283	221
Below 2°C – High	589	1413	1478	765	412	278
Below 2°C – Low	39	158	289	554	822	555
Delayed transition – High	185	320	1291	1702	1096	634
Delayed transition – Low	0	0	662	2285	743	255
Divergent Net Zero – High	1166	2645	1405	695	348	241
Divergent Net Zero – Low	623	1632	1820	963	450	251
Net Zero 2050 - High	1022	2594	1162	726	539	300
Net Zero 2050 - Low	623	1610	1720	800	282	110

Source: Capacity projections adopted from NGFS scenarios and cost estimates based on PNNL 2020 data (Mongird et al., 2020b)

Table 8. Estimated investment requirement (USD billion) for all systems adopting Li-NMC (excluding other batteries)

Scenarios	2020-25	2025-30	2030-35	2035-40	2040-45	2045-50
Current Policies - High	191	334	573	522	432	314
Current Policies - Low	0	0	0	40	55	10
NDC - High	352	733	1016	838	601	336
NDC - Low	0	2	170	68	301	238
Below 2°C - High	608	1471	1549	810	438	299
Below 2°C - Low	40	165	303	586	875	596
Delayed transition - High	191	334	1353	1801	1167	681
Delayed transition - Low	0	0	694	2417	791	274
Divergent Net Zero – High	1203	2755	1473	735	371	259
Divergent Net Zero - Low	643	1700	1907	1019	479	269
Net Zero 2050 - High	1054	2702	1218	768	574	322
Net Zero 2050 - Low	643	1677	1803	847	300	118

Source: Capacity projections adopted from NGFS scenarios and cost estimates based on PNNL 2020 data (Mongird et al., 2020b)

Table 9. Estimated investment requirement (USD billion) for all systems adopting LABs (excluding other batteries)

Scenarios	2020-25	2025-30	2030-35	2035-40	2040-45	2045-50
Current Policies - High	203	392	728	733	656	526
Current Policies - Low	0	0	0	56	83	17
NDC - High	375	862	1291	1177	913	563
NDC - Low	0	3	216	95	457	399
Below 2°C – High	647	1729	1969	1137	665	501
Below 2°C – Low	43	194	386	823	1330	1000
Delayed transition – High	203	392	1720	2529	1772	1143
Delayed transition – Low	0	0	881	3394	1202	460
Divergent Net Zero - High	1279	3238	1872	1032	563	435
Divergent Net Zero - Low	684	1998	2424	1431	727	452
Net Zero 2050 – High	1121	3175	1548	1079	871	541
Net Zero 2050 – Low	684	1971	2291	1189	456	198

Source: Capacity projections adopted from NGFS scenarios and cost estimates based on PNNL 2020 data (Mongird et al., 2020b)

Table 10. Estimated investment requirement (USD billion) for all systems adopting VRFB (excluding other batteries)

Scenarios	2020-25	2025-30	2030-35	2035-40	2040-45	2045-50
Current Policies - High	263	491	886	861	748	579
Current Policies - Low	0	0	0	65	94	18
NDC - High	487	1080	1570	1382	1041	620
NDC - Low	0	4	263	112	521	439
Below 2°C – High	840	2167	2395	1335	758	552
Below 2°C – Low	56	243	469	966	1516	1100
Delayed transition – High	263	491	2092	2969	2020	1258
Delayed transition – Low	0	0	1072	3985	1370	506
Divergent Net Zero - High	1661	4057	2277	1211	642	479
Divergent Net Zero - Low	888	2503	2949	1680	829	497
Net Zero 2050 – High	1456	3979	1883	1267	993	595
Net Zero 2050 – Low	888	2470	2788	1396	520	218

***Source**: Capacity projections adopted from NGFS scenarios and cost estimates based on PNNL 2020 data (Mongird et al., 2020b)*

3.2 Levelized cost of storage (LCOS)

The economics of different storage technology choices is analysed using a levelized cost framework. Levelized cost represents the uniform annual cost incurred over the life of the storage unit. With different technology choices having different lifetimes and other differing parameters, a comparison of the levelized costs can help in technology choice on an economic basis (Schmidt et al., 2019). The basic assumption of this comparison is that all the choices are equally available to a grid scale BES investor. The basic assumptions and reference data are included in annexure 6.

The levelized generation cost is compared across different BES technologies. Across different technologies, there is a variation in capital costs, operation and maintenance expenses, and other costs which are spread over different lifetimes. BES parameters and cost have been collected for 2020 and 2030 from 2020 Grid Energy Storage Technology Cost and Performance Assessment and 2022 Grid Energy Storage Technology Cost and Performance Assessment authored by PNNL and Mustang Prairie Energy (Viswanathan et al., 2022). These studies compare well with other studies like The Future of Energy Storage, an Interdisciplinary MIT Study which provides cost estimates for 2020 and 2050 (*MIT,* 2022).

The capital cost including the balance of system and the maintenance costs vary across different sources. The study has made efforts to reconcile these to the extent possible. Our analysis shows that LFP batteries and Li-NMC batteries have comparatively lower levelized cost compared to other technologies evaluated (figure 9 & figure 10). Traditional LABs may require further R&D for cost improvement. One promising technology being discussed in the literature includes Na-ion batteries, though cost estimates vary widely.

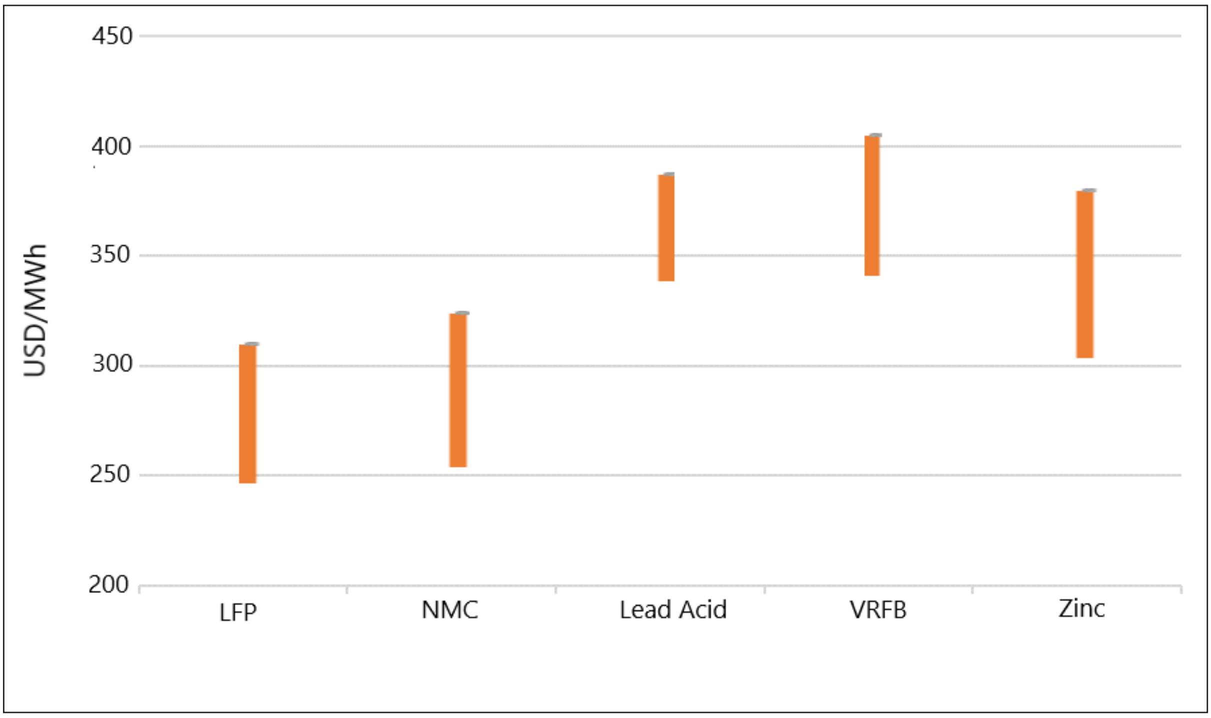


Figure 9. Levelized cost range of grid scale BES (without battery degradation) including all systems (10 MW/4 hrs)

Source: *Cost estimates based on PNNL 2020 data (Mongird et al., 2020b)*

One unique feature of this study is that the study considered levelized costs also with battery degradation which affects the performance of BES in the long run. The study considered both kinds of degradation – capacity degradation and time degradation which would in effect affect the levelized cost.

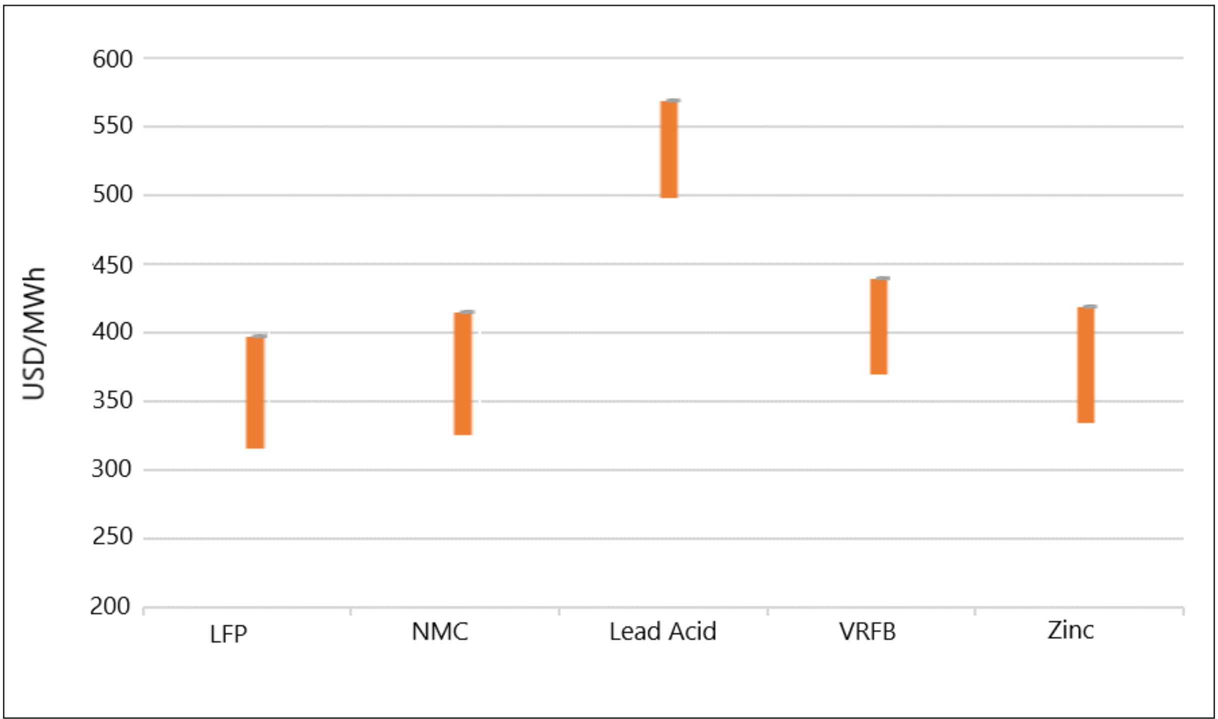


Figure 10. **Levelized cost range of grid scale BES (with battery degradation) including all systems (10 MW 4 hrs)**

Source: *Cost estimates based on PNNL 2020 data (Mongird et al., 2020b)*

Thus, considering battery degradation, after lithium batteries, Vanadium Redox flow batteries or Zinc batteries exhibit lower levelized cost over LABs.

3.3 Risks, investment challenge and measures to improve bankability of BES project

With the focus on increasing the share of renewable energy globally, BES is crucial to integrate VRE systems with the grid and efficiently manage day-night and peak demands, thereby reducing overall system costs of VRE systems. The deployment of BES could also reduce the frequent ramp-up and ramp-down requirement in existing thermal and nuclear power plants. Since there are multiple technologies at the development stage, the scalability of BES technologies at a commercial scale in various countries pos a significant risk to the project developers. As discussed earlier, BES systems based on LiBs are currently prevalent but the availability of critical minerals to manufacture LiBs may constrain the expansion of new BES projects in the future. This may also affect the replacement of LiBs after the completion of useful life in existing BES projects.

LIBs are also susceptible to thermal runaways which may result from several factors like operational errors, failure of battery management systems, external environmental conditions, and internal cell failures. The results could be fire, toxic gas and explosions (Sebastian, 2022). A case in point is South Korea which saw the highest growth in Li-ion battery capacity in recent years but had to slow down the installations when fire broke in around 23 battery storage sites in 2019. This led to the government closing 522 out of the about 1500 energy storage facilities for safety audits. The fires were attributed to manufacturing defects in LIBs and other operational factors. This has led to cautious expansion on the part of project developers in the newer BES technologies. To support further expansion of BES, the risks associated with the availability critical minerals and technologic factors would need attention from investors and policy makers.

In case of financing risks, the cost of BES projects could be subsumed in the cost of electricity to make BES projects viable. However, low-cost financing of BES projects is crucial to improve the viability of BES projects so that escalation in the cost of electricity is as minimum as possible. Reduction in weighted average cost of capital (WACC) is required to make BES projects viable.

Further, to improve the bankability of BES, the proposed projects need to exhibit strong financial, economic, and technical plans along with a viable risk mitigation plan. So, in effect, the project organization must exhibit the ability to repay the principal and interest and mitigate the project risks. BES projects are characterized by large upfront capital investments and most BES capacities being discussed in future cover a duration of 4 - 6 hours with some stretching till 10 hours. In this regard, an example of risks assessment and mitigation is presented which is partly adapted from ADB's first Utility-Scale Energy Storage Project in Mongolia which mentions some of these risks and their mitigation options to make BES projects more bankable (Table 11) (ADB, 2020).

Table 11. Various types of risks and mitigation options for BES projects

Types of risks	Risks and Mitigation Options	Quality of risk
Technology Risks	Cost curves of BES installations are declining sharply with many newer technologies being included in the consideration set. Early movers may be locked into high capital costs and technologies compared to late entrants. This risk may be covered by suitably understanding research data around various technologies. Overcharging and discharging of the battery module could result in fire incidents. This risk can be mitigated by proper maintenance contracts and ensuring training of staff.	Low
Procurement Risks	There may be insufficient number of qualified bidders to participate in the bidding of the BESS system. This may be mitigated by proper bidding criteria and having access to technical support.	Moderate

Types of risks	Risks and Mitigation Options	Quality of risk
Financer's Risk	Lenders may have concerns with debt recovery and the legal enforceability of claims. This risk may be addressed if project managers can demonstrate previous experience of accessing and repaying debt and also the reputation of the bidder.	Moderate
Market Risk	With rapid build-up of BES capacities planned, and possibilities of fossil fuel sources operating due to various constraints, BES shall be facing various market risks without a PPA. To mitigate this risk, it may be advised to get into long term PPA which may cover the debt repayment period.	Moderate
Revenue Risk	BES players depend on time shifting. Implementation of TOD tariff may make planning for charging an integral part of the BES business model as peak power is likely to be costly. Constant monitoring for energy arbitrage may cover this risk. In addition, BES players may participate in other markets like the ancillary market including frequency regulation, reactive power control, transient smoothing etc.	Low

Sources: (ADB, 2020; "Pv Magazine," 2018)

Chapter 4

International cooperation and policy interventions

4.1. International financial mechanism and financial models to develop and deploy BES Projects

Low-carbon and sustainable development initiatives need dedicated investments to satisfy Paris Agreement goals. Climate change mitigation and adaptation programs need US$ 3 trillion to US$ 6 trillion per year, compared to the present US$ 630 billion (Ehlers et al., 2022). EMDCs need investments to the tune of $1 trillion per year until 2030 in climate change energy infrastructure projects (IMF, 2022). Due to the investment gap, the Paris agreement's aim of limiting global warming to 2 degrees Celsius would be impossible to achieve. According to the OECD database, more than 90 funds (multilateral, bilateral, donor, and private) are currently financing projects related to climate change mitigation and adaptation, capacity-building, disaster risk reduction, REDD, clean energy, technical assistance, and technology transfer (Climate Fund Inventory Database, n. d). Multilateral Development Banks (MDBs) fund climate change initiatives via de-risking and blended finance mechanisms. Concessional loans (including co-financing), grants, guarantees, policy-based and outcome-based financing, lines of credit, and equity investment are primary climate financing methods adopted by MDBs and other funds.

Many market participants have established projects like GFANZ and the Network of Greening the Financial Systems (NGFS). GFANZ is a partnership of 550 financial institutions from 50 countries working to achieve net zero emissions by 2050. (Glasgow Financial Alliance for Net Zero, n.d.). NGFS is a consortium of central banks and supervisors sharing best practices in climate financing and risk management to fund low-carbon and climate-resilient development (NGFS, n.d.). Fund managers are launching and advertising ESG-focused funds to attract climate-conscious investors to help the transition to a low-carbon economy. Some of the major funds involved in climate financing are discussed here.

i. **Green Climate Fund (GCF) -** Green Climate Fund was founded under UNFCCC to support climate change mitigation and adaptation initiatives in developing countries, with an emphasis on Least Developed Countries (LDCs) and Small Island Developing States (SIDS). Initial funding of $10.3 billion was given till 2019 for climate change programs. The first replenishment cycle (GCF-1) pledged $10 billion for 2020-2023. GCF has committed $11.4 billion to 209 projects in 128 developing countries, according to its portfolio dashboard. GCF arranged $31.4 billion in co-financing. GCF sponsored approved projects using grants ($4.6 billion), concessional loans ($4.8 billion), equity ($1 billion), result-based payments ($0.496 million), and guarantees ($0.348 million) (Fund, G.C., 2021). EMDCs need to invest at least $1 trillion per year through 2030 in climate-related energy infrastructure projects. According to tables 3.2 to 3.6 of this report, various BES projects require a $7 trillion investment to reach net zero by 2050. GCF's capital funding for BES projects is insufficient to make real energy transformation progress.

ii. **Global Environment Facility (GEF) -** Global Environment Facility was established before the 1992 Rio Earth Summit to finance projects related to international conventions and agreements such as UNFCCC, CBD, UNCCD, Minamata Convention on Mercury, Stockholm Convention on Persistent Organic Pollutants. Some agencies undertake GEF projects are mentioned in annexure 7. GEF provides grants and co-financing. Since its founding, GEF has approved 5200 projects and awarded US$ 18.57 billion in grants and co-financing. Donor countries have contributed $30.08 billion after eight replenishments since 1991. In GEF-8 for 2022-2026, donors have contributed $5.33 billion in capital resources (GEF Funding, 2022). The last replenishment of US$ 5.33 billion for five years (2022-2026) is grossly inadequate for undertaking BES projects globally.

iii. **Climate Investment funds (CIF)** – Climate Investment Fund is one of the largest multilateral trust funds committed to climate change. Developed countries contributed $10.3 billion in initial capital funding. The United Kingdom and Spain primarily contributed to the initial funding. Other developed countries contributed capital in the form of loans and grants. CIF established specialized trust funds to finance clean technologies, climate resilience, forest preservation, renewable energy in low-income countries, and technical support initiatives. As implementing partners, funds are disbursed through six designated MDBs: The Asian Development Bank, European Development Bank, International Finance Corporation, Inter-American Development Bank, and African Development Bank. CIF invests funds through and by combining instruments like as grants, concessional loans, equity, guarantees, and contingent grants to de-risk and lower the cost of capital (Davis, 2022). As per the annual report of the CIF for 2021, figure 11 depicts the contributed resources of each specialized fund under CIF.

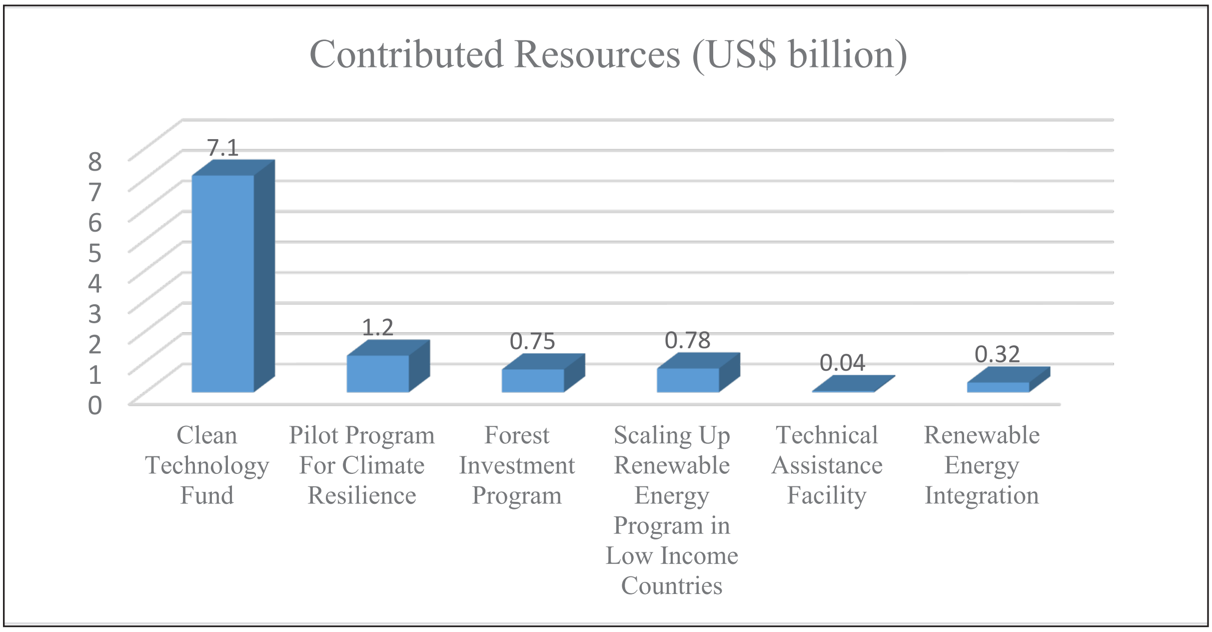


Figure 11. Contributed capital resource of each fund under CIF

Source: (Davis, 2022)

Clean Technology Fund (CTF) is the most suitable for implementing BES projects. However, considering the scale requirement of climate financing, existing capital resources of CTF (US$ 7.1 billion) are not enough for all clean technology projects globally, leave alone supporting BES projects. Therefore, creating a specialized fund for BES projects within the ambit of MDBs may be instrumental in arranging low-cost funding.

iv. **Funding by Multilateral Development Banks (MDBs)** – According to the joint report on multilateral development banks' climate finance for the year 2021, eight major MDBs[3] have facilitated climate financing totalling US$ 50.66 billion to low- and middle-income economies and US$ 31.05 billion to high-income economies in 2021. Climate financing totalled US$ 182.01 billion, including co-financing. MDBs contributed $81.71 billion in climate financing. Total climate financing for low- and middle-income economies was 94.26 billion USD and 87.75 billion USD, respectively. Investment loans, grants, guarantees, equity, result-based financing, policy-based financing, and lines of credit are the most common instruments used by MDBs (MDBs, 2022).

Given the worldwide funding requirement of US$ 3 trillion to US$ 6 trillion each year, major MDBs financing of only US$ 182.01 billion is totally insufficient to have any noticeable impact. Similarly, US$ 94.26 in finance is insufficient for low- and middle-income economies. Because of the significant risk associated with low- and middle-income countries, the percentage of co-financing in low- and middle-income economies was lower than in high-income economies. As a result, in order to attract private investors, low- and middle-income nations require innovative instruments to de-risk climate financing.

Overall, the goal of all funds is to reduce the risk of investing in climate change initiatives by using blended finance tools to crowd in private capital. Grants, concessional loans from MDBs, and other funding are being used to entice private investors by enhancing project profitability. However, present fund capital resources are insufficient to meet current climate financing requirements in order to reach Paris Agreement commitments and achieve net zero emissions. Many EMDCs are unable to deploy public finances to climate action programs due to development demands and a difficult macroeconomic position. Climate change programs funded by the governments will result in a high debt-to-GDP ratio, thereby affecting macroeconomic stability. An increase in interest rates to an adverse country risk profile will push out private investment, causing economic growth to suffer. Because many climate action initiatives are capital-intensive and require low-cost finance to boost project viability, the capital resources of MDBs and other funds must be significantly increased.

4.2. Financing BES projects

One of the ways the cost of financing BES projects can be reduced is to facilitate access to low-cost international financing through MDBs and public funds from OECD countries. The strategy to attract low-cost financing is to understand the risks associated with BES projects in EMDCs and allocate each risk to market participants who are best suited to manage it through

[3]Asian Development Bank (ADB), African Development Bank (AfDB), Asian Infrastructure Investment Bank (AIIB), European Bank for Reconstruction and Development (EBRD), European Investment Bank (EIB), Inter-American Development Bank Group (IDBG), Islamic Development Bank (IsDB), World Bank Group (WBG)

an appropriate instrument. For example, if technological and political risks are in the case of BES projects, guarantees from MDBs to cover technology risks can be a mechanism to de-risk the investment.

The short-term landscape of BES technologies indicates that the cost of batteries, a significant component of capital costs, is still very high and that BES projects are fraught with technological risk as many novel technologies are still in the demonstration stage. The availability of raw materials, such as critical minerals, poses a threat to the supply and replacement of batteries. The business model to generate revenues to improve the viability of BES projects is also uncertain. Therefore, following international financing mechanisms are suggested to scale up BES projects in the short term.

1. MDBs and other funds should integrate the financing of BES projects which should be combined with the financing of renewable energy projects such as solar and wind energy. Integrating BES projects with renewable energy projects will allow project developers to subsume the LCOS within the levelized cost of electricity.
2. In the short to medium term, grants should be a significant component of financing by MDBs and other funds to assess the commercial viability of various BES technologies and achieve economies of scale. Grant-based financing is critical to facilitate technology transfer in EMDCs for the demonstration and capacity assessment of BES technologies. GEF and GCF can provide grants to BES projects.

   Political risk and technological guarantees by MDBs and OECD countries are necessary to crowd in private investment in BES projects to test various revenue generation models and stabilize BES businesses for further long-term investment in BES to achieve commercial scale. Globally, pilots to support BES projects can be set up through Public Private Partnerships (PPP) mode.

4.3 Policies interventions for enabling BES

The policy interventions for enabling BES can be broadly categorized into regulatory, economic, and other instruments. The economic instruments include price instruments like carbon taxes and subsidies and quantity instruments like emissions trading schemes. The regulatory instruments include emission, technology, and product-based standards. In addition, there are other policies and institutional mechanisms like information policies, government interventions to provide public goods and services and voluntary actions by citizens, businesses and other non-government actors (Dubash et. al., 2022; Somanathan et al., 2014).

According to the Climate Policy Database[4], there are over 4000 climate related policies in force across G20 countries as of 2022 in sectors like electricity and heat, buildings, transport, and land use. A majority of these policies are in the electricity and heat sector which could be attributed to policy instruments like feed-in-tariffs (FITs) and renewable portfolio standards that were implemented since early 2000s (Nascimento et al., 2022). Owing to these policy instruments,

[4] https://www.climatepolicydatabase.org/G20-coverage

the cost of renewables has gone down considerably in past decade or so. However, more policy push is required to integrate renewables in the electricity grids. One of the major steps in this direction could be the policy instruments to promote grid-scale electricity storage technologies.

4.3.1 Regulatory or non-monetary instrument

Regulatory or non-monetary instruments like subsidies on clean energy technologies and public programs to promote energy storage infrastructure could be deployed to promote BES technologies. Governments could consider grid-scale battery storage as part of their long-term energy transitions to promote flexibility in power planning and renewable energy integration. In this direction, project tenders from the government agencies that promote the co-location of BES with solar and wind energy projects could be explored. Co-location of BES systems with VRE sources like solar and wind could also help in managing peak demand to improve system flexibility. BES could therefore reduce the dependence on peak generators with suitable policy interventions in power systems. As the electricity demand grows in the future, additional investments would be required in upgrading the grid infrastructure. These additional investments could be deferred by strategically deploying BES withing the transmission and distribution networks. Electricity could be stored in the BES at the distribution end when surplus generation is available from VRE sources which could then be used to meet the electricity demand during peak hours. As a result, investments in upgrading the transmission systems to meet the rising peak demand could be deferred. To this end, regulatory support to help transmission and distribution companies to use energy storage as an alternative to additional investments in grid infrastructure could be explored.

One of the advantages of regulatory instruments is that the costs of these instruments are not generalized and the redistributive effects are less regressive, compared to economic instruments like carbon tax (Finon, 2019). In fact, governments have chosen a mix of policies that consist of non-market-based instruments (for example, command and control regulation, information and voluntary approaches, active technology support) and economic instruments (e.g. taxes, emissions trading) in promoting renewables and other clean energy technologies. The choice of policies has depended on institutional capacities, technological maturity, and other developmental priorities of the government. It is also found that governments favour regulatory instruments over fiscal policies like taxes, subsidies and FITs when it has sufficient institutional capacity to implement and monitor the regulations and standards (Hughes & Urpelainen, 2015). However, as the technologies mature, market instruments coupled with a regulatory framework could be a favourable strategy (Kitzing et al., 2018; Polzin et al., 2015). For example, an analysis of 137 countries found that policy instruments like FITs followed by fiscal measures like tax incentives and renewable portfolio standards (RPS), have played significant role in attracting foreign direct investments in renewable energy sector, globally (Wall et al., 2019) contributing to the diffusion of RE globally. In the field of climate policy, there are multiple policy instruments aimed at attracting investments in renewable energy. This article aims to map the FDI flows globally including source and destination countries. Furthermore, the article investigates which policy instruments attract more FDI in RE sectors such as solar, wind and biomass, based on an econometric analysis of 137 Organisation for Economic Co-operation and Development (OECD). Policy support for FITs with the option of net metering could also help in promoting decentralized roof-top solar installations along with BES in the future. The policy lessons from promotion of renewables like solar and wind could very well be extended to promote BES technologies in coming years.

4.3.2 Economic and other instruments

In the earlier section (4.1 and 4.2), we have discussed the financing mechanisms and business models to facilitate the deployment of BES technologies. In this section, we discuss how economic and other instruments could be used to scale-up investments in energy storage.

MDBs and funds such as Clean Technology Fund are already financing renewable energy projects globally. A dedicated fund supported by MDBs could be created to finance BES projects globally, especially EMDCs. A dedicated fund would provide a single window for project application and appraisal, reducing the time and effort required for project documentation. Experience and expertise of MDBs in project appraisal and monitoring can be leveraged to address adverse risk perceptions about EMDC by bridging information asymmetry. Various international financial instruments to provide low-cost and long-term financing to BES projects are discussed below. The case examples referred for these instruments are not necessarily of BES projects. However, they are supporting green transition and could be deployed for low-cost financing of BES projects.

1. **Green Bonds –** Green bonds are typically issued to fund a specific green project that contributes to climate action. Many institutions, primarily the European Union (EU) and the Climate Bond Initiative (CBI), have established a taxonomy of green activities in order to facilitate and encourage climate finance through green bonds. BES has been incorporated in the EU and CBI taxonomies, subject to strict screening criteria. Given the massive expenditure necessary to fund BES projects, green bonds can be useful in gaining access to substantial sums of money. Green Bonds may have lower yields than comparable regular bonds because these bonds also attract altruistic investors prepared to forego some returns for the greater good of society. In terms of BES, Green Bonds can be used in two ways. First, the BES project developer issues green bonds in the market directly. Second, by using their highest credit rating, MDBs can establish a specialized facility and issue Green Bonds to raise a relatively big sum to assist BES project developers in recipient countries through concessional loans. The objective here is to use MDBs' balance sheets (particularly callable capital) to crowd in private investment globally.

   World Bank group has been raising funds through green bonds since 2008. Till now, the world bank has issued 200 green bonds worth US$ 18 billion in 25 currencies[5]. Many renewable energy developers have also been raising funds through green bond issuances.

[5] See https://treasury.worldbank.org/en/about/unit/treasury/ibrd/ibrd-green-bonds

Case example - Nacional Financiera S.N.C. of Mexico issued green bonds worth US$ 500 million in 2015 with a maturity of 5 years to fund wind energy generation projects in Mexico. The coupon rate of the bond was 3.375% per annum. International financial institutions, insurers, pension funds, and banks purchased these bonds at the time of issuance[6].

2. **Outcome-based sustainability debt (Bonds/Loans) –** Outcome-based sustainability debts are primarily deployed to fund green transition and are not tied to a particular green project. Reduction in interest rates is generally linked with the achievement of certain goals of climate action.. In the case of BES projects, this instrument can be issued by linking the share of power supply during night time/peak hours with the rebate in interest rates. As the goals are achieved, funding cost is reduced for project developers. This instrument helps in managing technology and greenwashing risk for investors.

   Case example – In September, ENEL issued Outcome-based sustainability debt worth US$ 1.5 billion in the USA. The coupon rate was linked to achieving 55 percent of the renewable energy capacity of its total installed capacity by December 2021. As per the bond covenant, the coupon rate would be increased by 25 bps if ENEL fails to meet the laid-down target[7].

3. **Collective investment vehicle (Structured Equity Funds) –** To de-risk investment in BES projects, blended finance instruments can be used to create a waterfall structure and assign risk to various categories of funding institutions. Tier 1 is supported by subsidies from OECD member countries and donor funds. Tier 2 is funded by MDBs and other Development Financial Institutions (Mezzanine capital). Tier 3 funding is provided by institutional investors (private equity, hedge funds, etc.). Tier 1 de-risks Tier 3 and Tier 2 investments, whereas Tier 2 de-risks Tier 3 investments. De-risking via the waterfall structure allows Tier 3 investors to provide cash with the assumption of reduced future returns due to lower risks. The project Finance method of project execution enables the project's primary sponsor to enlist Structured Equity Funds as equity partners to de-risk the project and generate more loan capital by leveraging the overall equity contribution in the project. Many Venture Capital and Private Equity funds have funded independent BES initiatives in the United States. Structured Equity Funds, as a result, enable project developers to crowd-in private investment from a variety of equity investors, including venture capital, private equity, and institutional investors.

   Case example – Climate Investor One (CI1) facility has been created to fund renewable energy projects such as wind, solar, and run-of-the-river hydro. CI1 facility has instituted a Construction equity fund, which is a 3- tier collective investment vehicle. Tier 1 equity capital (junior tranche) amounting to US$ 160 million has been provided by donors such as the Green Climate Fund (GCF), the European Union (EU), the Nordic Development Fund (NDF), the Directorate General for International Cooperation (DGIS) within the Ministry of Foreign Affairs of the Netherlands and USAID via PowerAfrica. Tier 2 equity capital (mezzanine tranche) amounting to US$ 320 million has been provided by Commercial

[6] See https://emsdialogues.org/wp-content/uploads/2020/04/STA_GB_InternationalEdition_20180522_WEB-1.pdf
[7]See https://www.nortonrosefulbright.com/en-in/knowledge/publications/8a104da8/sustainability-linked-bonds#:~:text=Whilst%2C%20sustainability%2Dlinked%20financing%20has,explicitly%20linked%20to%20a%20 sustainability

investors and development finance institutions. The institutional investors have provided tier 3 equity capital (senior tranche) amounting to US$ 320 million. The Climate Investor One (CI1) facility aims to provide funds for the project's whole life cycle. Funds in the form of development loans and technical assistance will support the development phase. Construction equity funds support the construction phase and refinancing. Fund in the form of senior debt funds operation phase (*Funds – Climate Fund Managers*, n.d.). CI1 has funded Ampyr I Balenahalli wind power project of Ampyr Energy Pvt. Ltd. In India. CI1 provided US$ 3.14 million of development funding and US$ 37.90 million of construction equity (*Ampyr I Balenahalli – India | Wind – Climate Fund Managers*, n.d.).

4. **Syndicated Loans (Co-financing)** – A syndicated loan (co-financing) is a type of financing that allows numerous lenders to join forces to invest in a climate action initiative. The risks connected with the projects might be spread across multiple lenders through co-financing. Co-financing helps project developers to acquire more considerable capital at a lower cost for a substantially longer term due to risk diversification and the participation of numerous lenders. In the case of co-financing, the aim is to harness the financial resources and expertise of MDBs (and other similar financial institutions) in project financing and project monitoring to offset the negative risk perception associated with EMDCs. A syndicate might be made up of a single MDB or multiple MDBs, as well as a single or multiple private investors (domestic or foreign). Donor grants can also be combined to reduce the risk of the investment and increase the size of the investment. Private investors can benefit from preferred creditor status and immunities typically granted to MDBs by creating a syndicate, reducing the default risk for private investors.

   Case example – GreenYellow Solar 1 (Thailand) Co., Ltd., raised US$ 33.9 million through A/B and Parallel loan structure to fund 92 rooftop solar PV systems (total installed capacity 60.2 MW) on the premises of large consumers. The contribution of A loan, B loan, and parallel loan was US$ 11.3 million each, and the tenor of the loan was 13 years. ADB structured the loan in multiple currencies (local and USD) through a local currency parallel loan[8].

5. **Guarantees –** To reduce the cost of finance, MDBs and OECD countries can also guarantee investment in BES projects. In the event of certain occurrences, such as default, technology failure, or political instability, the private investor will receive their investment back, partially or fully. Guarantees can be constructed in multiple ways to reduce the cost of funding for BES projects, depending on the project characteristics and risk profile of a country. A partial Credit Guarantee can be used to coverall risks associated with climate action projects, but the investment may be protected partially. While Partial risk guarantees cover some of the risks covered, the investment may be covered fully or partially. There can also be risk-specific guarantees such as technology risks, political risks, and default risks.

   Case example – For constructing a 20 MW solar PV plant in Malawi, the Multilateral Investment Guarantee Agency (MIGA) provided a guarantee amounting to US$ 24 million to JCM Golomoti UK Limited to protect equity and debt investment in the project. This guarantee will protect against the risks of breach of contract and transfer restriction. The

[8] See https://www.adb.org/projects/documents/tha-53283-001-rrp

proposed plant also includes constructing and developing a battery energy storage system. This guarantee will be in force for twenty years (*MIGA Supports Construction of Solar Photovoltaic Plant in Malawi*, 2022).

6. **BES Investment Trusts –** BES projects can be sold to a Special Purpose Vehicle called the Investment Trust for operation and management after the commissioning. Investment trusts raise capital from the market in the form of debt and equity to purchase the asset. Equity holders are issued units against their capital, and these units are traded on stock exchanges. As per statutory requirements in respective countries, a fixed percentage of profit from the project's operation is distributed to equity unit holders as a dividend, thereby making an equity investment in investment trusts a fixed-income investment. A sponsor of investment trusts can purchase multiple BES projects from different projects developer. Since the risk is more during the construction phase than the operation phase, investors usually provide capital at a higher cost during the construction phase. And the higher the time horizon, the higher the cost of capital. Therefore, investment trusts, by taking over commissioned projects, provide an exit avenue to existing investors, thereby reducing the overall cost of the capital.

7. **Leasing batteries for BES projects –** Since the cost of the batteries is a significant component of BES projects. Instead of procuring batteries, BES can build the rest of the infrastructure as required and take batteries lease from the battery manufacturers/owners at a consideration or rentals for a specified duration. Leasing batteries will significantly reduce the initial capital needed to commission BES projects. BES project developers will not have to worry about technological obsolescence and the cost of disposal of batteries at the end of useful life, thereby reducing overall cost and risk. The lessor (the battery owners) will be responsible for ensuring that the batteries are in good condition during the contract period. Leasing allows the project developer to keep pace with upcoming technologies of batteries and improve the efficiency of the project over a period of time.

8. **Credit Default Swaps (CDS) –** CDS is a financial product that reduces the risk of debt instrument default (bonds/loans). Many worldwide private investors are hesitant to participate in EMDCs due to information asymmetry and perceived risk. Private investors (debt providers) can protect themselves against default risk on their investment (debt provided) by paying a periodic premium to CDS sellers. CDS sellers pay the default sum to private investors in the case of default. MDBs or any other funding agency might establish a dedicated mechanism for BES projects by pooling grants and contributions from donors to purchase CDS on behalf of private investors (debt suppliers) and support BES initiatives worldwide. The strategy is to crowd in private investment in urgent and crucial climate change projects like BES by leveraging grants and donations. Because projects will be located worldwide, CDS sellers will diversify various risks such as country risk, project risk, and technology risk, allowing them to offer lower premiums to MDBs.

Chapter 5

Recommendations

- Invest in research and development, LIBs are currently the best choice for grid storage and RE integration. However, LIBs also face risks arising from the availability of critical minerals and thermal runaways. As the demand for BES increases in the future, G20 countries could build an international consortium to research, develop and finance alternatives technologies like flow batteries and NaS battery technologies
- As the technology landscape is changing rapidly, efforts to update the future BES projections under different scenarios and the underlying demand for critical minerals could be supported through collaborations like the NGFS
- Critical minerals are important to fulfil the future demand for BES. Given their limited availability and concentration in few geographic locations, international co-operation to share these resources is recommended. Further, refurbishing, recycling, and mineral recovery would play a vital role in sustainable use of mineral resources. G20 countries could invest in technology development and build international cooperation in these areas
- Since there are multiple technologies at the development stage, the scalability of BES technologies at a commercial scale in various countries poses a significant risk to the project developers. This could also pose uncertainties in terms of cost of storage and, in turn, the cost of electricity. Financing mechanisms and regulatory support to address such concerns by project developers would help in future development of these technologies
- Non-monetary or regulatory instruments like subsidies on clean energy technologies and public programs to promote energy storage infrastructure could also be deployed to promote BES technologies. Banks could be mandated to allocate a fixed percentage of their lending capacity to finance climate action projects such as battery energy storage.
- Public funding of research on energy storage technologies should be promoted. OECD countries and MDBs, through grants, can help in developing research capabilities globally.
- Governments could consider grid-scale battery storage as part of their long-term energy transitions to promote flexibility in power planning and renewable energy integration. In this direction, project tenders from government agencies that promote the co-location of BES with solar and wind energy projects could be explored.
- With regard to low-cost financing to BES, it is recommended that
    - A dedicated fund supported by MDBs could be created to finance BES projects globally, especially in the EMDCs.
    - Capital resources of MDBs and other funds should be increased substantially to scale up funding for BES projects globally. Paid-in capital and callable capital of MDBs should be increased periodically to enhance financing capabilities of MDBs for fund BES projects in EMDCs.

- International financing instruments such as green bonds (also loans), outcome-based sustainability debts, Structured equity funds, Co-financing, Guarantees, BES Investment Trusts, Leasing of Batteries and CDS may be adopted to de-risk investment in BES projects and crowd-in private investments.

In terms of international co-operation, the G20 could develop an ecosystem to support clean energy transitions. This would involve BES demand estimation for net-zero scenarios for the world, fair share deploying just energy transitions, promoting start-ups, low-cost financing, critical minerals sharing, and national grid stability

Annexures

Annexure 1. Other energy storage technologies with their suitability for grid services

Technology suitability	CAES	LAES	TES	FES	Scap	RHFC	PtX
Upgrade deferral	√	√	√	√	√	√	√
Energy Arbitrage	√	√	√	√		√	√
Capacity firming	√	√	√	√		√	√
Seasonal storage			√			√	√
Stability				√	√	√	√
Frequency regulation	√	√		√	√	√	√
Voltage support	√	√		√	√	√	√
Black start	√	√				√	√
Short term reserve	√	√				√	√
Fast reserve	√	√		√		√	√
Islanding	√	√	√			√	√
Uninterruptible power supply				√	√	√	
Opportunity to reduce costs over next decade	Low	Low	Medium	Medium	High	High	Medium

Sources: *(IPCC, 2022)*

Notes: *CAES - Compressed Air Energy Storage, LAES - Liquid Air Energy Storage, TES - Thermal Energy Storage, FES - Flywheel Energy Storage, Scap – Supercapacitors, RHFC - Reversible Hydrogen Fuel Cells*

Annexure 2. Description of BESS cost components referred in chapter-2

Source: (Mongird et al., 2020a)

I. **Battery Energy Storage System (ESS) Installed capital Cost Components**

i) Storage Block (SB) ($/kilowatt-hour [kWh]) – this component includes the price for the most basic direct current (DC) storage element in an ESS (e.g., for lithium-ion, this price includes the battery module, rack, and battery management system, and is comparable to an electric vehicle (EV) pack price).

ii) Storage - Balance of System (SBOS) ($/kWh) – includes supporting cost components for the SB with container, cabling, switchgear, flow battery pumps, and heating, ventilation, and air conditioning (HVAC).

iii) Storage System ($/kWh) – this cost is the sum of the SB and SBOS costs and is an appropriate level of granularity for some studies.

iv) Power Equipment ($/kilowatt [kW]) – this component includes bidirectional invertor, DC-DC converter, isolation protection, alternating current (AC) breakers, relays, communication interface, and software. This is the power conversion system for batteries, the powerhouse for PSH, and the power island/powertrain for CAES.

v) Controls & Communication (C&C) ($/kW) – this includes the energy management system for the entire ESS and is responsible for ESS operation. This may also include annual licensing costs for software. The cost is typically represented as a fixed cost scalable with respect to power and independent of duration.

vi) System Integration ($/kWh) - price charged by the system integrator to integrate sub-components of a BESS into a single functional system. Tasks include procurement and shipment to the site of battery modules, racks with cables in place, containers, and power equipment. At the site, the modules and racks are containerized with HVAC and fire suppression installed and integrated with the power equipment to provide a turnkey system.

vii) Engineering, Procurement, and Construction (EPC) ($/kWh) – includes non-recurring engineering costs and construction equipment as well as shipping, siting and installation, and commissioning of the ESS. This cost is weighted based on E/P ratio.

viii) Project Development ($/kW) – costs are associated with permitting, power purchase agreements, interconnection agreements, site control, and financing.

ix) Grid Integration ($/kW) – direct cost associated with connecting the ESS to the grid, including transformer cost, metering, and isolation breakers. For the last component, it could be a single disconnect breaker or a breaker bay for larger systems.

II. **Operating Costs**

i) Fixed Operations & Maintenance (O&M) ($/kW-year) – includes all costs necessary to keep the storage system operational throughout the duration of its economic life that do not fluctuate based on energy throughput, such as planned maintenance, parts, and labor and benefits for staff. This also includes major overhaul-related maintenance which depends on throughput.

ii) Basic Variable O&M ($/megawatt-hour [MWh]) – includes usage impacted costs associated with non-fuel consumables necessary to operate the storage system throughout its economic life.

iii) Round Trip Efficiency (RTE) Losses ($/kWh) – Round trip efficiency is simply the ratio of energy discharged to the grid to the energy received from the grid to bring the ESS to the same state of charge. RTE for is < 1 due to losses related to thermal management, electrochemical losses, power conversion losses, powertrain-related losses, energy conversion losses, evaporation, or gas/air leakage losses. This value for RTE losses is estimated through the cost of the additional electricity purchased or fuel required per unit kWh of energy discharged due to the losses described.

iv) Warranty ($/kWh) – fees to the equipment provider for manufacturability and performance assurance of designated lifespan.

v) Insurance ($/kWh) – insurance fees to hold a policy to cover unknown and/or unexpected risks. The terms of this cost may depend on vendor reputation and financial strength.

III. **Decommissioning Costs**

i) Disconnection ($/kW) – costs associated with the removal of ESS interconnection from grid.

ii) Disassembly/removal ($/kW) – includes deconstruction of ESS and components for disposal or recycle.

iii) Site Remediation ($/kW) – costs required to return the ESS site to either a brownfield or greenfield state.

iv) Recycle/Disposal ($/kW) – costs associated with separating out recyclable components, shipping to a recycling plant, and recycling the material in the plant.

Annexure 3A. Component-wise installed capital cost and operating cost for various BES technologies for 1MW (4 hours) capacity

Parameters	Units	LFP batteries	Li- NMC batteries	LAB	VRFB
Storage Systems (2020)					
Storage Block	$/kWh	164 - 200	175 - 213	169 - 190	260 - 317
		182	194	180	289
Storage Balance of System	$/kWh	38 - 47	30 - 45	46 - 52	52 - 63
		42	37	49	58
Energy storage systems (ESS) (2020)					
Power Equipment	$/kW	76 - 93	76 - 93	146 - 164	139 - 170
		85	85	155	155
Controls & Communication	$/kW	36 - 44	36 - 44	38 - 42	36 - 44
		40	40	40	40
System Integration	$/kWh	37 - 56	38 - 58	45 - 50	50 - 61
		50	51	47	55
ESS installed cost (2020)					
Engineering, Procurement, and Construction	$/kWh	48 - 74	49 - 77	49 - 55	57 - 69
		61	63	52	63
Project Development	$/kWh	57 - 90	58 - 94	63 - 71	72 - 88
		73	75	67	80
Grid Integration	$/kW	28 - 34	28 - 34	29 - 33	28 - 34
		31	31	31	31
Total ESS Installed Cost* (2020)	$/kW	1517 - 2040	1537 - 2122	1658 - 1956	2163 - 2644
		1793	1838	1808	2404
	$/kWh	379 - 510	384 - 531	414 - 489	541 - 661
		448	459	452	601
Total ESS Installed Cost (2030)	$/kW	1105 - 1460	923 - 1239	1405 - 1673	1614 - 2163
		1266	1089	1538	1922
	$/kWh	276 - 365	231 - 310	351 - 418	403 - 541
		317	272	385	480
Operating Cost (2020)					
Fixed O&M	$/kW-yr	3.96 - 4.84	4.06 - 4.96	5.59 - 6.3	6.11 - 7.47
		4.4	4.51	5.94	6.79
Variable O&M	$/MWh	0.5125	0.5125	0.5125	0.5125
System RTE Losses	$/kWh	0.005	0.005	0.008	0.014

*Notes: *indicates that it does not include warranty, insurance, or decommissioning costs*

Source: (Mongird et al., 2020a)

Annexure 3B. Component-wise installed capital cost and operating cost for various BES technologies of 100 MW (4 hours)

Parameters	Units	LFP batteries	Li-NMC batteries	LAB	VRFB
Storage Systems (2020)					
Storage Block	$/kWh	149 - 182	158 - 194	153 - 172	235 - 287
		165	176	162	261
Storage Balance of System	$/kWh	35 - 42	27 - 41	42 - 47	47 - 57
		38	34	45	52
Energy storage systems (ESS) (2020)					
Power Equipment	$/kW	57 - 69	57 - 69	108 - 122	103 - 126
		63	63	115	115
Controls & Communication	$/kW	[1 - 2]	[1 - 2]	[1 - 2]	[1 - 1]
		2	2	2	2
System Integration	$/kWh	33 - 49	34 - 51	39 - 44	43 - 53
		44	45	41	48
ESS installed cost (2020)					
Engineering, Procurement, and Construction	$/kWh	42 - 64	42 - 67	43 - 49	49 - 60
		53	54	46	54
Project Development	$/kWh	49 - 78	50 - 81	54 - 61	61 - 75
		63	65	58	68
Grid Integration	$/kW	18 - 22	18 - 22	19 - 21	18 - 22
		20	20	20	20
Total ESS Installed Cost* (2020)	$/kW	1302 - 1752	1320 - 1827	1419 - 1672	1863 - 2277
		1541	1581	1544	2070
	$/kWh	326 - 438	330 - 457	355 - 418	466 - 569
		385	395	386	517
Total ESS Installed Cost (2030)	$/kW	944 - 1249	965 - 1279	1211 - 1436	1388 - 1864
		1081	1128	1322	1656
	$/kWh	236 - 312	241 - 320	303 - 359	347 - 466
		270	282	330	414
Operating Cost (2020)					
Fixed O&M	$/kW-yr	3.41 - 4.16	3.5 - 4.27	4.8 - 5.42	5.3 - 6.48
		3.79	3.89	5.11	5.89
Variable O&M	$/MWh	0.5125	0.5125	0.5125	0.5125
System RTE Losses	$/kWh	0.005	0.005	0.008	0.014

*Notes: *indicates that it does not include warranty, insurance, or decommissioning costs*

Source: (Mongird et al., 2020b)

Annexure 4. Country-wise total companies operating in the BES space, their market capitalizations and their equity

Country	Number of Companies	Total Market Capitalization (USD Million)	Total Equity (USD Million)
China	50	263443.34	42481.35
United States	23	14802.74	4419.40
Taiwan	20	10150.76	3348.29
India	12	2186.63	917.63
South Korea	12	98653.37	11381.09
EU	10	3032.85	1569.63
Canada	6	363.43	94.53
Australia	4	141.46	73.18
Hong Kong	4	499.95	848.33
Japan	4	590.77	603.43
Vietnam	3	78.71	45.82
United Kingdom	2	36.83	15.65
Jersey	1	57.81	69.32
Norway	1	16.62	15.78
Peru	1	3.26	29.86
Singapore	1	247.88	345.11
Sri Lanka	1	2.54	2.19
Switzerland	1	238.25	-28.47
Thailand	1	141.81	67.66
Tunisia	1	8.41	11.79
Russia	1		49.00
Bosnia and Herzegovina	1	0.72	
Jamaica	1	20.51	
Bangladesh	1	40.18	

Source: (Refinitive, 2022)

Annexure 5. Case examples of BES projects around the world

Sr. No.	Project name	Project type	Country	Entities involved	Project Capacity	Total Investment & Financing Mechanism	Month & Year of Investment	Reference
1	Elandskop BESS project		South Africa	Eskom	343MW/ 1440MWh	630 Million USD	December, 2022	https://www.energy-storage.news/south-africas-eskom-starts-building-first-battery-storage-system/
2	Vanadium redox flow battery (VRFB) project		Dalian, China	VRFB developer and manufacturer Rongke Power supplied the battery technology, Energy storage system is connected to Dalian grid	100 MW/ 400MWh		July, 2022	https://ieefa.org/articles/china-commissions-100-megawatt-flow-battery-worlds-largest
3	Energy Superhub Oxford	Lithium-vanadium hybrid BESS	Oxford, UK	Lithium-ion system, supplied by Wärtsilä, Vanadium flow battery from Invinity Energy Systems and Optimiser Habitat Energy taking the assets into market with its AI-enabled trading platform	BESS made up of a 50 MW/50MWh Lithium-ion system, and a 2MW/5MWh vanadium flow battery	55.8 Million USD	July, 2022	https://www.energy-storage.news/project-with-worlds-largest-lithium-vanadium-hybrid-bess-officially-launched-in-oxford-uk/
4	Hale Kuawehi Solar	Transmission interconnected (Front-of-the-meter) solar and storage asset contracted to the local utility	Hawaii, United states	Innergex is an IPP (private entity); Hawai'i Electric Company is an investor-owned utility that has contracted the asset	30 MW with 4-hour duration	149 Million USD		Role of policy in the development of business models for battery storage deployment: Hawaii case study - ScienceDirect

Sr. No.	Project name	Project type	Country	Entities involved	Project Capacity	Total Investment & Financing Mechanism	Month & Year of Investment	Reference
5	Sunrun – OATI – HECO Project	Multiple BTM residential aggregated capacity contracted to the local utility.	Australia	OATI is a private entity that aggregates various resource types and provides grid services; Sunrun is a solar & battery storage solutions provider and aggregator sub contracted by OATI for aggregating residential solar and storage systems; HECO is the parent company of IOUs in Hawaii that has contracted capacity from OATI	Total contract capacity between HECO and OATI varies by the island and delivery year; OATI-Sunrun subcontract is for a total of 4.3 MW in the island of O'ahu; Individual Brightbox system is a 5 kW system with 1.25-hour storage time			Role of policy in the development of business models for battery storage deployment: Hawaii case study - ScienceDirect
6	Vistra Moss Landing Battery Energy Storage	Transmission interconnected (Front-of-the-meter) asset contracted to the local utility	United States	Vistra Energy is a project developer and owner (private entity); Pacific Gas & Electric/PG&E is an investor-owned utility that has contracted the asset	300 MW with 4-h duration	Self-financed Returns		Role-of-policy-in-development-of-business-models-for-battery-storage-deployment.pdf (reglobal.co)
7	Downey Unified School District – ENGIE Storage		United States	ENGIE Storage is a private energy solutions provider; Downey Unified School District is a public-school system and the end customer	3.5 MW with 2 h duration (Distributed over 7 Sites with 9 Systems)			Role-of-policy-in-development-of-business-models-for-battery-storage-deployment.pdf (reglobal.co)

Sr. No.	Project name	Project type	Country	Entities involved	Project Capacity	Total Investment & Financing Mechanism	Month & Year of Investment	Reference
8	AMS Irvine & AMS West LA Basin	Multiple Behind the meter, C&I aggregated capacity contracted to the local utility	California, USA	AMS is a private entity that provides battery storage service and grid services as an aggregator; Southern California Edison is an investor-owned utility that has contracted capacityfrom the aggregator; C&I customers are private entities that have contracted service from battery storage service provider	Total contract capacity is 50 MW @ 4 h but following are some of the fleets installed by AMS to meet contract requirement: 27 MW @ ~5 h (aggregated fleet); 10 MW @ ~6 h (21 sites aggregate)	Infrastructure investment firm Macquarie Capital (secured financing with CIT bank) - $200 million – 30 % debt & rest equity		Role-of-policy-in-development-of-business-models-for-battery-storage-deployment.pdf (reglobal.co)
9	Our Next Energy (ONE)	EV Battery cell manufacturing	Michigan, United States		Annual capacity of 20 GWh	1600		Energy Storage Firm ONE to Invest $1.6 Billion for a EV Battery Gigafactory in Michigan - Mercom India
10	RE Developer	Long Duration Energy Storage (LDES)	Australia		Potential LDES system: 150 MW/1200 MWh (8 hours); systems of longer durations would be required in locations with lower annual RE yield	Total value: 300-360 Million USD; Capital Invested: 250 Million USD; Fixed O&M:50 Million USD		Net-zero-power-Long-duration-energy-storage-for-a-renewable-grid (mckinsey.com)
11	Integrated utility		United States		Potential LDES system: 1.3 GW/104 GWh (80 hours)	Total value: 6700-1000 Million USD; Capital Invested: 5400 Million USD; Fixed O&M: 700 Million USD		Net-zero-power-Long-duration-energy-storage-for-a-renewable-grid (mckinsey.com)

Sr. No.	Project name	Project type	Country	Entities involved	Project Capacity	Total Investment & Financing Mechanism	Month & Year of Investment	Reference
12	Xtreme Power's battery system	Advanced lead-acid battery solution for off-grid frequecy response	Alaska, United States	Xtreme Power, acquired by Younicos, delivered advanced lead-acid solution to the utility KEA	3 MW/750 kWh	$1 million / MW $ 4 million / MWh	2012	Case studies: battery storage (irena.org)
13	Wind Power Plus Energy Storage System Project		Korea		2 MWh	Installation price: 1100 per MWh; Total Investment: 3.7 Million USD		Handbook on Battery Energy Storage System (adb.org)
14	Enel Green Power	wind turbines and a 34MW battery energy storage system (BESS)	Chile		22 wind turbines of 4.8MW each, totalling 105.6MW of power, and a 34.3MW lithium-ion BESS	190 Million USD	October, 2022	https://www.energy-storage.news/enel-green-power-building-wind-plus-storage-project-in-chile/
15	Meridian Energy	two-hour duration (200MWh) resource	New Zealand		100 MW	118.2 Million USD of capital investment	December, 2022	https://www.energy-storage.news/new-zealand-energy-generator-retailer-meridian-proceeds-with-100mw-200mwh-bess-project/
16	Eskom Holdings SOC Limited	Eskom Investment Support Project (EISP) and Eskom Renewable Support Project (ERSP)	South Africa		First phase of BESS procurements by Eskom totalling around 800MWh of energy storage plus 2 MW PV	Phase one with total investment of 406 Million USD from Eskom	March, 2022	https://www.energy-storage.news/south-africas-eskom-issues-notice-for-36mw-146mwh-battery-storage-as-ceo-resigns/

Sr. No.	Project name	Project type	Country	Entities involved	Project Capacity	Total Investment & Financing Mechanism	Month & Year of Investment	Reference
17	Guyana Utility Scale Solar Photovoltaic Program (GUYSOL)	Battery energy storage project	Guyana	The country received US$83 million in financing from Inter-American Development Bank (IDB) and Norwegian Agency for Development Cooperation	The eight ground-mounted solar PV plants will total 33 MWp while BESS will amount to 34 MWh of capacity	83 Million USD	Start in March 2023	https://www.energy-storage.news/guyana-launches-34mwh-tender-for-battery-energy-storage-alongside-solar-pv/
18	Qcells	Energy storage projects	United States	Qcells secured funding from European banks BNP Paribas and Crédit Agricole CIB	Two-hour 190 MW/380MWh energy storage system	150 Million USD	2022	https://www.energy-storage.news/acciona-energia-buys-380mwh-ercot-battery-storage-project-from-qcells/
19	Battery storage system in North Rhine-Westphalia	Battery storage project	Germany	RWE	690 battery blocks installed across a total area of 21,000 square metres, giving a combined output of 220 MW.	149 Million USD	Start in 2023	https://www.rwe.com/en/research-and-development/battery-storage-system-projects/220-mw-battery-storage-system-in-germany
20	Cactos' smart energy storage system	Battery storage project from recycled Tesla batteries	Finland	Cactos	100 kWh battery storage facility from recycled Tesla batteries.	2.6 Million USD	Start in 2024	https://en.cactos.fi/news
21	Australian Renewable Energy Agency (ARENA)	Eught grid scale batter projects	Australia	ARENA	2 GW/ 4.2 GWh	1.8 Million USD	Operational by 2025	https://mercomindia.com/australia-provide-118-million-battery-projects-country/

Sr. No.	Project name	Project type	Country	Entities involved	Project Capacity	Total Investment & Financing Mechanism	Month & Year of Investment	Reference
22	JSW Renew Energy Five Limited	Battery energy storage project	India	JSW Energy with joint intiative of the Ministry of New and Renewable energy and Ministry of Power	500MW/1000 MWh	0.014 Million USD/MW per month	Aug-22	https://mercomindia.com/jsw-renew-energy-wins-seci-tender-1gwh-bess/
23	Greenko Energies	Battery energy storage project	India	Greenko	3000 MWh	0.034 Million USD/MWh per year	Jan-22	https://mercomindia.com/greenko-wins-ntpcs-3000-mwh-energy-storage/
24	Acciona Energia	Battery energy storage project	United States	Acciona Energia	190 MW/ 380MWh	Not disclosed	Start in first quarter 2023	https://mercomindia.com/acciona-buys-seven-battery-energy-storage-gw-pipeline-in-texas/
25		US Battery Utility-Scale Storage	United States	Project developers and project owners in Texas, California, Florida, etc.	20.8 GW capacity is expected to be added between 2022-2025 and to reach 30 GW by 2025	3160 Million USD funding announced by USDoE from President Biden's "Bipartisan Infrastructure Law"	2022-2025	https://mercomindia.com/us-battery-utility-scale-storage-capacity-to-gw-by-2025/
26	Battery energy storage system (BESS)	Five standalone BESS with build, own, operate and transfer mode	Uttar Pradesh, India	Uttar Pradesh Power Corporation (UPPCL)	10 MW/40MWh	Bidders net worth 0.14 million USD/MW	Bids to be submitted by Dec. 24, 2022 and will be opened on Dec. 27, 2022	https://mercomindia.com/tender-issued-for-five-bess-projects-in-uttar-pradesh/

Annexure 6. Levelized cost methodology

The methodology consists of projecting the annual costs and generation over the lifetime of the plant and using this data to calculate the steady annual generation cost after discounting them to their present value. The following equation represents the basic idea of the methodology in a simplified manner.

$$C_L = \frac{Present\ Value\ of\ Costs}{Electricity\ Discharged}$$

Further detailed methodology is provided in the annexure.

$$Costs = Investment + \sum_{n=1}^{N}\left(\frac{O\&M}{(1+r)^n} + \frac{Charging}{(1+r)^n}\right) + \frac{End\ of\ Life}{(1+r)^{N+1}} + \frac{Replacement}{(1+r)^{N+1}}$$

$$Discharge = \sum_{n=1}^{N} \frac{Electricity\ Discharged}{(1+r)^n}$$

A6.1 Investment Cost

Investment cost takes into account nominal power ($Cap_{nom,P}$) and specific power cost (C_P) and using the same for energy equivalents.

Investment Cost = $Cap_{nom,P}$ x C_P + $Cap_{nom,E}$ x C_E

A6.2 O&M Cost

O&M cost depends on power and energy specific operation and maintenance cost (C_{P-OM}, C_{E-OM}) relative to nominal power capacity and energy capacity, cycle degradation (Cyc_{Deg}), time degradation (T_{Deg}), depth-of-discharge (DoD) and annual cycles (Cyc_{pa}).

$$\sum_{n}^{N} \frac{O\&M\ cost}{(1+r)^n} =$$

$$\sum_{n=1}^{N} \frac{C_{P-OM} \cdot Cap_{nom,P} + C_{E-OM} \cdot \left(Cyc_{pa} \cdot DoD \cdot Cap_{nom,E}\right) \cdot \left(1 - Cyc_{Deg}\right)^{(n-1) \cdot Cyc_{pa}} \cdot \left(1 - T_{Deg}\right)^{(n-1)}}{(1+r)^{n+T_c}}.$$

A6.3 Charging Cost

Charging cost depends on the electricity price (P_{el}) and round-trip efficiency (η_{RT}).

$$\sum_{n=1}^{N} \frac{Charging\ Cost}{(1+r)^n} = \frac{P_{el}}{\eta_{RT}} \sum_{n=1}^{N} \frac{Electricity\ Discharged}{(1+r)^n}$$

A6.4 Replacement Cost

Replacement cost depends on cost of replacement of the battery per unit (C_r), and nominal capacity ($Cap_{nom,P}$) covering all replacement periods R.

$$Replacement\ Costs = \sum_{r=1}^{R} \frac{C_r\ x\ Cap_{nom,P}}{(1+r)^r}$$

A6.5 End of Life Cost

BES are usually disposed off at the end of life. End of life cost depends on salvage value of the battery per unit (C_{EL}), and nominal capacity ($Cap_{nom,P}$) covering all replacement periods R.

$$End\ of\ Life\ Costs = \sum_{r=1}^{R} \frac{C_{EL}\ x\ Cap_{nom,P}}{(1+r)^r}$$

A6.6 Electricity Discharged

Discharged electricity depends on annual cycles (Cyc_{pa}), nominal energy capacity ($Cap_{nom,E}$), depth-of-discharge (DoD), round-trip efficiency (η_{RT}), cycle degradation (Cyc_{Deg}), time degradation (T_{Deg}), self-discharge (η_{self}), and construction time of the technology (T_C).

$$\sum_{n}^{N} \frac{Elec_{Discharged}}{(1+r)^n} = Cyc_{pa} \cdot DoD \cdot Cap_{nom,E} \cdot \eta_{RT} \cdot (1-\eta_{self}) \cdot \sum_{n=1}^{N} \frac{(1-Cyc_{Deg})^{(n-1)*Cyc_{pa}} \cdot (1-T_{Deg})^{(n-1)}}{(1+r)^{n+T_c}}.$$

Annexure 7. Current global policies for energy storage technologies since 2007

Sr. No.	Policy for Energy Storage Technologies	Country	Year	Jurisdiction
1	Inflation Reduction Act 2022: Sec. 13501 Extension of the Advanced Energy Project Credit	US	2022	National
2	National EV Infrastructure Formula Program	US	2022	National
3	Antonis Tritsis Programme	Greece	2021	National
4	Australian CEFC investment in 300MW big battery in Victoria	Australia	2021	National
5	Australian government support for solar hydro power plant in Mildura	Australia	2021	National
6	Budget 2021 - tax reduction on green technology installation	Sweden	2021	National
7	Climate Innovation Research Opportunity investment program	US	2021	National
8	Cross-border energy infrastructure, new rules for TEN-E	EU	2021	International
9	DOE fund to Small Businesses for Clean Energy R&D Projects	US	2021	National
10	Domestic Battery Production Subsidies	Japan	2021	National
11	Domestic fund for the environment	Austria	2021	National
12	Economic Recovery and Resilience "New Generation Lithuania" / Green Transformation / Refueling Infrastructure	Lithuania	2021	National
13	Economic Recovery and Resilience "New Generation Lithuania" / Green Transformation / Sustainable Electricity	Lithuania	2021	National
14	Energy Storage Strategy	Spain	2021	National
15	Estonian Recovery and Resilience Plan - Renewable Energy in Electricity Grids	Estonia	2021	National
16	Federal government/ South Australian Energy and Emissions Reduction Deal	Australia	2021	National
17	Funding for fossil-based hydrogen production, transport, storage, and utilisation coupled with carbon capture and storage capabilities	US	2021	National
18	German-Czech research collaboration for sustainable production	Czech Republic	2021	International
19	German-Czech research collaboration for sustainable production	Germany	2021	International
20	Grid Storage Launchpad (GSL)	US	2021	National

Sr. No.	Policy for Energy Storage Technologies	Country	Year	Jurisdiction
21	Immediate actions on battery storage	US	2021	National
22	Indigenous community-led clean energy projects	Canada	2021	National
23	Innovation Fund - Investments in Innovative Clean Technology Projects	EU	2021	International
24	Israel - US Clean Energy Projects	US	2021	International
25	Korea & Spain to expand green, digital partnerships	Korea	2021	National
26	Maori & Public Housing Renewable Energy Fund	New Zealand	2021	National
27	New Energy Vehicle Industry Development Plan (2021-2035)	China	2021	National
28	Public funding for innovative photovoltaic projects	Austria	2021	National
29	Recovery and resilience plan / CTD / Hydrogen and renewables/ Energy transition in Azores	Portugal	2021	National
30	Recovery and resilience plan / CTD / Hydrogen and renewables/ Potentiation of renewable electricity in the Madeira Archipelago	Portugal	2021	National
31	Review domestic supplies of batteries, key battery minerals and semiconductors	US	2021	National
32	Sustainable battery cell production	Germany	2021	National
33	Sweden's Recovery Plan / industrial sector	Sweden	2021	National
34	Ten milestones in 2021 - Massification of renewables	Colombia	2021	National
35	USD 100 million to support cutting-edge clean energy technology	US	2021	National
36	Australian Technology Investment Roadmap	Australia	2020	National
37	Canada Infrastructure Bank - Growth Plan - clean power investment	Canada	2020	National
38	Fourth supplementary budget 2020 - Finland's battery cluster development	Finland	2020	National
39	Green Deal: Sustainable batteries for a circular and climate neutral economy	EU	2020	International
40	Guiding opinions on Promoting the Development of the West and Forming a New Pattern	China	2020	National
41	Methods and conditions for self-consumption and energy communities	Italy	2020	National
42	NECP - LIFE-IP North-HU-Trans project	Hungary	2020	National
43	National Infrastructure Bank Growth Support	Canada	2020	National

Sr. No.	Policy for Energy Storage Technologies	Country	Year	Jurisdiction
44	Self-Reliant India Scheme - Production-Linked Incentive (PLI) Scheme	India	2020	National
45	Ten Point Plan for a Green Industrial Revolution - Point 10: Green Finance and Innovation	UK	2020	National
46	Ten Point Plan for a Green Industrial Revolution - Point 2: Low Carbon Hydrogen	UK	2020	National
47	3.2 billion euros fund for research and innovation in battery technology	EU	2019	International
48	Future Fuels Cooperative Research Centre	Australia	2018	National
49	Hy4Heat: Hydrogen for Heating Demonstration Porgramme	UK	2017	National
50	Research and Development (R&D) Program	Australia	2014	National
51	Development Programme for Second Generation Transport Biofuels	Finland	2007	National
52	Energy Storage Technology Advancement Act of 2007	US	2007	National

Source: *(IEA, 2022a)*

Annexure 8. Agencies involved in executing GEF approved projects

- African Development Bank
- Asian Development Bank
- Brazilian Biodiversity Fund
- Conservation International
- Development Bank of Latin America
- Development Bank of Southern Africa
- European Bank for Reconstruction and Development
- Food and Agriculture Organization
- Foreign Economic Cooperation Office, Ministry of Environmental Protection of China
- Inter-American Development Bank
- International Fund for Agricultural Development
- International Union for Conservation of Nature
- United Nations Development Programme
- United Nations Environment Programme
- United Nations Industrial Development Organization
- West African Development Bank
- World Bank
- World Wildlife Fund- US

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