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Energy Storage for Mini Grids

Status and Projections of Battery Deployment

An Energy Storage Partnership Report

Energy Storage for Mini Grids

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This report of the Energy Storage Partnership is prepared by the Energy Sector Management Assistance Program (ESMAP) with contributions from the Alliance for Rural Electrification (ARE), Ricerea sul Sistema Energetico (RSE), Loughborough University, and the Inter-American Development Bank (IADB). The Energy Storage Partnership is a global partnership convened by the World Bank Group through ESMAP Energy Storage Program to foster international cooperation to develop sustainable energy storage solutions for developing countries. For more information visit: https://www.esmap.org/the_energy_storage_partnership_esp

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ABBREVIATIONS

CAPEX	capital expenditure
CSR	Corporate Social Responsibility
DER	distributed energy resource
EE	Engie-Equatorial
ESP	Energy Storage Partnership
ESS	energy storage system(s)
FESS	flywheel energy storage system(s)
GWh	gigawatt hour(s)
kg	kilogram
kVA	kilovolt ampere
kW	kilowatt
kWh	kilowatt hour(s)
kWp	kilowatt peak
LCOE	levelized cost of electricity
LCOS	levelized cost of storage
LFP	lithium ferro-phosphate
MWh	megawatt(s)
NMC	nickel manganese cobalt
O&M	operations and maintenance
PALECO	Palawan Electric Cooperative
PV	photovoltaic
SIPCOR	S.I. Power Corporation
VRFB	vanadium redox flow battery
W	watt
Wh	watt hour
Wp	watt peak

All currency is in United States dollars (US$, USD), unless otherwise indicated.

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KEY FINDINGS

This report specifically focuses on battery energy storage in decentralized off-grid mini grids located in remote areas. It provides an overview of battery technologies used in mini grids globally, demand forecasts for various battery technologies, a comparison of characteristics of different batteries, an exploration of costs and trends in battery technologies, case studies, and recommendations.

In the high-case scenario, it is projected that annual demand for mini grid batteries is projected to increase to over 3,600 MWh by 2030 from around 180 MWh in 2020. In a base-case scenario, annual demand exceeds 2,200 MWh, while in the low case annual demand is around 1,500 MWh.

The selection of battery technology for mini-grid projects is a multi-faceted decision based on factors such as cycle life, depth of discharge, type of load connected to the grid, energy density, C-rating, thermal runaway, maintenance, after-sales service, hardware compatibility, maturity, cost, battery degradation, operating conditions, and environmental concerns.

The levelized cost of storage (LCOS) is critical for optimal decision-making in mini grid development. Though upfront costs often dominate the technology selection process, the LCOS provides a more comprehensive perspective by considering the lifetime cost of storage technologies. The LCOS calculation incorporates the capital expenditure, operations and maintenance costs, residual value, and cost of charging the battery. While lead acid batteries cost less per nameplate capacity ($/kWh), the superior cycle life, efficiency, and permissible routine depth of discharge of lithium-ion batteries result in a lower LCOS.

Lithium-ion batteries have grown in popularity and are displacing lead acid batteries, thanks to reduced prices, longer lifespan, and minimal maintenance requirements. Historically, lead acid batteries were the go-to choice due to their maturity, availability, and low upfront cost.

Lithium-ion prices are forecasted to decline until 2030. In contrast, lead acid, a mature technology, may not witness significant price drops. Forecasts suggest that lithium-ion batteries will extend their lead as the lowest-cost battery technology for mini grids dropping from 2022 LCOS of $0.37 per kWh to $0.34 in 2026 and $0.32 by 2030, notwithstanding the likelihood that raw material costs for lithium-ion batteries rise due to demand from the electric vehicle industry. The cost of lead acid batteries will decline only slightly, from $0.55 to $0.54 per kWh over this time period.

In the near future, other battery storage options are promising, including “second-life” lithium-ion batteries, sodium-ion batteries, iron-air batteries, hydrogen, and flywheel energy storage

This report includes case studies of mini grids from Africa and Asia that highlight global deployment of battery technologies ranging from conventional lead acid to lithium-ion, to VRBF and flywheel storage. Each case study describes the mini grid’s rating, energy storage rating, battery chemistry, businesses served, communities electrified, and the way in which the electricity is used.

Mini grid energy storage recommendations include: studying battery performance in actual operating conditions, considering total cost and not just upfront battery cost, adopting safety and performance standards, promoting recycling practices, encouraging the use of repurposed battery technologies, exempting mini grid batteries from import duties, providing technical skills training, and creating standard operating procedures to understand battery technology performance.

EXECUTIVE SUMMARY

The Energy Storage Partnership (ESP), established by the World Bank in 2019, aims to develop and implement energy storage solutions for developing countries. These solutions, coupled with renewable energy sources, could provide electricity to over 1 billion people who currently lack reliable access. A mini grid is an interconnected system of distributed energy resources (DERs) – generally including renewable energy and electricity storage — that operates independently, servicing customer groups of various sizes, from remote areas to urban locations. These mini grids support a range of facilities including primary health centers, agricultural activities, learning centers, hospitals, airports, and commercial establishments.

This report specifically focuses on battery energy storage in decentralized off-grid mini grids located in remote areas. It provides an overview of battery technologies used in mini grids globally, demand forecasts for various battery technologies, a comparison of characteristics of different batteries, an exploration of costs and trends in battery technologies, case studies, and recommendations. It also includes appendices that offer a broad overview of mechanical, electrochemical, and thermal storage, as well as performance optimization of lead acid batteries in mini grids.

Global electricity needs, particularly in remote and rural areas, are a significant challenge. As of 2020, an estimated 740 million people still lack access to electricity, 577 million of whom live in Sub-Saharan Africa (SSA). Though SSA has an electrification rate of 48% as of 2020, ambitious national electrification plans in countries such as Ethiopia, Ghana, Kenya, Nigeria, Rwanda, and Senegal aim to attain universal access by 2030. Some of these 2030 targets have been impacted by the COVID-19 pandemic, with many developing countries likely to experience delays. Under the existing trajectory, it is expected that about 800 million people will gain access to electricity between 2021 and 2030, leaving 560 million unelectrified. To achieve full electrification by 2030, it is necessary to provide electricity to around 1.3 billion people.

Growing deployment of mini grids are reaching some of this unelectrified population, with 21,000 mini grids currently serving about 48 million people worldwide. To serve half a billion people by 2030, the world needs a fleet of 217,000 mini grids, most of which will be predominately powered by solar electricity with battery backup.

South Asia presently leads with the highest number of installed (9,600) and planned (19,000) mini grids. Afghanistan, India, and Myanmar comprise about 80% of mini grids in this region. Africa is estimated to have about 3,100 installed mini grids with about 9,000 in the pipeline. In Africa, Nigeria, Tanzania, Senegal, and Ethiopia are among a number of countries that have embarked on ambitious projects to boost their national electrification rates using mini grids. Initiatives such as the Nigerian Electrification Project and the Rural Electrification Agency of Senegal intend to provide power access to over a million households and enterprises using mini grids.

The paradigm is shifting from traditional diesel and hydro-based grids to third-generation mini grids powered by solar and hybrid energy systems and employing advanced technologies like prepaid meters and online monitoring. The declining cost of solar panels, coupled with the abundant availability of sunshine in developing countries, is making solar-powered mini grids an economically feasible and environmentally conscious choice.

In 2021, approximately 1,100 rural mini grid projects were installed globally, providing 80 MW of capacity. South Asia led in annual installations, followed by Sub-Saharan Africa and Southeast Asia. Projections for global demand for mini grids between 2022 and 2030, alongside the need for battery storage systems to support these mini grids, have been formulated under three scenarios—high case, base case, and low case.

In the high-case scenario, it is projected that annual demand for mini grid batteries is projected to increase to over 3,600 MWh by 2030 from around 180 MWh in 2020. In a base-case scenario, annual demand exceeds 2,200 MWh, while in the low case annual demand is around 1,500 MWh. Lithium-ion batteries, in particular, have seen increased usage in mini grids, especially in Sub-Saharan Africa. By 2030, lithium-ion battery penetration is projected to rise to 70 percent from 55 percent in 2021 (Figure ES.1).

Expanding the role of mini grids for productive uses, beyond basic electricity access, allows for increased grid utilization without a corresponding rise in peak load. The outcome is lower levelized costs of electricity (LCOE) and expedited return on investment for developers. Case studies from Bangladesh and India validate the effectiveness of this approach.

Despite their immense potential, mini grids face various challenges, including remote project locations, difficulties in monitoring and maintenance, sustainability concerns, taxation issues, risk of stranded assets, lack of financing, and an absence of standardization. Operational challenges related to temperature also present difficulties, particularly for storage technologies. Overcoming these barriers will be vital to leverage the full potential of mini grids in meeting the world's energy access goals.

Storage technologies are central to the efficiency and reliability of mini grids. The selection of battery technology for mini-grid projects is a multi-faceted decision that investors base on factors such as cycle life, depth of discharge, type of load connected to the grid, energy density, C-rating, thermal runaway, maintenance, after-sales service, hardware compatibility, maturity, cost, battery degradation, operating conditions, and environmental concerns (Table ES.1).

Historically, lead acid batteries were the go-to choice due to their maturity, availability, and low upfront cost. Based on a database of 170 mini grids using 30 MWh of combined storage, lithium-ion batteries have grown in popularity and are displacing lead acid batteries, thanks to reduced prices, longer lifespan, and minimal maintenance requirements. A qualitative Pugh matrix assessment with responses from mini grid developers reveals lithium-ion as the most suitable technology, despite redox flow batteries scoring high on battery life and environmental friendliness.

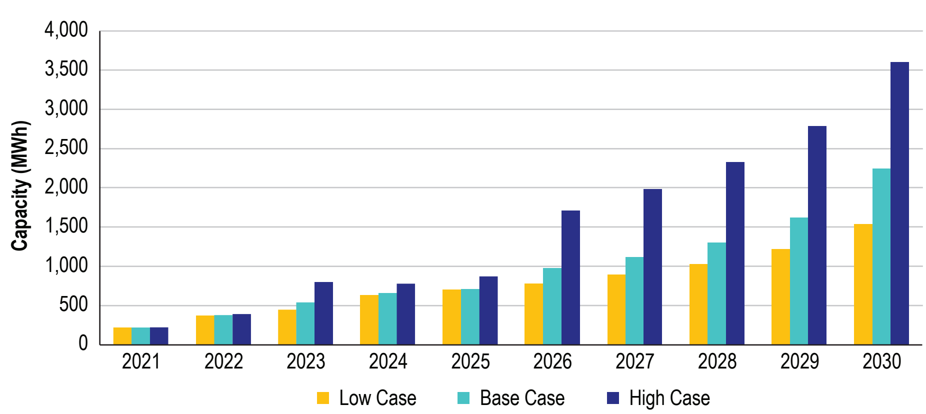
Vanadium Redox Flow Batteries (VRFBs) also show promise due to their long operational life, high depth of discharge, robust performance across a range of temperatures, and potential for cost reduction through innovative business models such as vanadium leasing.

When considering the capital cost of batteries, lead acid, a mature technology, may not witness significant price drops. In contrast, lithium-ion prices are forecasted to decline until 2030, notwithstanding the likelihood that raw material costs for lithium-ion batteries rise due to demand from the electric vehicle industry.

Considering the levelized cost of storage (LCOS) is critical for optimal decision-making in mini grid development. Though upfront costs often dominate the technology selection process, the LCOS provides a more comprehensive perspective by considering the lifetime cost of storage technologies. The LCOS calculation incorporates the capital expenditure, operations and maintenance costs, residual value, and cost of charging the battery. While lead acid batteries cost less per nameplate capacity ($/kWh), the superior cycle life, efficiency, and permissible routine depth of discharge of lithium-ion batteries result in a lower LCOS. For VRFBs, the CAPEX per kWh significantly drops as storage duration increases.

Forecasts suggest that lithium-ion batteries will extend their lead as the lowest-cost battery technology for mini grids dropping from 2022 LCOS of $0.37 per kWh to $0.34 in 2026 and $0.32 by 2030, while the cost of lead acid batteries will decline only slightly, from $0.55 to $0.54 per kWh over this time period. VRFBs are expected to become increasingly competitive with lead acid batteries (Figure ES.2).

FIGURE ES.1: Projected Global Demand for Batteries for Rural Mini Grids, 2021–30



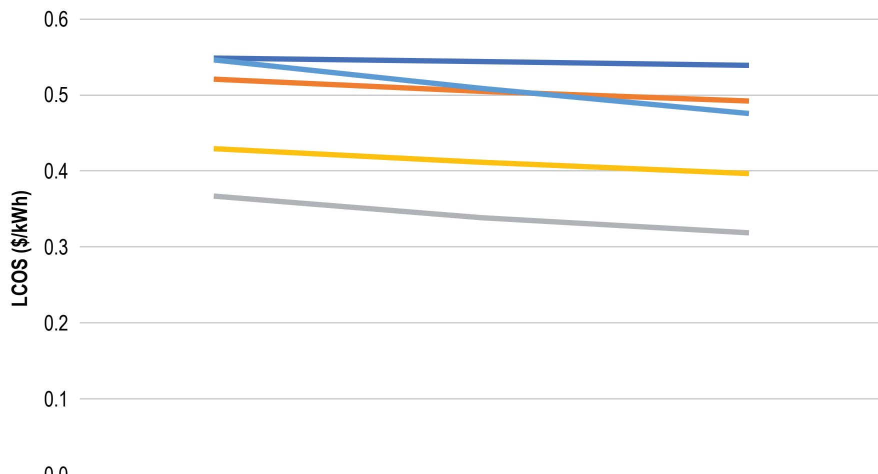
Source: CES.

TABLE ES.1: **Technical Parameters of Selected Battery Technologies**

Parameter	Battery Type					
	Lead Acid	Advanced Lead Acid	Lithium-Ion	NiNaCl2	Vanadium Redox Batteries (VRB)	Zn–Br (flow tech)
Battery chemistry	Lead	Lead, carbon electrodes	NMC/LFP	Nickel, sodium chloride	Vanadium	Zinc, bromine
Round-trip efficiency (percent)	60–80	80–90	85–95	70–90	60–70	68–70
C-rate	C/10	C/5	C/4-2C	C/6-C/8	C/5-C/8	C/3–C/4
Depth of discharge (percent)	50–60	70–80	90	80	100	100
Energy density (Wh/kg)	40–60	27–30	80–150	65–70	7–8	15–25
Cycle life	500–1,000	1,200–1,800	2,000–6,000	4,500–5,000	7,000–10,000	3,000–3,500
Safety	High	High	Medium	Medium	High	Medium
CAPEX ($/kWh)	80–150	120–300	250–350	750–1,000	600–1000	750–800
Toxicity of chemicals	High	High	High	Medium	Medium	High
Operating temperature (°C)	–20–50	–20–50	0–55	270–350	15–55	20–50
Self-discharge (percent/month)	10–15	3–5	0.5–2	5	5	60

Source: CES.

FIGURE ES.2: Estimated and Projected Levelized Cost of Storage for Six-Hour Duration System, by Battery Type



	2022	2026	2030
Lead Acid	0.55	0.54	0.54
Adv. Lead Acid	0.52	0.50	0.49
Li-ion LFP	0.37	0.34	0.32
Vanadium Redox	0.43	0.41	0.40
NiNaCl2	0.55	0.51	0.48

Source: CES.

In the near future, other battery storage options are promising. “Second-life” lithium-ion batteries presents a potential stationary storage solution after they have been cycled out of use in automotive applications and thoroughly tested. Sodium-ion batteries have emerged as a potential solution for energy storage in solar mini-grids, with advantages over lithium-ion batteries in terms of raw material abundance, reasonable cycle life, comparable energy storage capacity, adaptable manufacturing processes, and improved safety and stability. Iron-air batteries might offer a viable path for low-cost long-term energy storage, despite their lower energy density. Hydrogen-powered storage solutions, capable of storing energy for longer periods than batteries, are being proposed as alternatives to traditional diesel generators and could potentially power mini grids in remote areas. Flywheel energy storage, which stores kinetic energy in a rotating mass, offers significant advantages, such as a long lifetime, increased charge-cycle capabilities, and rapid output, while lacking hazardous chemicals or fire hazards. Its current constraints include cost, rapid self-discharge, and limited capacity for extensive energy storage.

Case studies highlight global deployment of emerging storage technologies. Each case study describes the mini grid’s rating, energy storage rating, battery chemistry, businesses served, communities electrified, and the way in which the electricity is used.

Husk Power Systems in India and Nigeria uses hybrid systems combining solar PV, batteries, and biomass gasification to power over 200 community solar mini grids. Their system employs machine learning to optimize the battery management and increase the lifetime of its lead-acid batteries. The company’s careful approach to monitoring and controlling lead acid charge-discharge cycles and its ability to obtain attractive volume pricing on Indian-made lead acid batteries are two reasons it uses lead acid batteries.

In the Lolwe Islands, Uganda, Engie Energy Access and Equatorial Power deployed a hybrid solar mini grid with Lithium Iron Phosphate (LFP) battery storage. The mini grid, supplying over 3,800 consumers, is supplemented with a business incubation and asset financing program that includes water purification, ice making, electric mobility, and agro-processing. These activities limit the dependence on diesel generators and help the developers utilize the mini grids at their full capacity.

In San Seth, Bogale, Myanmar, Mandalay Yoma developed a hybrid solar mini grid with lithium-ion nickel manganese cobalt (NMC) batteries. A 713 Wp hybrid solar mini grid with storage capacity of 1,312 kWh of lithium-ion nickel manganese cobalt (NMC) batteries is paired with a 315 kVA genset. The grid, supplies over 1,300 households and 20 businesses. The selection of NMC battery technology is primarily due to its lifespan of over 3,000 cycles.

In Nigeria, more than 250 mini grids are currently. PowerGen mini grid at Dancitagi village uses a 200 kWp solar hybrid mini grid with 500 kWh of lithium iron phosphate batteries and a 200 kVA diesel genset at. This grid has brought significant improvements in power supply, and two years after installation, the load on the site had increased, and there was a demand for additional storage capacity.

In India, Amperehour and the Maharashtra Energy Agency Development Authority (MEDA) have established solar mini grids at Makhala, Amravati, and Maharashtra. These mini grids rely on 110 kWh of containerized lithium iron phosphate (LFP) batteries, providing connections to over 127 customers. No diesel generators are used. A machine learning-based algorithm control optimizes the load profile and informs decision making

In Maldives, the Korean company H2 built a system combining solar power and a vanadium redox flow battery (VRFB). This system was designed to produce 1 MWh per day and store electricity for use during peak hours or when solar power is unavailable. The system was specifically engineered to withstand the challenging maritime conditions in the Maldives.

In the Philippines, the Palawan Electric Cooperative (PALECO) and S.I. Power Corporation (SIPCOR) are implementing a micro grid project using solar PV, diesel generators, and flywheel energy storage systems (FESS) from Amber Kinetics. This system provides energy to the inhabitants, reducing their reliance on the unreliable grid and promoting economic growth. It is also environmentally friendly as it reduces carbon emissions and the island’s dependence on diesel fuel for power generation.

Recommendations for improving the implementation and success of decentralized renewable energy mini grids, with a focus on energy storage technologies:

1. Study battery performance in the field: Conduct comprehensive analyses of different battery technologies under actual conditions where mini grids are built and operate.
2. Consider total cost: When planning mini grids, consider the Levelized Cost of Storage (LCOS) and how the batteries affect the Levelized Cost of Energy (LCOE), not just the upfront cost of batteries.

3. Adopt safety and performance standards: These standards will reduce risks and increase industry acceptance, particularly if they align with standards developed by international organizations.
4. Carefully draft regulatory documents and procurement specifications: This ensures safety, quality, and performance without restricting innovation in storage technologies.
5. Promote best recycling practices: As the industry shifts toward lithium-ion technologies, it's crucial to develop and implement strategies for recycling these batteries.
6. Encourage the use of repurposed battery technologies: Develop a standard for testing and certifying second-life battery packs to increase confidence in their use for mini grids.
7. Exempt mini grid batteries from import duties: To make battery technology more affordable and expedite their deployment in mini grids.
8. Provide skilling and upskilling programs: These will enhance technical competency, reduce downtime of mini grid systems, and create employment opportunities in communities.
9. Create standard operating procedures for understanding battery technology performance: This will help mini grid players optimize their asset utilization and reduce risks, for example, by understanding the effects of environmental conditions on battery performance.

1 BATTERY TECHNOLOGIES IN MINI GRIDS ACROSS THE WORLD

In 2019, the World Bank convened the Energy Storage Partnership (ESP), a global partnership to adapt, develop, and roll out energy storage solutions for developing countries. Storage technologies, in tandem with renewable energy sources, have great potential to provide access to electricity to the more than 1 billion people who either lack access or are served poorly. To enable the rapid uptake of variable renewable energy sources in developing countries, the ESP is working on developing power systems, disseminating knowledge, building capacity, developing testing protocols, validating performance, providing flexible sector coupling, developing decentralized energy storage solutions, crafting procurement frameworks, enabling energy storage policy, and recycling systems and standards. This report is a knowledge product of the project lead by Working Group 5, which focuses on developing knowledge products to support the development and expansion of energy storage solutions.

A mini grid is a group of interconnected multiple or single distributed energy resources (DERs) and loads that work independently in remote locations or grid connected areas (SE4All 2022). Mini grids cater to customer groups of different sizes, ranging from a few consumers in remote areas to thousands of consumers in urban areas. In remote areas, mini grids have improved energy access to primary health centers, lighting, agricultural activities, including productive use applications like agricultural processing and cold storage and learning centers. Urban mini grids serve hospitals, airports, Special Economic Zones, universities, and small commercial establishments. Some successful mini grids are already connected to the central grid; others may be connected in the future. Yet others are in locations that are too remote to be connected in the foreseeable future.

This report focuses on decentralized off-grid mini grids in remote locations. It is organized as follows.

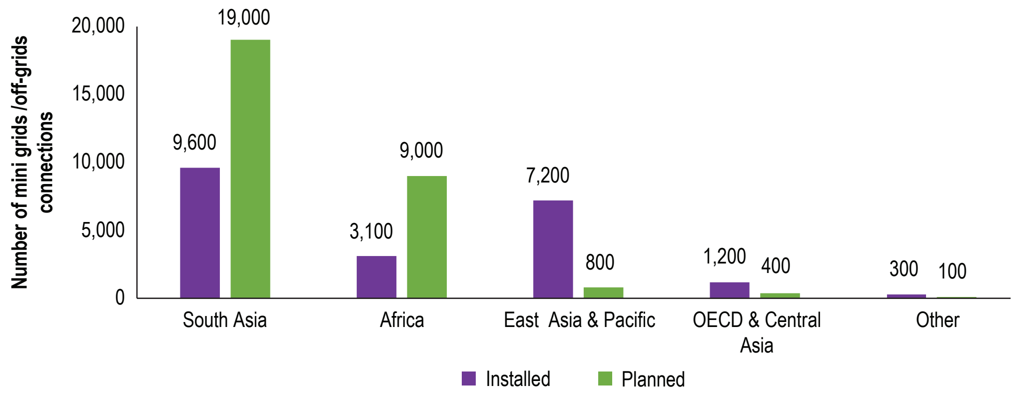
- Section 1 provides an overview of battery technologies in mini grids across the world, using information collected through interviews with major project developers and plant operators.
- Section 2 forecasts demand for various battery technologies deployed or targeted.
- Section 3 compares various storage technologies for mini grid applications.
- Section 4 explores costs and trends in battery technologies deployed in mini grids.
- Section 5 presents seven case studies.
- Section 6 proposes recommendations.
- Appendix A provides a broad overview of mechanical, electrochemical, and thermal storage.
- Appendix B discusses performance optimization of lead acid batteries in mini grids.

OVERVIEW

In 2020, around 9.5 percent of the world's population (approximately 740 million people) lacked access to electricity (World Bank 2020a). Around 500 million of them live in Sub-Saharan Africa (World Bank 2019a). The lack of access to electricity can be attributed to sparse population densities, the remote locations of the villages, financially stressed state-owned electric companies, low willingness to pay, and lack of capital investment.

As of 2022, around 21,500 mini grids worldwide were serving around 48 million people. Another 29,400 projects, with the capability to serve another 35 million people, were in the pipeline. This pipeline will serve less than 5 percent of the population without access to electricity. To serve half

FIGURE 1.1: Number of Installed and Planned Mini Grids, by Region, 2021



Source: ESMAP 2022.

a billion people by 2030, the world needs a fleet of 217,000 mini grids powered by solar and hybrid energy systems (ESMAP 2022).

1.1 THE GLOBAL STOCK OF MINI GRIDS

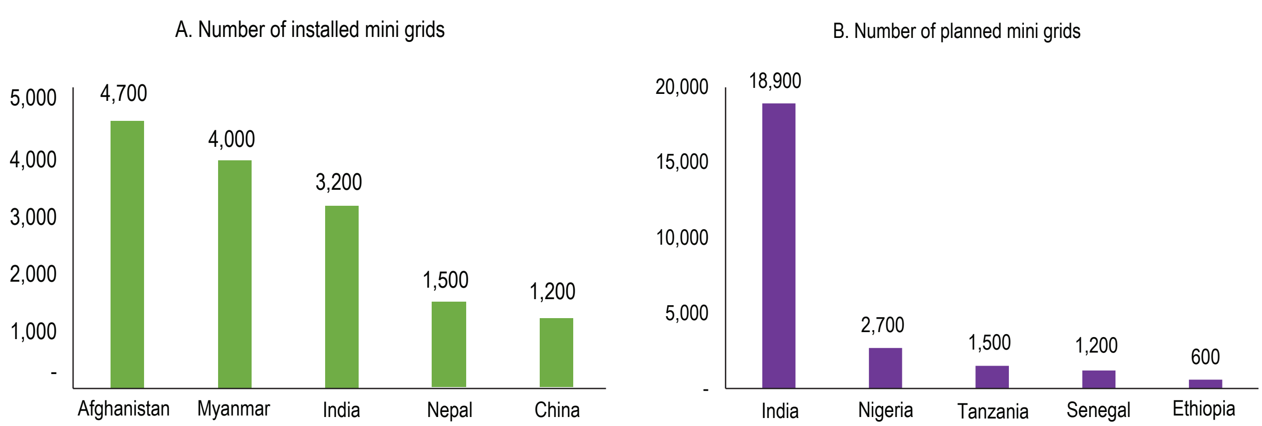
South Asia leads the world in terms of both the number of mini grids installed (9,300) and planned (19,000) Figure 1.1 shows the regional distribution.

Together, Afghanistan, India, and Myanmar have about 80 percent of the world's installed mini grids in Asia. Afghanistan has the largest number of mini grids installed (around 4,700). By 2018, India had brought electrical poles and wires to all of its settlements. It now aims to increase the reliability and productive use of power. Achieving these objectives requires a large fleet of solar-powered mini grids.

The national electrification rate in Nigeria is around 55 percent, with a rural electrification rate of only 39 percent. To achieve universal energy access by 2030, Nigeria needs to connect 500,000 to 800,000 households every year, with a focus on rural areas. The Nigerian Electrification Project (NEP), with support from the World Bank, the African Development Bank, and other partners, aims to provide energy access to under- and unserved communities in Nigeria using renewable energy. The project promotes electricity access for households; micro, small, and medium-size enterprises (MSMEs); and public education institutions. It aims to provide cost-effective power to 250,000 MSMEs and 1 million households through off-grid and mini grid systems by 2023. The plan will install mini grid systems in 250 sites and target 15 mini grids at federal universities (Nweke-Eze 2022).

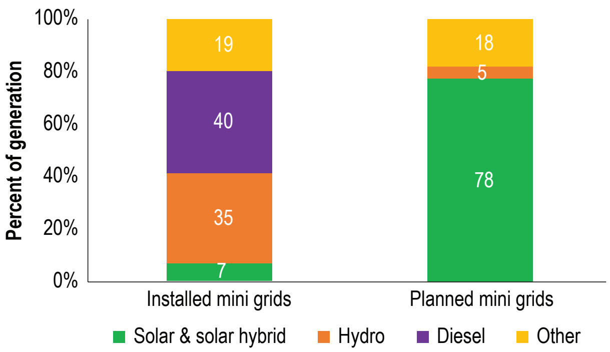
In Senegal, the Rural Electrification Agency of Senegal (ACER) aims to install 1,000 mini grids, in order to achieve

FIGURE 1.2: Number of Installed and Planned Mini Grids in Selected Countries, 2022



Source: ESMAP 2022.

FIGURE 1.3: Generation Mix of Installed and Planned Mini Grids, 2019



Source: Analysis by CES.

a 2025 target of universal access to electricity by 2025 (Burger 2022).

1.2 THE GENERATION MIX OF MINI GRIDS

Many mini grids are either first- or second-generation grids using diesel or hydro as the main sources of generating electricity. Most of the projects in the pipeline are third-generation grids. These grids generally use solar or solar/diesel hybrids to generate electricity; they use advanced technologies like remote monitoring and smart pre-paid meters to ensure the seamless functioning of mini grids. Third-generation mini grids installed by members of the African Mini Grid Developers Association (AMDA) report average uptimes of 99 percent (AMDA 2022).

With the decline in the cost of solar panels, diesel generators no longer make financial sense as the primary source of electricity in mini grids. They are now used as backup generators, deployed during extended cloudy periods.

The increased popularity of solar/solar hybrid mini grids reflects three main factors:

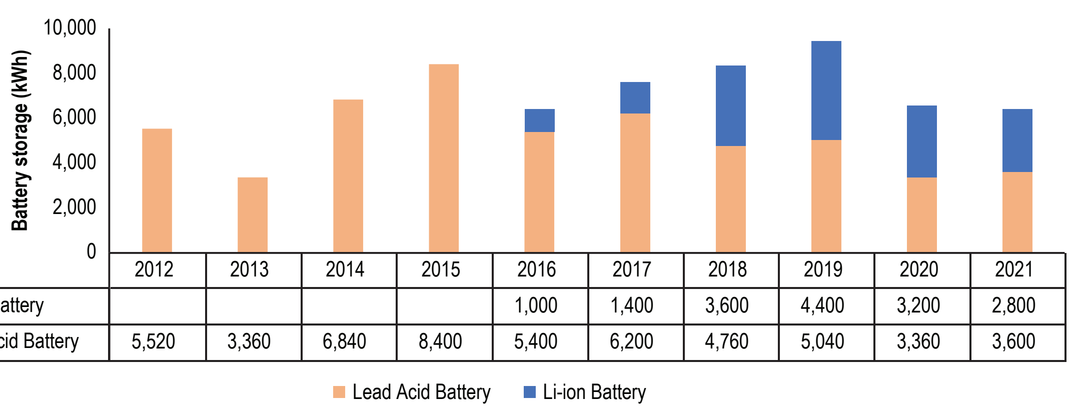
- Sunshine is abundantly available.
- Most developing countries under study depend on imports for the supply of fossil fuels.
- Capital expenditure (CAPEX) per kilowatt (kW) is projected to fall from $3,659 in 2021 to under $2,500 by 2030 (ESMAP 2022). This decline has the potential to make each unit of electricity generated by these grids competitive with electricity supplied by the main/central grid in many areas.

1.3 THE ROLE OF STORAGE

Newer mini grids generally pair renewables with batteries supplying four to six hours of electricity in the evening and morning hours, when solar generation is low or unavailable. To learn about the use of battery technology in mini grid applications, CES interviewed developers representing 382 mini grids and 72 megawatt hours (MWh) of battery storage usage.[1] In 2017–21, 202 of these mini grids, with 39 MWh of storage were built by 8 mini grid developers (figure 1.4). Ten mini grids—with 3 MWh of flow battery and sodium-based battery energy storage technology comprised of flow battery (manufactured by VFLOW technologies) and sodium-based technologies (Dielectrik)—were also added (figures 1.5 and 1.6).

A database of 170 mini grids, with 30 MWh of storage, was developed based on secondary sources. Over 80 percent of the sampled mini grids were operating in Asia. The rest were operating in Africa.

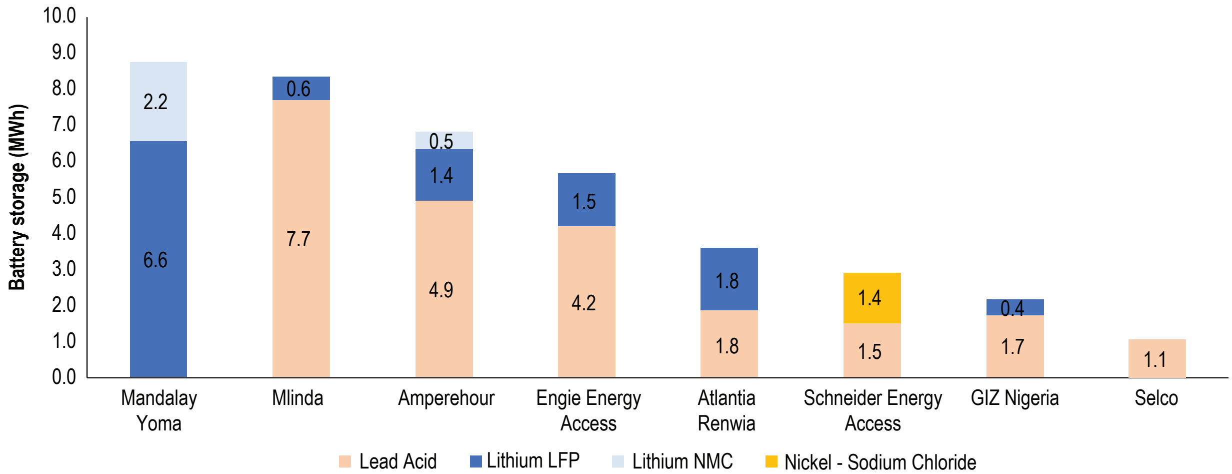
FIGURE 1.4: Battery Storage Transition in Rural Mini Grids in Asia and Africa, 2012–21



	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Li-ion Battery					1,000	1,400	3,600	4,400	3,200	2,800
Lead Acid Battery	5,520	3,360	6,840	8,400	5,400	6,200	4,760	5,040	3,360	3,600

Source: CES.

FIGURE 1.5: Primary Source of Battery Storage by Selected Mini Grid Developers in 2017–21



Source: CES.

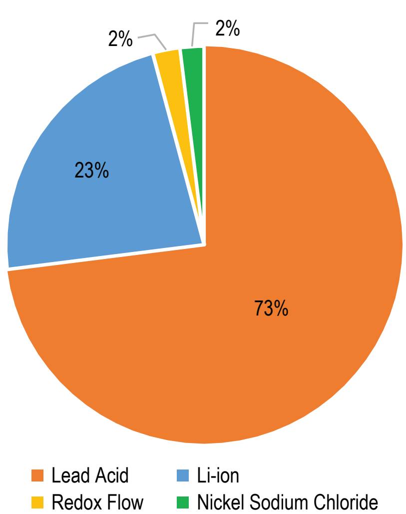
Lead acid storage technology was the dominant choice for mini grid developers before 2018. Since then, lithium-ion batteries have been increasingly popular, reaching 44 percent of deployed battery storage technologies in 2021. Their increased popularity in the electric vehicle sector has led to reductions in the price of lithium-ion cells. Lithium-ion batteries have become more attractive for mini grid developers because of this price reduction and the batteries' increased availability.

Mandalay Yoma—a solar energy provider in Myanmar—uses only lithium-ion battery technology (figure 1.7), because of its increased life and maintenance-free operation. It expressed confidence in the future of lithium-ion technology. Other respondents believed that lead acid battery technology is likely to be used for many more years, although most mini grid developers are slowly beginning to use lithium-ion technology in their energy storage mix.

Because of its robust performance in a broad range of temperatures, redox flow battery technology can be a good option for mini grids. It is still in the initial phase of development. Some developers expressed interest in experimenting with flow batteries. Invinity Energy, VFlow Tech, and Delectrik manufacture redox flow batteries for the mini grid market.

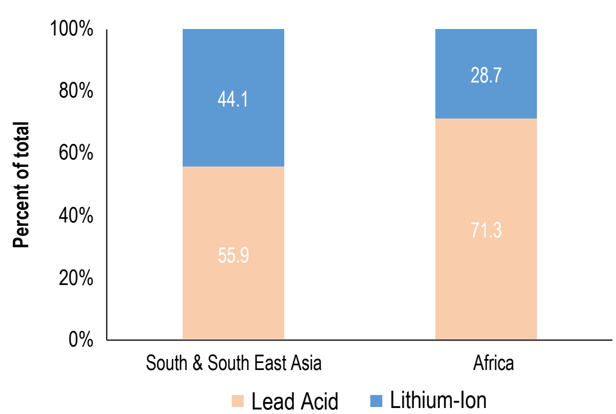
Of the 37.4 MWh of storage deployed in mini grids (see figure 1.7), 65 percent of storage capacity is in South and Southeast Asia and 35 percent is in Africa.

FIGURE 1.6: Mini Grid Battery Storage as Percentage of Total Capacity, by Technology Type, 2012–21



Source: CES.

FIGURE 1.7: Shares of Lead Acid and Lithium-Ion as Sources of Battery Storage by Mini Grids in South and Southeast Asia and Africa, 2022



Source: CES.

(Redox flow batteries and sodium-based technologies were excluded from the analysis in order to compare lead acid and lithium-ion technologies deployed.)

1.4 THE ROLE OF THE LEVELIZED COST OF STORAGE IN THE TECHNOLOGY SELECTION PROCESS

The levelized cost of storage (LCOS) is a financial term for the average cost of storing each unit of energy in a storage project over its lifetime. It takes into consideration different cost items and their timing, the time value of the money, and the opportunity cost of the invested capital.

For mini grid developers, upfront cost (CAPEX) is an important factor determining the selection of a technology, and can overshadow other key parameters such as the useful life of the project, efficiency parameters, and the cost of operations and maintenance (O&M). Indeed, despite the lower lifetime cost of lithium-ion batteries, lead acid technology is still used by many developers because of the low upfront cost. Using the LCOS can help decision makers make better choices about technology.

1.5 USING MINI GRIDS FOR PRODUCTIVE USES: BEYOND BASIC ACCESS TO ELECTRICITY

With an average uptime of 99 percent, third-generation mini grids provide highly reliable supplies of electricity that go beyond basic access to electricity. Most of the new-generation mini grids are promoting productive-use applications, such as egg incubators, grinders for pulses, water pumps, flour mills, and other small business uses.

Increased use of productive appliances can increase the load factor of the grid. Domestic load peaks during mornings and evenings; the grid is relatively load free in the middle of the day. The addition of productive appliances creates load during business hours, leading to increased utilization without an increase in peak load. When electricity used to power productive appliances is consumed at the same time the electricity is generated, the levelized cost of electricity (LCOE) falls (figure 1.8). Doubling the load factor from 20 percent to 40 percent has the potential to reduce the LCOE by 25 percent. Lower levelized costs support sustainable business models and help developers achieve their targets earlier.

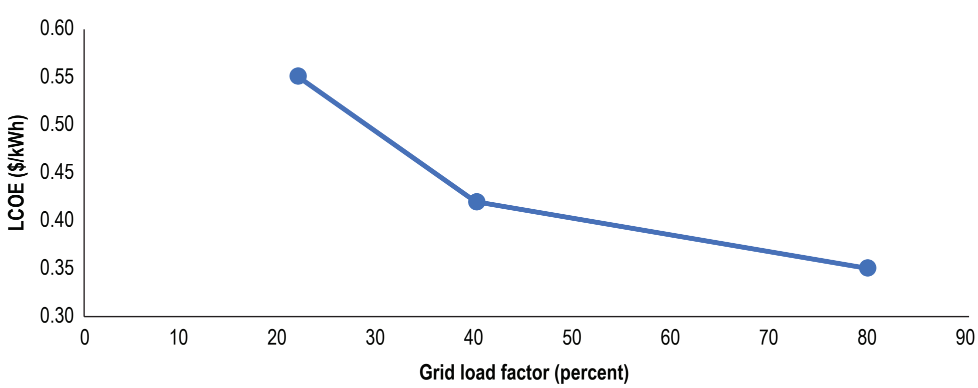
The Suro Bangla mini grid in Bangladesh, developed by the Infrastructure Development Company Limited (IDCOL), generated its full potential within 1.5 years, a year earlier than initially projected, thanks to the use of productive loads (ESMAP 2022). The mini grid in Shivpura (Uttar Pradesh, India) powers many productive loads, including a bank, a sweets shop, a school, and other small businesses.

1.6 CHALLENGES FACED BY MINI GRID DEVELOPERS

Mini grids around the world face operational and financial challenges, including the following:

- **Remote location:** High transport costs of equipment and raw materials increase the costs of mini grides in remote locations. Safety requirements for battery transportation can add costs.

FIGURE 1.8: Effect of Grid Load Factor on Levelized Cost of Electricity



Source: ESMAP 2019.

- **Monitoring:** Remoteness makes it difficult to send personnel for periodic monitoring. As most mini grids are far from telecommunication networks, monitoring through technological interventions like wireless communication devices can be difficult. Battery technologies that require periodic monitoring present challenges.
- **Periodic maintenance:** It is difficult to find competent technicians to carry out periodic maintenance in remote areas. Developers try to bridge the gap by identifying local entrepreneurs and training them in maintenance.
- **Business sustainability:** Consumers' willingness to pay for electricity is often low. Some mini grid developers/companies charge as much as $0.75/kWh—far more than the average cost of electricity offered by some utilities in African countries. Storage choices require balancing cost against the reliability of supply and the impact on tariffs, which affect the amount of electricity customers can afford to purchase.
- **Taxation:** Most mini grid players operate in developing countries that must import the required equipment, including the batteries. Some countries have differential import duty regimes, in which duties on separate components (20–30 percent) are higher than duties levied on integrated units (as low as 5–10 percent).
- **Stranded assets:** Mini grid developers face the financial risk of their asset becoming stranded when the main grid arrives. The addition of CAPEX-intensive battery technologies increases this financial risk. In a bid to recoup their investment early and reduce this risk, developers opt for lower payback periods. Lower payback periods need higher annual capital depreciation and increase the cost of each unit of electricity generated. The higher cost of each unit generated negatively affects users and hence the large-scale deployment of mini grids.
- **Financing:** Some mini grid projects have been funded exclusively by grants. These projects tend to be unsustainable, coming to a halt when funding ends.
- **Absence of standardization:** The size of individual equipment like inverters, batteries, and switch gear lack mini grid-specific standardization. As a result, some components are over-designed and not fully utilized. There is no standard mini grid size that grid developers can use for deployment. A standard size could be based on the size of the community to be served or the available load.
- **Operational challenge related to temperature:** The performance of some storage technologies is sensitive to ambient temperature. Some storage technologies perform better when they are cooled by air conditioning systems. Air conditioning uses some of the power stored in the batteries, however, reducing the amount of energy available for other uses, and air conditioning systems can be challenging to maintain in remote locations.

NOTE

1. The mini grid developers interviewed for this project represent a small subset of global players and may not be representative. The results reported may over- or underestimate the prevalence of particular battery storage technologies used in mini grids.

2 SIZE OF THE GLOBAL MARKET FOR MINI GRID AND ENERGY STORAGE

2.1 NUMBER OF PEOPLE WITHOUT ACCESS TO ELECTRICITY

According to the Multi-Tier Framework (MTF), households with access below Tier 1 have electricity for less than four hours a day to light lamps or charge phones (Bhata and Angelou 2014). The International Energy Agency defines access to electricity as access to at least 250 kWh of electricity a year in rural areas and at least 500 kWh a year in urban areas of (IEA 2022c). The International Renewable Energy Agency (IRENA) estimates that in 2022 around 10 to 12 percent of the global population of 7.9 billion lacked access to electricity.

Sub-Saharan Africa

Sub-Saharan Africa has the world's largest unelectrified population (figure 2.1). The share of the population with access to electricity stood at 48 percent in 2020 (World Bank 2020b). Rates in several countries, such as Niger, Chad, and the Democratic Republic of Congo, were less than 20 percent.

The region's population of 1.1 billion is expected to exceed 1.4 billion by 2030. In a business as usual scenario, access to electricity is projected to hit 62 percent by 2030. Ethiopia, Ghana, Kenya, Nigeria, Rwanda, and Senegal have ambitious National Electrification Plans, which are expected to achieve universal access by 2030.[2] For rural electrification, around 45 percent of investments are for grid expansion to remote areas, 25 percent are for stand-alone solar home lighting systems, and 30 percent are for mini grids (EnDev 2022).

South Asia

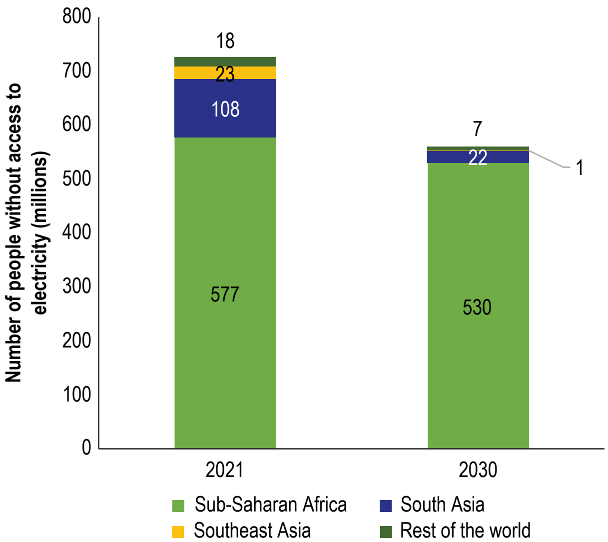
Around 108 million people in South Asia lacked access to electricity in 2020. In 2019 Pakistan, Nepal, and Bangladesh had the lowest access rates in the region at 73 percent, 89 percent, and 93 percent, respectively (World Bank 2022b). These countries aim to achieve universal electricity access by 2030.

In Afghanistan, a 3 MW solar hybrid mini grid project funded by the United Nations Development Programme (UNDP) is under evaluation (Green Climate Fund 2022). Bangladesh uses solar photovoltaic (PV) as the key source for powering rural mini grids. In India, 2019 and 2020 saw massive deployment of standalone solar home lighting systems to rural households. Under the Saubhagya Scheme Programme, around 30 million solar home lighting units were distributed in 2019–21 (See the Saubhagya Scheme Dashboard).

Southeast Asia

In 2020, Cambodia , Laos, and Myanmar had electrification rates of 70 percent, 94 percent, and 89 percent, respectively (World Bank 2022a). In 2022–23, 350 unelectrified villages in Cambodia are expected to be connected by solar mini grids. Most countries in Southeast Asia aim to achieve universal electricity access by or before 2030 (IEA 2022b). Indonesia plans to achieve universal access by 2024, Myanmar expects to reach it by 2030, and Lao PDR expects to reach 98 percent access by 2025. The Philippines and Indonesia have several unelectrified islands that are difficult to connect via the grid.

FIGURE 2.1: Number of People Without Access to Electricity, by Region, 2021 and 2030



Source: UN Population Division Data Portal and World Bank Access to Electricity Portal 2022.

2.2 PROJECTED ACCESS BY 2030

Globally, the electricity access rate increased steadily between 1996 and 2020, rising from 73.4 percent to 90.5 (Our World in Data n.d.). During 2020 and 2021, the COVID-19 pandemic slowed the pace of electricity access programs, as governments shifted their priorities toward healthcare and logistics (IEA 2022a) The universal electricity access targets for 2030 are likely to be delayed in several developing countries as a result of the pandemic.

In a business as usual scenario, some 800 million people are expected to receive electricity between 2021 and 2030, leaving 560 million unelectrified (IEA 2022a).

To achieve 100 percent electrification by 2030, around 1,300 million people need to be electrified.

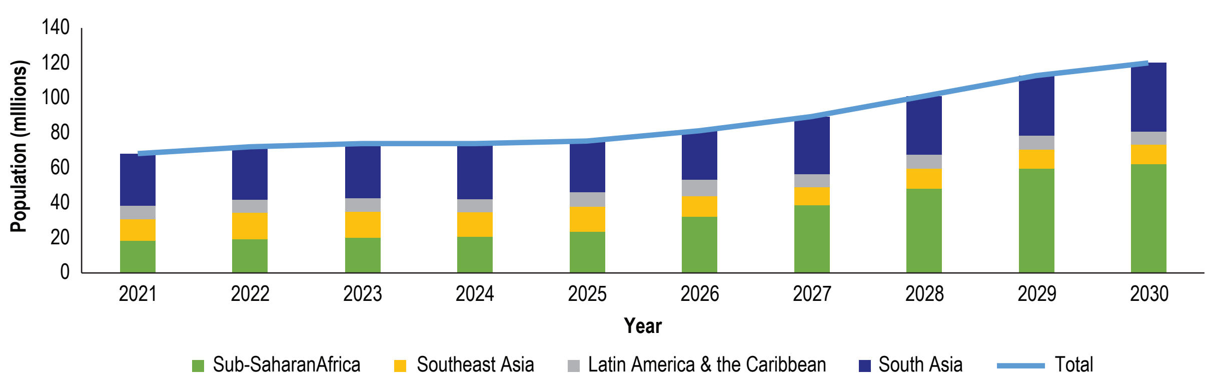
To achieve rural electrification targets, 800 million households must be electrified by 2030. In 2021, the annual electrified population was estimated to be around 30 to 40 million. CES estimates that achieving universal electricity by 2030 would require a compound annual growth rate of the electrified population of around 6.5 percent. This report assumes that all regions except Sub-Saharan Africa will achieve universal energy access by 2030 (figure 2.2).

2.3 RURAL MINI GRID INSTALLATIONS IN 2021

CES conducted a survey to estimate the number of mini grids installed in 2021 and the MW capacity those installations provided. It found that 1,100 rural mini grid projects across the world provided 80 MW of capacity. South Asia continued to lead in annual installations, at 35 percent of total MW installed, followed by Sub-Saharan Africa (30 percent) and Southeast Asia (28 percent) (figure 2.3).

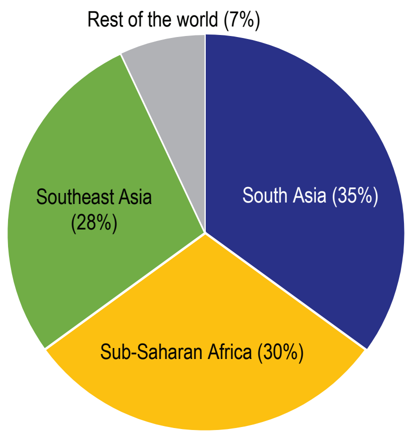
In South Asia, India, and Afghanistan lead, together accounting for at least 20 MW of capacity. The typical mini grid capacity was around 30 kilowatt peak (kWp) in India and over 1 megawatt peak (MWp) in Afghanistan. In Southeast Asia, Myanmar, Indonesia, the Philippines, and Malaysia have the largest number of installations. Mini grids of 100 kW and above have been installed in the region. In Africa, Nigeria, Sierra Leone, and Senegal lead. Uganda and Ethiopia have several projects underway. Mini grids with capacities of 50 kWp to 130kWp were installed in Sub-Saharan Africa in 2021.

FIGURE 2.2: Projected Annual Increase in Number of Rural People with Access to Electricity, by Region, 2021–30



Source: CES.

FIGURE 2.3: Distribution of Mini Grid Capacity, by Region, 2021



Source: CES.

2.4 FORECASTING GLOBAL DEMAND FOR MINI GRIDS AND BATTERY STORAGE SYSTEMS

This section forecasts global demand for mini grids between 2022 and 2030. It also estimates demand for battery storage systems to support these mini grids. The forecasts are based on assumptions about the share of mini grids in rural electrification and the capacity of the mini grid per household. Based on extensive interactions with mini grid players across Sub-Saharan Africa, South Asia, and Southeast Asia, CES estimates that in 2021, around 80 MW of mini grids were installed globally. Of the total rural population electrified in 2021, around 30 percent were electrified through mini grids.

Three scenarios for mini grid installations are projected for 2022–30:

- **High-case scenario:** From 2022 to 2025, of the rural population electrified in each year, the share that gains electricity access through mini grids is projected to increase from 30 percent to 50 percent, remaining at 50 percent until 2030. This scenario is consistent with the assumptions in the *State of the Global Mini Grids Market Report 2020* (SE4All 2022).
- **Base-case scenario:** In the business-as-usual scenario, mini grid penetration remains at 30 percent.
- **Low-case scenario:** In this scenario, mini grid penetration is projected to fall to 20 percent. Other methods of electricity access, such as grid expansion and solar home lighting systems, are assumed to be more prevalent.

Mini grids are designed to power households and commercial buildings, such as small shops and health centers, in villages. They vary in size from dozens of kWp to hundreds of kWp. The average size varies from region to region. Household consumption averages are based on inputs from mini grids developers across Africa and South and Southeast Asia.

Table 2.1 shows the average capacity of a mini grid assigned to a household[3] in each of the four regions in 2021 and 2030. These data are based on primary inputs. The connected loads for a typical household in these regions were typically up to four units of 7 watts (W) LED lights, two units of 25 W fans, and a socket to which the household connected a television unit of 40 W. These loads were connected on the microgrid network.

Figure 2.4 shows the annual installed capacity of mini grids in 2022–30 in the three scenarios. Figure 2.5 shows the cumulative installed capacity.

Table 2.2 describes a sample of mini grid projects installed during 2020 and 2021. Most of them are dependent on diesel generator sets for a few hours of power generation during the evening.[4] The ratio of battery kWh to kWp of solar power is typically limited to 2 to 2.5 when lithium-ion batteries are used for backup. If lead acid batteries are used, the ratio increases to 3 to 4, because the depth of discharge is lower for lead acid batteries (50 percent) than for lithium-ion ones (80 percent).

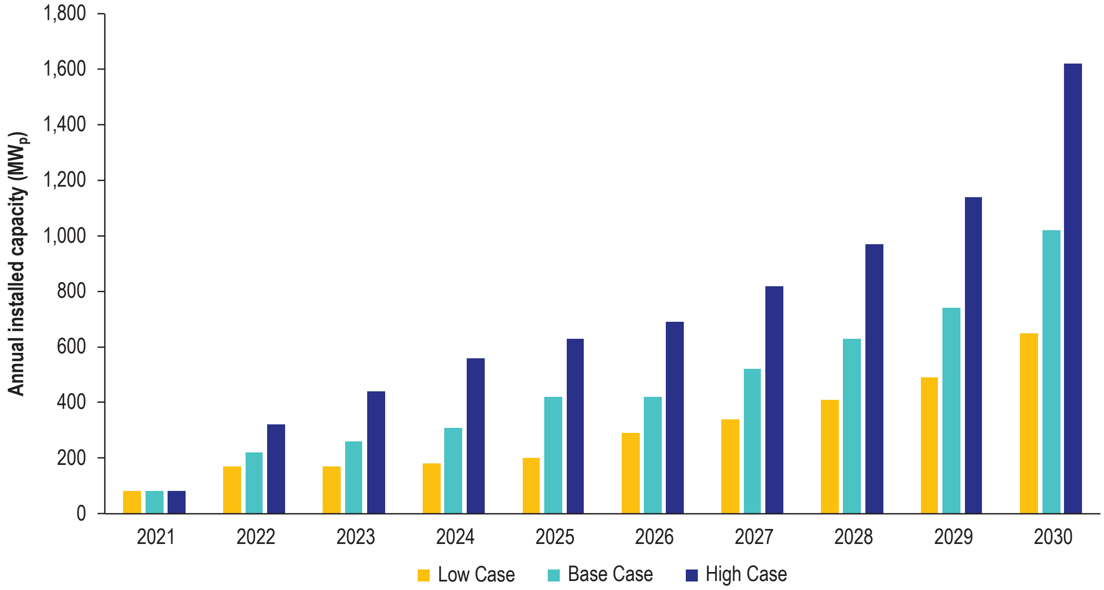
Mini grids paid for by government and Corporate Social Responsibility (CSR) funds appear to favor batteries with higher kWh to kWp ratios than mini grids built with private developer funds. In India, the government funded several mini grid projects in 2016–18 as part of its rural electrification strategy. These projects used lead acid batteries. The ratio of the size of the battery to the mini grid capacity was 7 to 12. In projects funded with CSR funding, the ratio was 3 to 6. In private mini grid projects, developers conduct load modelling and select the optimum size of batteries to support renewable

TABLE 2.1: Estimated and Projected Mini Grid Capacity per Household (Wp), by Region, 2021 and 2030

Region	2021	2030
Sub-Saharan Africa	120	150
Latin America and the Caribbean	100	150
South Asia	90	150
Southeast Asia	80	120

Source: Primary inputs collected by CES from mini grid players.

FIGURE 2.4: Projected Annual Global Demand for Rural Mini Grid in the Low-, Base-, and High-Case Scenarios, 2021–30



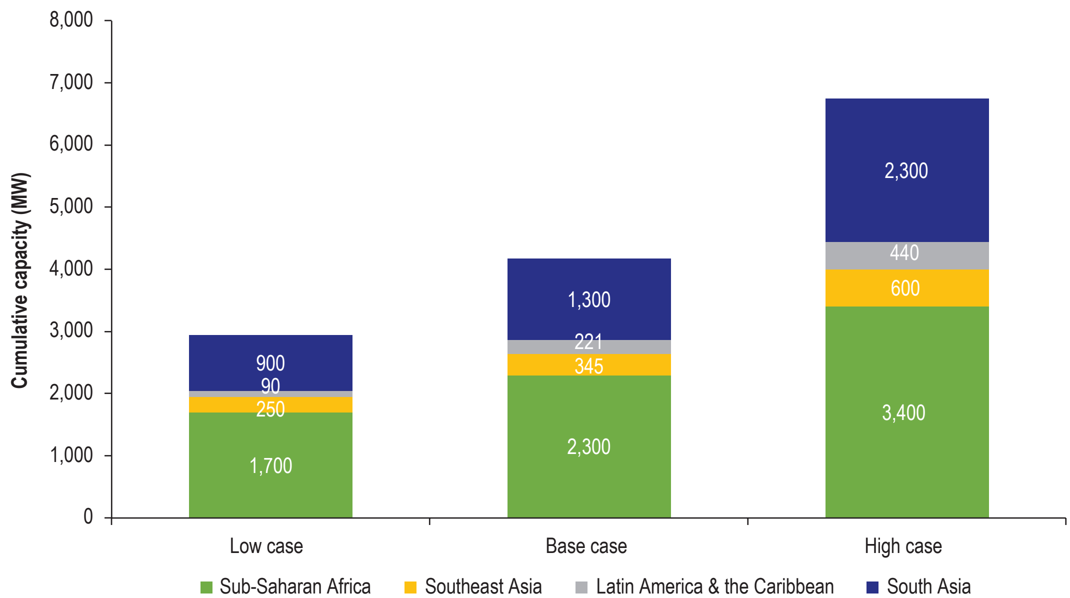
Source: CES.

power. The ratio of the battery to mini grid capacity in these projects was 2. Mini grids achieve one to two days of power autonomy in government-funded projects; in privately funded projects, the stored power was exhausted at night. Government-funded mini grid projects are now minimal, as governments increasingly choose grid expansion for rural electrification.

The penetration of lithium-ion batteries in mini grids was higher in Sub-Saharan Africa than in Asia in 2019–20. Several countries, such as Senegal, provide CAPEX subsidies for installation of mini grids. The ratio of the battery size to the mini grid installed capacity in Africa was 2 to 3, in most projects using lithium-ion batteries (table 2.3).

In 2021, demand for batteries is estimated to have been around 180 MWh. Battery storage is projected to rise to 3.6 gigawatt hours (GWh) by 2030 (figure 2.6).

FIGURE 2.5: Projected Global Cumulative Capacity Addition of New Rural Mini Grids, 2022–30



Source: CES.

TABLE 2.2: **Battery Capacity in Selected Mini Grid Projects Installed in 2020–21**

			Battery Size			
Country	Year Installed	Mini Grid Capacity (kWp)	kWh	kWh/kWp	Battery Technology	Genset Size (kVA)
India	2021	39	110	2.8	Lithium-ion/LFP	No
	2020	23	96	4	Lead acid- Valved Regulated Lead-Acid (VRLA)	15
Myanmar	2021	713	1,312	1.8	Lithium-ion/ nickel-manganese cobalt (NMC)	315
	2019	55	160	2.9	Lithium-ion/ lithium ferro-phosphate (LFP)	n.a.
	2021	120	264	2.2	Lithium-ion/LFP	n.a.
Nigeria	2020	200	500	2.5	Lithium-ion/LFP	100
Uganda	2021	600	358	0.60	Lithium-ion/LFP	315

Source: Interviews with mini grid developers; engineering, procurement, and construction (EPC) contractors; and mini grid solution providers.

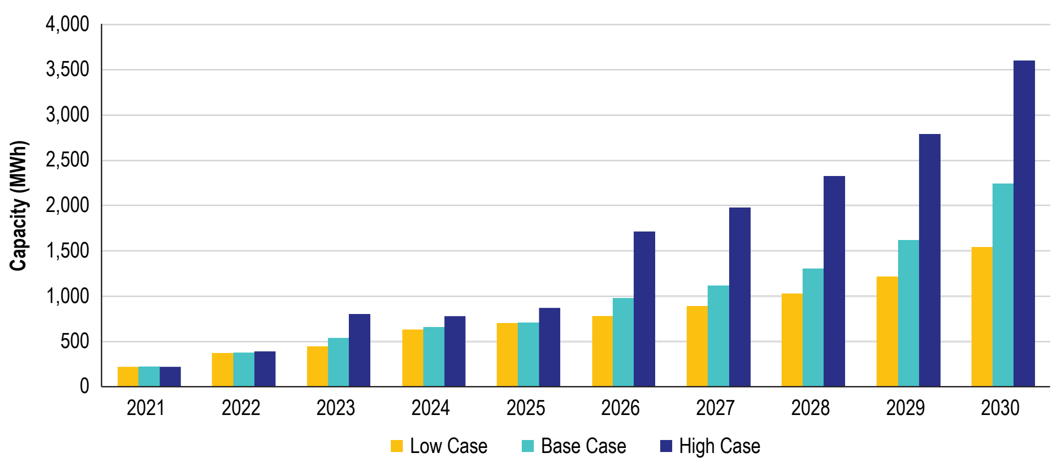
Note: n.a. Not applicable.

TABLE 2.3: **Ratio of Battery Capacity to Mini Grid Installed Capacity**

Battery Type	kWh/kWp
Lead acid	3
Lithium-ion	2
Other	3

Source: CES.

FIGURE 2.6: Projected Global Demand for Batteries for Rural Mini Grids, 2021–30



Source: CES.

NOTES

2. These plans are the Ethiopia Universal Electrification, the Ghana National Electrification Scheme, the Kenya Universal Electricity Access, the Rwanda Universal Electricity Access Program, and the Senegal Electrification Plan.
3. The number of rural households was calculated by estimating the average number of people per household in each region. Household size was assumed to be at least six in Sub-Saharan Africa and four to five in South Asia, Southeast Asia, and Latin America and the Caribbean (UNDESA 2022).
4. The Uganda mini grid is an outlier that relies more heavily on the diesel. It is an island mini grid in which the battery is used only to reduce diesel consumption. The battery is therefore smaller than in other mini grids. In many situations like this, batteries are much smaller than in mini grids in which solar PV and battery are the primary sources of energy.

3 SELECTION OF BATTERY TECHNOLOGY

3.1 FACTORS INVESTORS CONSIDER

Investors consider many factors in choosing a battery chemistry for a project, including the following:

- **Cycle life of the batteries:** Longer cycle lives are desirable, because battery replacement costs represent a significant share of overall project cost. Replacement cost is always higher than the original battery cost, because it includes the labor cost of replacement in addition to the battery cost.
- **Depth of discharge:** Batteries with higher depth of discharge capabilities can be more discharged without damaging the battery. They thus provide more available energy, reducing the cost of storing each unit of electricity.
- **Type of load connected to the grid:** In productive-end use applications (such as motors with high inductive loads that use a high initial current to start), lead acid batteries are not ideal, because high inrush currents can cause them to fail before the end of their expected lifetimes.
- **Energy density:** High-density products are more attractive than lower-density ones, because they offer more available energy. Energy density is a very important criterion for mobile applications, because more energy-dense technology has a higher payload capacity. Batteries need to be transported to remote locations; lighter versions reduce transport-related expenditure and ease the handling process.
- **C-rating (charge and discharge current rating):** The C-rating is a measurement of the maximum current a battery can be charged or discharged. Most mini grids use lead acid batteries with C-ratings of C/10, meaning that when discharging the battery can provide a level of current that would cause it to fully discharge in 10 hours. These batteries are not intended for heavy-duty applications with high discharge current requirements. When used for such applications, these batteries die quickly. Lithium-ion and redox flow batteries often have higher C-ratings.
- **Thermal runaway:** Thermal runaway is a phenomenon in which the internal impedance of a battery drops with increases in operating temperature. Reduced impedance results in increased current flow, exacerbating the temperature of the system and posing the risk of fire or explosion. Certain chemistries, including lithium-ion, face this issue, which requires attention.
- **Maintenance:** Battery technologies with fewer maintenance requirements fare better than technologies that require frequent or complicated maintenance. Flooded lead acid batteries require monitoring and the addition of distilled water. Redox flow batteries have pumps, seals, and cooling systems that require routine maintenance.
- **After-sales service:** After-sales service is very important, because capabilities to troubleshoot technologies may be limited in remote areas.
- **Integrated solution:** Plug-and-play solutions are operator friendly and can reduce tax costs in some jurisdictions. In some African countries, for example, import duties on individual grid components range from 20 to 30 percent while duties on an integrated unit can be as low as 5 to 10 percent.
- **Hardware compatibility:** Charge controllers and inverters have voltage windows within which they must operate; they also have built-in battery-charging cycles that are battery chemistry-specific. Many newer models have programmable settings that allow for different

types of technologies; some old equipment may not. For these reasons, developers can face compatibility issues when replacing a battery with a new chemistry type (for example, switching out old lead acid batteries with a new lithium-ion pack).

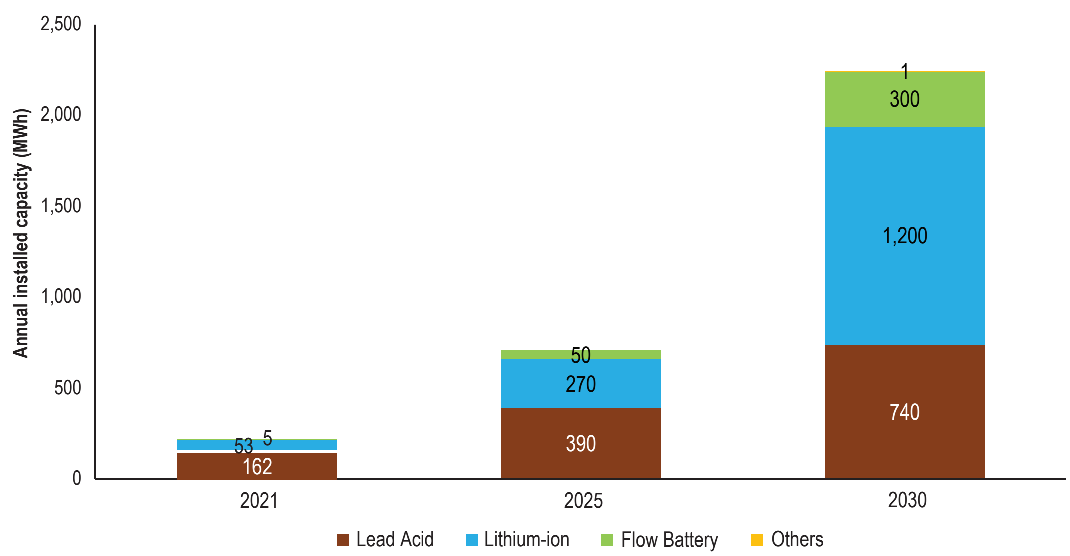
- **Maturity:** Developers tend to view mature storage technology as more reliable. Mature technologies tend to have well-developed supply chains and after-sale service.
- **Cost:** Cash-constrained developers may be more concerned with the upfront CAPEX than with the total lifetime cost of a technology. (See the Pugh matrix in table 3.2.)
- **Battery degradation:** Technologies with higher degradation rates need to be replaced more often and to have higher lifetime costs than other batteries.
- **Operating conditions:** Some storage technologies underperform or degrade more quickly than others, particularly in hot regions.
- **Environmental concerns:** End-of-life battery disposal can create environmental hazards. Some batteries contain heavy metals, such as cadmium and lead (a dangerous neurotoxin), which can leach into the ground water. Lithium-ion batteries pose fire hazards. Battery electrolytes are generally caustic. Developers need to take the recyclability of the battery technology into account in choosing a battery type. The ability to recycle lead acid and lithium-ion batteries varies across countries; recycling of lead acid batteries in many countries is generally easier and more commercially developed than recycling lithium-ion batteries. Some countries export battery waste.

Lead acid batteries long dominated the market for batteries for mini grid. These batteries are a mature, easily available technology with low upfront capital cost ($70–$100/kWh). They remain the battery technology of choice for some leading innovative mini grid developers (see case study 5.1).

Thanks to the declining cost of lithium-ion batteries, their lower LCOS, and longer battery life compared with lead acid chemistry, the trend is changing (figure 3.1). Lithium-ion battery penetration is projected to increase to 70 percent by 2030, from 55 percent in 2021, according to CES analysis.

In 2019, 19 percent of mini grid batteries in Asia and 29 percent in Sub-Saharan Africa were lithium-ion batteries. An ESMAP survey of 211 mini grids under construction or commissioned in 2020 and 2021 found that 69 percent used lithium-ion batteries and 31 percent used lead acid batteries (ESMAP 2022). Lithium-ion technology is used widely in stationary installations and electric vehicles. It provides a longer life and less maintenance than lead acid batteries. Case studies 5.2 to 5.5 profile mini grids using lithium-ion batteries in Uganda, Myanmar, Nigeria, and India.

FIGURE 3.1: Estimated and Projected Demand for Batteries for Mini Grids, by Type, 2021–30



Source: CES.

The upfront capital cost of lithium-ion batteries is projected to drop from a global average of $250/kWh in 2021 to $200/kWh by 2030. Driven by large-scale manufacturing plans for lithium-ion battery cells across the globe and increasing scale of production, the price of battery cells is projected to fall. However, most production will be used to satisfy demand for batteries in electric vehicles.

Vanadium redox flow batteries (VRFB) are batteries that use vanadium as an electrolyte to store energy. Several factors make them attractive for mini grid applications:

- They last six or more hours.
- They have operational lives of up to 10,000 cycles or 20 years.
- They allow 100 percent depth of discharge.

However, the upfront capital cost of VRFBs is $350 to $450/kWh, according to battery manufacturers interviewed in 2022. Case study 5.6 focuses on a solar mini grid using a VRFB battery on an island in the Maldives. An innovative business model involving vanadium leasing reduced the upfront cost by 40 percent. In this model, vanadium metal is leased to the end-user and purchased back at the end of life of the battery. Vanadium can be 100 percent recovered at the end of life of the battery. Mini grids in India, China, Korea, Sub-Saharan Africa, and Southeast Asia have already installed this battery chemistry.

Other technologies include advanced lead acid chemistry, sodium batteries, fuel cells, and flywheel storage. Together, these technologies are used in fewer than 0.5 percent of mini grids installations. Market share by 2030 is likely to remain below 1 percent of annual installations. Case study 5.7 profiles a mini grid with a flywheel energy storage system in the Philippines.

3.2 COMPARISON OF STORAGE TECHNOLOGIES

Table 3.1 compares storage technologies. The comparison is quantitative in nature; the importance of each parameter depends on the application of the battery.

Nickel sodium chloride technology is unique in requiring very high temperatures to keep the salt/electrolyte in a molten form. Achieving this requirement may be difficult in remote locations.

Table 3.2 presents a Pugh matrix to compare various advanced battery technologies. This tool helps users select the best option by scoring technologies on a scale of 1 to 10 on a set of parameters. Ranks are multiplied by assigned weights; the result is a weighted average for each option.[5] This analysis reveals that lithium-ion is the most suitable technology.

TABLE 3.1: **Technical Parameters of Selected Battery Technologies**

	Battery Type					
Parameter	Lead Acid	Advanced Lead Acid	Lithium-Ion	NiNaCl2	Vanadium Redox Batteries (VRB)	Zn–Br (flow tech)
Battery chemistry	Lead	Lead, carbon electrodes	NMC/LFP	Nickel, sodium chloride	Vanadium	Zinc, bromine
Round-trip efficiency (percent)	60–80	80–90	85–95	70–90	60–70	68–70
C-rate	C/10	C/5	C/4-2C	C/6-C/8	C/5-C/8	C/3–C/4
Depth of discharge (percent)	50–60	70–80	90	80	100	100
Energy density (Who/kg)	40–60	27–30	80–150	65–70	7–8	15–25
Cycle life	500–1,000	1,200–1,800	2,000–6,000	4,500–5,000	7,000–10,000	3,000–3,500
Safety	High	High	Medium	Medium	High	Medium
CAPEX ($/kWh)	80–150	120–300	250–350	750–1,000	600–1000	750–800
Toxicity of chemicals	High	High	High	Medium	Medium	High
Operating temperature (°C)	–20–50	–20–50	0–55	270–350	15–55	20–50
Self-discharge (percent/month)	10–15	3–5	0.5–2	5	5	60[a]

Source: CES.

Note: Using $(1-.03)^{30}$ a daily self-discharge of 3 percent equates to a monthly self-discharge of about 60 percent.

TABLE 3.2: **Pugh Matrix Ranking of Storage Technologies in Mini Grid Applications**

Parameter	Weight (Percent)	Li-Ion	Lead Acid	Advanced Lead Acid	VRFB	Zn-Br	Nickel Sodium Chloride
Battery life	25	8	5	7	9	8	9
Heavy-duty usage (higher C-rate)	15	9	5	7	7	7	7
Maintenance	10	9	6	8	7	7	6
After-sales service	15	8	9	8	6	6	5
Maturity of technology	10	8	10	6	7	7	6
Cost	25	9	10	8	6	6	5
Weighted-average score		8.5	7.5	7.4	7.1	6.9	6.5

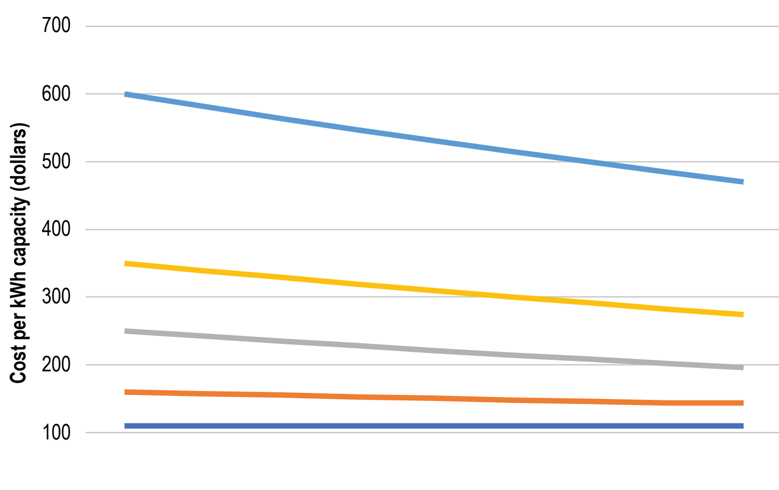
Source: CES.

Few companies manufacture redox flow batteries; they perform poorly on service and CAPEX compared with lead acid and lithium-ion. They score well in terms of battery life, however. Redox flow batteries are also considered environmentally friendly, with lifetimes of 20 to 25 years; their vanadium and zinc components are relatively easy to recycle. As more units are manufactured, the CAPEX of flow batteries might drop, making them an attractive choice for mini grid developers.

3.3 THE CAPITAL COST OF BATTERIES

Figure 3.2 provides CES' estimates and forecasts of battery costs for 2022–30. Lead acid is a mature technology and may not see significant price drops in the future. Lithium-ion is benefitting from significant learning curves; price levels are forecast to drop until 2030. There is upward pressure on the cost of raw materials used by lithium-ion technology, however, because of

FIGURE 3.2: Cost of Six-Hour Storage, by Battery Type, 2022–30



	2022	2023	2024	2025	2026	2027	2028	2029	2030
Lead acid	110	110	110	110	110	110	110	110	110
Adv. lead acid	160	158	155	153	151	148	146	144	144
Li-ion LFP	250	243	235	228	221	215	208	202	196
Vanadium flow	350	340	329	319	310	301	292	283	274
NiNaCl2	600	582	565	548	531	515	500	485	470

Lead acid   Adv. lead acid   Li-ion LFP   Vanadium flow   NiNaCl2

Source: CES.

demand from the electric vehicle industry. Prices are expected to become stable once the mining industry catches up with new demand.

Battery capacity is nominal capacity; it does not take into account different recommended depth of discharge to avoid damaging the battery. For a flow battery, the cost per kWh drops significantly as storage duration increases, because kWh capacity in a flow battery is a function of the size of the storage tanks and electrolyte volume.

3.4 THE LEVELIZED COST OF STORAGE

The levelized cost of storage (LCOS) is the ratio of the discounted value of total expenditure and total electricity delivered by the storage unit over its lifetime. It is given by equation 3.1 (Mayr 2016):[6]

$$LCOS = \frac{CAPEX}{\#cycles * DOD * C_{rated} * \sum_{n=1}^{N} \frac{(1 - DEG * n)}{(1+r)^n}} + \frac{O\&M * \sum_{n=1}^{N} \frac{1}{(1+r)^n}}{\#cycles * DOD * C_{rated} * \sum_{n=1}^{N} \frac{(1 - DEG * n)}{(1+r)^n}} - \frac{\frac{V_{residual}}{(1+r)^{N+1}}}{\#cycles * DOD * C_{rated} * \sum_{n=1}^{N} \frac{(1 - DEG * n)}{(1+r)^n}} + \frac{P_{elec-in}}{\eta(DOD)}.$$

The first term in the equation addresses the CAPEX-associated costs of storage, the second covers O&M costs, the third reflects the residual value after the project lifetime, and the fourth addresses the cost of the energy used to charge the battery, including the cost of electricity lost as a result of the battery's inefficiency (more electricity must be put into the battery when charging than comes out when discharging). Table 3.3 describes and provides values for these variables.

The LCOS formula includes a discount rate for the weighted-average cost of capital of 11.5 percent, reflecting a 15 percent expected return on equity and debt interest of 10 percent with a 70/30 debt to equity ratio. The calculations assume a linear degradation of battery capacity across the battery's lifetime. The LCOS includes costs associated not only with the battery but also with the battery inverter.

The calculation of LCOS also includes the cost of charging the battery. These costs need to be included, because efficiency losses during a complete charge-discharge cycle means that more energy has to be obtained for charging the battery than can be delivered when discharging. This loss of energy can constitute a significant cost factor. Not included in these energy loss calculations are auxiliary air conditioning, which may can help certain battery types (for example, lead acid and lithium-iron phosphate) achieve longer lifetimes.

Although the cost per nameplate capacity ($/kWh) of lead acid batteries is considerably lower than that of lithium-ion, the superior cycle life, efficiency, and permissible routine depth of discharge of lithium-ion batteries leads to a lower LCOS (figure 3.3).

Lithium-ferro-phosphate (LFP) battery technology offers low-cost storage for all the durations considered. The LCOS decreases as the storage duration increases from four to eight hours, because the per kW cost of the power conversion electronics, such as inverters, is spread over more kWh of storage.

VRFB technology decouples the power and energy ratings of the system. It expands storage capacity by adding extra electrolyte to the tank, which causes a significant drop in the CAPEX per kWh of the system as the system duration increases.

Figure 3.4 shows the contributions of CAPEX, O&M, residual value, and electricity cost to the LCOS for the five technologies. Levelized CAPEX costs incorporate not only the battery capital cost but also the battery lifetime and the allowable depth of discharge. Batteries with long lifetimes have a somewhat lower residual value, because the trade-in value is discounted farther into the future. Batteries with higher round-trip efficiencies have lower charging electricity cost, because less electricity is dissipated as heat in the charge/discharge process.

Figure 3.5 shows estimates and forecasts of the LCOS based on CAPEX and performance forecasts. Lithium-ion LFP batteries are expected to increase their lead as the lowest-cost battery technology for mini grids, thanks to increased performance and cost reductions through their widespread deployment in electric vehicles, stationary grid-based electricity storage, and other applications. Lead acid batteries remain a high-cost choice, with only a slight decline in their price (because the technology is mature). VRFB becomes increasingly competitive with lead acid batteries.

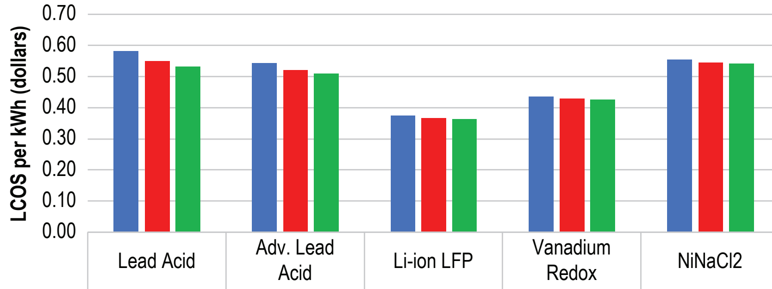
TABLE 3.3: **Descriptions and Assumed Values in Levelized Cost of Battery Storage Calculations**

Variable	Description	Comments	Lead Acid	Advanced Lead Acid	Li-ion LFP	Vanadium Redox	NiNaCl2
CAPEX	Upfront capital cost including battery inverter ($/kWh capacity)	Cost varies depending on hours or storage	135–160	185–210	275–300	314–507	625–650
	Hours of storage	Intermediate variable in CAPEX	4, 6, and 8				
	Battery cost ($/kWh capacity)	Intermediate variable in CAPEX	110	160	250	50–300[a]	600
	Inverter cost ($/kW)	Intermediate variable in CAPEX	200				
	Associated inverter cost ($/kWh capacity)	Intermediate variable in CAPEX	25–50 for systems with four to eight hours storage				
Number of cycles	Charge/discharge cycles per year	One cycle assumed per day	365				
DOD	Depth of discharge (percent)	Designed allowable depth of discharge	50	70	90	100	80
DEG	Degradation (percent of capacity degraded per year)	Degrades to 80 percent capacity by end of project life	5	5	1.5	0.7	1.3
N	Battery lifetime (years)	Calculated from number of cycles	4	4	13	27	15
r	Discount rate of weighted-average cost of capital (percent)	70 percent debt at 10 percent interest + 30 percent equity with 15 percent expected rate of return	11.5				
O&M	Operations and maintenance cost ($/year)		10	10	10	20	10
$V_{residual}$	Residual value of equipment at end of project lifetime ($)	Estimated at 10 percent CAPEX cost, discounted to end of project year	16	21	30	51	65
$P_{elec-in}$	Electricity tariff for battery charging ($/kWh)		0.16				
$\eta_{(DOD)}$	Total charge-discharge efficiency, including battery efficiency and two-way inverter efficiency (percent)		75	75	85	70	90

Source: Interviews and desk research conducted by CES.

Note: a. The cost of redox batteries declines with increasing hours, because electrical capacity depends on the volume of electrolyte in tanks.

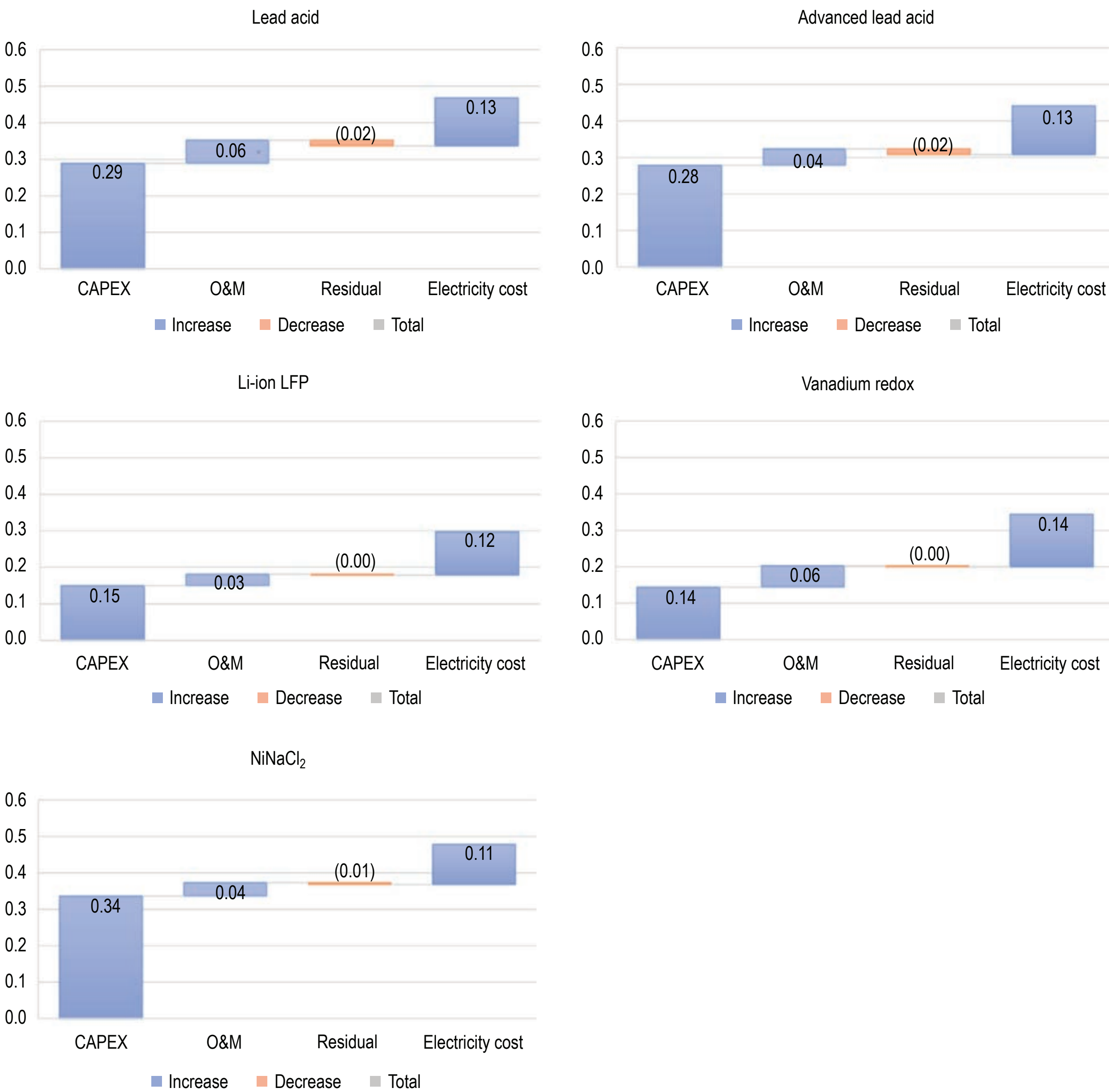
FIGURE 3.3: Levelized Cost of Storage (LCOS) of Selected Battery Types at Different Durations



	Lead Acid	Adv. Lead Acid	Li-ion LFP	Vanadium Redox	NiNaCl2
4 hours	$0.58	$0.54	$0.38	$0.44	$0.56
6 hours	$0.55	$0.52	$0.37	$0.43	$0.55
8 hours	$0.53	$0.51	$0.36	$0.43	$0.54

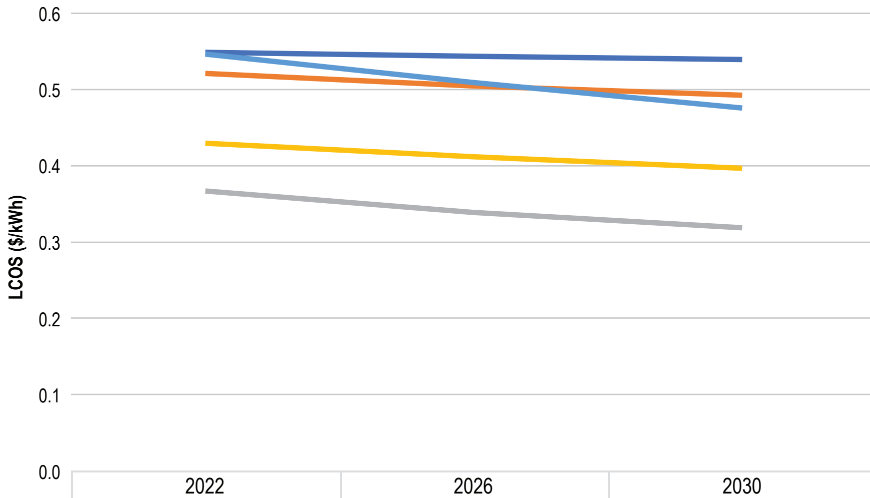
Source: CES assumptions applied to equation 3.1.

FIGURE 3.4: Contributions of Capital Expense, Operations and Maintenance, Residual Value, and Electricity Cost to the Levelized Cost of Storage, by Battery Type



Source: CES assumptions applied to equation 3.1.

FIGURE 3.5: Estimated and Projected Levelized Cost of Storage for Six-Hour Duration System, by Battery Type



	2022	2026	2030
Lead Acid	0.55	0.54	0.54
Adv. Lead Acid	0.52	0.50	0.49
Li-ion LFP	0.37	0.34	0.32
Vanadium Redox	0.43	0.41	0.40
NiNaCl2	0.55	0.51	0.48

Source: CES assumptions applied to equation 3.1.

NOTES

5. Several mini grid developers worked together to assign weights for each parameter.
6. Implementation of the LCOS methodology for this section and development of the accompanying spreadsheet was conducted by ESMAP senior consultant Chris Greacen, using cost and performance assumptions and battery CAPEX forecasts developed by CES. The LCOS spreadsheet model is available for download, so that interested readers can explore the implications of other assumptions.

4 FUTURE TRENDS IN BATTERY STORAGE FOR MINI GRID APPLICATION

Many mini grid developers are working to reduce the risk of stranded assets caused by expanding the grid. This financial risk can be mitigated by rolling out third-generation mini grids, which use advanced technology such as pre-paid meters that make them integration-ready. Advanced lithium-ion technology and associated battery management systems may allow transition to smart grids that can be operated remotely. The success of these new-generation mini grids in dealing with the risk of asset stranding depends on the proportions of productive-use appliances in consumption, because productive appliances require reliable power for longer hours and therefore require heavy-duty storage capability.

The spider web plot in figure 4.1 shows the projected improvement in the battery performance based on key performance parameters. These plots are application agnostic, and not all parameters are relevant for mini grid application.

Cost, cycle life, and roundtrip efficiency are highly important to the cost of service; increased roundtrip efficiency increases the available units of electricity and reduces the LCOS.

All of these technologies are poised for some degree of performance improvement. Flow battery technology, which looks promising for stationary energy storage application (see the Pugh matrix in table 3.2), is poised to witness some decline in CAPEX.

The rest of this section describes several promising alternatives. They include but are not limited to lithium-ion batteries, iron-air batteries, hydrogen-powered storage, and flywheel energy storage.

4.1 USED LITHIUM-ION BATTERIES AS A STATIONARY STORAGE SOLUTION

The average discarded lithium-ion battery still has a capacity of around 65 percent left. A German-Indian nonprofit startup—Nunam, funded by Audi Environmental Fund—is working on a way to use repurpose these used batteries for applications in which high energy density is not a requirement (Audi 2022).

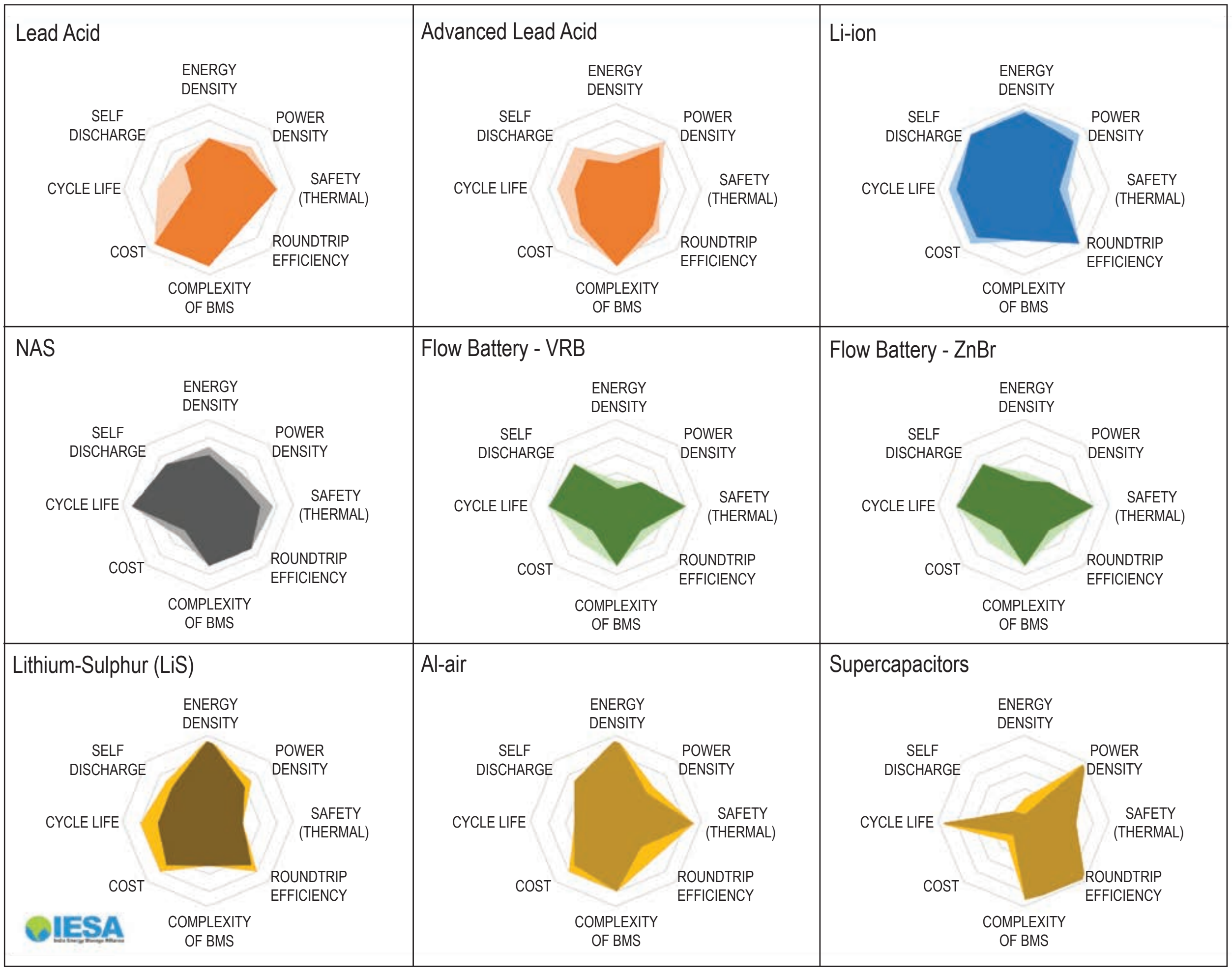
Korea launched a program to reuse lithium-ion batteries, in order to meet its goal of selling 1 million electric vehicles by 2025. Under this program, the government funded a project to demonstrate MWh-level reusing practices of old lithium-ion batteries. LG Chem will collect used electric vehicle batteries to build energy storage systems (ESS) (Crompton 2022).

A significant demonstration of large-scale usage of used batteries for ESS is the 3 MW/2.8 MWh energy storage system installed at Amsterdam's Johan Cruyff Arena. This ESS includes 590 battery packs, 250 of which are used modules from electric vehicles. Each of these modules had an original capacity of 24 kWh; during their second life at the stadium, they exhibited usable capacity of 20 kWh (Pagliaro 2019).

China decided to end the use of lead acid batteries in its fleet of telecom towers, powering them instead with used lithium-ion batteries. It has signed agreements with 16 electric vehicle and battery manufacturers. The cost of battery packs made of used lithium-ion batteries is around $100/kWh, on a par with the price of new lead acid batteries (Jaio 2018).

With growing electric vehicle uptake and a useful lifetime of around seven to eight years for lithium-ion batteries, there may be a burgeoning market of used lithium-ion batteries ready to be used for stationary ESS applications. Using such battery packs could reduce the CAPEX of mini grid projects.

FIGURE 4.1: Projected Changes in Battery Performance Between 2018 and 2025, by Type of Battery



Source: Sen 2019.

Note: Figure reflects data from commercially available products as of 2018. Expected performance improvements through 2025 are shown as darker regions. Performance metrices are rated on a 0 to 10 scale, where 10 indicates the best performance.

4.2 IRON-AIR BATTERIES FOR LONG-TERM ENERGY STORAGE

Batteries based on iron, which is plentiful on the Earth's crust and nontoxic, hold promise for longer-term energy storage. Iron-air batteries use iron as the anode and oxygen in the air as the cathode.

Form Energy, a US energy storage company, has developed an iron-air battery for utility applications that is designed for a 100-hour discharge. It is targeting a cost of $20/kWh—less than one-fifth the cost of large-scale lithium-ion batteries. The electrolyte used in these batteries is a nonflammable, water-based solution; the reaction involves reversible oxidation of iron pellets—essentially reversible rust (Plautz 2021).

One drawback of iron-air batteries is their low energy density. They are about 100 times heavier than lithium-ion batteries, with each battery unit about the size of a washing machine. Because they release energy slowly, they likely need to be coupled with energy storage that can release electricity more quickly, such as lithium-ion batteries. In this configuration, they could possibly replace diesel generators in some mini grids.

ESS Inc. is another company building long-term battery storage based on iron. It has developed a low-cost iron flow battery optimized for 6 to 12 hours of storage and a claimed cycle life exceeding 20,000 cycles.

4.3 SODIUM ION BATTERIES

Sodium-ion (Na-ion) batteries are quickly emerging as a candidate for energy storage for solar mini-grids. In November 2022, China's Hina Battery factory started to produce sodium ion batteries on a 1 GWh a year production line (Kang 2022), which it expects to expand to 5 GWh a year. The largest Chinese manufacturer of lithium-ion batteries, Contemporary Amperex Technology Co Ltd (CATL), also plans to start mass production of sodium ion cells in 2023 (CATL 2021).

These batteries have several advantages over lithium-ion batteries:

- Abundant and inexpensive raw materials: Unlike lithium, sodium is widely available and inexpensive, making Na-ion batteries more accessible and cost-effective. Sodium is about 1,000 times more prevalent on the Earth's crust than lithium; it is available from soda ash or sea salt. Initially, the fact that sodium ions are larger than lithium-ions presented challenges for cathode and anode materials in the battery, but recent developments by the Chinese battery manufacturer CATL in the use of inexpensive Prussian Blue as a cathode material and a porous hard carbon for the anode appear to have overcome these problems. Aluminum is used as a current collector in the cells; it is less expensive than copper used as a current collector in lithium-ion cells.
- Reasonable cycle life: Cycle life for sodium ion batteries is reportedly 3,000 cycles (SMM 2021). This is about half of lithium iron phosphate cycle life but may expand as manufacturing expertise grows.
- Comparable energy storage capacity: CATL recently released a sodium ion battery with energy density (160 Wh/kg), comparable to lithium-ion (>200 Wh/kg). The company has patented a sodium ion battery with an energy density of 200 Wh/kg. The lower energy density of sodium ion batteries make them suitable for low-end electric vehicles as well as stationary applications like mini grids.
- Ability to use adapted li-ion manufacturing processes: The production of sodium-ion batteries can follow the relatively mature lithium battery production process, with material changes but not manufacturing process changes in electrolytes, anodes, or cathodes (DNKPOWER 2022).
- Enhanced safety and stability: Sodium batteries have better thermal stability than lithium-ion batteries. They are therefore safer.

4.4 HYDROGEN-POWERED STORAGE

Some players are offering hydrogen-powered energy solutions as an alternative to traditional diesel generators. These solutions make use of hydrogen's ability to store energy for longer periods than batteries. They could be used to power mini grids in remote areas.

Tiger Power, in association with VITO (the Flemish Technological Research Institute), produces turnkey products that can harvest solar energy using a foldable solar panel unit that can be transported to areas of interest. The electricity generated is stored in batteries or converted to hydrogen for storage in tanks. The company's algorithms optimize the usage of the battery and electrolyzers. This product is offered as an alternative to diesel generators and used for fairs, music festivals, farms, and other remote locations that need temporary on-demand electricity (VITO 2022).

The state-run National Thermal Power Corporation (NTPC) Ltd., India's largest integrated power producer, awarded a green hydrogen project to one of its plants in southern India. The project's objective is to produce and store green hydrogen using a 240 kW solid oxide electrolyzer. The electricity it generates with 50 kW solid oxide fuel cells is meant to be used during the evening. This unique, large-scale project is envisaged to be a precursor to multiple such micro grids deployed in the future (Mint 2022).

The Japanese company Toshiba Energy Systems & Solutions Corporation produces an integrated hydrogen energy system called H2One. Each unit contains an electrolyzer, a fuel cell, a battery, and a storage tank. The units store renewable electricity in batteries and produce hydrogen that is held in storage tanks. The system delivers the stored electricity on demand (Green Car Congress 2022). An integrated solution using a small container could be used to power mini grids.

4.5 FLYWHEEL ENERGY STORAGE FOR MINI GRID STABILIZATION

OXTO Energy, a British company, has developed and patented a new flywheel energy storage device that will deliver safe, scalable storage at a competitive cost, with high energy density and low physical footprint (Gill 2022). The flywheel stores kinetic energy in a vacuum in the form of a rotating mass, which it converts back into electricity using an efficient switching mechanism. Its innovative power electronics allow the system to alternate between high power and energy. While providing fast response, it allows a quick switch between load and supply modes.

OXTO's flywheel has a lifetime of at least 25 years and can be built with readily available materials. Other advantages include increased charge-cycle capabilities (more than 100,000, compared with 5,000 to 10,000 for batteries); full output within 20 measurement signals; and the lack of hazardous chemicals or fire hazards. OXTO's flywheels can be produced as 65 kW modules for high power and low-energy applications like frequency and voltage regulation. The duration of storage for flywheel technologies is considered to be less than 30 minutes. Oxto's standard unit has a power output of 65 kW and the ability to store 5 kWh of energy.

Flores, another mini grid developer, uses a mix of diesel, wind, and hydro generation to power some islands in Portugal. The installed system consists of four hydro power generators (3×250 kW $+ 1 \times 600$ kW), two wind turbines (2×315 kW), and four diesel generators (3×550 kW $+ 1 \times 810$ kW). Because of the type of control used on the hydro and diesel generators, the renewable energy penetration of the Flores system was limited primarily by system stability; step response, spinning reserve, and reactive power requirements were not limiting factors. A 350 kW/5 kWh flywheel energy storage system was added to the system to improve frequency and voltage stability.

Flywheels have good technical characteristics, but cost, self-discharge, and the limited ability to store large quantities of energy still constrain their use in small standalone PV systems. They can be very useful in PV-hybrid systems, however, for both addressing power quality issues in inverter-dominated systems and bridging power until a diesel generating set is started and ready to be brought on-line in genset dominated ones.

5 CASE STUDIES

The case studies described in this section highlight global deployment of emerging storage technologies. Each case study describes the mini grid's rating, energy storage rating, battery chemistry, businesses served, communities electrified, and the way in which the electricity is used.

5.1 SOLAR MINI GRIDS WITH LEAD ACID BATTERIES: THE HUSK POWER MICROGRIDS INITIATIVE IN INDIA AND NIGERIA

Founded in 2008, Husk Power Systems owns and operates more than 200 community solar mini grids in India, Nigeria, and Tanzania. More than 130 mini grids in India, in the states of Bihar and Uttar Pradesh, have total installed capacity of about 8.5 MW. They provide 24/7 electricity to more than 10,000 small businesses.

In November 2021, Husk began operating its first six mini grids in Nigeria's Nasawara State. Within several months, it had installed 12. In addition to the sale of electricity, the company is engaged in a range of services, including water purification, agro-processing, and e-transportation.

Husk uses a hybrid supply system consisting of solar PV, batteries, and biomass gasification. When it first enters a village, it usually starts with about 50 kW of installed capacity. It considers the exact size of each component a commercial secret; the solar PV panels in India averaged 30 kWp of capacity, with the remaining capacity coming from biomass. In Nigeria, the minimum size of the installed solar PV is 50 kWp (figure 5.1). Husk can add generating capacity as demand of customers increases.

Battery backup

Husk's standard configuration includes a valve regulated lead acid (VRLA) battery that acts as the mini grid's main power source between 11 pm and 7 am. It can also act as a backup supply source between 7 am and 11 pm if the solar PV and biomass are not functioning as expected. The batteries are designed for up to six hours of autonomous operation. Using a machine-learning approach to battery management and generator dispatch, Husk has been able to increase the lifetime of its lead-acid batteries to about five years, from a previous average of about three and a half, by ensuring that batteries do not discharge too deeply or chronically overcharge. The company's careful approach to monitoring and controlling lead acid charge-discharge cycles and its ability to obtain attractive volume pricing on Indian-made lead acid batteries are two reasons it uses lead acid batteries.

Daytime operations

Solar PV is the main source of power at every location. The PV system is combined with the biomass power plant system to supply electricity demand on rainy and foggy days. When excess electricity is produced, it is used to charge the battery. Solar PV panels produce about 75 percent of the electricity generated at a typical Husk mini grid in India and Nigeria.

Night-time operations

Husk's biomass gasification system is switched on around 5 pm. It burns waste feedstock, such as rice husk or corn cobs, and can serve customers until 11 pm. Husk estimates that the LCOE from its gasification system at full load is 30 percent lower than the LCOE from diesel generation and

FIGURE 5.1: Husk Mini Grid in the Village of Akura, in Nasawara State, Nigeria

Source: Husk 2023.

35 percent lower than the LCOE from battery storage.[7] This gasification system ensures a lower cost of electricity production at night than withdrawing the electricity from batteries or generating it from a diesel genset. As it has largely automated the gasification system, Husk does not require a full-time onsite operator to manually run the system.

Tariffs and metering

Tariffs for all customers are based on time of use, with a discount of 15 to 20 percent for daytime use. The tariff rate declines once a customer crosses a minimum threshold of 120 kWh per month. Nearly all customers prepay for service. Meters can limit customers' maximum instantaneous loads. Power consumption and generation data are monitored in near real time (at five-minute intervals). Husk tracks how long it takes to resolve customer complaints, ensuring that that reported problems are fixed within four hours for households and two hours for commercial customers.

5.2 SOLAR HYBRID MINI GRID WITH LITHIUM IRON PHOSPHATE BATTERIES: THE LOLWE ISLANDS, UGANDA

Engie Energy Access is the leading mini-grid and off-grid pay-as-you-go solar energy solutions company in Africa. Equatorial Power is a Uganda-based renewable energy company with expertise in agro-processing, business incubation, water purification, and e-mobility. In January 2022, under it Engie-Equatorial (EE) joint venture, the two companies commissioned a solar mini grid in the Lolwe Islands, Uganda, situated in Namayingo District near Lake Victoria. The island's 15,000 people have limited access to electricity and are heavily dependent on diesel gensets for lighting and powering fishing boats around the lake. The intervention provides clean and reliable electricity for powering houses, enhancing livelihood opportunities, and limiting the use of fossil fuels for energy generation (Figure 5.2).

System sizing and distribution network

A hybrid solar mini grid of 600 kWp with LFP battery storage capacity of 600 kWh paired with emergency gensets of 200 kilovolt-amperes (kVA) is ensuring safe and reliable electricity to residents of the island. The mini grid provides connections to over 3,800 consumers, including 3,026 households. The connections are powered over 45 kilometers of medium- and low-voltage distribution networks.

Productive use of solar energy

Local businesses have been supported by EE's business incubation and asset financing program. EE's integrated program also features an electric mobility integration platform with electric outboard engines for boats and e-motorcycles, an agro-processing hub, water purification

FIGURE 5.2: Hybrid Solar Mini Grid in the Lolwe Islands, Uganda

Source: Engie Energy Access 2023.

FIGURE 5.3: Ice Manufacturing Unit Powered by Engie-Equatorial's Solar Mini Grid in the Lolwe Islands, Uganda

Source: Engie-Energy Access 2023.

systems, ice making, and other allied value-addition services, such as fish drying. All these productive end-use activities now rely less on diesel generators, and adding anchor and business loads has helped the developer use the mini grids up to their rated capacities. The mini grids will be able to generate around 800 MWh of energy annually, replacing 750 tons of carbon emissions.

The EE hybrid solar mini grid is not the only entity providing basic electricity access to inhabitants of the Lolwe Islands and contributing to overall development of the community. EE is engaging with New Energy Nexus to run a business incubation program in the region that will have compulsory 50 percent participation from women. One project outcome is EE's support of Lolwe female fishmongers to ensure inclusive recruitment and access to the services provided.[8]

5.3 SOLAR HYBRID MINI GRID WITH LITHIUM-ION NICKEL MANGANESE COBALT BATTERIES: SAN SETH, BOGALE, MYANMAR

More than 70 percent of Myanmar's population lacks access to electricity. To take electricity to the last mile, Mandalay Yoma has developed more than 45 solar hybrid mini grid projects across the country. With these efforts the company can touch more than 10,000 lives and generate more than 2,000 local jobs.

One successful mini grid installation is in San Seth, Bogale Township, in the Ayeyarwady region of Myanmar. A 713 Wp hybrid solar mini grid with storage capacity of 1,312 kWh of lithium-ion nickel manganese cobalt (NMC) batteries, paired with a 315 kVA genset, ensures safe and reliable electricity to residents of the township. The primary reason the developer selected NMC battery chemistry is the technology's life cycle of more than 3,000 cycles. The mini grid is providing connections to more than 1,300 households (MiTV 2023) and more than 20 businesses. All the connections are powered by an 11 kV, 400 volt multiple transformer and vacuum circuit breaker (VCB) switchgear protection for safer operations. The price at which electricity is delivered to these customers comes to around $0.20/kWh, with a contract period of 15 years with the township. The mini grids will be able to generate around 950 MWh of energy annually, replacing 900 tons of carbon emissions.

5.4 SOLAR HYBRID MINI GRID WITH LITHIUM IRON PHOSPHATE BATTERIES: DANCITAGI, NIGERIA

PowerGen started operation in 2011, with the vision of making clean, renewable energy accessible to more people in Africa. It now operates in Kenya, Nigeria, Tanzania, and Zambia. The company has installed more than 10,000 connections since its inception, commissioning more than 100 mini grids. Until 2019, the preferred choice of energy storage technology was maintenance-free lead acid. PowerGen has now shifted to lithium-based storage systems.

Nigeria has a low access to electricity, with only 55% of electrification rate (World Bank 2023). To achieve universal electricity access by 2030, it will need to connect 600,000 to 800,000 households a year, with a focus on rural areas.

More than 250 mini grids are currently installed in Nigeria. One installation is at Dancitagi, near Jutigi Edatti, where PowerGen has installed a 200 kWp solar hybrid mini grid with 500 kWh of lithium iron phosphate batteries and a 200 kVA diesel genset. Two years after installation, the load on the site had increased, and there was a demand for additional storage capacity. All connections are powered through low-voltage distribution networks of about 10 kilometers. Mini grids will be able to generate around 300 MWh of energy annually, replacing 250 tons of carbon emissions.

FIGURE 5.4: Hybrid Solar Mini Grid in San Seth, Bogale, Myanmar

Source: Mandalay Yoma 2023.

5.5 SOLAR MINI GRID WITH LITHIUM IRON PHOSPHATE BATTERIES: MAKHALA, AMPEREHOUR, INDIA

Amperehour, in collaboration with the Maharashtra Energy Agency Development Authority (MEDA), has commissioned solar mini grids at Makhala, Amravati, and Maharashtra, India. The technology—a combination of power electronics, software, and control systems—was developed by Amperehour. These features allow the mini grids to sustain variable loads and generation profiles. A machine learning-based algorithm control optimizes the load profile and informs decision making. Amperehour has deployed more than 200 such systems and software platforms on mini grids in India.

Amperehour has deployed 39 kWp of solar mini grids with 110 kWh of containerized LFP batteries and no backup diesel generators. These mini grids are providing connections to more than 127 customers. The electricity tariff shared by the developer is around $0.10/kWh, with a monthly fixed charge of $0.80 per connection. The mini grid developer has contracts with

FIGURE 5.5: Solar Hybrid Mini Grid with Containerized Energy Storage Solutions Installed by PowerGen in Dancitagi, Nigeria

Source: Power GEN Nigeria 2023.

FIGURE 5.6: Solar Mini Grid with Containerized Battery Energy Storage System in Makhala, India

Source: Amperehour 2023.

villages for periods of five years of O&M. These mini grids will be able to generate around 51 MWh units of energy a year, replacing 48 tons of carbon emissions annually.

These mini grids have brought access to electricity to more than 500 people in these villages. They power two drinking water pumps and two flour-milling units. People in these communities are now able to watch television, open new shops, and begin a digital education program at community schools.

5.6 SOLAR MINI GRID WITH VANADIUM REDOX FLOW BATTERY: MALDIVES

In 2020, H2, a Korean company specializing in redox flow batteries, built a 60 kW/250 kWh vanadium redox flow battery system (VRFB) linked to solar power generation at the Malahini Kuda Bandos Resort in Maldives. A 500 kW diesel generator alongside 293 kWp of photovoltaic power generation was installed at the resort utility facility building. It was designed and built to generate 1 MWh a day; the electricity stored through the redox flow battery was designed to be used when it rains or during power peak hours. The redox flow battery is capable of repeated full discharge/charge, from 0 percent state of charge to 100 percent. A diesel generator provides backup power.

The design, installation, and operation of the VRFB considered the installation environment, the container load distribution design, the impact load during maritime transportation, the special painting for the parts, and the salty environment of the resort island. Given the risk of a tsunami, the foundation was designed to be installed at a height of 60 centimeters or more from the ground. The electrical connection and the cooling piping were installed and insulated. The system was transported using barges and cranes; the electrolyte was injected at the site after separate transportation.

When solar power is generated during the day, some power is charged to the redox flow battery; constant voltage is discharged for a certain period of time in the evening. In order to improve efficiency, a weakness of redox flow batteries, power consumption was reduced through on/off control of the fan and the chiller; to reduce balance of plant (BOP) power consumption, it was configured by quantifying the flow rate by output.

The system was designed to be managed through remote monitoring in order to reduce follow-up management (given the characteristics of the island area), ensure safety, and improve efficiency through scenarios operations. Spare parts that are difficult to procure locally were procured in advance and built to be managed smoothly. Local engineers were trained to ensure stable post-management, and an operation manual was created.

5.7 SOLAR MINI GRID WITH FLYWHEEL ENERGY STORAGE SYSTEMS: THE PHILIPPINES

The island of Palawan, in the Philippines, has abundant sunshine but frequent power outages, because of an unreliable grid based on fossil fuels. The Philippine

FIGURE 5.7: Vanadium Redox Flow Battery Energy Storage System at the Malahini Kuda Bandos Resort, Maldives

Source: H2 2023.

government has undertaken several efforts to bolster energy supply in Palawan, including the use of solar PV for power generation. Using solar power systems in the province could provide significant benefits, including reduced carbon emissions, lower electricity costs, and improved energy security.

In 2023, following the publication of the study, the Palawan Electric Cooperative (PALECO) and S.I. Power Corporation (SIPCOR) signed a power supply agreement for a 15-year supply to the main grid in the province. SIPCOR will install a micro grid with solar PV and diesel generating sets along with flywheel energy storage systems (FESS) from Amber Kinetics to provide a reliable and sustainable solution. SIPCOR will support the main grid of Palawan with 20 MW of conventional and renewable solar energy technology backed up with FESS. This micro grid project consists of installing 20 MWp of solar technology and a 23.1 MW diesel genset plant; it will be supported with a 2.5 MW/10 MWh FESS.

SIPCOR will be responsible for the installation, operation, maintenance, and supply of power. The FESS will store excess generation, which can be discharged at nighttime, when the energy from the sun is no longer available. This energy-shifting application can provide continuous electric supply from the renewable energy sources to the electric cooperative, PALECO. While the FESS is in charging mode during the daytime, it can perform solar + storage application to address the intermittency and variability of solar PV, mitigate the effect of such intermittency on the PALECO distribution system, and ensure the stability and reliability of the system. The Amber Kinetics FESS will be electrically connected to PALECO, but all flywheel management systems will be integrated to the energy management system that SIPCOR is going to install and control.

The flywheels store electricity by spinning a large rotor at high speeds using an electric motor. When electricity is needed, the flywheel releases the stored energy, which can be converted back into electricity (Figure 5.8).

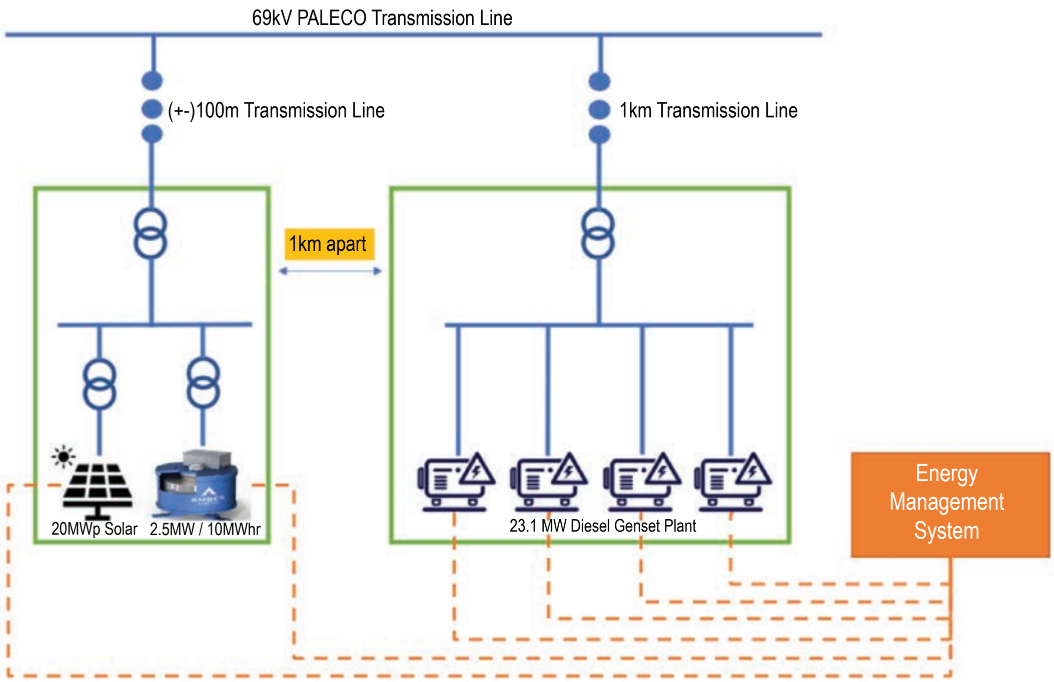
Flywheel-based energy storage systems have several advantages, including high efficiency, low maintenance costs, and long lifespans. Flywheels are made from recycled steel and do not contain any hazardous chemicals or toxic materials, making them environmentally friendly.

This project will provide numerous benefits:

- The system will provide reliable and sustainable energy to the island's inhabitants, reducing their dependence on an unreliable grid.
- The system will reduce the island's carbon footprint, by decreasing the amount of diesel fuel used to generate electricity.
- The system will promote economic growth by providing a stable source of energy that can support local businesses and industries.

SIPCOR will also install a diesel generator with a dependable capacity of 20 MW. It will be integrated into the solar + FESS system and connected along the distribution system. The generator will move from being the main source of power to becoming a back-up source of power.

FIGURE 5.8: Kinetic Energy Storage Systems in the Palawan islands, the Philippines



Source: Amber Kinetics 2023.

NOTES

7. If gasification has an LCOE that is 30 percent lower than battery storage, one might wonder why systems use batteries at all. The reason has to do with partial loads. After 11 pm, loads taper off, but some remain. Keeping the biomass gasifier running at these times would be inefficient and more expensive than cycling electricity through the battery. During the day, batteries provide a buffer between the production of solar electricity and consumption, without which electricity supply would be unstable.
8. For information on the project, see Equatorial Power (n.d., 2022) and Nomvuyo (2022).

6 RECOMMENDATIONS

Decentralized renewable energy mini grids are crucial to achieving universal energy access by 2030. Their success depends critically on the technologies used to store the energy they produce.

Until 2020, solar hybrid mini grids used primarily lead acid batteries for storage. In 2021, 44 percent of the newly built mini grids studied for this report used lithium-ion technologies. The next generation of energy storage will likely be dominated by lithium-ion and flow battery technologies, causing the LCOS of lithium-ion technologies to fall as technologies scale up for stationary and mobile applications.

The analysis conducted for this report yields several recommendations for energy storage practitioners:

- **Study battery performance in the field**. A ground-up analysis of the performance of the battery technologies at existing sites would increase understanding of storage solutions have measured up. This information would be useful for comparing battery performance in the challenging environments where mini grids are built and operate. Case studies of mini grids using battery technologies other than lead acid or lithium-ion would be particularly valuable.
- **Look beyond the upfront cost of batteries.** Teams considering mini grids should consider the LCOS or how the batteries affect the LCOE of the mini grid modeled in simulation/optimization software like HOMER Pro. Both of these approaches take into account operating expense, cycle lifetime, charge/discharge efficiency, and CAPEX.
- **Adopt battery safety and performance standards appropriate for mini grids,** in order to reduce risks and increase acceptance across the industry. Drawing on safety standards for batteries developed by the International Electrotechnical Commission (IEC), the United Nations, the Underwriters Laboratories (UL), and others, development institutions could suggest standards for mini grids that governments could adopt. Examples include the following:
  - **IEC 61427:** Secondary cells and batteries for renewable energy storage systems
  - **UL 1642:** Safety of lithium batteries (for cells)
  - **UN 38.3:** Transportation testing for lithium batteries
  - **IEC 62619:** Safety requirements for lithium-ion batteries for stationary applications
  - **IEC 62620:** Performance requirements for lithium-ion batteries for stationary applications.
- **Draft regulatory documents and procurement specifications carefully**, to ensure safety, quality, and performance while avoiding restricting choices in ways that lock in incumbent technology and rule out innovative storage technologies.
- **Identify and promulgate best recycling practices for energy storage technologies.** The lead acid battery recycling industry and supply chain is well established. Lithium-ion supply chains are more complex and involve multiple chemical and mineral processing plants, many of which are located in China. This geographic separation increases the challenges of lithium recycling. Anticipating the energy transition to lithium-ion technologies, government agencies should engage with industries and research institutes to develop management strategies for recycling lithium-ion batteries. National governments could collaborate with research institutes and

industry players to set up regional recycling hubs to help address regional collection issues.

- **Reuse repurposed battery technologies in stationary storage applications.** A standard to test and certify second-life battery packs would increase the confidence of mini grid players and funders for deploying repurposed batteries.
- **Exempt mini grid batteries from import duties, to make battery technology affordable and fast-track their deployment in mini grids.** One way to ensure that the tax exemption is not captured by standard internal combustion vehicle starting, lighting, and ignition (SLI) batteries is to restrict the exemptions to batteries above a certain capacity (for example, above 10 kWh or 15 kWh, with appropriate interpretive guidance provided to customs officials to recognize these capacity amounts when expressed in voltage and ampere-hour readings).
- **Provide skilling, reskilling, and upskilling programs to enhance the technical competency of technicians and engineers,** in order to reduce the down time of mini grid systems. Such training could improve troubleshooting and create employment opportunities in communities. Programming requires government, nongovernmental organization, and private sector support. During mini grid commissioning, batteries often reach sites months in advance; they require proper handling and storage. Detailed guidelines for safe handing, storage, and inspection of battery solutions would help avoid deep discharges, fires, and safety hazards.
- **Create standard operating procedures for understanding battery technology performance,** to help mini grid players get the most out of the asset. For example, understanding the effect of temperature and other ambient climatic conditions on life cycle and performance of a battery would help mini grid developers design cooling for the storage compartments. A standard operating procedure on the management of fire hazards could help reduce risks.

REFERENCES

AMDA (African Minigrids Developers Association) 2022. *Africa Minigrid Benchmarking Report Launched*. https://africamda.org/2020/08/13/africa-minigrid-benchmarking-report-launched/

Anderson, Jonathan O., Josef G. Thundiyil, and Andrew Stolbach. 2012. “Clearing the Air: A Review of the Effects of Particulate Matter Air Pollution on Human Health.” *Journal of Medical Toxicology: Official Journal of the American College of Medical Toxicology* 8 (2): 166–75. https://doi.org/10.1007/s13181-011-0203-1.

Audi. 2022. *Second-Life Battery: Green Power from Used Batteries*. https://www.audi-umweltstiftung.de/umweltstiftung/en/projects/greenovation/nunam.html

Bhata, M., and N. Angelou. 2014. “Capturing the Multi-Dimensionality of Energy Access.” *Live Wire* 2014/16, World Bank, Washington, DC. https://openknowledge.worldbank.org/entities/publication/12790d0f-87de-59e2-b5c6-9f33b2f4a759

Burger, J. 2022. *Mini-Grids Providing Electricity to Remote Areas in Senegal*. Nanyang Technological University, Singapore. https://www.ntu.edu.sg/cas/news-events/news/details/mini-grids-providing-electricity-to-remote-areas-in-senegal

CATL (Contemporary Amperex Technology Co., Ltd.). 2021. “CATL Unveils Its Latest Breakthrough Technology by Releasing Its First Generation of Sodium-Ion Batteries.” July 29. https://www.catl.com/en/news/665.html

Crompton, Paul. 2021. “South Korea Launches Four-Year Lithium-Ion Battery Reuse Scheme.” *Best Magazine*, February 18. https://www.bestmag.co.uk/south-korea-launches-four-year-lithium-ion-battery-reuse-scheme/.

DNKPOWER. 2022. *Will Sodium Batteries Replace Lithium Batteries?* https://www.dnkpower.com/will-sodium-batteries-replace-lithium-batteries/

EnDev. 2022. *Tiers, Markets and Sustainability: Trends in Rural Off-Grid Electrification Report*. https://endev.info/wp-content/uploads/2021/07/EnDev_Learning_and_Innovation_Agenda_Rural_Electrification.pdf

Equatorial Power. n.d. “Lolwe Island: About the Project.” https://equatorial-power.com/portfolio/lolwe-island/.

———. 2022. “Engie Equatorial Inaugurates Game-Changing Lolwe Mini-Grid in Uganda.” Press release, January 14. https://engie-energyaccess.com/uploads/banners/PRESSRELEASE_ENGIE-Equatorial-Lolwe-Island.pdf.

ESMAP (Energy Sector Management Assistance Program). 2022. *Mini Grids for Half a Billion People: Market Outlook and Handbook for Decision Makers*. Washington DC: World Bank Group.

Gill, R. 2019. “OXTO Energy–Flywheeling into the 21st Century.” Crowdforangels, June 6. https://crowdforangels.com/blog/oxto-energy-flywheeling-into-the-21st-century/

Green Car Congress. 2022. “Toshiba Integrated Hydrogen Energy System Starts Operation at Toranomon Hills Business Tower in Tokyo.” June 21. https://www.greencarcongress.com/2020/06/20200621-toshiba.html

Green Climate Fund. 2022. *Afghanistan Rural Energy Market Transformation Initiative: Strengthening Resilience of Livelihoods through Sustainable Energy Access*. https://pims.undp.org/attachments/6485/217063/1731085/1755460/FP-UNDP-27032020-6485-Annex%206b%20ESAR.pdf

IEA (International Energy Agency). 2022a. *SDG7 Data and Projections: Access to Electricity 2021*. Paris. https://www.iea.org/reports/sdg7-data-and-projections

———. 2022b. *Southeast Asia Energy Outlook 2022*. https://iea.blob.core.windows.net/assets/e5d9b7ff-559b-4dc3-8faa-42381f80ce2e/SoutheastAsiaEnergyOutlook2022.pdf

IRENA (International Renewable Energy Agency). 2022. *Tracking SDG7: The Energy Progress Report 2022*. Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jun/SDG7_Tracking_Progress_2022.pdf?rev=fbde91b736274cee985e00696df60cb4

Jaio 2018. China Tower can ‘absorb’ 2 million retired electric vehicle batteries. IDTechEx. https://www.idtechex.com/de/research-article/china-tower-can-absorb-2-million-retired-electric-vehicle-batteries/15460

Kang, L. 2022. “World’s First GWh-Class Sodium-Ion Battery Production Line Sees First Product off Line.” *CnEVPost,* December 2. https://cnevpost.com/2022/12/02/hina-gwh-sodium-ion-battery-production-line-first-product/

Mayr, F. 2016. “How to Determine Meaningful, Comparable Costs of Energy Storage.” Blog, March 3. https://apricum-group.com/how-to-determine-meaningful-comparable-costs-of-energy-storage/

Mint. 2021. “NTPC Gives First Green Hydrogen Microgrid Project to Simhadri Plant.” December 16. https://www.livemint.com/industry/energy/ntpc-awards-india-s-first-green-hydrogen-microgrid-project-at-simhadri-plant-11639558600422.html

MiTV (Myanmar International TV). 2023. "Sustainable Rural Development: Small-Scale Solar Power System Inaugurated in Bogale." March 15. https://www.myanmaritv.com/news/sustainable-rural-development-small-scale-solar-power-system-inaugurated-bogale

Nomvuyo, Tena. 2022. "Innovative Lolwe Hybrid Solar 600kwp Minigrid Inaugurated in Uganda." *ESI Africa*. https://www.esi-africa.com/industry-sectors/generation/innovative-lolwe-hybrid-solar-600kwp-minigrid-inaugurated-in-uganda/.

Nweke-Eze, C. 2022. *The Nigerian Electrification Project: An Example of a Successful Rural Electrification Design?* Research Institute for Sustainability (RIFS), Helmholtz Center, Potsdam, Germany. https://www.iass-potsdam.de/en/blog/2022/01/nigerian-electrification-project-example-successful-rural-electrification-design

Our World in Data. n.d. *Electricity Access, 2020.* https://ourworldindata.org/grapher/share-of-the-population-with-access-to-electricity

Pagliaro, M. 2019. "Lithium battery Reusing and Recycling: A Circular Economy Insight." *Heliyon* 5 (6).

Plautz, J. 2021. "Form Energy's $20/KWh, 100-Hour Iron-Air Battery Could Be a 'Substantial Breakthrough." Utility Dive, June 9. https://www.utilitydive.com/news/form-energys-20kwh-100-hour-iron-air-battery-could-be-a-substantial-br/603877/

SE4All (Sustainable Energy for All). 2022. *State of the Minigrids Market Report, 2020*. Vienna. https://www.seforall.org/publications/state-of-the-global-mini-grids-market-report-2020

Sen, R. 2019. *Solar PV Battery Manual*. Clean Network. https://www.thecleannetwork.org/pdf/Manual_0410.pdf

SMM. 2021. *Sodium-Ion Batteries Released by CATL, Potentially Threats to Li-Ion Batteries*. https://news.metal.com/newscontent/101556644/Sodium-ion-batteries-released-by-CATL-potentially-threats-to-Li-ion-batteries/

UN (United Nations). 2022. United Nations Population Division Data Portal. https://population.un.org/dataportal/.

UNDESA (United Nations Department of Economic and Social Affairs). 2022. *Population Facts*. https://www.un.org/en/development/desa/population/publications/pdf/popfacts/PopFacts_2019-6.pdf

VITO. 2022. *Tiger Power with the Help of VITO/Energyville Launches Solar and Hydrogen-Driven Alternative to Diesel Generators*. https://vito.be/en/news/tiger-power-help-vitoenergyville-launches-solar-and-hydrogen-driven-alternative-diesel

World Bank. 2019a. *Access to Electricity (% of Population).* World Bank Global Electrification Database. Washington, DC. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS

———. 2019b. *Population, Total.* Washington, DC. https://data.worldbank.org/indicator/SP.POP.TOTL

———. 2020a. *Access to Electricity (% of Population).* World Bank Global Electrification Database. Washington, DC. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS

———. 2020b. *World Bank Global Electrification Database: Access to Electricity (% of Population) – Sub-Saharan Africa*. Washington, DC. Accessed November 28. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=ZG

———. 2022a. *Access to Electricity (percent of population) – East Asia Pacific*. World Bank Global Electrification Database. Washington, DC. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=Z4

———. 2022b. *Access to Electricity (percent of population) – South Asia*. World Bank Global Electrification Database. Washington, DC. https://data.worldbank.org/indicator/EG.ELC.ACCS.ZS?locations=8S

APPENDIX A: TYPES OF ENERGY STORAGE

Energy storage technologies can be divided into five groups.

MECHANICAL STORAGE

Mechanical storage includes the following:

- Pumped hydro storage (PHS) stores electrical energy as the potential energy of water. It generally involves pumping water into a large reservoir at a high elevation, usually the top of a mountain or hill. When energy is required, the water in the reservoir is guided through a hydroelectric turbine, which converts the energy of flowing water to electricity. PHS is often used to store energy for long periods. It would be difficult to deploy for rural mini grids, given the need for topographical features to store large amounts of water and the difficult of making the technology competitive at mini grid scales.
- Compressed air energy storage (CAES) converts electrical energy into compressed air, which is stored in an underground cave or an above-ground high-pressure container. When excess or low-cost electricity is available from the grid, it is used to run an electric compressor, which compresses and stores air. When electrical energy is required, the compressed air is directed toward a modified gas turbine, which converts the stored energy into electricity. Several start-ups are testing storing the heat produced during compression. This type of CAES does not use natural gas to reheat the air upon decompression and is therefore emissions-free as well as more efficient. Storing energy at scale generally requires geological features such as a cavern.
- Flywheel energy storage stores electrical energy as rotational energy in a heavy mass. A typical flywheel energy storage system (FESS) consists of a large rotating disk or cylinder supported on a stator, the stationary component found in electric motors and generators. Stored electric energy increases with the square of the speed of the rotating mass, so materials that can withstand high velocities and centrifugal forces are essential. Flywheel technology is a low-maintenance and low environmental impact type of energy storage. It is suitable for high-power applications, thanks to their capacity to absorb and release energy in a very short period. Flywheel storage is more practical for high-power, high reaction time storage, to smooth out energy flows on the scale of milliseconds or seconds, not hours or days.

ELECTROCHEMICAL STORAGE

Electrochemical storage includes various battery technologies that use different chemical compounds to store electricity. Each of the numerous battery technologies has slightly different characteristics and is used to store and then release electricity for different durations, ranging from a few minutes to several hours.

There are two main categories of batteries: (a) traditional solid rechargeable batteries, where the chemical energy is stored in chemical reactions on the surface of solid metal electrodes, and (b) flow batteries, where chemical energy is stored in liquid electrolytes kept in tanks and pumped through the electrochemical cells.

Rechargeable batteries include the following.

- Lead acid batteries have been in commercial use in different applications for over a century (see case study 5.1). Lead acid is the most widely used battery technology worldwide.

High-performance variations of lead acid batteries are classified as advanced lead acid and have a longer life. Advanced lead acid batteries include carbon and bipolar lead acid type. Lead carbon lead acid batteries use carbon additives to improve energy density, cycle life, and charging-discharging properties. Bipolar lead acid batteries have bipolar plates, which eliminate the high current density seen around the terminals in a conventional design. Each point on an electrode is in contact with the current collector. This type of battery has higher specific energy and energy density, a footprint that is about 40 percent smaller footprint than the monopolar type, and is made of recyclable materials. It can be used in place of lead acid batteries.

- Lithium-Ion batteries are lightweight and have high density (see case studies 5.2–5.5). They are particularly well suited for portable applications (electric vehicles and electronic devices). Performance characteristics depend on the internal chemistry. Improvements have increased usage in stationary storage. Progress has led to a scale-up of manufacturing and installation and a subsequent rapid price reduction. Increasing energy densities in lithium-ion batteries have been key in tilting interest toward them.
- High-temperature sodium batteries are made from inexpensive nontoxic materials. They operate at a high temperature (above 300°C) and have long cycle lives. Sodium sulfur (NaS) batteries are manufactured with molten sodium and liquid sulfur enclosed in a steel casing and a cell container (usually cylindrical in shape). Nihon Gaishi kabushikigaisha (NGK) Insulators, a Japanese company, is the only company manufacturing this battery. Key applications include spinning reserve, frequency regulation, energy time shift, and transmission congestion relief. In India, NGK's NaS battery was trial tested by the National Thermal Power Corporation (NTPC) for its feasibility in Indian grid conditions in a solar system. Sodium nickel chloride ($Na\text{-}NiCl_2$) batteries operate at a lower temperature with molten sodium as a cathode, $NaAlCl_4$ as the electrolyte, and nickel chloride as the anode. Major applications include black start, renewable energy time shift, and frequency regulation.
- Zinc-based batteries combine zinc with various chemicals. They are at an earlier development stage than some other battery technologies. Historically, zinc batteries were not rechargeable, but developers are overcoming challenges to produce fully rechargeable zinc-based chemistries. This technology is lightweight, low-cost, and nontoxic. Zinc air batteries (also known as zinc air fuel cells) function by oxidizing zinc with oxygen while controlling the reaction rate by controlling the air flow. They come in both rechargeable and nonrechargable forms. Applications include vehicle propulsion and grid storage. Urban Electric Power (UEP), a US company, has developed a rechargeable zinc manganese ($ZnMnO_2$) battery with a two- to eight-hour discharge duration. These batteries are safe and nontoxic, with no lead, heavy metals, or flammable electrolytes. The company is scaling up production and is expected to provide a cheaper replacement for lithium-ion batteries.

Flow batteries (see case study 5.6) differ from conventional batteries in that energy is stored in the electrolyte (the fluid) instead of the electrodes. The electrolyte solutions are stored in tanks and pumped through a common chamber, separated by a membrane, that allows for transfer of electrons or flow of electricity between the electrolytes.

There are many different types of flow batteries. At least three are currently commercially available: redox flow, zinc-iron flow, and zinc-bromine batteries. Variations such as zinc-iron flow batteries and hydrogen-bromine flow batteries are also under development.

This technology has reached commercialization, with 326 MW grid connected flow batteries across 108 projects installed to date. In India, technology adoption is limited to test trials. A 30 kW vanadium redox battery was installed in 2015 for mini grid capability by Imergy Power Systems.

THERMAL ENERGY STORAGE

Thermal energy storage includes ice-based storage systems, hot and chilled water storage, molten salt storage, and rock storage technologies:

- In latent heat storage, energy is stored in a material that undergoes a phase change (transition between solid and liquid) as it stores and releases energy. One example of latent heat storage is an ice storage tank for domestic or industrial cooling.
- In sensible heat storage, available energy is stored in the form of an increase or decrease in temperature of a material, which can be used to meet a heating or cooling demand. Variations of this technology include molten salt storage (generally coupled with concentrated solar power plants, hot water storage,

and chilled water storage), designed to serve households or a community.

- In thermochemical storage, reversible chemical reactions are used to store thermal energy in the form of chemical energy. Variations are in initial developmental stages.

In these systems, excess thermal energy is collected for later use. Given the Second Law of Thermodynamic inefficiencies in converting low-grade heat to electricity and the challenges of storing high temperature heat at small scales, this kind of storage is generally not viable for mini grids.

ELECTRICAL STORAGE

Super capacitors and superconducting magnetic energy storage (SMES) systems store electricity in electric and electromagnetic fields with minimal loss of energy. A few small SMES systems are commercially available, mainly for power quality control in manufacturing plants (such as microchip fabrication facilities). These technologies are ideal for storing and releasing high levels of energy in short bursts.

CHEMICAL STORAGE

Chemical storage typically uses the electrolysis of water to produce hydrogen as a storage medium. Hydrogen can subsequently be converted to electricity (via fuel cells or engines) or heat and transportation fuel (power-to-gas). In power-to-gas storage, excess electrical energy is used to electrolyze water to produce hydrogen and oxygen. The stored hydrogen can be used directly as fuel for heating applications or in fuel cells. Electrolyzers are unidirectional devices allowing for only the storage of energy.

Chemical energy stored in fuels (ethanol, hydrogen, or natural gas) can be converted to electrical energy. Several variations exist, including solid oxide fuel, proton exchange membrane, and phosphoric acid fuel cells. These systems can be used for stationary storage or in transportation applications.

APPENDIX B: IMPROVING THE PERFORMANCE OF LEAD ACID BATTERY STORAGE MINI GRIDS

Most battery technologies in use today are lead acid. Most batteries are sulphated, reducing their charge acceptance rate and forcing mini grid players to use diesel generators to meet the shortage. A project on battery performance in India and the CLEAN Battery O&M manual highlight the challenges of lead acid batteries in many mini grids. This appendix shows how the performance of mini grids was deteriorating and provides recommendations on how it can be improved.

Figure B.1 plots battery capacity against the age of battery banks at selected sites. It shows that most of the batteries monitored were operating below 80 percent of their rated capacity within six months of installation; modelling had projected capacities of over 80 percent for at least three years after installations. It also shows that valve regulated lead acid (VRLA) gel performed better than flooded tubular and that VRLA absorbed glass mat after five years of operation. Laboratory tests conducted by CES confirm these results.

Timely and adequate equalization of flooded lead acid battery banks greatly increased the capacity of the plants (figure B.2).

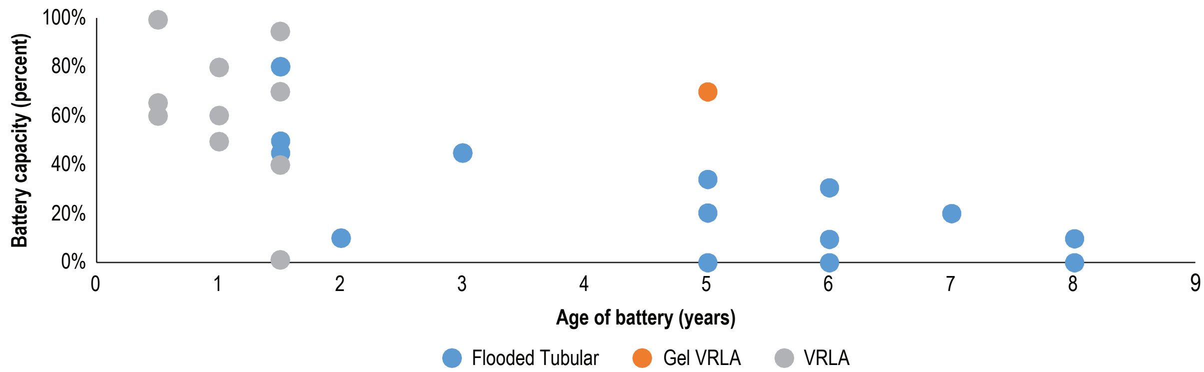
Revival of older lead acid batteries can take about a month. It took almost 25 days to bring six-year old batteries up to a certain capacity (table B.1). For this reason, is very important to regularly maintain batteries throughout their lifetimes.

Battery efficiency exceeded 80 percent for most plants that were no more than two years old two years (figure B.3). Most plants that were more than two years old had efficiencies of less than 80 percent. Battery efficiency in these solar plants did not show significant improvement after equalization.

Battery utilization data recorded at these sites challenges two industry perceptions. One is that batteries die early from overuse. Another is that as the plant ages, utilization of the battery increases as the load at the site increases. The data show that utilization of older plants was lower than that of newer plants. They also show that none of the plants had batteries that exceeded 60 percent of their rated capacity (figure B.4)

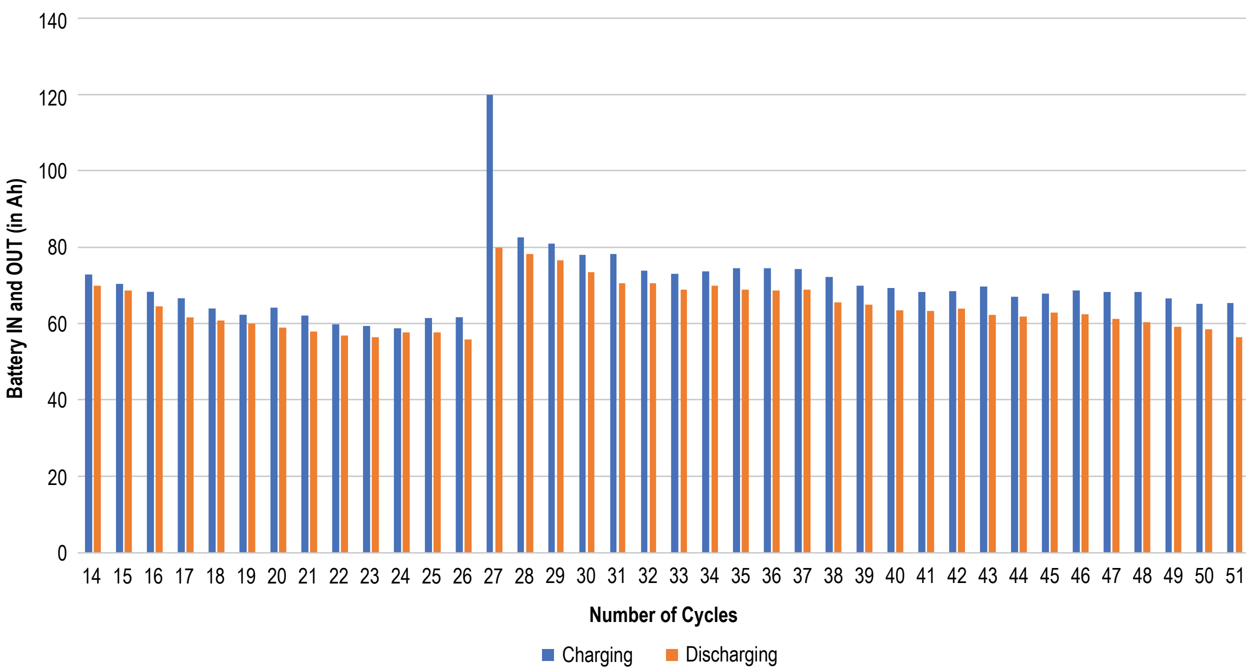
Battery utilization was plotted against battery size (the ratio of battery-to-solar PV installed capacity) (figure B.5). All batteries that used 30 to 60 percent of their capacity had battery-to-solar ratios of 2.0 to 4.0 kWh/kWp, suggesting that this range could be considered the optimum battery size for rural mini grids. Most government tenders suggest that sizes should be over 7.0 kWh/kWp. Underutilization is found in plants with all sizes of batteries.

FIGURE B.1: Capacity of Flooded Tubular, Valve Regulated Lead Acid (VRLA), and VRLA Gel Batteries in First Eight Years



Source: Sen 2019.

FIGURE B.2: Tubular Battery Under 80 Percent Discharge and Recharge Cycle in Solar Charging Conditions Demonstrating Drop and Increase in Capacity Before and After an Equalizing Charge



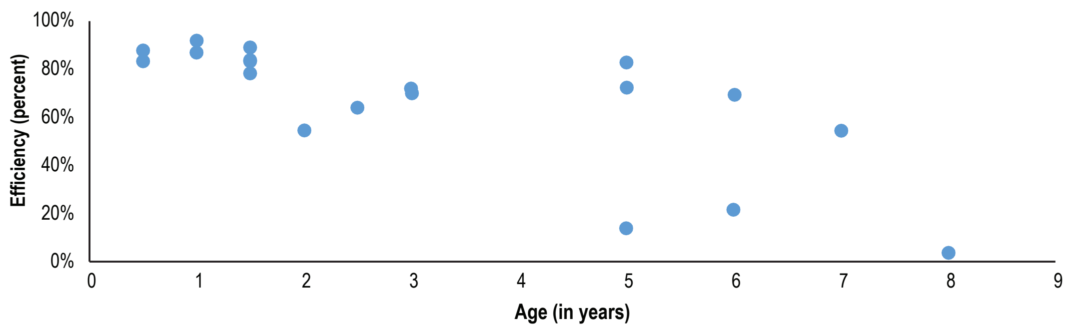
Source: CES battery lab tests.

TABLE B.1: **Revival of Old Lead Acid Batteries**

Battery Make	Battery Type	Age of Plant (years)	Initial Capacity (percent)	Capacity After Revival (percent)	Duration of Revival (days)	Observations
Reliance	Flooded tubular	6.0	30	80	25	Most sites can be revived to similar capacity and provide two to three years more life with regular O&M.
HBL	Gel tubular	4.5	10	25	0	This cell totally dried out, because of o overcharging at the site, and could not be revived. This battery bank can be discarded.
Agni	Flooded tubular	6.0	20	55	25	Most sites deploying batteries from reputable manufacturers will get revived better.

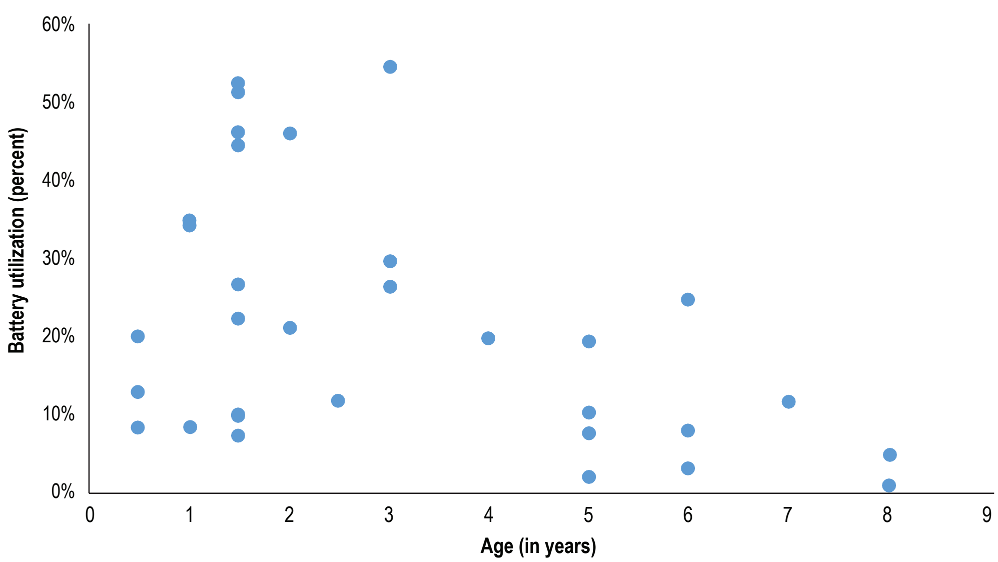
Source: CES lab test.

FIGURE B.3: Efficiencies of Batteries at Plants of Different Ages



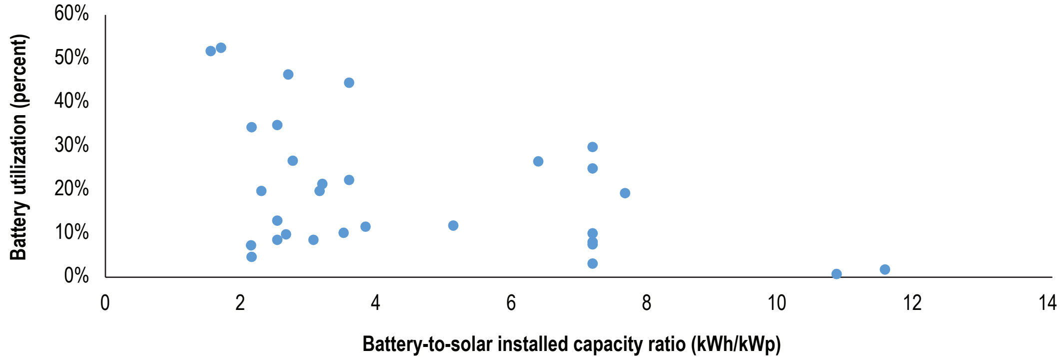
Source: Sen 2019.

FIGURE B.4: Battery Utilization at Plants of Different Ages



Source: Sen 2019.

FIGURE B.5: Battery Utilization at Various Battery-to-Solar Installed Capacity Ratios



Source: CES lab tests.

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