

Charging Ahead: Battery Ecosystems, Energy Transitions and Electrification in Emerging Economies



This report was funded by the UK government via the Ayrton Fund. However, the views expressed do not necessarily reflect the UK government's official policies.

Front cover image: MOPO's solar battery-swap charging station. Courtesy of MOPO. MOPO is a pay-per-use battery technology company delivering sustainable energy to individuals and businesses across Africa.

Table of Contents

Glossary.....	7
Introduction	8
Part I: Sub-Saharan Africa	12
Ghana	13
1. Introduction	13
2. Key research areas in battery technologies.....	14
3. Material sourcing and local manufacturing.....	14
4. Key research institutions and collaborations	15
5. Regional collaboration efforts	16
6. Industry and start-up ecosystem	17
7. Startups and innovations	18
8. Policy, funding and challenges.....	18
9. Case studies and success stories.....	20
10. Future directions.....	21
11. Conclusions	22
References	22
Kenya.....	25
1. Introduction	25
2. Key research areas in battery technologies.....	26
3. Material sourcing and local manufacturing.....	29
4. Key research institutions and collaborations	30
5. Battery skills assessment	31
6. Industry and start-up ecosystem	32
7. Policy, funding and challenges.....	32
8. Case studies and success stories.....	34
9. Future directions.....	36
10. Conclusions	37
References	38
Malawi.....	42
1. Introduction	42
2. Key research areas in battery technologies.....	44

3. Material sourcing and local manufacturing.....	45
4. Policy, funding and challenges.....	46
5. Case studies and success stories.....	46
6. Conclusions	47
References	47
Nigeria.....	50
1. Introduction	50
2. Material sourcing and local manufacturing.....	51
3. Key research institutions and collaborations	52
4. Battery skills assessment	54
5. Industry and start-up ecosystem	55
6. Policy, funding and challenges.....	56
7. Case studies and success stories.....	59
8. Future directions.....	60
9. Conclusions	63
References	64
South Africa.....	68
1. Introduction	68
2. Key research areas in battery technologies.....	69
3. Material sourcing and local manufacturing.....	69
4. Key research areas, institutions, and collaborations.....	75
5. Battery skills assessment	78
6. Industry and start-up ecosystem	79
7. Policy, funding and challenges.....	82
8. Case studies and success stories.....	84
9. Future directions.....	85
10. Conclusions	87
References	87
Zambia.....	92
1. Introduction	92
2. Key research areas in battery technologies.....	93
3. Material sourcing and local manufacturing.....	94

4. Key research institutions and collaborations	95
5. Battery skills assessment	95
6. Industry and start-up ecosystem	96
7. Policy, funding and challenges.....	96
8. Case studies and success stories.....	97
9. Future directions.....	98
10. Conclusions	98
References	98
Zimbabwe.....	101
1. Introduction	101
2. Key research areas in battery technologies.....	104
3. Material sourcing and local manufacturing.....	105
4. Key research institutions and collaborations	109
5. Battery skills assessment	111
6. Industry and start-up ecosystem	112
7. Policy, funding and challenges.....	113
8. Case studies and success stories.....	116
9. Future directions.....	116
10. Conclusions	117
References	118
Part II: South Asia and Indo-Pacific.....	121
Bangladesh.....	122
1. Introduction	122
2. Key research areas in battery technologies.....	123
3. Material sourcing and local manufacturing.....	128
4. Key research institutions and collaborations	130
5. Battery skills assessment	133
6. Industry and start-up ecosystem	135
7. Policy, funding and challenges.....	137
8. Case studies and success stories.....	138
9. Future directions.....	139
10. Conclusions	139

References	140
Nepal	144
1. Introduction	144
2. Key research areas in battery technologies.....	146
3. Material sourcing and local manufacturing.....	146
4. Key research institutions and collaborations	146
5. Battery skills assessment	146
6. Industry and start-up ecosystem	147
7. Policy, funding and challenges.....	147
8. Future directions.....	147
9. Conclusions	147
References	147
Pakistan	149
1. Introduction	149
2. Key research areas in battery technologies.....	150
3. Material sourcing and local manufacturing.....	151
4. Key research institutions and collaborations	152
5. Regional collaboration efforts	153
6. Industry and start-up ecosystem	153
7. Startups and innovations	154
8. Policy, funding and challenges.....	155
9. Case studies and success stories.....	156
10. Future directions.....	157
11. Conclusions	157
References	158
Malaysia	160
1. Introduction	160
2. Key research areas in battery technologies.....	164
3. Material sourcing and local manufacturing.....	165
4. Key research institutions and collaborations	167
5. Battery skills assessment	168
6. Industry and start-up ecosystem	169

7. Policy, funding and challenges.....	170
8. Case studies and success stories.....	171
9. Future directions.....	172
10. Conclusions	173
References	173
Fiji.....	176
1. Introduction	176
2. Key research areas in battery technologies.....	176
3. Material sourcing and local manufacturing.....	177
4. Key research institutions and collaborations	178
5. Battery skills assessment	179
6. Policy, funding and challenges.....	179
Summary and other Initiatives	181
1. Power mix and the key role of batteries	181
2. Challenges with battery deployment.....	182
3. Battery chemistries	182
4. Policy	183
5. Circularity and recycling.....	186
6. Capacity building, training and skills development	187
7. Collaboration across nations	188
8. Future perspectives	189

Glossary

BESS	Battery energy storage systems
BEVs	Battery electric vehicles
BMS	Battery management systems
EVs	Electric vehicles
HEVs	Hybrid electric vehicles
IEA	International Energy Agency
LCO	Lithium cobalt oxide
LCP	Lithium cobalt phosphate
LCoE	Levelised cost of electricity
LFP	Lithium iron phosphate
LFMP	Lithium iron manganese phosphate
Li-ion	Lithium-ion
LMO	Lithium manganese oxide
LMNO	Lithium manganese nickel oxide
LNO	Lithium nickel oxide
LPG	Liquefied petroleum gas
NCA	Lithium nickel cobalt aluminium oxide
NMC	Lithium nickel manganese cobalt oxide
PHEVs	Plug-in hybrid electric vehicles
PPPs	Public-private partnerships
PV	Photovoltaic
SDG	Sustainable development goals
SSBs	Solid-state batteries
UNDP	United Nations Development Programme
VRFBs	Vanadium redox flow batteries

Introduction

The Ayrton Challenge on Energy Storage

In April 2023, the Faraday Institution was selected to lead the Ayrton Challenge on Energy Storage (ACES), funded by the UK Government's £1 billion Ayrton Fund. ACES utilises the United Kingdom's expertise and partnerships to advance energy storage technology for emerging economies. Currently, 685 million people globally lack reliable electricity access. Energy storage is crucial for enhancing the reliability of electricity supply, reducing emissions, and meeting climate targets.

As part of ACES, the Faraday Institution leads a research programme to December 2026. It aims to expand energy access, reduce emissions, and support energy transitions in emerging economies by developing lower-cost energy storage solutions that enable cleaner transport and distributed energy access.

The £5 million R&D programme is part of a broader coordinated ACES package of at least £42 million across a range of partners for skills development, technology accelerators, and market building activities. These partners include the Shell Foundation, Acumen, the World Bank's Energy Sector Management Assistance Programme (ESMAP) and Innovate UK's Energy Catalyst, as well as a range of academic and industry leaders. Innovations will reduce the cost and improve the performance of energy storage systems for static off-grid and weak-grid applications, and for e-mobility solutions, in target countries. The target geographies for ACES are sub-Saharan Africa, South Asia, and the Indo-Pacific.

The Ayrton Fund aims to accelerate the clean energy transition in developing countries by creating innovative clean energy technologies and business models, supporting the Sustainable Development Goals (SDGs), particularly progress on Affordable and Clean Energy (SDG7) and Climate Action (SDG13). ACES builds on the UK's existing partnership with the wider global movement for energy access, through the extensive networks of the FCDO (Foreign, Commonwealth and Development Office)'s Transforming Energy Access (TEA) platform.

Battery Ambassadors

As part of the commitment to supporting skills enhancement, knowledge transfer and battery technology development for emerging economies as part of ACES, in July 2024 the Faraday Institution selected a [cohort of Battery Ambassadors](#) – individuals and universities involved in battery research in the target regions.

Introducing the Battery Ambassadors:

- Dr Chrispin Gogoda, Mzuzu University, **Malawi**
- Prof Emeka Oguzie, Federal University of Technology Owerri, **Nigeria**
- Dr Julius Butime, Strathmore University, **Kenya**

- Dr Sekove Vodo, University of Fiji, **Fiji**
- Dr Mohd Najib Mohd Hussain, Universiti Teknologi Mara, **Malaysia**
- Dr Enzoh Langi, Copperbelt University, **Zambia**
- Prof Nawraj Bhattarai, Tribhuvan University, **Nepal**
- Eng Hilton Chingosho, University of Zimbabwe, **Zimbabwe**
- Dr Gifty Mensah, University of Energy and Natural Resources, **Ghana**
- Prof Ghulam Ali, National University of Sciences and Technology, **Pakistan**
- Prof Khosru Salim, Independent University of Bangladesh, **Bangladesh**
- Dr Nithyadharseni Palaniyandy, University of South Africa-Florida Science Campus, **South Africa**

The group is coordinated by Dr Elvis Shoko of Afrionics Energy Ltd.

While initially launched with a narrow focus on university battery research, it quickly became clear that broader engagement to include actors from industry, government, and civil society organisations would be necessary to translate the ambition of the Battery Ambassador programme into reality in the varied local contexts of the target countries.

Focus areas of the Battery Ambassador Programme

The Ambassadors were funded to attend the Faraday Institution Annual Conference in September 2024 and 2025, fostering knowledge transfer and collaboration with each other and with the UK battery research community. Attending this in-person meeting also enables effective strategic planning, providing direction and cohesion for the group for the next 12 months when all contact is conducted online.

The Battery Ambassadors set up the following strategic initiatives:

- A joint paper on the battery ecosystem landscape in each country that the Battery Ambassadors represent, led by Julius Butime, Strathmore University, Kenya. This report is the output of this initiative and its aims are described further in the following section.
- Building Global South battery networks, led by Hilton Chingosho, University of Zimbabwe. The aim is to overcome fragmentation in battery activities across sub-Saharan Africa and South Asia by fostering a cohesive battery community through webinars from subject experts on a range of topics.

To September 2025, seven Battery Network webinars have been hosted, attracting more than 1,100 participants from a total of 50 countries. [Watch previous webinars at this link](#). For future webinars, see Faraday Institution's LinkedIn page.

- Capacity building, led by Chrispin Gogoda, Mzuzu University, Malawi. The aim is to identify and address key battery knowledge and skill gaps in countries represented

by the ambassadors by gathering input for targeted interventions to guide initial capacity-building efforts.

The joint paper: Charging ahead: battery ecosystems, energy transitions and electrification in emerging economies

This report is a collection of independent contributions from the 12 Faraday Institution Battery Ambassadors, which provides a snapshot of the battery landscape in each of the Ambassador countries. By examining the main battery technology research areas, the status of local manufacturing and material sourcing, institutional partnerships, regional initiatives, industry and start-up ecosystems, and the funding and policy environment, it attempts to capture the key features of the sector for a wide audience. It documents the progress of the electrification transition in each nation and lays out the opportunities and challenges in battery research, technology integration and policy regulation. Accordingly, it should prove useful to researchers looking for opportunities for collaboration, entrepreneurs and investors seeking commercial opportunities, and policymakers interested in understanding the impact of various policy tools in different contexts.

The paper also signposts ongoing needs to meet electrification targets, including in:

- fundamental research
- demonstrator projects
- training, skills and knowledge development
- national and international collaborations, both industrial and academic.

The contribution from each Ambassador listed above follows a similar format:

- Introduction
- Key research areas in battery technologies
- Material sourcing and local manufacturing
- Key research institutions and collaborations
- Battery skills assessment
- Regional collaboration efforts
- Industry and start-up ecosystem
- Start-ups and innovations
- Policy, funding and challenges
- Case studies and success stories
- Future directions
- Conclusions

The report is divided into two major sections based on region.

- Part I: Sub-Saharan Africa. Seven countries are included in this section, namely, Ghana, Kenya, Malawi, Nigeria, South Africa, Zambia, and Zimbabwe.
- Part II: South Asia and Indo-Pacific. There are three contributions from South Asia: Bangladesh, Nepal, and Pakistan, with Malaysia and Fiji from the Indo-Pacific region.

Each section should be read as the perspective of the individual Battery Ambassador and does not necessarily reflect the Faraday Institution's opinion. The Faraday Institution has not attempted to verify the accuracy of the contributions.

Contact details for the Battery Ambassadors

Readers are encouraged to contact the Battery Ambassador in their country for follow-up conversations:

- Dr Chrispin Gogoda, **Malawi**, gogoda.c@mzuni.ac.mw
- Prof Emeka Oguzie, **Nigeria**, emeka.oguzie@futo.edu.ng
- Dr Julius Butime, **Kenya**, jbutime@strathmore.edu
- Dr Sekove Vodo, **Fiji**, sekovev@unifiji.ac.fj
- Dr Mohd Najib Mohd Hussain, **Malaysia**, najibmh@uitm.edu.my
- Dr Enzoh Langi, **Zambia**, enzoh.langi@cbu.ac.zm
- Prof Nawraj Bhattarai, **Nepal**, bnawraj@ioe.edu.np
- Eng Hilton Chingosho, **Zimbabwe**, hchingosho@eng.uz.ac.zw
- Dr Gifty Mensah, **Ghana**, giftyserwaa.mensah@uenr.edu.gh
- Prof Ghulam Ali, **Pakistan**, ali@uspcase.nust.edu.pk
- Prof Khosru Salim, **Bangladesh**, khosru@iub.edu.bd
- Dr Nithyadharseni Palaniyandy, **South Africa**, palann@unisa.ac.za

For discussions regarding the Battery Ambassador programme as a whole please contact:

- Andrew Deadman, Faraday Institution, andrew.deadman@faraday.ac.uk
- Dr Elvis Shoko, Afrionics Energy Ltd, elvis.shoko@afriionicsenergy.com

Part I: Sub-Saharan Africa

Ghana

This section was written by Dr Gifty Mensah, Postdoctoral Research Associate at the Regional Centre for Energy and Environmental Sustainability (RCEES) at the University of Energy and Natural Resources. She investigates sustainable battery (waste) management.

1. Introduction

Ghana is ahead of most of its sub-Saharan counterparts with a national electricity access rate of 89%. However, while there is universal access at the urban level, the rural rate is about 74% [1]. This indicates that more must be done to provide universal access to modern energy to drive the country's development agenda.

Less than 1% of the population use electricity as a cooking fuel. Around 40% of the population use liquefied petroleum gas (LPG) as their primary fuel for cooking. The remaining 59% of the population use biomass sources such as firewood and charcoal as their main source of cooking fuel. Among the urban population, 56% use LPG and 0.5% use electricity as their main source of cooking fuel compared to about 17% and 0.2% respectively in the rural areas [1]. These statistics indicate a need to accelerate efforts to provide universal access to clean cooking fuels for Ghanaians. Access to clean cooking fuels will eliminate the diseases and deaths associated with using inefficient fuels and technologies for cooking.

A mix of sources, including fossil fuels and renewable energy resources, provide Ghana's electricity. Hydropower used to be Ghana's only source of electricity, but the growth in electricity demand and provisions made to meet this demand with fossil sources have reduced the hydro share from 92% in 2000 to 35% in 2022. The fossil fuel share is now 64% with other non-large-hydro renewable sources accounting for the remaining 1% [2].

The non-electrified communities are rural and isolated, and are mostly island communities [3]. Such communities tend to be isolated from the main grid and therefore grid connections are too expensive. Distributed energy, off-grid, and mini-grid solutions with renewable energy sources often present the best opportunities to electrify them. The deployment of distributed renewable energy will not only provide sustainable energy, but it will also contribute to climate change mitigation.

Ghana, like many other countries, has an energy transition agenda as part of global efforts to stem climate change and its impacts. The government has a target of a 10% increase in renewable energy in the share of its electricity generation mix by 2030 [4]. The shift towards renewable energy creates opportunities for the deployment of battery storage technologies to support grid stability and integrate renewable energy sources.

Ghana is not advanced in battery research, but the ongoing research is important for the nation. For instance, some studies have been carried out to determine the potential for

certain elements available locally for battery manufacturing, particularly the synthesis of nanostructured manganese oxide from locally available manganese ore. Studies have shown this material's promising potential for lithium-ion battery applications, with high initial discharge capacities but only modest retention of performance over several cycles. Some studies have also investigated the disposal of dry cell battery (DCB) waste in Accra, revealing widespread issues with improper disposal, which poses risks to public health and the environment [5]. Studies are also ongoing to estimate the number of batteries in use in Ghana and the management practices of these batteries at their end-of-life, as well as the policies that govern this space.

2. Key research areas in battery technologies

Some of the key research areas in battery technologies in Ghana include the following:

2.1 Lithium-ion (Li-ion) batteries

Li-ion batteries have applications in electric mobility, renewable energy storage and consumer electronics, and are used for all these applications in Ghana. This battery technology is therefore a key research area for a country that has an electric vehicle policy and an energy transition policy. Research is required in the production of efficient Li-ion batteries and end-of-life management.

A team of researchers at the University of Ghana, in collaboration with the [Council of Scientific and Industrial Research](#) Ghana (CSIR) and other institutions, synthesised nanostructured manganese oxide from Ghanaian manganese ore to use as an anode in Li-ion batteries. Their findings indicated an initial discharge capacity of 1,550 mAh/g; by the 27th cycle, the cell preserved roughly 38% of the discharge capacity recorded during the second cycle [6].

Another team at the Kwame Nkrumah University of Science and Technology are also investigating optimising material recovery and life cycle management of spent Li-ion batteries.

2.2. Hydrogen storage

Ghana has ongoing research to explore the feasibility of hydrogen storage. As part of the GH2GH initiative (Green Hydrogen for Decentralised Energy Systems in Sub-Saharan Africa), a pilot system was set up at the Don Bosco Solar & Renewable Energy Centre in Tema, Ghana. The installation enables the production, storage, and on-demand conversion of green hydrogen to provide a fully off-grid power supply, in collaboration with project partners Bochum University of Applied Sciences and Green Power Brains [7].

3. Material sourcing and local manufacturing

Local production of Li-ion battery-grade materials (e.g. lithium and manganese salts) and battery packs will be essential for Ghana's energy transition. The economic viability of local

refining of battery minerals to produce battery-grade materials is highly dependent on economies of scale and therefore requires large-scale local mining of the ores.

Lithium was discovered in Ghana in 2018 and the mining of this mineral is yet to commence. Atlantic Lithium announced a definitive feasibility study for the Ewoyaa Project in 2023 for lithium mining [8].

Manganese is another raw material present in Ghana that can aid in building a local upstream battery value chain. Manganese dioxides are considered promising cathode materials for Li-ion batteries. Tantalum deposits have been discovered in the Kibi-Winneba belt in Ghana, specifically the pegmatites in the Bewadze-Mankoadze area, that contain manganese minerals [9]. However, there are concerns about the environmental, social, and economic impacts of mining activities within the country [10, 8].

Ghana has efforts underway to develop a battery recycling industry and sustainable battery disposal and recycling methods [11]. This is important for building a circular economy for battery materials and reducing reliance on primary mineral extraction. The informal economy in Ghana, such as the recycling of e-waste at Agbogbloshie, is an important source of secondary raw materials that could be leveraged for a local battery value chain.

Opportunities for local electric vehicle (EV) manufacturing in Ghana could address critical adoption barriers like range anxiety and charging infrastructure, while simultaneously catalysing a domestic battery production industry [12].

In summary, Ghana has the potential to develop a domestic battery pack production industry based on its mineral resources but must address environmental, social, and responsible sourcing challenges to realise this potential. Efforts are underway to build a circular economy for battery materials through recycling and sustainable disposal methods.

4. Key research institutions and collaborations

4.1 Key research institutions

There are not many institutions in Ghana focused on battery research. However, one notable collaboration involves researchers from the CSIR Ghana and the University of Ghana. Their joint efforts include studying manganese ore deposits with the goal of treating and converting the naturally occurring manganese oxide-containing ore into nanostructured manganese oxide with enhanced properties suitable for use in Li-ion batteries.

Leading institutions in Ghana include the CSIR Ghana, the University of Ghana, Kwame Nkrumah University of Science and Technology, and the University of Energy and Natural Resources.

4.2 International collaborations in battery technology development

Ghana is actively engaging in various international collaborative initiatives to enhance its battery technology development, particularly in EVs and energy storage solutions. These

collaborations involve partnerships with institutions from Europe, America, and Asia, focusing on leveraging Ghana's lithium resources and promoting sustainable energy practices.

Some key international collaborations include:

4.2.1 ReElement Technologies and TECHGULF Ghana

In December 2023, ReElement Technologies Corporation partnered with TECHGULF Ghana to establish Africa's first battery-grade lithium processing plant in Ghana. This initiative aims to improve lithium processing capabilities within the country [13]. The partnership reflects a commitment to advancing local expertise in lithium refinement and contributing to sustainable energy solutions in Africa.

4.2.2 Kofa Technologies and PASH Global

Kofa Technologies has launched a significant battery-swapping network across Ghana, supported by a £6.15 million investment from the Shell Foundation and the UK Government. This initiative aims to deploy 6,000 batteries and establish up to 100 swapping stations, promoting the adoption of EVs while reducing reliance on fossil fuels [14]. The collaboration with PASH Global focuses on operational management and transitioning these stations to solar power, enhancing their environmental impact.

4.2.3 Bosch Ghana

Bosch has initiated a lead-acid battery recycling project in collaboration with local stakeholders. This project aims to manage used batteries responsibly, addressing environmental concerns associated with battery disposal [15]. Bosch's efforts highlight the importance of sustainable practices in battery management within Ghana's growing automotive sector.

5. Regional collaboration efforts

Ghana is also participating in broader regional initiatives aimed at enhancing energy storage and battery research across Africa. Some key regional collaborations include:

5.1.1 African Union initiatives

The African Union has been promoting various initiatives focused on energy storage technologies and sustainable energy solutions across member states. These efforts align with Ghana's strategic goals of becoming a leader in e-mobility and battery production, particularly through investments in lithium mining and processing [16].

5.1.2 Investment from Ghana's Sovereign Fund

Ghana's minerals sovereign fund is backing projects aimed at establishing the country as a leader in battery production. This includes significant investments in local lithium projects that are crucial for the development of battery technologies [17].

6. Industry and start-up ecosystem

6.1 Vantom Power

Vantom Power is recognised as Ghana's leading provider of battery energy storage systems (BESS). With over a decade of experience in the energy storage industry, the company has built a strong reputation as a reliable dealer and supplier of lithium batteries in the country. Their expertise lies in the development and supply of lithium batteries, enabling them to offer affordable and dependable battery products and solutions to customers throughout Ghana.

6.2 Bosch Ghana

Bosch has emerged as a significant contributor to the lead-acid battery recycling project in Ghana, which was established through a reverse logistics system in collaboration with local market players, including City Waste Management Ghana, battery distributors, used battery collectors, and end consumers. Automotive lead-acid car batteries contain various heavy metals and toxic chemicals that can be harmful to both the environment and human health [18].

6.3 Atlantic Lithium Ltd

This company is advancing the Ewoyaa Lithium Project, which aims to be Ghana's first lithium-producing mine [19]. The project is positioned to produce spodumene concentrate suitable for EV batteries, highlighting its potential impact on the local battery supply chain.

6.4 Battery Planet

Battery Planet is a prominent supplier of automotive and solar batteries in Ghana, providing products for both vehicles and home energy systems.

6.5 Nastech Power Solutions

Nastech Power Solutions develops and manufactures solar generators, power inverters, and lithium battery packs from recycled electronic waste collected from discarded waste. The firm employs a circular economy model in the manufacturing of solar energy systems to provide affordable renewable energy systems generating electricity to support businesses and communities in Africa struggling with accessing electricity. The company's approach has been to touch the unreachable communities and people who are deprived of access to electricity with its products. Its engineers have designed their own innovative technologies including the programming systems, motherboards and circuit systems, which run its inverters and solar generators to generate electricity.

6.6 Solar Taxi

Solar Taxi is an e-mobility company in Africa. They innovate across various sectors to make electric mobility more accessible and environmentally sustainable.

Currently, they are indigenising Li-ion battery pack engineering and production to meet the growing power needs of EV users in Africa and beyond through research and development.

7. Startups and innovations

7.1 Kofa

Kofa, a dynamic startup based in Ghana, has secured funding to revolutionise the energy sector with its pioneering battery-as-a-service (BaaS) model. In a bid to overcome the limitations of traditional energy storage systems, Kofa has set its sights on powering the nation's future with a sustainable and innovative approach. Kofa's game-changing BaaS model allows customers to access advanced battery technology without the hassle of upfront costs or ownership. This transformative service allows residential and commercial clients to tap into the advantages of energy storage without bearing the burden of heavy capital investment. By proactively harnessing renewable energy sources, Kofa aims to bridge the gap between intermittent power supply and constant demand. Kofa's recent funding round was led by Mercy Corps Ventures, Shell Foundation, UK's FCDO (Foreign, Commonwealth & Development Office), and Wangara Green Ventures.

7.2 Public-private partnerships

The government of Ghana has a role to play in funding and developing initiatives to drive battery research in Ghana. The Ghana Automotive Development Policy, launched in 2020, aims to position Ghana as a competitive hub for the automotive industry in West Africa. With significant lithium reserves and a new green minerals policy, the government is promoting investments in domestic refining with forward linkages to battery manufacturing.

8. Policy, funding and challenges

8.1 Policies

Subsection 4.5.3 of the National Energy Policy of Ghana, developed in 2021, addresses Ghana's energy transition. One objective of the policy is to generate electricity from cleaner sources to achieve the policy goal of developing "a low-carbon energy resources infrastructure to deliver clean energy in an environmentally responsible manner for socio-economic growth" [4]. Considering the intermittent nature of renewable energy (RE) resources, the policy document provides the following directions:

- Ensure the hybridisation of mini-hydro power with intermittent renewable energy
- Promote the sustainable production of biofuel for electricity and transport
- Explore options for hydrogen fuel and large battery storage systems [4].

Although the policy document does not mention energy storage or battery research specifically, it takes into account the need for research and development in the energy sector. Specifically, it mentions investing in research and development of cleaner fuels to promote carbon reduction. Policy directions include establishing the research infrastructure,

research fund and promoting linkages and collaborations between government, academia, and the private sector.

Ghana's National Energy Transition Framework (2022-2070) document is the official document that outlines plans by the government to attain net zero status by 2070. This document does not explicitly mention battery or energy storage research; however, it makes a general mention that the relevant institutions shall be adequately resourced to execute research and development in the RE sector to promote RE innovation [20]. Efforts to achieve the 10% integration of non-large-hydro renewable sources into Ghana's electricity mix by 2030 and/or net zero by 2070 must have energy storage and battery research at their core. It is safe to conclude therefore that these policy documents account for research and development in the area.

8.2 Funding opportunities

As in most developing countries, several development projects in Ghana, including research, are supported by donor agencies. For instance, in June 2024, the World Bank approved a \$250 million credit from the International Development Association (IDA) and a \$10 million grant from the Energy Sector Management Assistance Program (ESMAP) for a 4-year Ghana Energy Sector Recovery Programme for Results (PforR). This is to support Ghana in improving the financial viability of the electricity distribution system [21]. The Green Climate Fund (GCF) also approved funding for the Accelerating Solar Action Programme (ASAP). The project amount is \$31.6 million, with funding from the GCF constituting 51.3% of the total, with the remaining 48.7% being co-funding from the Ghanaian government. The funding is meant to support Ghana's transition from fossil fuels to more sustainable and cleaner energy sources [22]. These funds are intended to support the energy sector but not research specifically.

The Renewable Energy Fund in Ghana, in addition to providing funding for renewable energy projects, provides funding for research and development related to renewable energy technologies [2]. Although this fund supports research, it does not mention battery research specifically. However, batteries and energy storage are central to RE technologies and therefore funds can be used for battery research. In other words, an entity can apply to the fund seeking funds for battery research.

8.3 Challenges

The battery research space in Ghana is limited although important. The key challenge affecting battery research in Ghana is financial. For instance, a team of researchers have proposed a project called the African Green Minerals Strategy, with the aim of leveraging African institutions of higher learning for innovation in Li-ion battery technology in collaboration with the Pan African Decarbonisation Institute (P-ADI).

Some African universities are collaborating with the African Green Minerals Strategy to spearhead Li-ion research on the continent. However, this project is still awaiting funding.

While funding remains the central challenge, another challenge is a lack of coordination among researchers, which could pose a problem of duplication of efforts. It will be helpful for battery research in Ghana if there is coordination and cooperation among researchers from different institutions.

9. Case studies and success stories

This section discusses both successful and failed cases of battery storage deployment, examining what factors contributed to the successes or failures.

9.1 Successful deployment of battery storage for off-grid solar energy in rural communities

There has been successful deployment of battery storage for off-grid installations in Ghana in both rural and urban areas. All the installed mini-grids in Ghana have been accompanied by battery energy storage [23]. The success of these storage systems has been mainly attributable to high-quality batteries.

In 2016, the World Bank-funded project under the Ghana Energy Development and Access Project (GEDAP) deployed mini-grid installations to the 5 island communities of Kudorkope, Aglakope, Atigagome, Wayokope, and Pediatorokope in the Sene East, Krachi West, Krachi East, and Ada districts. These mini-grids were designed to provide electricity for the 3,500 residents of the islands. Field visits in 2024 to assess the status of these installations revealed that the batteries installed at the onset of the project were still functional. However, the batteries were not performing optimally. According to residents, power is turned off at 9 pm to avoid running down the batteries completely [23].

This reduction in performance is expected since these batteries are about eight years old. This case shows that batteries can successfully support the deployment of RE to promote energy access and reliability.

9.2 Cases of failed battery storage in Ghana

Not all storage installations have been successful. In Tarkwa, in the Western part of Ghana, the batteries for an off-grid installation for the Ghana Private Road Transport Union (GPRTU), failed after 4 months of operation. At another off-grid installation for a hospitality facility at Lake Bosomtwe in the Ashanti Region, the attached battery storage failed to function after just a week [24]. According to Bukari et al that reviewed five pilot mini-grid projects in Ghana, a key factor in the underperformance and premature failures is poor quality of batteries and technical design flaws. In choosing batteries for a mini-grid project, a number of factors need to be considered. These include depth of discharge, cycle life, energy density, thermal runaway, and the C-rating of the batteries [23]. If any of these factors aren't considered appropriately, batteries can fail.

10. Future directions

10.1 Emerging trends

Battery research in Ghana is at a fairly early stage. However, Ghana stands at the cusp of a transformative era in battery technology, with opportunities to adopt and innovate new energy storage solutions. Emerging technologies such as sodium-ion batteries offer a cost-effective and sustainable alternative to Li-ion batteries, particularly suited to the African context due to sodium's abundance and affordability. Research into solid-state batteries, which promise enhanced safety and energy density, also holds potential, albeit at an early stage. Additionally, flow batteries, especially redox flow systems, could provide scalable solutions for integrating renewable energy into Ghana's power grid, offering longer lifespans and flexibility for large-scale applications. The increasing adoption of circular economy models in battery manufacturing and recycling further highlights a shift towards sustainability in the energy sector.

10.2 Roadmap

To capitalise on these trends, Ghana's battery research and innovation efforts must focus on:

- **Innovation and material development:** Strengthening research into locally sourced materials for battery production, such as manganese and lithium, to reduce costs and environmental impacts. This includes exploring advanced cathode and anode materials for sodium ion and Li-ion batteries.
- **Infrastructure and commercialisation:** Establishing a domestic battery manufacturing industry by leveraging Ghana's mineral resources and fostering public-private partnerships. Initiatives like the Ghana Automotive Development Policy and support for startups such as Solar Taxi and Kofa provide a foundation for scaling local production.
- **Capacity building and collaboration:** Encouraging collaborations between universities, research institutions, and industries to accelerate innovation and create a skilled workforce in battery technology. International partnerships could also facilitate knowledge transfer and access to cutting-edge research.
- **Policy support and funding:** Implementing supportive policies for renewable energy integration and battery storage systems, backed by increased funding from global climate finance initiatives and local government programmes like the Renewable Energy Fund.
- **Sustainability and circular economy:** Develop robust recycling systems to handle battery waste, reduce dependency on raw material extraction, and ensure ethical sourcing practices.

11. Conclusions

11.1 Summary of key points

Ghana's energy landscape is evolving, with batteries playing a critical role in renewable energy integration and off-grid electrification. The Ghana battery research space is not advanced yet. However, this is expected to change as batteries will be critical to the integration of RE in the country's energy transition. Funding will be a key driver in the research advancement. Collaborations between national institutions should be encouraged to prevent duplication of efforts.

With the availability of battery manufacturing materials, Ghana has the potential to manufacture batteries locally. However, there are social and environmental concerns with mining these minerals. The government and other relevant stakeholders need to put the right structures in place to ensure that these resources are mined sustainably.

While Li-ion batteries dominate the market due to their performance advantages, emerging technologies such as sodium-ion and solid-state batteries are promising alternatives. Challenges such as high costs, grid unreliability, and environmental concerns remain significant but are being addressed through research, policy, and innovation. Efforts by local startups, international collaborations, and government initiatives highlight the country's commitment to advancing battery technologies.

11.2 Outlook

With its abundant mineral resources, growing research capabilities, and innovative local enterprises, Ghana is poised to become a key player in the sustainable battery industry. By fostering collaboration, addressing challenges, and investing in advanced technologies, Ghana can position itself as a leader in energy storage solutions, driving its energy transition and contributing to global sustainability efforts.

References

- [1] Energy Commission, National Energy Statistical Bulletin, 2023.
<https://www.energycom.gov.gh/index.php/media-center/latest-news/239-national-energy-statistical-bulletin-2023>
- [2] B. Aboagye, S. Gyamfi, E.A. Ofosu, and S. Djordjevic, 'Status of renewable energy resources for electricity supply in Ghana', *Sci. Afr.*, vol. 11, e00660, 2021, doi: 10.1016/j.sciaf.2020.e00660.
- [3] SNV, 2018. <https://www.snv.org/update/lighting-isolated-communities-ghana-mini-grids>
Accessed: 19 December 2024.
- [4] Ministry of Energy, National Energy Policy, 2021.

- [5] J. K. Debrah, G. K. Teye, and M. A. P. Dinis, 'Factors influencing management of dry cell battery waste: a case of Greater Accra Region in Ghana', *Environ. Monit. Assess.*, vol. 196, no. 1181, 2024, doi: 10.1007/s10661-024-13297-4.
- [6] L. Mohammed *et al.*, 'Nanostructured manganese oxide from Ghana's manganese ore for lithium-ion battery anode', *J. Ghana Sci. Assoc.*, vol. 20, no. 2, pp. 71-80, 2021.
- [7] Hydrogen Central, 2024. <https://hydrogen-central.com/sfc-energy-is-participating-in-a-pilot-project-gh2gh-with-a-fuel-cell-energy-solution-as-part-of-the-export-initiative-environmental-protection-in-tema-ghana> Accessed: 27 November 2024.
- [8] J. Boafo, J. Obodai, E. Stemn, and P. N. Nkrumah, 'The race for critical minerals in Africa: A blessing or another resource curse?', *Resources Policy*, vol. 93, 105046, 2024.
- [9] E. D. Sunkari, J. Nkansah & S. J. Adams, 'Geochemical exploration for tantalum in coltan-rich pegmatites at Bewadze-Mankoadze area of the Kibi-Winneba Belt, southern Ghana: Constraints from exploratory data analysis.' *Heliyon*, vol. 10, no.18, e38176, 2024. [doi:10.1016/j.heliyon.2024.e38176](https://doi.org/10.1016/j.heliyon.2024.e38176)
- [10] G. Bridge and E. Faigen, 'Towards the lithium-ion battery production network: Thinking beyond mineral supply chains', *Energy Res. Soc. Sci.*, vol. 89, 102659, 2022.
- [11] S. Atiemo, L. Faabeluon, A. Manhart, L. Nyaaba & T. Schleicher, 'Baseline assessment on e-waste management in Ghana'. Sustainable Recycling Industries, 2016. https://www.sustainable-recycling.org/wp-content/uploads/2025/03/2016_baseline-assessment-e-waste-management-ghana_atiemo.pdf
- [12] Adu-Gyamfi, G., Song, H., Obuobi, B., Nketiah, E., Wang, H., & Cudjoe, D. (2022). Who will adopt? Investigating the adoption intention for battery swap technology for electric vehicles. *Renewable and Sustainable Energy Reviews*, 156, 111979
- [13] American Resources Corporation. (2023, December 6). ReElement Technologies and TechGulf Ghana to establish Africa's first battery-grade lithium processing plant in Ghana <https://www.americanresourcescorp.com/news-releases/reelement-technologies-and-techgulf-ghana-to-establish-africas-first-battery-grade-lithium-processing-plant-in-ghana>
- [14] K Shell Foundation (2024, September 19). Kofa Technologies and PASH Global lead £6.15 million battery swapping network launch in Ghana with support from Shell Foundation and UK Government <https://shellfoundation.org/news/kofa-technologies-and-pash-global-lead-6-15-million-battery-swapping-network-launch-in-ghana-with-support-from-shell-foundation-and-uk-government/>
- [15] The Business & Financial Times (2021, February 4). Environmental protection: BOSCH introduces eco-friendly battery recycling programme... gives 5% discount to old batteries returned. <https://thebftonline.com/2021/02/04/environmental-protection-bosch->

[introduces-eco-friendly-battery-recycling-programme-gives-5-discount-to-old-batteries-returned/](#)

[16] African Union Commission (2024). The African energy transition strategy and action plan (ETSAP). African Energy Commission (AFREC). <https://au-afrec.org/sites/default/files/2025-09/ETSAP%20Report%20publication.pdf>

[17] Natural Resource Governance Institute (2025). Refining the strategy: The economics of lithium value addition in Ghana. https://resourcegovernance.org/sites/default/files/2025-04/refining_strategy_economics_lithium_value_addition_ghana_2025.pdf

[18] Bosch Ghana, Bosch Ghana automotive battery project, 2020. <https://www.bosch.africa/news-and-stories/bosch-ghana-automotive-battery-project/> Accessed: 12 December 2024.

[19] Atlantic Lithium Ltd EWOYAA, GHANA, 2023. <https://www.atlanticlithium.com.au/projects-ghana> Accessed: 22 December 2024.

[20] Ministry of Energy, Ghana's National Energy Transition Framework (2022-2070), 2022.

[21] World Bank, 'World Bank Supports Policy Reform of Ghana's Energy Sector and Access to Clean Cooking', 2024. [https://www.worldbank.org/en/news/press-release/2024/06/13/afw-world-bank-supports-policy-reform-ghana-energy-sector-and-access-to-clean-cooking#:~:text=WASHINGTON%2C%20June%2012th%2C%202024%20-,Program%20for%20Results%20\(PforR\).](https://www.worldbank.org/en/news/press-release/2024/06/13/afw-world-bank-supports-policy-reform-ghana-energy-sector-and-access-to-clean-cooking#:~:text=WASHINGTON%2C%20June%2012th%2C%202024%20-,Program%20for%20Results%20(PforR).) Accessed: 22 December 2024.

[22] Green Climate Fund, The Accelerating Solar Action Programme (ASAP), 2024. <https://www.greenclimate.fund/project/fp231> Accessed: 22 December 2024.

[23] D. Bukari, F. Kemausuor, D. A. Quansah, and M.S. Adaramola, 'Towards accelerating the deployment of decentralised renewable energy mini-grids in Ghana: Review and analysis of barriers', *Renew. Sustain. Energy Rev.*, vol. 135, 110408, 2021.

[25] ESMAP, Energy Storage for Mini Grids, 2023. https://www.esmap.org/sites/default/files/esmap-files/ESMAP%20RPT_Energy%20Storage%20for%20Mini%20Grids_WEB.pdf Accessed: 23 December 2024.

Kenya

This section was written by Dr Julius Butime, Dean in the School of Computing and Engineering Sciences at Strathmore University, who focuses on testing second-life batteries. Additional contributions by Neema Oribó, Daniel Simiyu, and Lilian Mukhoya, all at Strathmore University.

1. Introduction

1.1 Background

The global demand for sustainable energy storage solutions is increasing, driven by the need for renewable energy integration and the electrification of various sectors. In Kenya, this need is pronounced due to the growing adoption of solar energy, particularly in rural areas, as well as the rise of electric mobility. As battery technologies advance globally, Kenya is positioning itself to tap into these innovations to enhance its renewable energy infrastructure and transportation sector.

Kenya boasts abundant sunlight throughout the year, with average daily insolation ranging from 4 – 6 kWh/m² and a global horizontal irradiation (GHI) of approximately 2,400 kWh/m²/year [1]. This substantial solar potential is further demonstrated by a study conducted in Machakos County, Kenya, which reported a daily insolation of 5.8kWh/m² and highlighted the feasibility of hybrid wind solar systems [1]. Additionally, a performance analysis of Strathmore University's solar power system revealed an annual production of 743 MWh, a capacity factor of 13.97, and a competitive levelised cost of electricity (LCoE) at \$0.143/kWh. Regions such as Marsabit and Turkana, with direct normal irradiance (DNI) values ranging from 670 to 1,662 MWh, show high potential for concentrated solar power (CSP) in the country.

Kenya has significant wind energy potential, particularly in regions such as Marsabit, Turkana, and Ngong, where high wind speeds make wind power a viable and sustainable energy source. The Lake Turkana Wind Power (LTWP) project, Africa's largest wind farm, contributes approximately 310 MW to the national grid, significantly enhancing the country's energy capacity [2]. Studies have highlighted the feasibility of hybrid wind-solar systems in areas with strong winds, allowing for a more stable and reliable renewable energy supply [1]. The government, in collaboration with private investors, has been actively expanding wind energy infrastructure to diversify Kenya's renewable energy portfolio.

The rise of electric mobility in Kenya, especially for short-distance transport like electric two-wheelers and public service vehicles (PSVs) underscores the importance of energy storage. Nearly 85% of Kenya's electricity comes from renewables, making it well positioned to support e-mobility, reducing reliance on fossil fuels and minimising emissions [3]. Advanced battery technologies, such as lithium-ion (Li-ion) systems, are essential for powering electric

vehicles (EVs) and supporting the infrastructure required for widespread adoption [4]. Additionally, initiatives like the reduction of excise duty on battery electric vehicles (BEVs), the development of EV standards, and pilot projects deploying electric two-wheelers in Kisumu underscores the country's commitment to advancing electric mobility [3].

The battery industry faces several challenges such as high costs, limited local manufacturing capacity, end-of-life management and supply chain constraints despite Kenya's renewable energy advantages. However, there are significant opportunities for growth, such as expanding local battery assembly plants, enhancing research on alternative battery chemistries, and strengthening battery-swapping and charging infrastructure to support electric mobility. Kenya's battery industry is also positioned to attract investment in Li-ion and emerging energy storage technologies to improve grid reliability and off-grid electrification.

1.2 Objective

This document outlines the current state of battery research in Kenya, highlights key areas of innovation, and identifies major players in the sector, while exploring prospects for enhancing energy storage capabilities. It also examines policy frameworks, investment trends, and emerging technologies that can drive Kenya's transition toward a more sustainable and resilient battery industry.

2. Key research areas in battery technologies

The need to achieve net-zero goals has resulted in the increased adoption of renewable energy sources for energy generation. Using renewables such as wind and solar brings challenges of intermittency and reliability. Energy storage systems overcome these challenges by contributing to grid stability and promoting improved access to green energy and energy security. As a result, massive research initiatives around the world aim to build robust energy storage systems. Energy density, stability, and safety are key components in storage system development, and researchers are constantly improving battery technologies to mitigate these constraints. The need for lighter, yet powerful battery technologies will provide storage systems that are versatile and applicable to more industries, including the power grid, aviation, energy storage, and e-mobility, among others.

2.1 Li-ion batteries

Li-ion batteries are a versatile electrochemical energy storage technology that relies on shuttling lithium ions between negative and positive electrodes [5], [6]. These batteries are made up of cathodes of various battery chemistries, which can increase their energy density [5]. Li-ion batteries are widely used across various sectors due to their high energy density, low maintenance requirements, and lightweight design.

Common applications include:

- EVs: The primary power source for EVs, Li-ion batteries enable the global shift toward clean mobility solutions [7]. Retired EV batteries can be repurposed for less demanding applications such as home energy storage or backup power systems [8], [9].
- Off-grid solar energy systems: These batteries store energy generated by solar photovoltaic (PV) systems, enabling a reliable electricity supply in remote or underserved areas. Second-life batteries are particularly cost-effective in such systems, reducing costs while maintaining performance.
- Portable electronics: Li-ion batteries power devices such as smartphones, laptops, and wearable technology [5].
- Grid storage: They are used in large-scale energy storage systems to stabilise grids, integrate renewable energy, and manage peak demand [10].

2.2 Second-life Li-ion batteries

Second-life Li-ion batteries, which are previously used batteries that are repurposed for other applications, are a key component of sustainable energy solutions, particularly in mitigating environmental and social challenges [11]. Li-ion batteries contain hazardous materials that can pose serious environmental and safety risks if improperly handled at the end-of-life. Improper disposal of used batteries can lead to soil and water contamination or even fires, making the repurposing of these batteries a critical step in waste reduction. Companies such as Inno-Neat in Kenya play a crucial role in this process by converting used Li-ion cells into solar-ready battery packs, particularly for low-income communities [12]. These initiatives not only promote affordability but also contribute to sustainability by giving batteries a second life and reducing the demand for new resources. According to published research by the World Bank in partnership with ESMAP [13], these batteries serve for about a decade in EVs before options like disposal, recycling, or reuse are needed. Reuse often involves reconditioning, including testing, dismantling, and reassembling battery cells to ensure compatibility in new applications such as off-grid solar PV systems.

Current research aims to improve battery energy density, safety, and reduce costs for both consumer and industrial applications. In Kenya, efforts to explore local sourcing of materials and manufacturing capabilities are still in the early stages [14]. Partnerships such as those offering renewable energy solutions on a pay-as-you-go (PayGo) model [15] highlight the potential for scaling second-life battery applications to underserved communities. These efforts are still in their infancy with significant opportunity for growth.

Kenya currently imports most of its Li-ion batteries. However, regional partnerships with countries like Zimbabwe, which has significant lithium reserves, offer potential future avenues for local production and research. Strengthening domestic capabilities would not only enhance sustainability and energy access but also foster a local ecosystem for battery technology innovation.

2.3 Sodium-ion batteries

Sodium-ion batteries are emerging as a cost-effective alternative to Li-ion technology, particularly for their potential in large-scale energy storage solutions and rural electrification in Kenya [16]. While sodium-ion batteries currently exhibit lower energy density than Li-ion batteries, their advantages include lower cost, sustainability, and the abundance of sodium in comparison to lithium [17]. Further research is, however, required to determine advanced cathode and anode materials with higher specific capacities and voltage to enhance viability of the sodium-ion battery technology [17], [18].

Local universities, such as the University of Nairobi, are exploring materials used in sodium-ion batteries that can be sourced more abundantly and at lower costs compared to lithium.

Given Kenya's growing renewable energy capacity and the need for affordable storage solutions, sodium-ion batteries present a promising long-term option for grid and off-grid applications, particularly where cost considerations outweigh energy density requirements.

2.4 Solid-state batteries (SSBs)

Solid-state battery technology promises to be the next frontier in energy storage due to its potential higher energy density and improved safety over conventional liquid electrolyte batteries [18]. In Kenya, SSB research is at a nascent stage, though opportunities exist to leverage local mineral resources and international collaborations to accelerate technology development.

2.5 Flow batteries

Redox flow batteries have become a critical technology for large-scale energy storage, offering scalable, flexible solutions that decouple energy and power [18]. The cells of a flow battery use two chemical solutions containing ions, an anolyte adjacent to the anode and a catholyte near the cathode. An electrochemical reaction between the two solutions pushes the electrons through a circuit. The solutions can be charged in place by a current moving in the opposite direction or spent solutions can be replaced with charged ones. Typical redox flow batteries are based on iron, chromium or vanadium chemistries. Recent advances include hybrid battery designs, redox-targeting strategies, photoelectrode integration, and organic redox-active materials, improving cost-effectiveness and sustainability [19].

Flow batteries are especially suitable for large-scale energy storage, integrating intermittent renewable sources, such as wind and solar, into the grid. In the Kenyan context, exploration of vanadium resources and collaborations could support deployment of flow batteries for both grid and off-grid storage solutions.

2.6 Grid-tied battery systems

Grid-tied battery systems are becoming increasingly important in Kenya as the country seeks to enhance grid reliability and stability amid growing renewable energy penetration. Notable projects include KENGEN's 100 MW battery storage system [20, 21]. The 100MW

battery project aims to mitigate renewable energy intermittency while capturing geothermal energy that would otherwise be lost to curtailment during off-peak periods [20]. Supercapacitors are also being explored as preferred solutions for massive energy storage, due to their high power density and low maintenance requirements [16]. Large-scale renewable projects such as the Lake Turkana Wind Power project are exploring battery integration to enhance grid stability and optimise energy utilisation.

2.7 Novel battery technologies

Zinc-air batteries and other emerging technologies are being considered in Kenya for both off-grid applications and sustainable energy storage [22]. Amongst the novel battery technologies is the flywheel energy storage system [23], which offers high efficiency during both charging and discharging phases, long cycle life and rapid response time, though energy capacity and initial costs remain constraints [16]. Bio-inspired batteries, characterised by use of abundant and renewable materials, offer a sustainable alternative with low environmental impact. However, they are still in the developmental stage, exhibiting limited performance and scalability [24]. Similarly, Moringa paste-based batteries offer advantages such as low cost and ready availability of materials, but they are also in the early developmental stages, lacking comprehensive performance data [25]. They however hold potential for large-scale deployment in the future. Vegetable electroactive antioxidants for rechargeable bio-batteries represent a sustainable approach that could be scaled, yet their performance requires improvement for practical applications [26].

Kenyan researchers contribute to international collaborations, primarily through academic research, pilot demonstrations, materials characterisation, performance testing, and feasibility studies under local climatic and operational conditions [16]. International collaborations enhance technical capacity, enable knowledge transfer in battery chemistry, and generate context-specific data to inform deployment of emerging storage technologies in off-grid and rural electrification applications.

3. Material sourcing and local manufacturing

3.1 Raw materials

Kenya has several mineral resources that can contribute to battery manufacturing, including lead, manganese, graphite, and fluorspar. To enhance Kenya's regional and global participation in the battery value chain, the development of local refining, processing, and value-addition capabilities is essential. Manganese, found in Kilifi, Kwale, and Taita Taveta counties, is essential for lithium manganese oxide (LMO) cathodes, where it enhances thermal stability and cost-effectiveness. Although mining operations are active in Kilifi and Kwale, local processing industries for battery-grade manganese do not yet exist. Graphite, which is primarily used in Li-ion battery anodes, has deposits in Homa Bay, Samburu, and Kitui counties but similarly lacks processing facilities for battery applications. Fluorspar, sourced from Kerio Valley in Elgeyo Marakwet County, plays a role in the production of

electrolytes for Li-ion and sodium-ion batteries [1]. While fluorspar mining has historically been significant in Kenya, most of the extracted material is used for industrial applications such as steel production and hydrofluoric acid manufacturing.

Despite having mineral deposits, Kenya has yet to develop a robust local battery manufacturing sector. The lack of refining and processing facilities is one of the main limitations as raw materials are exported leading to a heavy reliance on imported battery components. Additionally, Kenya lacks large-scale lithium and cobalt reserves, which are critical for Li-ion battery production. Beyond resource availability, policy and investment gaps further hinder development of domestic refining, processing, and value-addition capabilities. Strengthening infrastructure, implementing targeted policies, and encouraging research and investment are critical for Kenya to participate more fully in the regional and global battery value chain.

3.2 Environmental and social impact

Although Kenya currently has limited mining activity, the development of a local battery value chain would necessitate proactive governance of environmental and ethical issues related to mineral extraction and processing. Improper recycling of lead-acid batteries can result in significant soil and water pollution, with informal recycling practices exposing workers and nearby communities to lead poisoning. Manganese mining in Kilifi and Kwale generates tailings that may lead to heavy metal contamination in soils and waterways, while fluorspar mining in the Kerio Valley has been linked to acid drainage issues that negatively impact local communities. Beyond extraction, battery production and disposal introduce broader environmental considerations, including emissions, resource efficiency, degradation during use, and end-of-life management.

3.3. Recycling and circular economy

To ensure sustainability, Kenya is beginning to develop battery recycling initiatives. Pilot projects are exploring safe methods for disposal and material recovery from used Li-ion batteries in EV and solar storage systems. However, recycling infrastructure remains limited, and improper disposal continues to contribute to e-waste concerns. Expanding domestic recycling capacity is essential to close the material loop, reduce environmental risks, and create a sustainable local supply chain for battery technologies.

4. Key research institutions and collaborations

4.1 Research institutions and collaborative networks

Battery research in Kenya is primarily driven by universities, applied research institutes, and international development partners. The University of Nairobi (UoN), Jomo Kenyatta University of Agriculture and Technology (JKUAT), Strathmore University, and Dedan Kimathi University of Technology (DeKUT) play leading roles in advancing battery chemistry, materials science and energy storage applications. Research efforts span Li-ion and

alternative chemistries, renewable energy integration, microgrids, and recycling technologies.

Strathmore University has emerged as a focal point for applied energy storage research, particularly in renewable energy integration and community-scale deployment. Demonstration projects, such as the 1.6 kWp solar-battery installation on Wasini Island implemented in collaboration with the Kwale County Government, highlight the role of pilot systems in validating battery technologies under real operating conditions. UoN collaborates with initiatives such as the African Centre of Excellence in Energy and Sustainability (ACE-ESD) to support off-grid and clean energy research, while JKUAT focuses on battery materials, recycling pathways, and sustainable disposal methods in partnership with government agencies and private industry.

Beyond academia, applied research institutions such as the Kenya Industrial Research and Development Institute (KIRDI) contribute to battery recycling, alternative materials, and technology commercialisation. International organisations, including the United Nations Environment Programme (UNEP), support pilot projects in electric mobility, battery recycling frameworks, and energy storage deployment. Collectively, these collaborations facilitate knowledge transfer, capacity building, and alignment with global battery innovation trends.

5. Battery skills assessment

Kenya faces a shortage of skilled personnel across the battery value chain, including design, diagnostics, manufacturing, and end-of-life management despite growing interest in energy storage and electric mobility. Skills gaps are particularly evident in advanced battery diagnostics, safe dismantling, and recycling processes necessary for a circular economy.

Government-backed initiatives, such as the Kenya Youth Employment and Opportunities Project (KYEOP), have begun integrating energy storage modules into technical training programmes. Institutions like SERC and the Kenya Industrial Training Institute offer targeted training in Li-ion battery pack assembly, maintenance, and system integration.

Industry-led pilots, including second-life Li-ion battery projects supported by international partners, further demonstrate the performance advantages of repurposed Li-ion systems compared to lead-acid batteries, while highlighting emerging service-based business models for localised circular economies. However, the absence of large-scale, standardised training programmes for battery recycling and materials recovery remains a constraint. Addressing this gap will require coordinated efforts between academia, industry, and international partners to develop curricula aligned with emerging market and regulatory needs.

6. Industry and start-up ecosystem

Kenya's battery ecosystem is closely linked to the rapid growth of electric mobility, renewable energy integration, and off-grid electrification. Start-ups and private companies play a central role in deploying Li-ion battery systems tailored to local conditions, particularly in two- and three-wheeled EVs and solar-based energy systems.

Electric motorcycle adoption has driven innovation in battery pack design, battery-as-a-service models, and swapping infrastructure. Companies such as Roam, E-ride, Autopax Kenya in collaboration with Kofa Energy, Ampersand, ARC Ride, Enzi Electric and Mazi Mobility focus on locally assembled electric motorcycles, optimised Li-ion battery packs, and rapid battery-swapping networks to address range anxiety and charging downtime.

Similar advances are occurring in electric buses, where companies like BasiGo and Roam are at the forefront. BasiGo's electric buses demonstrate the viability of high-capacity lithium iron phosphate (LFP) systems for daily urban operations, supporting extended driving ranges with fast-charging capability. Similarly, Roam has expanded from electric motorcycles to electric buses, deploying modular LFP-based battery systems to address diverse public transport needs.

Collectively, these deployments indicate a transition toward locally adapted, safety-oriented battery architectures for electric mass transit in Kenya, while highlighting the role of smart battery management systems (BMS) in ensuring durability and operational reliability.

Beyond mobility, renewable energy integration in Kenya has been advanced through decentralised energy systems led by companies such as PowerGen Renewable Energy and E-Safiri, which deploy solar and hybrid generation coupled with Li-ion battery storage to support productive use and community-scale electrification. Off-grid electrification has been significantly enabled by M-KOPA, whose pay-as-you-go model combines solar technologies, battery storage, and mobile financing to expand electricity access for low-income and rural households. Gogla Africa also engages in research and deployment of next-generation Li-ion and sodium-ion battery solutions tailored for rural and urban settings. Together, these approaches illustrate how renewable energy technologies, when integrated with innovative delivery and financing mechanisms, can address affordability, reliability, and access challenges in emerging energy markets.

7. Policy, funding and challenges

Kenya has established a supportive policy and regulatory environment for battery deployment, particularly in electric mobility and renewable energy storage. National strategies such as Vision 2030 and the Kenya National Electrification Strategy recognise energy storage as a critical enabler of grid stability and energy security.

Regulatory oversight by the Kenya Bureau of Standards (KEBS) ensures compliance with international safety and performance standards for batteries used in EVs and solar energy storage. From January 1, 2024, all EV batteries must undergo Pre-Export Verification of Conformity (PVoC) in their country of origin, with only those issued a Certificate of Conformity (CoC) from KEBS-appointed agents being permitted for import. Compliance with ISO 12405-4 and IEC 62619 standards further ensures adherence to international best practices, reducing the risk of substandard and hazardous battery imports. Infrastructure development is guided by the Energy and Petroleum Regulatory Authority's Electric Vehicle Charging and Battery Swapping Infrastructure Guidelines, which define licensing, safety certification, inspection, and battery traceability requirements.

Operators are required to implement BMSs with unique identifiers for each battery, ensuring real-time monitoring, safety, longevity, and traceability. Large-scale grid storage initiatives in Kenya are led by utilities such as Kenya Power and KenGen, which are deploying battery energy storage systems (BESS) to integrate renewable generation into the national grid. Under the World Bank-supported Kenya Green and Resilient Expansion of Energy (GREEN) programme, KenGen plans an initial 100 MW BESS across key regions to store surplus hydro, geothermal, and wind energy, improving grid stability and mitigating the intermittency challenges of variable renewables. These projects highlight the growing role of large-scale energy storage in complementing decentralised solutions and enabling reliable renewable integration at the national level.

7.1 Environmental governance, recycling, and circular economy

Battery waste management remains a growing challenge, particularly for Li-ion and lead-acid batteries. Kenya's National E-Waste Management Strategy promotes extended producer responsibility, recycling fees, and the establishment of collection and recycling infrastructure. Stricter enforcement of lead-acid battery recycling regulations reflects concerns over pollution and public health impacts from informal smelting. While pilot recycling initiatives are emerging, large-scale Li-ion battery recycling capacity remains limited. Strengthening recycling infrastructure is essential to support a circular economy, reduce environmental risks, and recover valuable materials as battery deployment accelerates.

7.2 Funding landscape and challenges

Battery research and deployment in Kenya is supported through a mix of public funding, international development finance, and private investment. Multilateral institutions, bilateral partnerships, and national research funds provide grants and concessional financing for energy storage, electric mobility, and grid resilience projects. Public-private partnerships play a key role in enabling pilot manufacturing, recycling facilities, and workforce development.

Despite this progress, challenges persist, including high technology costs, infrastructure limitations, fragmented research–industry linkages, and skills shortages. Environmental and social risks associated with mining, recycling, and disposal further underscore the need for integrated policy, technical capacity development, and long-term investment strategies to ensure sustainable growth of Kenya’s battery sector.

8. Case studies and success stories

8.1 Case study 1: expanding energy access through off-grid battery storage – M-KOPA Solar

M-KOPA Solar has pioneered the deployment of off-grid solar energy systems with integrated Li-ion battery storage, providing energy access to over 1 million households across Kenya and other African countries. By leveraging a pay-as-you-go (PAYG) model, M-KOPA enables low-income families to afford solar energy systems through micro-instalments via mobile money. This has reduced reliance on kerosene, leading to improved indoor air quality and reduced health risks; enabled micro-enterprises to operate beyond daylight hours, fostering local economic growth; and lowered carbon emissions, contributing to Kenya’s clean energy transition. Batteries are designed to withstand high temperatures and prolonged charging cycles, ensuring longer operational life. Real-time Internet of Things (IoT)-enabled monitoring optimises battery performance and prevents premature failure.

8.2 Case study 2: electrification of Kenya’s motorcycle transport – Gogo Electric & Bodawerk

The motorcycle taxi (boda boda) sector is a crucial part of Kenya’s transport ecosystem but has historically relied on fossil fuel-powered motorcycles, contributing to pollution and high operational costs. Initiatives like Gogo Electric and Bodawerk have successfully piloted electric motorcycle conversions, offering an affordable and sustainable alternative. Advantages include reduced fuel costs: riders save up to 50% on daily fuel expenses by switching to electric motorcycles; swappable Li-ion batteries that ensure quick turnaround times, reducing range anxiety; lower emissions and noise pollution, improving urban air quality and liveability; custom BMS optimised for Kenya’s rugged terrain, and fast-swap battery stations, enabling riders to exchange depleted batteries in under five minutes. The initiatives have partnerships with fintech firms to provide leasing options, reducing the upfront cost of electric motorcycles.

8.3 Case study 3: advancing affordable battery storage solutions – Strathmore University

Strathmore University is leading research into sodium-ion battery alternatives to Li-ion batteries. With local sodium deposits from Kenya’s soda ash reserves, Strathmore Energy

Research Centre (SERC) aims to develop low-cost, scalable energy storage solutions tailored to off-grid applications.

8.4 Case study 4: KenGen's BESS project

As part of the World Bank-funded Kenya GREEN programme, the Kenya Electricity Generating Company PLC (KenGen) has initiated a 100 MW BESS project aimed at bolstering grid reliability and enhancing renewable energy integration. This project is strategically located in regions with high renewable potential, primarily in the Central Rift and geothermal-rich areas, where surplus energy from geothermal and other renewable sources is frequently curtailed due to grid limitations. The BESS project employs state-of-the-art Li-ion battery technology combined with advanced power conversion systems and real-time energy management software. These innovations facilitate precise load balancing and monitoring, ensuring that surplus energy is efficiently stored and later deployed during peak demand periods. The project involves a collaborative framework among KenGen, the Kenyan government, and international stakeholders, including technology providers and engineering firms.

Early pilot outcomes indicate that the BESS project has led to a measurable improvement in grid stability, with a reduction in energy curtailment and enhanced capacity to integrate intermittent renewable energy sources. The project's advanced energy management system provides continuous data analytics, enabling operators to optimise performance, predict maintenance needs, and make real-time decisions that align with grid demand fluctuations. This integrated approach not only modernises Kenya's energy infrastructure but also lays the foundation for future scaling of energy storage solutions across the region, thereby contributing to a more resilient and sustainable energy supply network.

8.5 Case study 5: BasiGo electric bus pilot in Nairobi

BasiGo, a startup dedicated to advancing electric mobility in Kenya, launched a pilot project aimed at deploying electric buses in Nairobi. This initiative served as a demonstration of how locally assembled battery packs, integrated with advanced energy management systems, can power public transport efficiently while reducing urban air pollution. In this project, battery packs are manufactured on-site, which not only supports local industry but also enhances the technical expertise required for battery assembly and maintenance. The energy management system implemented in these buses enables real-time monitoring of battery performance, facilitates predictive maintenance, and helps optimise the overall lifespan of the batteries. By generating and analysing operational data, the project provides actionable insights that can be used to improve battery performance and refine energy storage strategies.

This pilot project is significant because it offers a replicable model for transitioning to sustainable public transport systems, reducing operational costs, and lowering greenhouse gas emissions in urban environments.

9. Future directions

9.1 Emerging trends

Kenya is poised to explore new battery technologies such as sodium-ion and zinc-air batteries, which may offer more cost-effective and sustainable solutions for local energy needs [16]. The electrification of motor bikes and the integration of grid-tied battery solutions are likely to accelerate the demand for efficient and reliable battery solutions. As the global transition to net zero intensifies, energy storage will remain a key area of interest to ensure maximum utilisation of intermittent renewables such as solar and wind in applications including e-mobility, mini-grids and utility-scale grid stability [27]. Following the increased demand for batteries, new battery technologies with longevity, optimal utilisation of rare metals and decreased costs continue to be key research interests [28]. To avoid the hazard of battery waste after batteries are retired from their initial use, especially in EVs, studies continue to investigate battery repurposing and reuse in various applications including energy storage, and less energy intensive application in grid stabilisation [27]. The excessive demand on lithium-battery chemistries will constrain battery raw material resources, hence the need to refocus research on optimisation of battery recycling technologies to improve recovery rates of the useful metal components, making the remanufactured batteries more robust and affordable [29], [12].

As African countries strive to attain the ambitions of the UN SDG 7 goals to reach full energy access across Africa by 2030 [9], the development of micro and mini grids supported by battery storage in place of diesel generators for energy generation is key. There will be demand for increased circularity in the battery ecosystem through building of sustainable, recyclable and upgradable battery packs [30].

Enhancement of battery monitoring and communication technology in BMS and key safety features to ensure stability and safety of Li-ion batteries has seen lots of development, especially for EV BMS [27], which incorporate diagnostic tools to continuously assess the state-of-charge and state-of-health of batteries. In addition, the expansion of EV charging infrastructure is another area with great potential, as it will ultimately promote the increased adoption of EVs [31]. Automated battery swapping stations for two-wheeler e-motor bikes reduce downtime for businesses that have adopted e-mobility as a means to promote net-zero goals in their supply chain [15].

Standardisation of e-mobility is continuing with standards such as ISO 15118-20 that offer guidelines for vehicle-to-grid communication, including electric power transfer between EVs and the grid [32]. Standardisation also continues in the battery development space: features such as CE marking and a digital battery passport for batteries to ease remanufacture and sustainable reuse practices can be adopted globally [33] in addition to ensuring responsible manufacturing and e-waste management practices from battery manufacturers.

9.2 Roadmap

With strategic investment in local manufacturing, skills development and research, Kenya has the potential to become a leader in the development and deployment of battery technologies in East Africa. Despite the challenges of achieving a scenario where batteries can support the roll-out of renewable energy without negative economic or environmental costs, such as financing options, battery delivery timelines and battery quality and durability, there are great strides in the Kenyan batteries landscape. Some pathways to be explored in the battery research and development sector include increasing the impact of sustainable batteries by improving finance options through cost reduction, incentives, and favourable policies that encourage investment in the sector [12]. This will also improve capacity for local manufacturing of batteries.

Training and capacity building in various aspects of battery management is also needed to ensure local capacity for assembly of battery packs [30]. Technical skills must align with leadership and innovation, making it important for interdisciplinary research teams to collaborate and find solutions for gaps identified in battery development [34]. Further collaborations can be achieved through research hubs such as SERC, which offer various strategic approaches to bridging the gap in technical expertise in addition to promoting innovations [35].

Battery quality and durability should be improved through standardisation and enabling policies. This will cushion consumers against the risk of buying batteries that do not meet globally acceptable standards in quality and safety [30]. Research collaborations and funding towards technical skills development for sustainable battery management practices are vital factors to produce a competitively trained workforce in the entire batteries value chain [36].

10. Conclusions

Kenya is making strides in battery research, with significant progress in renewable energy integration, off-grid solutions, grid stability, and electric mobility. The electrification of boda bodas and the adoption of grid-tied battery solutions are important aspects of this transition, representing both challenges and opportunities for sustainable transportation and energy management.

Challenges remain, but opportunities for innovation and collaboration, particularly through institutions like SERC, promise a bright future for Kenya's energy landscape.

There is an optimistic outlook for Kenya to leverage its unique position in the African battery landscape, driven by local innovation, international collaboration, and a commitment to sustainable energy practices.

References

- [1] I. K. Rotich, H. Chepkirui, and P. K. Musyimi, 'Renewable energy status and uptake in Kenya,' *Energy Strategy Reviews*, vol. 54, 101453, 2024.
- [2] S. Gyamfi, F. Diawuo, C. Kyeremeh, S. K. Nyarko, and E. Tetteh, 'Renewable energy deployment in Africa: Policy framework, emerging opportunities and challenges,' *Energy Reports*, vol. 7, pp. 2177–2190, 2021. doi: 10.1016/j.egy.2021.03.017.
- [3] Electric Mobility – Renewable Energy Portal, n.d.
- [4] T. Winther, K. Ulsrud, and A. Saini, 'Solar powered electricity access: Implications for women's empowerment in rural Kenya,' *Energy Research & Social Science*, vol. 44, pp. 61–74, 2018.
- [5] M. Armand *et al.*, 'Lithium-ion batteries – Current state of the art and anticipated developments,' *Journal of Power Sources*, vol. 479, 228708, 2020. doi: 10.1016/j.jpowsour.2020.228708.
- [6] A. Zanoletti, E. Carena, C. Ferrara, and E. Bontempi, 'A review of lithium-ion battery recycling: Technologies, sustainability, and open issues,' *Batteries*, vol. 10, no. 1, p. 38, 2024. doi: 10.3390/batteries10010038.
- [7] T. Khan, Z. Yang, S. Kohli, and J. Miller for ICCT, 'A critical review of ZEV deployment in emerging markets,' 2022. <https://theicct.org/publication/zev-market-review-global-feb22/>
- [8] R. Best, 'Assets power solar and battery uptake in Kenya,' *Energy Economics*, vol. 123, 106723, 2023.
- [9] D. Ockwell *et al.*, 'Transforming access to clean energy technologies in the Global South: Learning from Lighting Africa in Kenya,' *Energies*, vol. 14, no. 14, p. 4362, 2021.
- [10] M. Ngala, S. Opana, J. Kilonzi, A. Nabaala, and K. Wachira, 'Optimal sizing of battery energy storage system for grid stability in Western Kenya,' *Proc. IEEE PES/IAS PowerAfrica*, 2022, pp. 1–4. doi: 10.1109/PowerAfrica53997.2022.9905373.
- [11] Y. Zhao *et al.* 'A review on battery market trends, second-life reuse, and recycling,' *Sustainable Chemistry*, vol. 2, no. 1, pp. 167–205, 2021. doi: 10.3390/suschem2010011.
- [12] J. Hegenbart and S. Rosmark, 'Conditions for circular electric vehicle battery value chains: Exploring opportunities for circular economy implementation in the value chain of electric vehicle batteries in Nairobi, Kenya,' Linköping University, 2023. <https://www.diva-portal.org/smash/record.jsf?dswid=-7561&pid=diva2%3A1779793>
- [13] The World Bank, 'Climate Smart Mining Initiative & Energy Sector Management Assistance Program, Reuse and Recycling: Environmental Sustainability of Lithium-Ion Battery energy storage systems', 2020.

<https://documents1.worldbank.org/curated/en/593961599738208006/pdf/Reuse-and-Recycling-Environmental-Sustainability-of-Lithium-Ion-Battery-Energy-Storage-Systems.pdf>

- [14] M. Shahjalal *et al.*, 'A review on second-life of Li-ion batteries: Prospects, challenges, and issues,' *Energy*, vol. 241, 122881, 2022. doi: 10.1016/j.energy.2021.122881.
- [15] G. Song'e, 'Tech advancements driving the uptake of e-mobility in Kenya,' *Business Daily*, Aug. 20, 2024. <https://www.businessdailyafrica.com/bd/opinion-analysis/columnists/tech-advancements-driving-the-uptake-of-e-mobility-in-kenya-4731350>
- [16] G. G. Njema, R. Ben, and J. K. Kibet, 'A review on the recent advances in battery development and energy storage technologies,' *Journal of Renewable Energy*, pp. 1–35, 2024.
- [17] K. M. Abraham, 'How comparable are sodium-ion batteries to lithium-ion counterparts?' *ACS Energy Letters*, vol. 5, no. 11, pp. 3544–3547, 2020. doi: 10.1021/acsenerylett.0c02181.
- [18] S. Lou *et al.*, 'Interface issues and challenges in all-solid-state batteries: Lithium, sodium, and beyond,' *Advanced Materials*, vol. 33, no. 6, 2000721, 2021. doi: 10.1002/adma.202000721.
- [19] Z. Zhou, S. Henkel, S. Kasten, and M. Holtappels, 'The iron 'redox battery' in sandy sediments: Its impact on organic matter remineralization and phosphorus cycling,' *Science of The Total Environment*, vol. 865, p. 161168, 2023.
- [20] M. Masyuko, 'Kenya to implement 100MW battery energy storage system project,' *Market Intelligence*, 19 Dec, 2023. <https://www.trade.gov/market-intelligence/kenya-implement-100mw-battery-energy-storage-system-project>
- [21] J. Mutua, 'KenGen to build battery storage for maiden Sh8bn solar plant,' *Business Daily*, 29 Jan, 2025. <https://www.businessdailyafrica.com/bd/corporate/industry/kengen-to-build-battery-storage-for-maiden-sh8bn-solar-plant-4906294>
- [22] F. Lashgari, S. M. Babaei, M. Z. Pedram, and A. Arabkoohsar, 'Comprehensive analysis of a novel integration of a biomass-driven combined heat and power plant with a compressed air energy storage (CAES),' *Energy Conversion and Management*, vol. 255, 115333, 2022. doi: 10.1016/j.enconman.2022.115333.
- [23] O. Bamisile *et al.*, 'Development and prospect of flywheel energy storage technology: A citespace-based visual analysis,' *Energy Reports*, vol. 9, pp. 494–505, 2023. doi: 10.1016/j.egyr.2023.05.147.
- [24] S. Choi, 'Biofuel cells and biobatteries: Misconceptions, opportunities, and challenges,' *Batteries*, vol. 9, no. 2, p. 119, 2023. doi: 10.3390/batteries9020119.

- [25] J. W. D. Therik, P. Siwindarto, and A. Susuilo, 'Potential bio battery of Moringa paste (Moringa Oleifera) as a source environmentally friendly electricity,' *Natural Volatiles and Essential Oils Journal*, 2021. <https://www.nveo.org/index.php/journal/article/view/856>
- [26] Z. Hussain *et al.*, 'Construction of rechargeable bio-battery cells from electroactive antioxidants extracted from wasted vegetables,' *Cleaner Engineering and Technology*, vol. 5, p. 100342, 2021. doi: 10.1016/j.clet.2021.100342.
- [27] N. Kertész and L. Szabó, 'Advances and future trends in battery management systems,' *SMTS 2024*, p. 66, 2024. doi: 10.3390/engproc2024079066.
- [28] A. Kalair *et al.*, 'Role of energy storage systems in energy transition from fossil fuels to renewables,' *Energy Storage*, vol. 3, no. 1, e135, 2021. doi: 10.1002/est2.135.
- [29] J. Fan, H. Teng, and Y. Wang, 'Research on recycling strategies for new energy vehicle waste power batteries based on consumer responsibility awareness,' *Sustainability*, vol. 14, no. 16, p. 10016, 2022. doi: 10.3390/su141610016.
- [30] L. Dr. Allerston, S. Stacey, M. Carberry, and A. Dr. Chandan, *Enabling Batteries to Die another Day: Improving Battery Economics through the Circular Economy for Africa*, Shell Foundation, 2021. <https://shellfoundation.org/wp-content/uploads/2022/07/ENABLI1.pdf>
- [31] N. D. Smidt and R. Balthasar, *Unlocking the Growth Potential of Kenya's E-Mobility Sector*, Siemens Stiftung, 2024. <https://www.siemens-stiftung.org/wp-content/uploads/2030/09/studie-unlocking-the-growth-potential-of-Kenya-E-Mobility-Sector.pdf-1.pdf>
- [32] D. Großmann and F. Eisele, 'Intelligent charging with the new ISO 15118-20 standard,' Vector, 2021. https://cdn.vector.com/cms/content/know-how/technical-articles/Emobility_ISO15118-20_Charging_emobliltytec_202210_PressArticle_EN.pdf
- [33] A. Kendall *et al.*, *Electric Vehicle Lithium-ion Batteries in Lower- and Middle-income Countries: Life Cycle Impacts and Issues*, 2023. doi: 10.7922/G22Z13VD.
- [34] B. I. Chigbu, F. H. Nekhwevha, and I. Umejesi, 'Electric vehicle battery remanufacturing: Circular economy leadership and workforce development,' *World Electric Vehicle Journal*, vol. 15, no. 10, p. 441, 2024. doi: 10.3390/wevj15100441.
- [35] S. Wakhu, 'Strathmore joins Pan-African initiative to transform Africa's energy future,' *Circular Economy Powered Renewable Energy Centre*, 2 Nov, 2025. <https://strathmore.edu/news-articles/strathmore-joins-pan-african-initiative-to-transform-africas-energy-future/>
- [36] C. Rossler, K. Hartmann, E. M. N. Wanjiru, K. K. G. Kaberere, and K. Mwangi, *Kenya's Path to a Power-To-X Economy: A Skills Development Perspective*, Renac Renewables Academy, 2024. <https://ptx-hub.org/wp-content/uploads/2024/07/International-PtX-Hub-202407-Skills-development-Kenya.pdf>

Other references

- I. T. Bello *et al.*, 'Charging ahead: The evolution and reliability of nickel - zinc battery solutions,' *EcoMat*, 2024.
- H. Odero, C. Wekesa, and G. Irungu, 'Wind energy resource prediction and optimal storage sizing to guarantee dispatchability: A case study in the Kenyan power grid,' *Journal of Electrical and Computer Engineering*, pp. 1–25, 2022.
- N. Kebir *et al.*, "Second-life battery systems for affordable energy access in Kenyan primary schools," *Scientific Reports*, vol. 13, no. 1, p. 1374, 2023. doi: 10.1038/s41598-023-28377-7.
- E. Kelleher, Gracestone Inc, and E. Millette, 'Research Study on Reuse and Recycling of Batteries Employed in Electric Vehicles', American Petroleum Institute, 2019.
- W. Lore and G. Baragu, 'Accelerating e-mobility to remedy greenhouse gas emissions in Kenya,' The Kenya Institute for Public Policy Research and Analysis, 7 May 2023.
<https://kippra.or.ke/accelerating-e-mobility-to-remedy-greenhouse-gas-emissions-in-kenya/>
- Shell Foundation, 'New Energy Asset Financing Company Launched by Davis & Shirtliff and 4R Digital', 2024. <https://shellfoundation.org/news/new-energy-asset-financing-company-launched-by-davis-shirtliff-and-4r-digital/>
- R. Sommerville *et al.*, "A qualitative assessment of lithium-ion battery recycling processes," *Resources, Conservation and Recycling*, vol. 165, 105219, 2021. doi: 10.1016/j.resconrec.2020.105219.
- Roam Electric, 'Roam introduces the Roam Move: An electric shuttle bus,' <https://www.roam-electric.com/post/roam-introduces-the-roam-move>
- Roam Electric, 'Roam launches Roam Rapid: The first electric mass transit bus in Kenya,' <https://www.roam-electric.com/post/roam-launches-roam-rapid-the-first-electric-mass-transit-bus-in-kenya>
- A. H. Kazimierczuk, 'Wind energy in Kenya: A status and policy framework review,' *Renewable and Sustainable Energy Reviews*, vol. 107, pp. 434–445, 2019.

Malawi

This section was written by Dr Chrispin Gogoda, Lecturer in the Energy Systems Department at Mzuzu University, Coordinator of the Test and Training Centre for Renewable Energy Technologies (TCRET) and the Postgraduate Program Energy Systems Department, Head of the Solar PV and Energy Storage Research Group and member of the Community Energy and the Sustainable Energy Transition (CESET) team.

1. Introduction

Malawi has one of the lowest electrification rates in the region with 25.9% of the population having access to electricity in 2025, up from 19% in 2018 [1], [2]. The increase in access is mainly due to the proliferation of off-grid renewable energy solutions dominated by solar photovoltaic (PV) systems. Access to grid electricity has stagnated at about 12% for a long time [2]. This scenario suggests that off-grid renewable energy systems will continue to play a central role in increasing access to electricity. The country's short-term target is to reach 70% electricity access by 2030 with 40% coming from off-grid solution and 30% from grid connection [1].

The country's access to clean cooking fuels is even worse, with 90% of the population using firewood and charcoal according to the 2018 national population census [2], [3]. Cooking constitutes 90% of household energy needs in Malawi. Women and children, in particular, continue to suffer from the effects of exposure to harmful fumes from burning unclean fuels, as well as the drudgery of traveling long distances to collect firewood [4]. In some local communities households go without a meal not for lack of food but because they don't have cooking fuel. One of Malawi's efforts to increase access to clean cooking is growing support for solar electric cooking with battery energy storage [5].

The data on energy access given above, with the aim to raise both access to electricity and clean cooking fuels [6], clearly favours renewable energy solutions especially solar PV through off-grid systems for powering electric appliances from light bulbs, televisions, and phone charging to electric cooking, especially through electric pressure cookers (EPC). Solar power is a free and abundant resource, but the inherent intermittence of solar energy is the major consideration for every planner or designer of a renewable energy system [7]. There are a few possible options such as demand side management to manage the mismatch between power generation and utilisation but energy storage remains the more plausible option. While there are a wide array of options for energy storage such as pumped hydropower, compressed air, flywheels, and so on, battery energy storage continues to dominate for solar PV technology [6]. This confirms the extent to which battery energy storage is important in promoting access to electricity and clean cooking in Malawi and societies facing similar challenges. Apart from renewable energy applications, batteries play

a major role in providing electricity services for lighting in 53% of households [2], as show in Fig. 1.

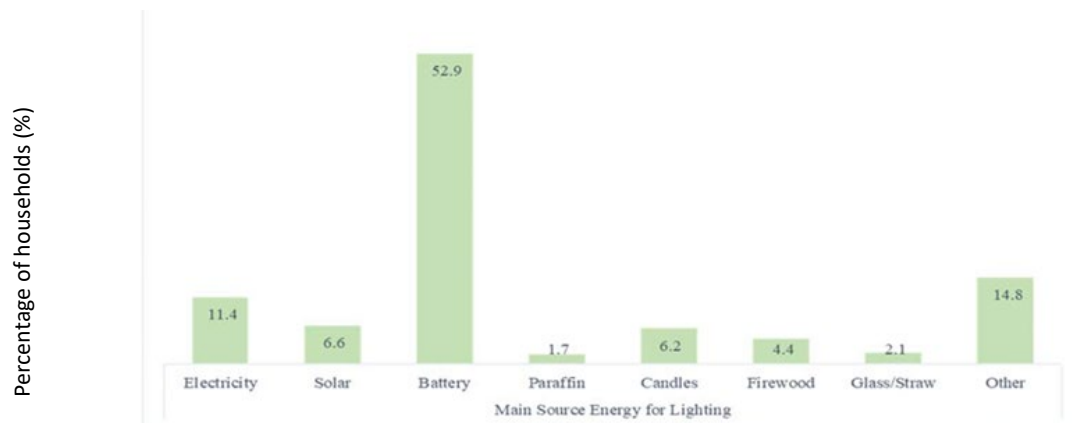


Fig. 1. Household reported main source of energy for lighting in Malawi (2018 Population Census Report) [2]

Solar PV continues to grow as a share of the country’s electricity generation mix. That brings with it challenges for grid stability, such as a lack of inertia. Currently, Malawi has an installed capacity of 550MW, a generation mix that includes 444MW hydropower and 101MW solar PV generation [1], [8]. The introduction of solar into the grid was aimed at diversifying power generation to reduce the impact to the economy associated with power interruptions. For example, when the country was hit by cyclone Ana in 2022, taking away 129.6MW of hydropower generation from Kapichira power station, the country went into prolonged blackouts that affected many aspects of business and life in general [9]. The bulk of the country’s hydropower generation is concentrated on one river, Shire, flowing from Lake Malawi, a situation that makes the country’s power generation very vulnerable to changing weather events. In trying to manage the challenges with grid stability on increasing penetration of solar power into the national grid, the country is embarking on the first large scale battery installation of 20MW with funding from the Global Energy Alliance for People and Planet [10].

Electrification of transport is another sector relevant to Malawi. Batteries have seen a rapid reduction in cost due to emerging trends in the electrification of transport with the likes of Tesla engaging in big manufacturing facilities. This has knock-on effects for Malawi and other countries in the developing world. Consider the following:

- Cost reduction leads to more renewable energy deployment. For example, a decade ago, solar electric cooking was considered very expensive because of the need for large battery energy storage to meet the high energy demand. The e-cooking concept was projected to start becoming cost effective by 2020 because of the reduced battery cost from the increased electrification of transport. Today, in Malawi, there are several institutions that support solar electric cooking now that cost dynamics are favourable when compared to other traditional cooking fuels such as charcoal and gas.

- There is a growing discussion on second use of batteries from electric vehicles (EVs). One candidate application is in renewable energy applications for developing nations that are relying on off-grid systems to increase energy access rates.
- Management of higher numbers of EVs and the capacity of the national grid to handle them is an area that needs more debate to increase the chances of success in embracing electrification of transport.

The considerations above are a clear indication of the growing attention needed towards battery energy storage. In addition, empirical evidence shows that when solar PV systems with battery energy storage fail, the fault has tended to lie with the battery energy storage component. Batteries have historically formed the larger cost of renewable energy installation both in terms of capital cost and operation and maintenance costs. Rapid failure of batteries sends a negative image of renewable energy as a failed technology, affecting its adoption and uptake by different communities. To address these challenges, there is a need for increased technical capacity for designing, deployment and management of battery energy storage.

2. Key research areas in battery technologies

Battery energy storage research in Malawi is scarce as is evident from the low output of research specifically looking at battery energy issues. One of the reasons is the cost of equipment for undertaking battery research. Developing countries often have low research budgets. However, a few years ago, the Malawi Bureau of Standards (MBS) acquired, with funding from the United Nations Development Programme (UNDP), a state-of-the-art battery testing facility to support local testing of batteries imported into the country after observing an increased proliferation of substandard renewable energy products [11].

Mzuzu University, as a leading institution delivering renewable energy training, has a Test and Training Centre for Renewable Energy Technologies (TCRET), which was supposed to be championing cutting edge research activities including battery energy storage. However, to date, the centre has a testing facility that is under-equipped to support active research in battery energy storage. One of the researchers at the university, during his training abroad at Loughborough University in the UK, designed and developed a low-cost battery test rig with prospects for deployment to developing nations that often have budgetary constraints [12]. However, due to lack of a local support mechanism, such innovation is unlikely to see the light of the day.

Generally, the country has visible gaps in promoting battery research despite clear evidence of the growing deployment of battery energy storage. In the absence of active research, the prospect of supporting local manufacturing with the aim of reducing battery imports, becomes a difficult proposition to pursue. Despite low engagement on battery research, the government of Malawi continues to show interest in supporting local research and

manufacturing of battery energy storage to support the renewable energy deployment agenda [13].

More recently, the deployment of grid-scale storage with support from the Alliance, a Southern Africa Battery Energy Storage System Centre of Excellence has been set up at Mzuzu University to provide a platform for supporting research in battery energy storage systems including grid frequency control [14].

3. Material sourcing and local manufacturing

For renewable energy applications, lead-acid batteries continue to be the leading technology in Malawi owing to the technology's maturity and lower upfront cost compared to Li-ion batteries, which are considered expensive. However, supported by the increased electrification of transport, Li-ion batteries, especially lithium iron phosphate (LFP), have increased their presence in the local market. Despite a higher upfront cost, lithium batteries compare favourably on a lifetime cost basis.

There is growing evidence of efforts toward increasing local manufacturing capacity as can be seen with a local organisation, Solar Kumidzi, that is assembling lithium titanate batteries locally for solar application. The organisation acquires manufactured cells from China together with printed circuit boards and they build the battery management system and assemble the battery module locally. This is considered a step forward in promoting local manufacturing. There is, however, a clear gap in supporting local manufacturing of the individual battery cells.

Electrified transport is slowly building market presence. For example Sky Energy Africa is a local company that is pioneering the selling of EVs in Malawi [15]. Another company produces electric motorcycles in Lilongwe. In 2024, the Malawi government announced the deployment of 50,000 electric motorcycles to revolutionise the country's transport sector [16] and further announced provision for a tax waiver on imports of electric motorcycles [17]. These developments illustrate the growing deployment of battery energy storage in the Malawi market.

3.1 Raw materials for battery manufacturing

The recent discovery of rutile graphite in Kasiya gives Malawi great potential for supporting battery manufacturing as it has the second largest flake graphite deposit globally [18]. Graphite is used in the manufacturing of anode materials for batteries, so the Kasiya rutile graphite could support local manufacturing of batteries.

Recently, mineral exploration company Kula Gold Limited has received formal approval of the grant of the Wozi niobium project tenement in Malawi, which is 225km north of the capital Lilongwe [19]. Titanium niobium oxide (TNO) compounds have been considered as one of the most promising intercalation-type anode materials. This family of materials possesses high theoretical capacities [20].

4. Policy, funding and challenges

Despite evidence of the deployment of renewable energy and the growing potential for more solar power in both grid and off-grid scenarios, the Malawi National Energy Policy does not tackle the important aspect of battery energy storage [21]. This absence of policy direction might lead to an unguided approach to tackling energy storage. Lack of discussion on batteries and energy storage at a national policy level is also observed in the national policy documents of neighbouring countries such as Zambia and Tanzania [22], [23]. Considering the role that energy storage plays in the renewable energy sector, especially for solar PV, it is important that developing nations should consider including guidance on energy storage in their national energy policies.

Despite absence of policy position in the Malawi National Energy Policy, the growing penetration of solar into the grid has seen the government of Malawi looking for policy direction on procurement of solar PV with battery storage, according to a report by Jacobs [24]. As in many other parts of the world [25], there are gaps in regulations supporting grid scale battery storage deployment in Malawi. For example, what licence does the battery developer obtain from the regulator? Is it generation, transmission or both?

One of the reforms in the country's energy sector was the unbundling of Electricity Supply Corporation of Malawi Limited (ESCOM), which was the sole utility responsible for generation, transmission and distribution of electricity in Malawi. The introduction of the independent power producer (IPP) model has seen more players investing in the energy sector. This has been the genesis of more solar coming into the grid, bringing the new challenge of grid instability. To ensure grid stability while increasing the penetration of renewable energy generation and in conformity with international standards, the country is now requiring all new IPP applicants to include a battery energy storage system (BESS) of at least 25% of the solar modules' AC capacity as a prerequisite for award of a power purchase agreement (PPA).

5. Case studies and success stories

5.1 Case study 1

The first ever grid scale solar farm of 20MW with 5MW battery storage in Southern Africa was installed in Dedza, Malawi and came into operation in 2022. The power plant with battery energy storage was designed to support the national grid by ensuring power generation during cloud cover as well as supporting off-peak demand [26].

5.2 Case study 2

The Malawi government, through ESCOM and with funding from GEAPP, is implementing a 20MW/ 30MWh energy storage system to support the national grid from the challenges associated with the integration of variable solar power into the grid. This will be the largest storage facility the country has had. The project, with funding of the order of \$20 million,

also supports capacity building: personnel involved in the implementation are attending short course training on battery energy storage [10]. According to Zalengera, the initiative is expected to cut carbon emissions by 10,000 tons annually while boosting the economy and improving energy security [27].

6. Conclusions

Clearly, renewable energy will continue to be one of the major energy sources for increasing access to electricity and clean cooking. Performance of batteries in solar PV power generation systems will continue to be critical to the success of renewable energy systems. In addition to increasing electricity access, the growing deployment of electric transport confirms the extent to which battery storage will continue to be important in the energy sector.

Some of the key challenges facing the deployment of renewable energy are the high cost of batteries, low local capacity in the energy battery space and overreliance on imported products.

Battery testing, research and manufacturing are critical areas requiring good attention from different stakeholders. This calls for active policy direction from the national energy policy for effective deployment of renewable energy.

References

- [1] World Bank, National Energy Compact for Malawi
<https://thedocs.worldbank.org/en/doc/fdcdb16b310a246ebb0fdbbfd50ca3a8-0010012025/original/M300-AES-Compact-Malawi.pdf> Accessed: 8 Aug, 2025.
- [2] 2018 Malawi Population and Housing Census
<https://malawi.unfpa.org/sites/default/files/resource-pdf/2018%20Malawi%20Population%20and%20Housing%20Census%20Main%20Report%20%281%29.pdf> Accessed: 8 Aug, 2025.
- [3] T. K. Mlowa, M. L. Chitawo, and V. Kasulo, 'Policy Analysis on Clean Cooking in Malawi: Case of Improved Cookstoves', *E3S Web Conf.*, vol. 487, p. 02003, 2024, doi: 10.1051/e3sconf/202448702003.
- [4] A. Eales, D. Frame, S. Keddar, A. Richter, D. Kloser, and S. Galloway, 'Opportunities and Challenges for eCooking on Mini-grids in Malawi: Case Study Insight', in *2022 IEEE PES/IAS PowerAfrica*, Kigali, Rwanda: IEEE, pp. 1–5, 2022. doi: 10.1109/PowerAfrica53997.2022.9905404.
- [5] Sustainable Energy for All, Malawi Integrated Energy Plan, Clean Cooking Report.
https://www.seforall.org/system/files/2022-10/Malawi_IEP-Clean_Cooking-Report.pdf
Accessed: 9 Aug, 2025.

- [6] P. Newell and F. Daley, 'Cooking up an electric revolution: The political economy of e-cooking', *Energy Res. Soc. Sci.*, vol. 91, p. 102730, Sep. 2022, doi: 10.1016/j.erss.2022.102730.
- [7] E. Sayed *et al.*, 'Renewable Energy and Energy Storage Systems', *Energies*, vol. 16, no. 3, p. 1415, Feb. 2023, doi: 10.3390/en16031415.
- [8] Egenco, 'EGENCO ENGAGES STAKEHOLDERS ON SALIMA SOLAR PROJECT', Electricity Generation Company (Malawi) Limited. <https://www.egenco.mw/egenco-engages-stakeholders-on-salima-solar-project/> Accessed: 9 Aug, 2025.
- [9] Egenco, 'OUTAGE OF KAPICHIRA POWER STATION DUE TO DAMAGES CAUSED BAY CLONE ANA', Electricity Generation Company (Malawi) Limited. <https://www.egenco.mw/outage-of-kapichira-power-station-due-to-damages-caused-bay-clone-ana/> Accessed: 9 Aug, 2025.
- [10] Global Energy Alliance for People and Planet, 'GEAPP, Government of Malawi launch the construction of 20 MW battery energy storage system (BESS) in Lilongwe'. <https://energyalliance.org/geapp-government-of-malawi-launch-the-construction-of-20-mw-battery-energy-storage-system-bess-in-lilongwe/> Accessed: 9 Aug, 2025.
- [11] UNDP, 'RENEWABLE ENERGY TECHNOLOGY TESTING EQUIPMENT'. <https://www.ungm.org/Public/Notice/129067> Accessed: 9 Aug, 2025.
- [12] C. G. Mbewe, R. Blanchard, G. Claudio, M. Bliss, N. Monk, and J. Barton, 'Promoting Battery Testing in Developing Countries Through Development of a Low-Cost Battery Test System', in *2021 IEEE International Humanitarian Technology Conference (IHTC)*, United Kingdom: IEEE, Dec. 2021, pp. 1–4. doi: 10.1109/IHTC53077.2021.9698932.
- [13] Malawi Renewable Energy Strategy, 2017. <https://conrema.org/wp-content/uploads/2019/01/Malawi-Renewable-Energy-Strategy-Final-.pdf> Accessed: 9 Aug, 2025.
- [14] South African Battery Energy Storage System Centre of Excellence <http://sabess.mzuni.ac.mw/about-us/>
- [15] Sky Energy Africa, 'Sky Energy Africa Leads Malawi's Electric Vehicle'. <https://www.skyenergyafrica.com/Leadsmalawi.html> Accessed: 9 Aug, 2025.
- [16] I. J. Ogungbangbe, 'Malawi Embraces E-Mobility with 50,000 Electric Motorbikes Rollout', *Energy News Africa Plus*. <https://energynews.africa/2024/03/06/malawi-embraces-e-mobility-with-50000-electric-motorbikes-rollout/> Accessed: 9 Aug, 2025.
- [17] ESI Africa, 'Malawi: EV pilot, electric motorbikes to be rolled out'. <https://www.esi-africa.com/news/malawi-ev-pilot-electric-motorbikes-to-be-rolled-out/> Accessed: 9 Aug, 2025.

- [18] Mining Technology, 'Kasiya Rutile-Graphite Project, Malawi'. <https://www.mining-technology.com/projects/kasiya-rutile-graphite-project-malawi/> Accessed: 9 Aug, 2025.
- [19] Kula Gold, image at https://www.kulagold.com.au/wp-content/uploads/2025/07/KulaGoldMedia_WoziNiobium_LicenceGranted_Figure1_July2025.jpg Accessed: 9 Aug, 2025.
- [20] H. Aghamohammadi, N. Hassanzadeh, and R. Eslami-Farsani, 'A comprehensive review study on pure titanium niobium oxide as the anode material for Li-ion batteries', *J. Alloys Compd.*, vol. 911, p. 165117, 2022, doi: 10.1016/j.jallcom.2022.165117.
- [21] Government of Malawi, National Energy Policy 2018. <https://www.energy.gov.mw/docs/uploads/National-Energy-Policy-2018-Final.pdf>
- [22] Ministry of Energy, Zambia, 'The National Energy Policy 2019'. <https://www.moe.gov.zm/irp/?wpdmpo=the-national-energy-policy-2019> Accessed: 9 Aug, 2025.
- [23] Tanzania National Energy Policy 2015. [https://www.nishati.go.tz/uploads/documents/en-1622283004-National%20Energy%20Policy%20\(NEP\),%202015.pdf](https://www.nishati.go.tz/uploads/documents/en-1622283004-National%20Energy%20Policy%20(NEP),%202015.pdf) Accessed: 9 Aug, 2025.
- [24] D. Jacobs & T. Couture for LEDSGP, 'Strategies for Procuring Solar PV and Grid-Scale Battery Storage' https://ledsgp.org/app/uploads/2021/12/20211203_Malawi-Report_LEDS-GP_FINAL.pdf Accessed: 9 Aug, 2025.
- [25] T. Bowen, I. Chernyakhovskiy, and P. Denholm, 'Grid-Scale Battery Storage: Frequently Asked Questions', NREL. <https://docs.nrel.gov/docs/fy19osti/74426.pdf>
- [26] Power Africa, 'Building Malawi's First Utility-Scale Solar-Plus-Storage Power Project', Medium. <https://powerafrica.medium.com/building-malawis-first-utility-scale-solar-plus-storage-power-project-6aadd0904727>
- [27] CNBC Africa, 'Malawi's first \$20mn battery energy storage system'. <https://www.cnbc.com/africa/media/6365320736112/malawis-first-20mn-battery-energy-storage-system-/> Accessed: 9 Aug, 2025.

Nigeria

This section was written by Prof Emeka Oguzie, Deputy Vice Chancellor and Professor of Physical Chemistry at the Federal University of Technology Owerri (FUTO). The founder and centre leader for the Africa Centre of Excellence in Future Energies and Electrochemical Systems (ACE-FUELS), he focuses on the optimisation of new cathode materials for greater energy density.

1. Introduction

Nigeria's energy is heavily dependent on fossil fuels, with oil and gas being the dominant sources [1]. As a result of incessant power outages and blackouts, about half the population of Nigeria, especially in rural areas, are in serious need of electricity. Trust in the national grid is further deteriorated after many instances of collapse, hampering businesses, endangering lives and stagnating economic growth and development [2]. However, there are abundant and underutilised renewable energy resources in Nigeria such as solar, wind, and hydroelectric power [3]. Benefitting from its strategic location in the tropics, Nigeria has a high solar irradiance ranging from 1.5 to 2.2 MWh/m² indicating significant potential for solar power generation. There is a need to integrate these renewable energy sources when one considers the energy deficit in Nigeria as well as the potential, environmental and economic benefits [4]. Renewable energy can help Nigeria unlock a clean energy system to support its decarbonisation ambitions.

Nigeria's electricity grid is severely unstable. There have been periods of total grid collapse when electricity transmission has entirely ceased as a result of poor infrastructure and outdated equipment. Blackouts and voltage fluctuations are common. Hence, many businesses and households depend on diesel generators, which are costly and detrimental to the environment [5].

To ensure grid stabilisation, efficiency in electricity distribution and to reduce energy losses, Nigeria needs a paradigm shift towards integration of renewable energy sources backed by energy storage, to manage demand and supply fluctuations [6]. For instance, battery energy storage systems (BESS) employing predominantly lithium-ion (Li-ion) batteries are increasingly proving viable for large-scale grid storage [7].

Off-grid solar home systems can also help solve Nigeria's energy problems [8]. These can power basic home devices such as phones, lighting, radios, and televisions, giving a quick solution to lack of electricity for regions that cannot access the grid. Mini-grids have also been suggested by the Nigerian Rural Electrification Agency (REA) to mitigate the need for electricity for people in rural areas who cannot access the grid [9]. The systems combine solar power, battery storage and diesel backup to function in settings demanding productive use of energy. Off-grid solutions give life to local businesses, small enterprises and farmers.

Solar energy is an ideal power source for refrigeration and irrigation and can also create employment opportunities [10].

The Nigerian government in the past has put forward many initiatives to establish off-grid renewable energy solutions, like tax breaks, subsidies, and the Solar Power programme, projected to achieve over 5 million new solar connections [4].

There is a huge consumption of energy in the transportation sector in Nigeria, mostly by fuel-based vehicles. A transition to renewable energy, for instance by using EVs, will reduce fuel dependency, encourage lower emissions and increase energy efficiency and mobility [11]. Adopting EVs can be a game changer in Nigeria's transport system but challenges that come with it will need to be addressed. These include charging infrastructure [12]. Building solar powered charging stations in areas with higher levels of sunlight will remedy the situation while ensuring a safer environment. The stations will also help in electrification for off-grid areas [13].

Energy storage systems pose a tougher challenge. For renewable energy to be reliable, integration with a strong energy storage system is paramount. Li-ion batteries can play a role by smoothing the intermittency of solar and wind energies; they can store the energy generated during the peak period of intense sunlight and release it later [14]. To provide long-lasting energy, batteries can be combined in solar home systems [15]. This innovation in battery technology is affordable, cost effective and encourages off-grid renewable solutions.

2. Material sourcing and local manufacturing

Nigeria has abundant natural resources that can play an important role in the production of Li-ion batteries and other battery technologies [16]. However, local manufacturing initiatives in Nigeria are still in their developing stages.

2.1 Raw materials for battery production

Lithium, cobalt, nickel, graphite, manganese, copper and aluminium are some of the raw materials used to produce Li-ion batteries [17]. Nigeria has abundant reserves of all these raw materials, among others. Niger, Zamfara and Kebbi states have large deposits of manganese. There are huge deposits of nickel in Sokoto state, graphite in Kaduna state, and large quantities of high-grade lithium in Nasarawa, Kogi, Ekiti, Kwara and Cross River states. Cobalt is found in large amounts in Plateau, Kogi, Nasarawa and Bauchi states. Aluminium can be found in Adamawa, Plateau, Edo and Delta states [18]. There are still opportunities for exploration and mining in these Nigerian states.

2.2 Local manufacturing initiatives in battery production

For advanced battery manufacturing technologies like Li-ion, Nigeria's production industry is still in its developmental stages. However, for renewable energy storage solutions and applications of electric mobility, there is increased interest in battery assembly plants.

Nigeria has demonstrated its ability to locally produce lead-acid batteries, which are used in small-scale solar systems, micro- and medium-sized businesses and homes [19]. Innoson, a Nigerian firm, produces lead-acid batteries for automotive and solar energy applications [20].

2.3 Renewable energy and off-grid applications

Nigeria's adoption of renewable energy and off-grid applications as a solution to electrification in rural areas has led rural electrification initiatives to consider the local manufacturing of batteries for off-grid solar systems [9]. Solar firms such as Lumos Global have received support from the Rural Electrification Agency (REA) to encourage solar home systems in Nigeria [4]. Regarding electric car initiatives, Nigerian automotive designer Jelani Aliyu and firms such as Jet Systems Motors and MAX have been demonstrating capacity in battery production and are exploring improved battery technologies for EVs.

3. Key research institutions and collaborations

In Nigeria, universities and some research institutions are participating in collaborative projects including on solid-state battery technology through development of solid electrolytes to enhance the safety and energy density of batteries. The following institutions are making positive strides.

3.1 National Agency for Science and Engineering Infrastructure (NASENI)

NASENI is involved in research and development of renewable energy technologies, especially battery production. The agency aims at improving local capacity for battery production and also collaborates with universities and other international agencies on the development of renewable energy, concentrating on materials and processes applicable for Nigeria's environment [21].

3.2 Project Development Institute (PRODA)

PRODA is investigating alternative energy sources, including battery technologies, and has experimented on lead-acid and Li-ion batteries for applications like solar energy storage. It also collaborates with Nigerian universities, research institutes, international bodies and local firms in the production of batteries.

3.3 Centre for Energy Research and Development (CERD)

CERD is involved in renewable energy research and energy storage solutions. It has worked on Li-ion batteries, solar PV systems, and other storage technologies. It collaborates with

local and international research institutions to work on improving battery technology and energy storage solutions in the Nigerian market.

3.4 University research centres

University research centres study energy storage and battery production. These partner with international institutions and funding bodies like the African Union (AU) and the World Bank, as well as industry partners, to develop cost-effective batteries for solar power systems and other renewable energy applications. Some of these university research centres are:

3.4.1 African Center of Excellence in Future Energies and Electrochemical Systems (ACE-FUELS).

ACE-FUELS is a research institute domiciled in the Federal University Technology Owerri (FUTO). It collaborates with the World Bank and other international agencies to catalyse the Nigerian and Africa transition to renewable and environmentally friendly energy. It has contributed greatly to the development of green and clean energy as it has developed, among other technologies, 3KVA, 4.5KVA, 7.5KVA fuel-less generators; and an ACE-FUELS inverter compliant with solar inverters. The centre is engaging in the development of renewable and sustainable energy through research, innovation and education.

3.4.2 Covenant University Centre for Research, Innovation, and Discovery (CUCRID)

CUCRID conducts research in renewable and sustainable energy and battery technologies for energy storage. It collaborates with international partners, local industry, and Nigerian government bodies on research projects working on battery technology and materials for the Nigerian environment.

3.4.3 National Metallurgical Development Centre (NMDC)

NMDC takes part in research related to metallurgical and materials science, which is important in manufacturing battery components like casings and electrodes. It collaborates with the Ministry of Mines and Steel Development, local mining industries, and international metallurgical organisations to source local materials for battery production.

3.4.4 African Centre of Excellence for Energy and Sustainable Development, University of Port Harcourt

This centre conducts research on sustainable energy technologies, including batteries for renewable energy storage. It collaborates with universities across Africa, international organisations and other energy institutes to address energy storage needs in Nigeria.

Through these institutions and their partnership with international organisations, battery production for renewable energy applications is on the increase in Nigeria.

4. Battery skills assessment

This section evaluates Nigeria's capacity and skills development in battery production as well as its maintenance, quality research and technical expertise. This assessment considers existing talent in battery technology, relevant educational programmes, industry capacity, and skills development programmes. Considerations of the current status and challenges include:

4.1 Educational institutions and training programmes

Universities and polytechnics in Nigeria such as FUTO, Ahmadu Bello University, Obafemi Awolowo University, and the University of Lagos, offer programmes in engineering and materials science that cover some aspects of battery technology. Specialised training on advanced battery technology, such as Li-ion and renewable energy storage systems, is limited.

Specialised centres like the African Center of Excellence in Future Energies and Electrochemical Systems (Federal University of Technology Owerri) are furthering research on battery technology. The African Centre of Excellence for Energy and Sustainable Development (University of Port Harcourt) is also working on improving energy systems in Nigeria.

4.2 Skills gaps

There is a skills gap in the areas of specialised battery chemistry, design, and the production of Li-ion batteries. This is increasingly relevant due to the global shift toward EVs and renewable energy [22].

4.3 Industry training and technical expertise

Considering the growth of renewable energy sector in Nigeria, particularly solar energy, there is a need for skills in battery installation, maintenance, and integration with solar systems. Rather than extensive training in battery technology, firms involved with the operation of renewable energy often offer basic installation and maintenance training [23].

4.4 Battery maintenance and repair

Nigeria has abundant skilled technical personnel in the repair and maintenance of lead-acid batteries but expertise in newer battery technologies, particularly Li-ion, remains scarce. [24].

4.5 Partnerships

In Nigeria, there are opportunities for those in research institutions and in some firms to undertake training in short courses or certification in advanced battery technologies, often through international collaborations facilitated by foreign experts. However, access to this training is still limited [25]. Overall, battery skills in Nigeria are currently focused on

traditional lead-acid battery maintenance, basic solar battery installation, and some limited research on battery technology.

To meet the growing demand for advanced energy storage solutions, Nigeria will need significant investments in specialised education, training, and access to modern materials and laboratories. Collaborative efforts between the government, educational institutions, and the private sector are crucial to addressing these skills gaps.

5. Industry and start-up ecosystem

Nigerian start-ups are focusing on innovative storage solutions as well as access to energy. Startups like Arnergy are working on integrating solar-plus-battery systems for residential and commercial clients, while Rubitec Solar focuses on mini-grid solutions [26]. Companies like Green Village Electricity (GVE) use battery storage for their off-grid solar installations, addressing the gap in reliable energy infrastructure [27]. Some of these companies make energy storage accessible even in low-income communities through a leasing model, in which customers pay for batteries and solar kits in instalments.

5.1 Battery industry and startups in Nigeria and key challenges

5.1.1 Imports of Li-ion batteries and currency fluctuations

Li-ion batteries are preferred for renewable energy storage and most start-ups depend on imported Li-ion batteries [28]. The challenge is that importing these batteries is very costly; in particular owing to constant fluctuations of the Naira and because of import taxes that can disrupt the supply chain [29].

The lack of processing and mining of local lithium and cobalt in Nigeria limits local large-scale manufacturing of Li-ion batteries.

5.1.2 Recycling and disposal challenges

Infrastructure for battery recycling is still under-developed in Nigeria, hence it is difficult to manage waste and the environmental impact associated with used batteries. Only a few firms have the facilities to effectively recycle Li-ion batteries [30].

5.2 Collaborations and funding

5.2.1 Government and international partnerships

Nigeria is partnering with international organisations such as the World Bank and African Development Bank (AfDB) to finance some of its renewable energy and storage projects.

5.2.2 Private investment and venture funding:

Some investors that prioritise energy solutions are funding some renewable energy and battery startups. Firms like All On (a Shell-funded impact investor) in Nigeria invest in startups like Arnergy and Rubitec Solar, supporting renewable energy and battery projects.

5.3 Opportunities and future

5.3.1 Electric mobility growth

Demand for batteries will increase in Nigeria following the recent investment in electric cars by Innoson. Nigeria's urban areas will begin to experience a surge in EVs and various forms of e-mobility. The electric mobility market will continue to expand, as startups innovate in charging infrastructure, battery life and affordability [31].

5.3.2 Renewable energy storage demand

As Nigeria continues to develop its renewable energy infrastructure, there will be rising demand for efficient and affordable battery storage and solar-plus-battery systems especially in off-grid areas. This development is likely to lead to more local production and assembly of batteries, and investment in the processing of battery materials and cell manufacturing capabilities.

5.3.3 Skills development

Growth of this sector will create a demand for skills in battery technology and maintenance, giving rise to potential employment opportunities in manufacturing, maintenance, and recycling. There will also be training of Nigerian engineers and technicians and international collaborations to support local battery industries.

The Nigerian battery industry and startup ecosystem is still emerging, with exciting developments in renewable energy storage, electric mobility, and recycling. Despite challenges such as high costs, reliance on imports, and limited local manufacturing infrastructure, there is substantial growth potential. With continued government support, investment and strategic collaborations, Nigeria's battery industry could help bridge the energy gap and meet the continent's growing demand for reliable, sustainable energy solutions.

6. Policy, funding and challenges

The battery production industry in Nigeria and Africa is promising but faces substantial challenges related to policy, funding, and operational infrastructure. However, with strategic policies that support local production, recycling, and skills development, along with increasing investment from both public and private sectors, the industry has the potential to grow significantly [28]. Such efforts would not only support Africa's clean energy transition but also position the continent as a key player in the global battery supply chain, given its rich resources and growing renewable energy market.

6.1 Policy

6.1.1 Renewable energy targets

Nigeria's energy policies promote renewable energy and energy access and also support battery adoption and production. For example, Nigeria's Renewable Energy Master Plan

aims to increase renewable energy's share in the energy mix, creating opportunities for batteries to store solar, wind, and other renewable sources [32].

6.1.2 Tax incentives

Import tariffs on battery components can increase the costs of batteries in the Nigerian market. Nevertheless, the recent tax reforms by the Nigerian government seek to introduce tax incentives and exemptions to firms in the renewable energy sector and other start-ups. This will support and attract battery manufacturers.

6.1.3 EV policies

As EVs are gaining attention in the world, Nigeria is considering policies to encourage the adoption of EVs and support for local battery manufacturing [33] but more work needs to be done.

6.1.4 Recycling regulations

Nigeria needs proper recycling and disposal policies to manage the waste accrued from battery use. Nigeria's government is already developing e-waste management policies [34], though specific enforcement to battery recycling is still limited.

6.2 Funding

6.2.1 Government and development funding

The Nigerian government and most governments in Africa are usually supported by international organisations such as the United Nations, the World Bank and the African Development Bank (AfDB). They fund renewable energy and energy storage projects to enhance production of batteries. For instance, the AfDB has invested in the Desert to Power initiative, targeted at expanding capacity of solar in the Sahel region, where the use of batteries is paramount [35].

6.2.2 Impact investors and venture capital

Startups that are battery-related, especially those that specialise in clean and sustainable energy, are increasingly attracting funding from impact investors. For instance, Nigerian firms such as Arnergy and Lumos have received investments for solar energy storage solutions. The venture capital ecosystem in Nigeria is growing, with investors like Shell's impact fund, All On, investing in battery production and renewable energy startups.

6.2.3 Public-private partnerships (PPPs)

In Nigeria the support of public-private partnerships towards battery adoption and production is demonstrated by the National Agency for Science and Engineering Infrastructure (NASENI) initiating partnerships with local companies and international bodies in support of indigenous battery manufacturing firms. These partnerships will reduce the need for imported batteries by bringing in technology and funding.

6.2.4 International grants and technical assistance

Nigeria has benefitted from international grants for renewable energy and electrification programmes that include battery storage. Programmes such as “Power Africa” and various European Union initiatives have provided funds for energy storage and research in Nigeria and Africa in general.

6.3 Challenges in battery production

6.3.1 High cost of raw materials and import dependency

Nigeria is rich in minerals like cobalt, lithium, and manganese, but a lack of processing and refining infrastructure hampers the exploitation of these resources. This causes the energy sectors in the country to depend on importing processed battery materials, thereby increasing costs and limiting Nigeria’s capacity in local battery production.

6.3.2 Limited technical expertise and skills

Production of batteries like Li-ion can be boosted in Nigeria with increased numbers of experts that specialise in material science, chemistry, and engineering. There is a limited number of such experts due to a lack of training programmes. To advance the course of battery technology, investment in technical training is crucial to develop a capable local workforce.

6.3.3 Insufficient infrastructure and manufacturing capacity

The necessary infrastructure for large-scale manufacturing of batteries, such as production facilities, clean energy sources and logistics, is still underdeveloped in Nigeria. It is very costly to establish production plants that have high environmental and safety standards, and only a few companies can afford the capital investment.

6.3.4 Supply chain and logistical challenges

Imports of raw materials, components, and machinery for battery production in Nigeria are often disrupted because of logistical challenges ranging from high costs of shipping and lengthy customs processes to inadequate infrastructure at the port. These factors encourage delay and high costs of production.

6.3.5 Environmental and regulatory compliance

Poor enforcement and lack of compliance to policies around the proper production, recycling and disposal of batteries, especially batteries that are made up of heavy metals, poses a serious health and environmental risk. The e-waste management policies of Nigeria still need to be adequately enforced.

6.3.6 Market demand and affordability

Although the demand for energy storage is high, the high costs of Li-ion batteries can make them unaffordable for Nigerians. This is why startups sometimes stick to leasing models, even though these business models need huge upfront capital that can be challenging to

secure. Demand for batteries of high capacity is also limited because Nigeria's local market for EVs is small at the moment.

7. Case studies and success stories

Several initiatives in battery production, energy storage solutions, and recycling have emerged across Nigeria, advancing the local battery industry. Some notable case studies and success stories are given here that highlight innovative approaches, partnerships and achievements of firms in the field of battery production and energy storage in Nigeria and across the continent.

7.1 Arnergy

Arnergy is a Nigerian solar energy firm founded in 2013, that deals in solar and battery-based energy storage solutions for homes and businesses. It produces and installs integrated solar-plus-battery systems that use Li-ion batteries to provide reliable off-grid power to users [36].

Arnergy addresses Nigeria's power challenges by providing a dependable alternative to diesel generators. When grids break down, its systems, such as battery backups, help customers to maintain power and reduce dependence on fuel-powered generators.

Arnergy received a \$9 million investment in 2019 from investors including Breakthrough Energy Ventures, a fund backed by Bill Gates, and All On, a Shell impact investment. This funding allowed Arnergy to expand its horizon, install more energy systems, and drive awareness of renewable energy's potential in Nigeria.

7.2 Rubitec Solar

Rubitec Solar is a Nigerian firm that specialises in off-grid solar energy solutions for rural areas [37]. This firm deploys mini-grids and solar home systems that use batteries to provide reliable power to rural communities.

Rubitec provides continuous power to households, schools, and businesses in rural areas through installation of solar-plus-battery systems. Its mini-grids, often powered by lead-acid or Li-ion batteries, are particularly beneficial for agricultural productivity, as they enable farmers to store perishable goods.

Rubitec Solar has been funded by international donors like USAID and Nigeria's REA. Their model has contributed to rural electrification efforts in Nigeria and demonstrated the potential of battery-powered mini-grids for boosting productivity in rural communities.

7.3 GVE Projects Ltd

GVE Projects Ltd, also known as Green Village Electricity (GVE), is a renewable energy company in Nigeria that makes use of solar mini-grids with battery storage to supply power to rural communities.

GVE's mini-grids use battery systems to store energy, ensuring continuous power for communities that lack grid access. The battery storage allows for round-the-clock energy supply, boosting local economies and improving the quality of life for residents.

GVE was funded by the World Bank and the Nigeria Electrification Project (NEP). With these partnerships, GVE has successfully deployed mini-grids in several Nigerian communities, demonstrating the effectiveness of solar-plus-battery solutions for rural electrification.

7.4 Zola Electric

Zola Electric is a solar energy company that combines solar power with smart battery storage in off-grid energy solutions [38]. Zola has operations in Tanzania and the Ivory Coast as well as Nigeria, and focuses on creating modular, Li-ion battery-based energy systems suitable for homes and businesses.

Zola's modular energy systems provide power solutions that scale with customer needs, helping households to begin with a small battery and then gradually increasing the capacity if required. This flexibility encouraged off-grid customers to affordably access reliable energy.

Zola has raised over \$100 million from investors including Tesla, EDF, and Total. Its breakthrough in provision of affordable energy storage for rural and off-grid communities has demonstrated the scalability of battery-powered solar solutions in sub-Saharan Africa.

The success stories of companies like Arnergy, Zola Electric, and GVE Projects highlight Nigeria's potential for innovative battery and energy storage solutions. While challenges remain, especially in local production, funding, and supply chain development, these case studies showcase the progress and adaptability of Nigeria startups and companies. In the continent's unique challenges in driving renewable energy, energy storage solutions and battery technology, Nigeria and other countries are capable of positioning Africa as a growing player in the global energy landscape.

8. Future directions

As Africa goes through challenges in the transition to renewable energies and energy storage, several promising directions for battery production in Nigeria and across Africa will emerge.

8.1 Development of local raw material processing facilities

Nigeria has battery-related minerals such as lithium, cobalt, nickel, and manganese in abundance but most of these minerals are exported. By developing processing facilities, Nigeria could capture more value within the supply chain and reduce its reliance on imports.

8.2 Development of affordable Li-ion

Li-ion is one of the preferred batteries for electronics, EVs and renewable energy storage. Nigeria could explore local Li-ion battery assembly and manufacturing and collaborate with international technology firms. Nigeria's Arnergy company is already assembling battery systems for solar energy storage.

8.3 Alternative battery technologies

Alternatives to Li-ion, such as vanadium redox flow batteries (VRFBs), sodium-ion batteries, and lead-acid batteries with enhanced cycle life, are also gaining attention. Vanadium-rich South Africa is at the forefront of VRFB development, which is promising for grid storage due to its long lifespan and stability. Exploring other affordable battery chemistries that do not rely on rare or expensive materials may create accessible, locally produced options for African energy storage.

8.4 Focus on electric mobility and battery swapping

8.4.1 Electric motorbikes and vehicles

Electric two- and three-wheelers are more affordable than cars and are well-suited to African cities. Companies like Ampersand in Rwanda and MAX in Nigeria are already pioneering electric motorcycle markets with battery swapping stations. Expanding this model across Africa could provide a convenient, cost-effective solution to transportation needs while reducing carbon emissions.

8.4.2 Battery swapping infrastructure

Establishing battery-swapping stations in urban areas will alleviate concerns about EV range and charging infrastructure. Swapping stations, where users can exchange depleted batteries for fully charged ones, are an ideal solution in markets where home charging may not be widely available. This model allows fleet operators and individuals to use EVs without investing heavily in charging infrastructure.

8.5 Home and community energy storage

Battery storage is essential to Africa's renewable energy growth, particularly for solar power in off-grid and rural areas. Companies like Lumos, Zola Electric, and GVE Projects are making strides in home and mini-grid battery storage solutions. Future development will likely involve affordable, modular battery systems that enable users to scale storage capacity according to their needs.

8.6 Utility-scale storage for grid stability

As African countries invest in renewable energy at a national level, utility-scale storage solutions will be vital for grid stability. Large-scale battery installations can help smooth the variable output of solar and wind power and provide backup power during peak hours. Utility-scale battery projects are already underway in South Africa, which is looking to enhance its grid with renewable energy support.

8.7 Battery recycling facilities

Considering the expected increase in battery usage, African countries will require effective battery recycling facilities. Proper recycling not only reduces environmental impact but also recovers important raw materials like lithium, cobalt, and nickel. Nigeria, for example, could establish regional recycling centres to process batteries from West African nations.

8.8 Circular economy initiatives

A circular economy model would involve manufacturers, recyclers, and users working in tandem to extend battery life, recover materials, and reduce waste. Policies promoting battery reuse, repair, and recycling could incentivise startups and businesses to develop sustainable models that optimise battery lifecycles.

8.9 Technical skills development and research

Developing local expertise in battery manufacturing, maintenance, and recycling is essential for sustainable growth. Programmes in technical institutes and universities could train engineers and technicians in battery technology, chemistry, and renewable energy systems. Partnerships with international institutions could also offer knowledge exchange and skill-building programmes.

8.10 Increased investment in R&D

Local research institutions in Africa are exploring battery technology to create affordable solutions for African needs. Supporting R&D in battery chemistry, energy density improvements, and locally sourced materials will ensure that battery technology can evolve to suit the unique conditions and constraints of African markets.

8.11 Policy and regulatory support for battery production

Governments can provide tax incentives, subsidies, and tariff exemptions for companies engaged in battery production, import of battery materials, and renewable energy projects. These incentives would make it financially viable for local companies and attract international battery producers to establish production and assembly facilities in Africa.

8.12 Environmental and recycling regulations

As battery use grows, African governments must establish environmental regulations for battery disposal and recycling. Clear policies around battery recycling and disposal, with enforcement mechanisms, will be critical to mitigate environmental hazards. This regulatory framework should align with international standards to attract partnerships with international companies that prioritise environmental sustainability.

8.13 Public-private partnerships (PPPs)

With financial incentives and reductions in the cost of start-ups, PPPs can attract investment and expertise for the battery industry. For instance, collaboration with companies like Tesla, BYD, or CATL can attract high-level technology and experience to local markets.

8.14 Battery-powered irrigation and cold storage

Batteries can provide dependable power for irrigation systems in agriculture, which will help lives in arid areas, as well as for cold storage for preservation of harvested crops, reducing damages and losses and improving productivity.

8.15 Battery-powered appliances and small business tools

Some small businesses in off-grid areas depend on batteries to operate their appliances, tools and lights. Future directions may be promotion of battery-backed solar solutions for small businesses, supporting entrepreneurship and encouraging economic growth in such areas.

9. Conclusions

Development of a robust battery production industry in Nigeria offers significant promise but faces notable challenges.

9.1 Promise and successes

The promise of battery production in Nigeria lies in addressing critical energy access issues, reducing reliance on fossil fuels, and fostering economic growth. Companies like Arnergy and Rubitec Solar have shown that locally produced and assembled battery systems can meet off-grid and rural energy needs, providing clean, reliable power for households and small businesses. Nigeria's efforts to support renewable energy storage through government initiatives, public-private partnerships, and foreign investments are catalysing growth in the sector. Success stories from startups and companies are proving that Nigeria can be a leader in solar energy storage systems, offering affordable, pay-as-you-go models and modular battery solutions that serve diverse energy demands.

9.2 Challenges

Despite these successes, Nigeria's battery manufacturing sector is limited by several recurring challenges:

- High dependency on imports. Nigeria lacks sufficient local processing facilities for raw materials like lithium and cobalt. This dependency on imports drives up production costs, making locally produced batteries less competitive.
- Limited technical expertise. There is a shortage of skilled labour with the specialised knowledge needed for advanced battery technology. Training programmes in battery production and maintenance are still at the developing stage, and this can limit growth of industry.
- Supply chain constraints and infrastructure. Battery manufacturing requires high-quality infrastructure, reliable power, and efficient logistics. Nigeria faces logistical bottlenecks and irregular power supply, affecting battery production and distribution.

- Environmental concerns and recycling. Battery recycling infrastructure is at an early stage, raising concerns about effects of the discarded batteries on the environment.
- Policies and facilities. Regulations and infrastructure covering recycling and disposal are important for sustainable growth but are still limited in coverage and enforcement.
- Access to funding. Financial barriers still persist for local, small and medium players in the industry as battery production requires a significant level of capital. Lack of funds can hinder industrial development.

The future of battery production in Nigeria and Africa is promising, with immense potential for economic growth and sustainability. Through investment in skills development, local raw material processing, renewable energy storage, and recycling, African countries can reduce dependence on imports and make affordable battery solutions more available. Public and private sector partnerships, alongside policies that foster a beneficial investment environment, will be critical to achieving this potential. With strategic initiatives, it is possible that Africa could become a competitive player rather than only a consumer in the global battery industry.

In order to advance the sustainability of battery production, Nigeria needs to strengthen policies, enhance technical training, and encourage private and public investments in local manufacturing and recycling. It is in addressing these challenges that Nigeria can position itself as a key player in Africa's emerging battery production ecosystem. Success in this industry would not only support Nigeria's renewable energy ambitions but also stimulate employment opportunities, innovation and energy security. Employing a strategic, collaborative approach, battery manufacturing in Nigeria can metamorphose from a limited sector to a cornerstone of the continent's clean energy future.

References

- [1] H. O. Oruwari *et al.* 'The Impact of Energy Transition on Sustainability of Oil and Gas Development in Nigeria.' In *SPE Nigeria Annual International Conference and Exhibition* (p. D032S029R004). SPE, 2024.
- [2] H. N. Amadi & L. Ekeng. 'A Critical Analysis of Voltage Collapse in a Fragile Grid: The Nigeria Experience.' *International Journal of Engineering Research and Development*, 20(1), pp. 47-56, 2024.
- [3] D.O. Obada *et al.* 'A review of renewable energy resources in Nigeria for climate change mitigation.' *Case Studies in Chemical and Environmental Engineering*, vol. 9, pp. 100669, 2024.
- [4] C. A. Umeh *et al.*, 'The Role of Renewable Energies for Sustainable Energy Governance and Environmental Policies for the Mitigation of Climate Change in Nigeria', *European Journal of Applied Science, Engineering and Technology*, vol. 2, no. 2, pp. 71-98, 2024.

- [5] I. A. Onyegbadue, S. N. Ukagu & D. O. Okonkwo, 'Voltage Stability Assessment of Nigeria 330 kV Power Grid: A Critical Bus Perspective', *UNIZIK Journal of Engineering and Applied Sciences*, vol. 3, no. 5, pp. 1382-1401, 2024.
- [6] O. A. Adelekan *et al.*, 'Energy transition policies: a global review of shifts towards renewable sources', *Engineering Science & Technology Journal*, vol. 5, no. 2, pp. 272-287, 2024.
- [7] A. Hamdan *et al.*, 'Next-generation batteries and US energy storage: A comprehensive review: Scrutinizing advancements in battery technology, their role in renewable energy, and grid stability', *World Journal of Advanced Research and Reviews*, vol. 21, pp. 1984–1998, 2024.
- [8] A. Abe, B. Adebajji & E. T. Fasina, 'Sustainable Energy Development in Nigeria: Issues, Challenges and Prospects', *European Journal of Theoretical and Applied Sciences*, vol. 2, no. 3, pp. 333-342, 2024.
- [9] I. O. Utoh, W. Ekpotu & M. Obialor, 'Assessing the Viability and Impact of Off Grid Systems for Sustainable Electrification of Rural Communities in Sub-Saharan Africa', In *SPE Nigeria Annual International Conference and Exhibition*, p. D031S020R005, SPE, 2024.
- [10] K. Ukoba *et al.*, 'Adaptation of solar power in the Global south: Prospects, challenges and opportunities.' *Heliyon*, vol. 10, no. 7, pp e28009, 2024.
- [11] A. R. Singh *et al.*, 'Electric vehicle charging technologies, infrastructure expansion, grid integration strategies, and their role in promoting sustainable e-mobility'. *Alexandria Engineering Journal*, vol. 105, pp. 300-330, 2024.
- [12] C. Scarpelli *et al.*, 'Charging electric vehicles on highways: Challenges and opportunities.' *IEEE Access*, 2024.
- [13] Y. M. Prianka, A. Sharma & C. Biswas, 'Integration of Renewable Energy, Microgrids, and EV Charging Infrastructure: Challenges and Solutions.' *Control Systems and Optimization Letters*, vol. 2(3), pp. 317-326, 2024.
- [14] M. Alhazmi, A. Alfadda & A. Alfakhri, 'Analysis of a grid-connected solar PV system with battery energy storage for irregular load profile.' *Energies*, vol. 17(14), pp. 3463, 2024.
- [15] P. Gandhimathi, B. A. Vijayalakshmi, R. M. Victoria & M. Gomathi, 'Solar-Powered LED Streetlights Integrated With VLC In Bridging Illumination And Communication.' *Journal of Optics*, pp. 1-10, 2024.
- [16] J. Shorinwa, J. Okorhi & R. Uhunmwangho, 'Resilience in waste management: A socioeconomic context for managing spent lithium batteries in Southeastern Nigeria', *Journal of Future Sustainability*, vol. 4, no. 2, pp. 107-116, 2024.

- [17] M. K. Tabrizi, D. Bonalumi & G. G. Lozza, 'Analyzing the global warming potential of the production and utilization of lithium-ion batteries with nickel-manganese-cobalt cathode chemistries in European Gigafactories', *Energy*, vol. 288, pp. 129622, 2024.
- [18] E. E. Imarhiagbe & D. A. Salami, 'Metal Mining in Nigeria: Critique on it's Environmental, Socio-Impacts and Mitigation Measures', *Journal of Energy Technology and Environment*, vol. 6, no. 2, pp. 34-45, 2024.
- [19] M. W. Ijeoma *et al.*, 'Technical, economic, and environmental feasibility assessment of solar-battery-generator hybrid energy systems: a case study in Nigeria', *Frontiers in Energy Research*, vol. 12, pp. 1397037, 2024.
- [20] E. J. Ekong, 'Barriers to the Adoption of EVs in Africa: A Case Study on Nigeria', Master's thesis, UIS, 2024.
- [21] A. S. Sambo, A. S. Mustafa & N. M. Bello, 'Alternative clean energy for sustainable growth and development of the Nigerian telecommunications sector', *Proceedings of the Nigerian Academy of Science*, 16(2), 2024.
- [22] K. Isaksson, & T. Saad, 'Skills Mapping and Training Facilitation in Battery Cell Production', Thesis at <https://odr.chalmers.se/items/6932e5a4-de82-40e8-85c4-1387d5734467>, 2024.
- [23] V. U. Oguanobi & O. T. Joel, 'Scalable business models for startups in renewable energy: strategies for using GIS technology to enhance SME scaling', *Engineering Science & Technology Journal*, vol. 5, no. 5, pp. 1571-1587, 2024.
- [24] W. Ekpotu *et al.*, 'Nigeria's Energy Transition Plan: A Technical Analysis, Opportunities, and Recommendations for Sustainable Development'. In *SPE Nigeria Annual International Conference and Exhibition* (p. D032S030R007). SPE, 2024.
- [25] F. O. Usman *et al.*, 'Integrating renewable energy solutions in the manufacturing industry: challenges and opportunities: a review.' *Engineering Science & Technology Journal*, vol. 5, no. 3, pp. 674-703, 2024.
- [26] M. Iwegbu, and U. Osokogwu, 'How Affordable is Minigrid Power for Sustainable Electricity Supply in Nigeria', In *SPE Nigeria Annual International Conference and Exhibition*, p. D021S009R001, SPE, 2023.
- [27] A. O. Amole *et al.*, 'Analysis of grid/solar photovoltaic power generation for improved village energy supply: A case of Ikose in Oyo State Nigeria' *Renewable Energy Focus*, vol. 44, pp. 186-211, 2023.
- [28] I. T. Bello *et al.*, 'Electrochemical Energy Conversion and Storage Systems: A Perspective on the Challenges and Opportunities for Sustainable Energy in Africa', *Energy Reviews*, 100109, 2024.

- [29] K. U. Onyenwe & H. O. Orah, 'Lithium-Ion Battery Production in Nigeria: Issues and Challenges', *European Journal of Engineering and Technology Research*, vol. 7, no. 3, pp. 88-93, 2022.
- [30] A. Manhart *et al.*, 'Management of End-of-life Li-ion Batteries through E-waste Compensation in Nigeria', 2022. https://prevent-waste.net/wp-content/uploads/2023/05/Management-of-End-of-life-Li-ion-Batteries-through-E-waste-Compensation-in-Nigeria_Feasibility-Study_ECoN.pdf
- [31] O. Agunbiade & P. Siyan, 'Prospects of electric vehicles in the automotive industry in Nigeria', *European Scientific Journal*, vol. 16, no. 7, pp. 1857-7431, 2020.
- [32] O. Bamisile *et al.*, 'An approach for sustainable energy planning towards 100% electrification of Nigeria by 2030', *Energy*, vol. 197, pp. 117172, 2020.
- [33] M. O. Dioha & K. Caldeira, 'Exploring the role of electric vehicles in Africa's energy transition: A Nigerian case study', *Iscience*, vol. 25(3), 2022.
- [34] N. Sani-Gwarzo *et al.*, 'Comparison of blood lead levels between battery recycling workers and controls in Northern Nigeria', *International Journal of Environmental Health Research*, pp. 1-10, 2024.
- [35] O. N Coulibaly, 'Mali-Land, climate, energy, agriculture and development: A study in the Sudano-Sahel Initiative for Regional Development, Jobs, and Food Security,' Working Papers 308805, University of Bonn, Center for Development Research (ZEF), 2021.
- [36] C. G. Ozoegwu & P. U. Akpan, 'A review and appraisal of Nigeria's solar energy policy objectives and strategies against the backdrop of the renewable energy policy of the Economic Community of West African States', *Renewable and Sustainable Energy Reviews*, vol. 143, pp. 110887, 2021.
- [37] A. C. Oniku & O. L. Kuye, 'Skyville Company Ltd.: A Case of Emerging Product in an Emerging Market.' In *Marketing in Developing Nations* (pp. 86-95). Routledge, 2024.
- [38] M. Otuko & V. Mathenge, 'Towards Energy Security in Africa: Unveiling Policies, Initiatives, and Opportunities', IEEE, 2024.

South Africa

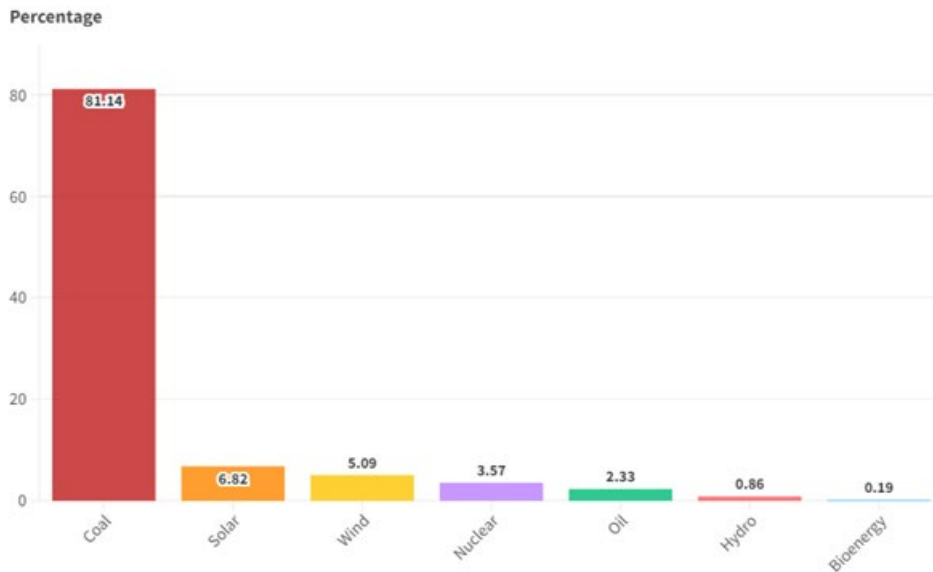
This section was written by Dr Nithyadharseni Palaniyandy, Associate Professor at the Institute for Catalysis and Energy Solutions (ICES), University of South Africa-Florida Science Campus (UNISA). She focuses on the development of electrode materials for lithium-ion (Li-ion) and sodium-ion batteries.

1. Introduction

Green, renewable energy solutions are growing exponentially worldwide, including in South Africa, as a contribution to the region's goal to limit CO₂ emissions. Currently, 80% of South Africa's electricity grid is powered by coal-fired power stations, making the carbon intensity of electricity generation higher than most other countries at over 800 gCO₂/kWh [1]. However, due to the depletion of coal reserves, South Africa is facing major energy challenges as the country has been suffering from power shortages for years, resulting in hours of blackouts and load shedding as part of efforts to protect the power grid.

On the other hand, to reduce its dependence on coal, South Africa sources 19% of its electricity from low-carbon sources, including 7% clean electricity from solar power and 12% [2] from other renewable energy sources as shown in Fig. 1. South Africa's renewable energy push is gaining momentum with the launch of three new bid windows for solar and wind projects, aiming to add 3,200 MW of solar and wind capacity to the grid [3]. This initiative seeks to alleviate the country's energy crisis, boost economic stability, and decrease dependence on coal. South Africa aims to generate 33% of its electricity from renewables by 2030, which is almost half of the global share of 60% set out in the International Energy Agency (IEA)'s net zero emissions scenario [2]. To meet this energy demand, a greater focus must be placed on renewable energy, energy storage and off-grid applications. This also applies to mobility applications such as electric vehicles (EVs) and public transportation to reduce greenhouse gas emissions and dependence on fossil fuels.

The transition to a sustainable energy system relies heavily on advanced energy storage solutions, notably Li-ion and vanadium redox flow batteries. These technologies are expected to play a crucial role in maintaining grid stability and facilitating the integration of increased renewable energy capacity into the power system [4].



Source: Ember, Energy Institute, Statistical Review of World Energy

Fig. 1. South Africa's electricity production by source

2. Key research areas in battery technologies

2.1 Raw material resources

South Africa is rich in raw material resources, and the country is taking steps to leverage these resources to boost local manufacturing initiatives.

South Africa is a significant producer of metals such as manganese, iron ore, nickel, and titanium, which are essential for various industries, including battery manufacturing and steel production.

The country also has substantial vanadium reserves, which are used in the production of vanadium redox flow batteries.

3. Material sourcing and local manufacturing

South Africa's role in the global battery value chain is primarily that of a raw material exporter, with a significant proportion of its critical minerals, such as manganese and vanadium, being exported to other countries. Only a small fraction of these minerals is utilised domestically, with approximately 5% of manganese (Manganese Metal Company) and 10% of vanadium (Bushveld) being used for local purposes [5]. Unlike China, which dominates the battery storage sector, producing nearly 85% of the world's cells and storage, South Africa does not currently fabricate Li-ion batteries locally. Instead, it imports batteries from other countries, as illustrated in Fig. 2. This highlights a potential opportunity for value addition and industrialisation in the battery sector.

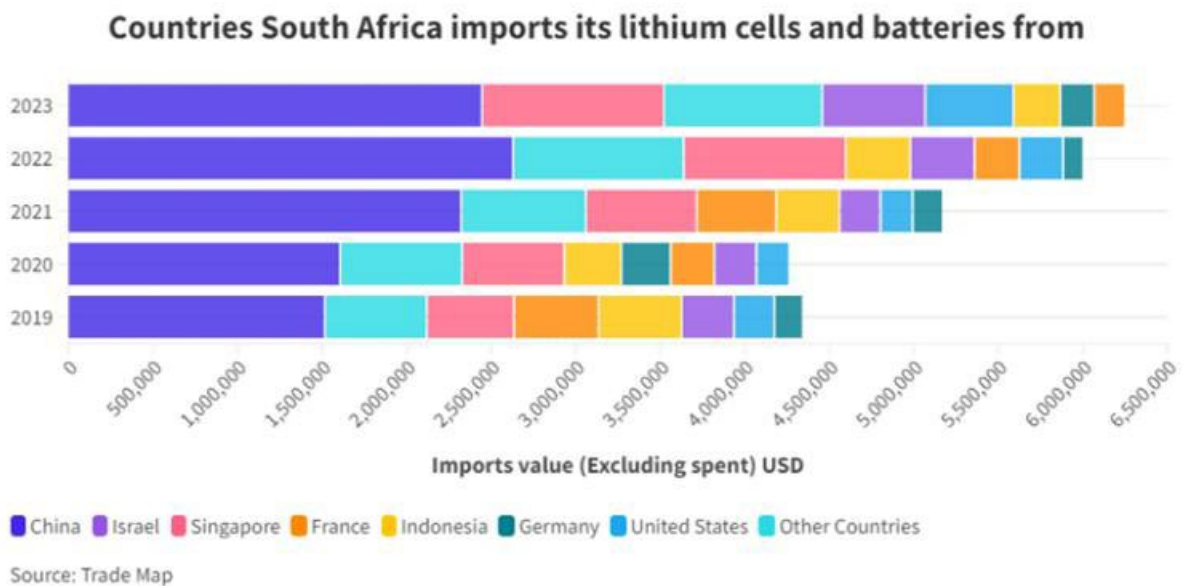


Fig. 2. Batteries imported to South Africa from various countries in US dollars

The extraction and processing of battery critical minerals, such as manganese and vanadium, are significant in South Africa. Two notable companies, Manganese Metal Company (MMC) and Bushveld Vanadium, play crucial roles in the production of these minerals.

3.1 Metal Manganese Company (MMC)

MMC's refinery in Mbombela, South Africa, has been operational since 1974, producing high-grade electrolytic manganese metal (EMM) with a purity of 99.9%. The company's products are utilised in various applications, including rechargeable Li-ion batteries. South Africa is the world's top producer of manganese [6] as shown in Fig. 3.

South Africa is the world's top producer of manganese

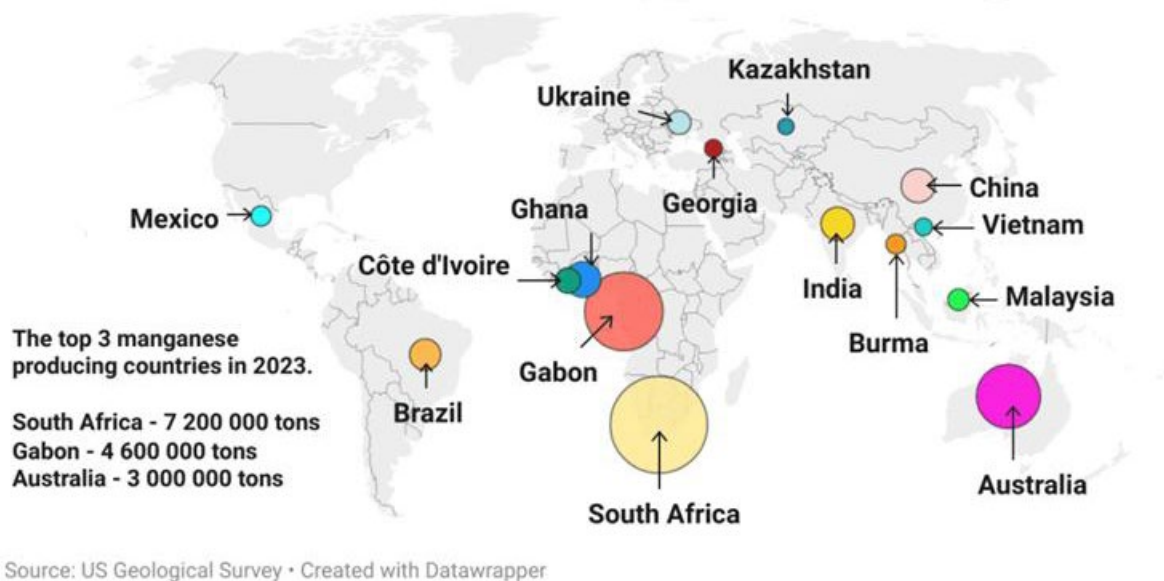


Fig. 3. Manganese producers in the world

3.2 Bushveld Vanadium

Bushveld Vanadium is a prominent producer of vanadium compounds, including vanadium pentoxide and ferrovandium. The company's vanadium electrolyte production facility in East London, South Africa, has an initial target capacity of 8 million litres per year, with potential expansion to 32 million litres. Most of South Africa's vanadium is exported, with the Netherlands being a primary destination. Between 2019 and 2023, vanadium exports to the Netherlands increased by approximately 56%.

3.3 Li-ion batteries

The growing demand for portable electronic devices and stationary energy storage for residential, commercial, industrial, military, renewable energy (mini- and micro-grids), and telecommunications are the key sectors in South Africa. In this context, Li-ion batteries are superior to other types of batteries on the market.

Li-ion is the preferred choice for energy storage and backup applications due to numerous advantages, including high energy density, high efficiency, low maintenance requirements, long cycle life, and high cell voltage [7], [8].

Li-ion batteries have a higher cell energy density, allowing for more compact and lightweight batteries ideal for space-limited backup installations. They maintain consistent performance throughout their cycle, with minimal voltage drop until 80-90% of capacity is discharged. They also charge at nearly 100% efficiency, reducing energy wastage and enabling faster recharge times. They do not require active maintenance like water top-ups or battery conditioning, making them easier to care for. They also offer long cycle lives and can last decades with proper settings, cell alignment, and temperature control.

These advantages make Li-ion batteries a cost-effective choice in the long run, despite their higher initial price point. Their benefits position Li-ion batteries as a leading solution for energy storage applications in South Africa's growing markets.

With the exponentially growing demand for environmentally friendly, renewable energy solutions, the use of Li-ion batteries is also increasing. For this reason, there are currently about 10 companies in South Africa (iG3N, Blue Nova, Freedom Won, Solar MD, Hanchu Energy, REVOV, Potensa, Esener, CTG EYIL, and Jdsolar SA) that manufacture Li-ion battery packs for the above applications (assembling and reusing EV batteries for stationary storage devices and EVs).

The number of EVs, i.e., battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plugin-hybrid electric vehicles (PHEVs), in South Africa is currently growing exponentially. The South African EV market generated revenue of US\$1,086.7 million in 2024 and is projected to reach US\$7,062.5 million by 2030, growing at a compound annual growth rate (CAGR) of 36.6% from 2025 to 2030 [9], [10], [11], as shown in Fig. 4 (a - c). The market for electric scooters in Africa was estimated at US\$54.5 million in 2024 and is expected to grow

at a CAGR of 7.5% from 2025 to 2030 (revenue forecast 2030: US\$84.3 million) [9]. This is because rapid urbanisation, rising fuel costs, and increasing vehicle emissions are prompting people in South Africa to switch from combustion engines to EVs.

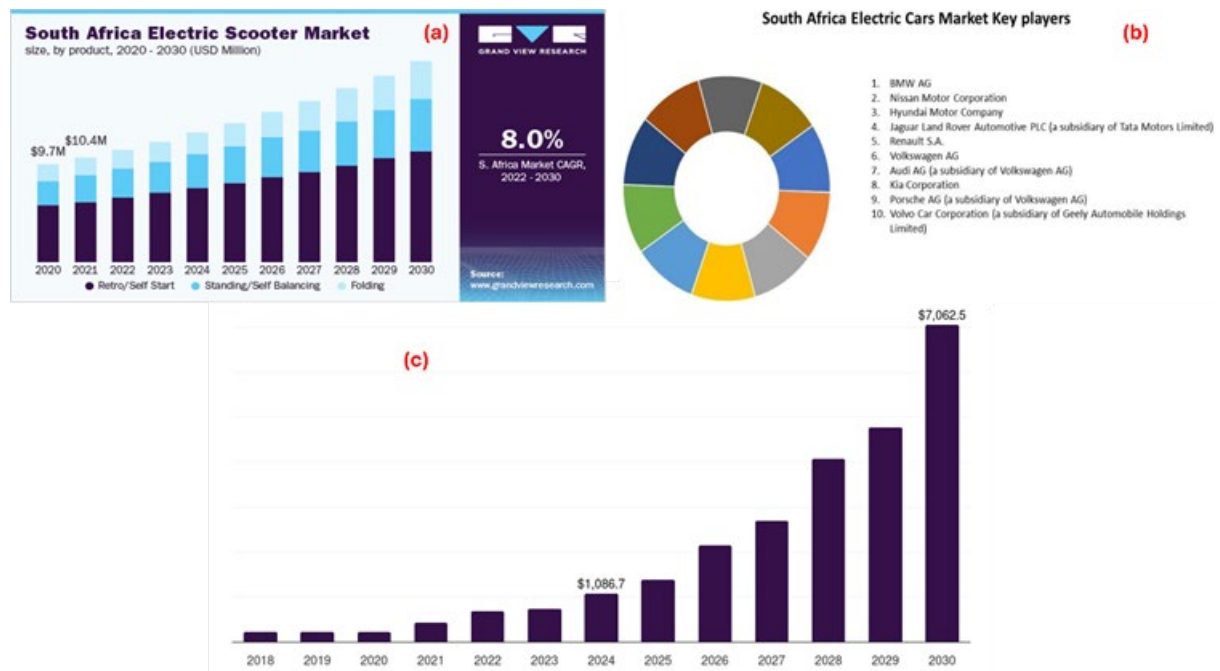


Fig. 4. South Africa's exponential growth of the electric scooter market (source: Market analysis report) (b) South Africa's electric cars market key players (source: marketwideresearch.com) (c) South Africa electric vehicle market, 2018-2030 (US\$M)

3.4 Vanadium redox flow batteries (VRFBs)

While Li-ion batteries currently dominate the market in terms of deployed capacity, VRFBs exhibit several benefits, including:

- Enhanced durability and longevity: VRFBs are designed to withstand extensive cycling, thereby ensuring a prolonged operational lifespan.
- Reduced operational expenditures: The minimal maintenance requirements and extended lifespan of VRFBs contribute to lower operating costs.
- Intrinsic safety: VRFBs are characterised by a lower risk of thermal runaway or explosion, thereby ensuring safe operation.
- Low environmental impact: The manufacturing and recycling processes associated with VRFBs have a relatively low environmental footprint.

These advantages render VRFBs an attractive option for energy storage applications that require long-duration discharge, extended operational life exceeding 20 years, and minimal maintenance requirements. VRFBs can complement existing battery chemistries, thereby catering to the increasing demand in the energy storage market. Recent advancements in flow battery technology, driven by significant research and development efforts, have further enhanced its viability for various applications.

The VRFB market faces commercial challenges despite its advantages. Specifically, misconceptions regarding costs and comparisons based on capital expenditures rather than levelised cost of energy hinder the adoption of VRFBs [12]. Furthermore, the prevailing dominance of Li-ion batteries in the market can overshadow the benefits of VRFBs. To overcome these barriers, enhancing stakeholder confidence and understanding, as well as achieving economies of scale through increased deployment, are essential for facilitating the growth of VRFBs in the energy storage industry.

Two major strategic moves are currently shaping the VRFB market, namely vertical integration by incumbent vanadium producers and the adoption of circular business models, usually centred on an electrolyte leasing model [13]. Bushveld Energy is developing an electrolyte leasing business model, where the company retains ownership of the vanadium electrolyte and leases it to users of VRFBs. At the end of the VRFB's operational life, the electrolyte is recovered, reprocessed, and either leased to another user or recycled into commodity-grade vanadium products, generating a financial return. This leasing model can potentially mitigate the high upfront costs associated with VRFB systems.

Several prominent vanadium producers are pursuing vertical integration into the VRFB market. Specifically, Bushveld Minerals, a major South African vanadium producer, acquired a majority stake in CellCube, a VRFB developer and manufacturer, in August 2020 [14]. Similarly, Canadian Largo Resources, another significant vanadium producer, recently established the vertically integrated joint venture, Storion Energy, via its subsidiary Largo Clean Resources [15]. Additionally, VRB Energy is majority-owned by Ivanhoe Electric, a minerals exploration and development company, while Australian Vanadium Limited has entered the VRFB market through its subsidiary VSUN Energy [16]. Invinity, through a joint venture with Bushveld Minerals, established Vanadium Electrolyte Rental Limited (VERL), a special purpose vehicle, in 2020. Through a 10-year leasing arrangement, VERL leased vanadium electrolyte to Pivot Power, the project developer, for utilisation in the VRFB system at the Oxford Superhub, thereby reducing Pivot Power's upfront capital expenditure [17].

3.5 Lead-acid batteries

First Battery (FB), established in 1931 in East London, South Africa, is a prominent manufacturer of lead-acid batteries, leveraging nearly a century of expertise to drive innovation in battery technology. The company's product portfolio encompasses a diverse range of applications, including high-performance automotive batteries designed for passenger vehicles and commercial trucks, specialised batteries engineered for the demanding requirements of marine vessels, reliable batteries for backup power applications, and advanced batteries optimised for solar and wind power systems.

FB has forged enduring partnerships with prominent original equipment manufacturers (OEMs) in South Africa, including Toyota, Nissan, General Motors, BMW, Volkswagen Group, Renault, Ford Motor Company, Nissan Diesel, and MAN Truck & Bus.

The company's long-standing relationships with these OEMs underscores the quality, reliability, and performance of FB's products from its installed production capacity of 10,000 batteries per day. FB also focuses on the recycling of used lead-acid batteries. It has an installed recycling capacity of 17,000 tons of lead per year, with around 98% of lead being recovered and re-used for new battery applications [18].

3.6 Recycling and circular economy

The growing demand for Li-ion batteries in South Africa's EV market, as illustrated in Fig. 5, is accompanied by an increasing waste stream. The disposal of Li-ion batteries poses significant environmental risks if not managed properly. Landfilling Li-ion battery waste can lead to soil and water contamination due to the presence of toxic metals. Furthermore, improper disposal results in the loss of valuable materials that could be recovered [19].

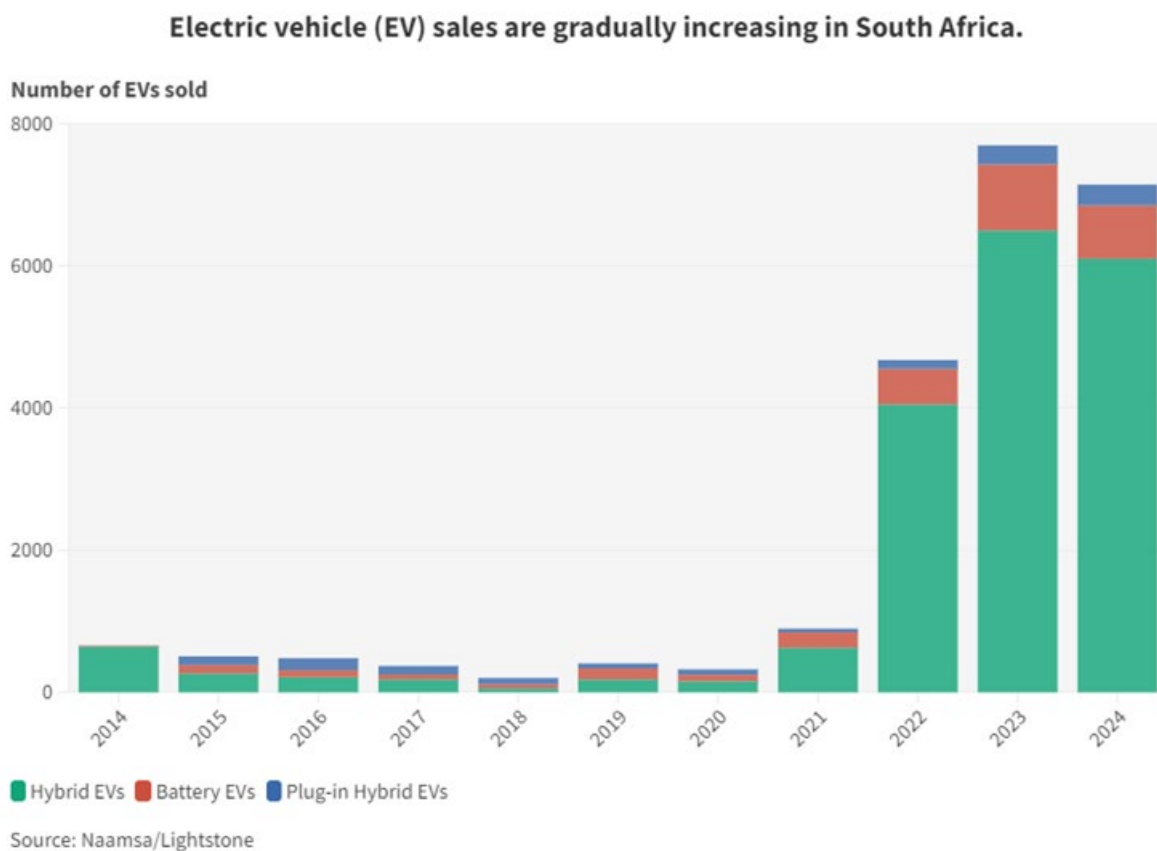


Fig. 5. Growth of the EV market in South Africa

Recycling Li-ion batteries offers several benefits, including reducing environmental damage and opening up significant economic opportunities. This offers the opportunity to recover high-value metals / value-added products such as lithium, manganese, copper, aluminium, cobalt and nickel for reuse, thereby reducing the need for primary metal extraction, conserving natural resources and supporting a circular economy. It also contributes to the economic growth of countries such as South Africa and other developing countries in Africa and around the world. Closing the loop of material use contributes to the circularity of the battery supply chain. Li-ion battery mining and production are worse for the climate than

the production of regular batteries for fossil fuel vehicles [20]. Thus, recycling batteries is an urgent need to ensure that the sustainable development goals (SDG) 7 on affordable and clean energy, and SDG 13 on climate action, enable both environmental protection and affordable energy production.

Battery recycling is a complex process, and South Africa has never had the infrastructure in place. In September 2024, Cwenga Lib [21] launched a small pilot recycling station for Li-ion batteries at its facility in Germiston, Gauteng. Without further recycling facilities in-country, recycling of Li-ion batteries would involve exporting them to China or Europe, which can be very expensive. In reality, this means that most of them end up in landfills. Also, Revive Africa is at the forefront of global efforts to tackle the challenges associated with Li-ion battery waste.

4. Key research areas, institutions, and collaborations

South Africa is positioning itself as a key player in the global shift towards battery-powered energy solutions. The country's battery technology market is expected to grow significantly, driven by increasing demand for EV and renewable energy storage solutions.

Key areas of innovation include:

- **Battery materials:** Research focuses on Li-ion batteries, lead-acid batteries, and alternative technologies like flow batteries.
- **EV batteries:** Advancements in battery technology, particularly Li-ion batteries, are expected to drive growth in the EV market.
- **Grid-scale energy storage:** Battery deployment can help stabilise the grid and provide backup power during outages.

4.1 Universities

4.1.1 University of the Western Cape (UWC)

The University of the Western Cape (UWC) is a leading institution in South Africa, and its research focus areas include energy storage and battery-related research [22]. The Energy Storage Innovation Laboratory (ESIL), launched in May 2015, focuses on advancing energy storage technologies, including Li-ion and sodium-halide batteries. Building on years of research and development in electrochemistry at the South African Institute for Advanced Materials Chemistry (SAIAMC), ESIL has developed various prototypes that have attracted industrial collaboration and potential commercialisation opportunities. This programme has fostered partnerships that position the UWC as an engaged university, contributing to cost-effective, high-quality, and sustainable electricity solutions. Furthermore, the technology is poised to play a critical role in South Africa's response to climate change and efforts to stabilise the electricity supply, ultimately benefiting the country's economy and citizens.

4.1.2 Wits University

The University of Witwatersrand (Wits University) has a research focus on electrochemical energy materials for various energy storage applications. The Materials Electrochemistry and Electrochemical Technologies research group explores technologies including Li-ion batteries, sodium-ion batteries, solid-state electrolytes for Li-ion batteries, rechargeable zinc-air batteries, and supercapacitors. This group has received funding as a Department of Science and Innovation (DSI) and National Research Foundation (NRF) Research Chair Initiative (SARChI) Chair and African-UK related project funds.

4.1.3 University of South Africa (UNISA)

The Institute for Catalysis and Energy Solutions (ICES) at UNISA is focusing on the development of advanced anode and cathode materials and a new manufacturing method for high-performance sodium-ion batteries. This method improves energy storage capacity and safety, making it suitable for EVs and domestic energy storage.

4.2 Research Institutes

4.2.1 uYilo

uYilo serves as the national electric mobility programme, playing a pivotal role in enabling the electric mobility ecosystem in South Africa since 2013. As a multi-stakeholder programme, uYilo's activities encompass government lobbying, industry engagement, pilot projects, capacity development, enterprise development, and thought leadership. The programme's name, derived from the Xhosa language, translates to "to create," reflecting its mission to foster an enabling environment for the electric mobility industry in South Africa and beyond. uYilo's technical facilities, hosted by Nelson Mandela University, include ISO 17025 accredited battery testing, materials testing, EV systems testing, and a live testing environment for interoperability between EVs and the smart grid. The programme aligns with various national and international frameworks, including the National Development Plan 2030, Automotive Masterplan 2035, and the Paris Agreement, contributing to South Africa's economic and social transformation.

4.2.2 Council for Scientific and Industrial Research (CSIR)

The CSIR launched a new indoor energy storage testbed in May 2024, a state-of-the-art facility that enhances South Africa's capabilities in renewable energy storage by supporting local players in the battery value chain [23].

The testbed is part of a collaboration between the CSIR and VITO, the Flemish Institute for Technological Research. The partnership aims to boost local battery industry capacity by providing access to test facilities and expertise, driving energy storage technology innovation through joint research and development initiatives, and promoting localisation by supporting the growth of local battery manufacturing and testing capabilities.

The testbed capabilities include:

- High-precision battery testing system, for testing battery modules and packs under various conditions.
- Multi-channel testing, allowing for parallel testing of multiple batteries under different test cycles.
- Advanced temperature chamber, simulating harsh climate conditions to evaluate battery performance and lifespan.

The testbed will provide valuable insights into battery performance, enabling:

- Optimised battery life, by understanding battery behaviour in various operating conditions.
- Improved safety, by identifying potential safety risks and defining safe operating zones.
- Industry growth, by supporting the development of local battery manufacturing and testing capabilities.

The testbed will have significant implications for industries such as mining, where battery-powered machinery is used in harsh environments.

The CSIR operates a research facility equipped with coin-cell and pouch-cell fabrication capabilities. This facility focuses on researching and developing manganese-based cathode materials, specifically lithium manganese oxide (LMO) and lithium manganese nickel oxide (LMNO), as well as titanium-based anode materials, such as lithium titanate (LTO), for Li-ion batteries. Additionally, the facility includes a cathode material production unit capable of scaling up production. Anode and cathode materials projects were funded by the Technology Innovation Agency (TIA), the Technology and Human Resources for Industry Programme (THRIP), and the Department of Science and Innovation (DSI) South Africa.

4.2.3 Mintek

Established in 1934, Mintek is an integrated Centre of Excellence across the minerals value chain, serving as “a one-stop shop metallurgical research and technology organisation.” Over nearly a century of its existence, it has had enormous impact on both talent and technology development and transfer, not only in South Africa but also globally [24]. Within its diverse programme it is currently running a pilot-scale demonstration of recovery and production of battery-grade salts of nickel, manganese and copper as well as battery-grade purified phosphoric acid. Alongside this, there is also a project focused on direct co-recovery of vanadium, titanium and iron from vanadium-titanium magnetite ores for use in batteries amongst other applications [24]. Mintek’s research and technology development programmes are industry-driven, ensuring more focused and accelerated commercialisation.

5. Battery skills assessment

As the skills requirements of the battery industry vary widely across the entire value chain, it is necessary to discuss them according to the different segments of the battery value chain: upstream, midstream, and downstream segments, as shown in Fig. 6.

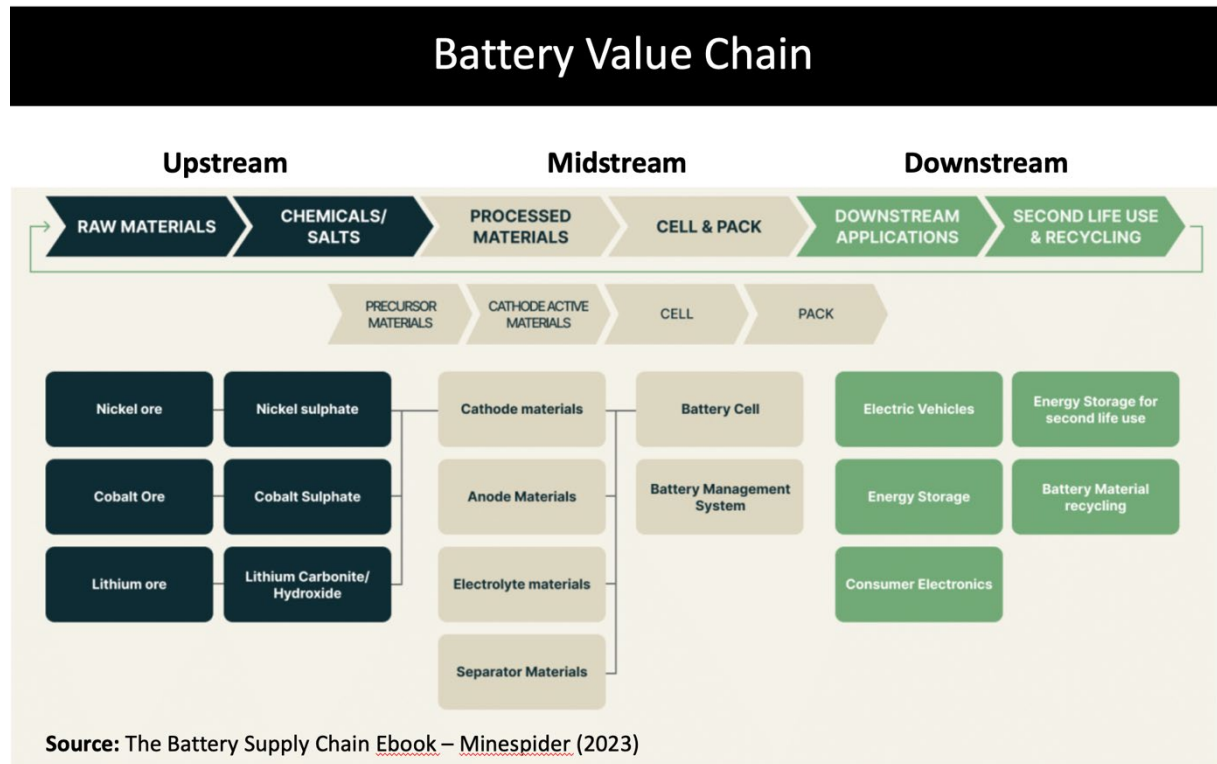


Fig. 6. Battery value chain (upstream, midstream and downstream)

5.1 Upstream segment

This segment comprises battery mineral mining, ore processing, and advanced processing (refining) of ore concentrates to produce battery-grade metal salts ready for precursor manufacturing. Associated R&D focused on this segment is also discussed in this section. The key battery minerals currently mined in South Africa on a large scale include manganese, nickel, vanadium, titanium, fluor spar, copper, and iron ore. South Africa boasts some of the best global mining expertise, especially in deep-level mining. The School of Mining Engineering at the University of the Witwatersrand is consistently ranked in the top 20 in the world [25]. Apart from universities, there are several other institutions providing education and training for skills in demand in this segment. Examples include Mintek (develops expertise and technology innovation across the minerals value chain) and the National Research Foundation of South Africa (NRF), which funds research, the development of high-end human capacity and critical research infrastructure to promote knowledge production across all disciplinary fields [26].

However, a widely held view is that while there may be an adequate talent pool at the graduate level of education, there is a crippling shortage of higher-level skills at the Masters

and PhD levels, especially in emerging areas [27], [28], [29]. These skills are critical to driving the research and innovation required to address new technological challenges of the sector. Recently, Mintek and the NRF entered into a strategic partnership to jointly build a platform that will produce a strong talent pipeline, particularly in areas of emerging talent demand across the minerals value chain, such as automation, AI in mineral processing, and big data [30]. Furthermore, Mintek undertakes training for the artisanal and small-scale mining sector [24].

5.2 Midstream segment

This segment comprises battery cell and component production. It requires skills in materials science, chemical engineering, electrical engineering, manufacturing engineering, and quality control and assurance. Specifically, South Africa needs professionals with expertise in:

- Materials science: Developing and processing materials for battery components, such as cathodes, anodes, and electrolytes.
- Chemical engineering: Designing and optimising chemical processes for battery production.
- Electrical engineering: Developing and testing battery systems and components.
- Manufacturing engineering: Overseeing the production process and ensuring efficient manufacturing systems.

5.3 Downstream segment

This segment comprises battery integration and application. It requires skills in electrical engineering, systems integration, software development, product management, and testing and validation.

- Electrical engineering: Integrating batteries into EVs, renewable energy systems, and energy storage solutions.
- Systems integration: Combining batteries with other systems, such as solar panels or wind turbines.
- Software development: Creating software for BMS and monitoring.
- Product management: Overseeing the development and launch of battery-powered products.

6. Industry and start-up ecosystem

6.1 ERINITE Energy

ERINITE Energy is a South African company that specialises in energy storage solutions, particularly Li-ion batteries. It offers energy storage systems for residential and commercial applications, designed to work with solar power or the grid. Their products utilise Li-ion technology, providing reliable and efficient energy storage catering to the local market's

energy storage needs. The company focuses on innovative energy storage solutions to address the country's energy challenges. Furthermore, ERINITE Energy is keen to collaborate with the University of South Africa (UNISA) on research and development of sodium-ion battery chemistries, exploring their potential applications and benefits in energy storage systems.

6.2 Elleyhill Power

Elleyhill Power is a South African company specialising in electrical engineering and power solutions. It offers a range of electrical engineering services, including design, installation, and maintenance of electrical systems for industrial, commercial, and residential applications. Additionally, Elleyhill Power provides power solutions, including energy storage systems utilising the lithium iron phosphate (LFP) battery chemistry from Sunsynk, and solar power systems, catering to the growing demand for renewable energy and energy storage in South Africa.

6.3 iG3N

iG3N is a leading South African manufacturer of Li-ion battery packs, specialising in the design, development, and production of battery storage solutions for residential and commercial applications. The company has secured substantial investments, including R20 million from Edge Growth and the ASISA ESD initiative, as well as \$1.3 million in a previous funding round. iG3N's battery storage solutions are engineered to integrate seamlessly with solar power systems or the grid, providing a reliable and sustainable electricity supply for businesses and households. With a network of over 60,000 installers of solar and backup power systems in Southern Africa, iG3N offers high-quality products characterised by low failure rates. As the demand for energy storage solutions continues to grow in South Africa, iG3N is well-positioned for further expansion.

6.4 Sunsynk

Sunsynk is a leading energy storage company in South Africa, specialising in innovative solutions for residential and commercial applications. Their product portfolio includes a range of energy storage systems, featuring Li-ion batteries and hybrid inverters that integrate seamlessly with solar power systems. These hybrid inverters enable users to store excess solar energy in batteries for later use, reducing grid reliance and providing backup power during outages. Sunsynk's battery storage solutions are engineered to optimise energy utilisation, lower electricity bills, and ensure a reliable backup power source. The company offers comprehensive installation services and technical support to guarantee smooth integration of their products into existing solar power systems. Notably, Sunsynk's batteries employ LFP chemistry, renowned for its inherent safety, durability, and environmental benefits.

6.5 Blue Nova

BlueNova is a South African company specialising in energy storage solutions, particularly LFP batteries. Their product portfolio encompasses a range of battery systems designed for residential and commercial applications, including:

- SBB (Single Box Battery); 14.5kWh high-performance battery capacity, expandable up to >130kWh.
- MPS (Mobile Power Series): Lightweight, ultra-reliable batteries for 12V and 24V systems, suitable for security systems, outdoor applications, and camping equipment.
- BP/DU (RacPower Batteries): 48V-compatible batteries for telecommunications, residential, and commercial sectors, with capacities up to 46kWh.
- HV Series: High-voltage batteries with advanced safety features and active cell balancing, compatible with industry-leading inverters.
- iESS (Intelligent Energy Storage Solutions): Customised energy storage systems with high-voltage LFP batteries, fire suppression, temperature regulation, and remote monitoring.

6.6 Freedom Won

Freedom Won is a prominent South African manufacturer of Li-ion battery packs, specialising in the development and deployment of energy storage solutions. Their product portfolio features LFP batteries, which are distinguished by their exceptional safety, durability, and environmental sustainability. Freedom Won's high-performance battery systems are designed to facilitate efficient energy storage and grid stabilisation, enabling seamless integration with renewable energy systems and supporting a wide range of residential and commercial applications.

6.7 Giga Africa 1 and Afrivolt

Both Giga Africa 1 and Afrivolt represent some very early-stage ambitious start-up activity that could lead to the eventual localisation of Li-ion battery cell manufacturing in South Africa. It must be acknowledged that cell manufacturing is a highly complex technical endeavour and with the current technologies, business failure risk remains high [31].

6.8 Solar MD

Solar MD is a prominent energy storage company in Africa, specialising in the design and manufacture of Li-ion battery storage solutions for residential, commercial, and utility-scale applications. Their battery systems utilise advanced LFP chemistry, with packs characterised by an advanced battery management system, flexible modular design, and high performance. Solar MD's product portfolio comprises residential battery solutions designed for integration with solar PV systems, and commercial and industrial energy storage solutions suitable for grid-connected or off-grid applications. Their battery products include

3.7 kWh, 7.4 kWh, 8.3 kWh, and 14.3 kWh LFP batteries featuring flexible modular design and parallel connection capability [32].

6.9 Zero Carbon Charge

As of 2025, there are over 500 public EV charging stations across South Africa. While most of these are grid-connected, Zero Carbon Charge is a start-up taking a different approach. With a few charging stations already operational, its mission is to build a fully off-grid solar-powered EV charging network on South Africa's major roads. To ensure that these ultra-fast charging stations deliver 100% renewable power, they integrate a custom design LFP BESS (typically 645 kWh) with a biodiesel generator for backup. Being fully off-grid, Zero Carbon Charge overcomes the challenges of South Africa's weak power grid.

7. Policy, funding and challenges

South Africa has been actively promoting battery research and energy storage through various national and regional policies [33], [34].

7.1 National policies

South Africa has established policy frameworks to support the development of renewable energy, including the White Paper on Renewable Energy and the Integrated Resource Plan (IRP) [35]. Research and development initiatives focus on integrating battery technology, particularly Li-ion batteries, into the energy mix to support EVs and renewable energy storage.

The South African government has demonstrated a strong commitment to integrating renewable energy and battery technology [35], [36]. South Africa aims to generate a significant portion of its electricity from renewable sources, with a target of reducing greenhouse gas emissions by 30% by 2030. The government has launched projects to integrate battery storage into the national grid, including a flagship project with a 360 MW battery energy storage system [36]. The government has attracted significant investment in renewable energy, with the Climate Investment Funds (CIF) providing concessional finance to support large-scale clean energy projects [35]. The Integrated Resource Plan (IRP) recognises the importance of energy storage in addressing the country's electricity supply issues. Although the plan's revision has been delayed, it is expected to include a more prominent role for energy storage. The Department of Science and Innovation (DSI) and the National Research Foundation (NRF) provide funding for research and development in energy storage technologies, such as Li-ion batteries and VRFBs.

Policies governing green technology transfer are also crucial to the success of the emerging battery industry. It is essential that the sector can attract appropriate technology, knowledge, and capital at scale both locally and globally. South Africa's Intellectual Property law, supported by key agencies such as the National Intellectual Property Management Office (NIPMO) and the Technology Innovation Agency (TIA), is robust for technology

transfer. The challenge lies in the high costs of international patent filing, often leading to low domestic patent use and potentially limited enforcement. Worse still, significant conflicts currently exist between policies aiming to advance rapid decarbonisation, hence the need to integrate into green global markets on the one hand, and those seeking to deliver social equity through local content quotas, on the other. These factors can create an uncertain environment for technology transfer and should be addressed through policy and institutional harmonisation [37].

7.2 Regional initiatives

The African Continental Power Systems Masterplan includes support studies for BESS, highlighting the importance of energy storage in regional power systems [38]. The Southern African Power Pool (SAPP) has been working to promote regional energy cooperation and planning, including the integration of energy storage solutions. The SAPP electricity market is enabling project viability for both BESS and renewable energy integration as attested to by the growth of Africa GreenCo, a private regional BESS and Renewable Energy operator.

The World Bank's \$1 billion programme aims to support investments in battery storage, leveraging an additional \$4 billion in public and private funds. This programme will support large-scale distributed battery storage in South Africa [39]. The Energy Sector Management Assistance Program (ESMAP) and the Middle East and North Africa Knowledge and Innovation Program (MENA KIP) have supported events and research initiatives focused on energy storage and battery technology in South Africa [39]. The Accelerated Partnership for Renewables in Africa (APRA) is promoting the uptake of renewables and green industrialisation in Africa [34].

7.3 Challenges and opportunities

South Africa already has some existing capabilities in the battery value chain, including:

- Manganese processing: South Africa holds about 80% of the world's reserves of manganese, essential for NMC batteries [30].
- Aluminium refining: Existing aluminium refining capabilities can be leveraged to manufacture battery-grade foil for current collectors in Li-ion battery production.
- Battery assembly: Companies like Bushveld Energy are developing local vanadium redox flow batteries, and some firms are assembling battery packs from imported Li-ion cells for the battery energy storage systems (BESS) market.
- Automotive industry linkages: South Africa's automotive industry can be leveraged for EV production, similar to Morocco's trajectory.

Despite the initiatives noted above, South Africa still faces challenges in deploying grid batteries, including a lack of understanding, disjointed planning processes, and financial obstacles. To develop a robust battery value chain, South Africa needs to address challenges such as:

- Skills development: Investing in education and training programmes to develop the necessary skills for the battery industry [28], [40].
- Infrastructure development: Improving infrastructure, including reliable and affordable electricity, to support battery production and integration.
- Regional integration: Collaborating with neighbouring countries to develop a regional battery value chain and leverage economies of scale.

Key opportunities for batteries include:

- Grid storage demand: South Africa faces power shortages with frequent load shedding, a result of decades of underinvestment in power infrastructure, which currently includes a large fleet of aging coal-fired power plants. Balancing energy security and decarbonisation goals, the government, under the Just Energy Transition Partnership (JETP), is gradually replacing the aging fleet with renewable generation capacity. Successful integration of renewable energy demands significant BESS to stabilise the grid, hence a high demand for battery storage solutions.
- Economic benefits: Renewable energy and battery technology integration can create jobs, stimulate economic growth, and reduce reliance on fossil fuels.
- Sustainable development: Integrating renewable energy and battery technology can contribute to sustainable development and reduce greenhouse gas emissions [41].

8. Case studies and success stories

8.1 Successful deployment of battery storage for off-grid solar energy

- Ntabankulu Local Municipality Case Study: A study on an off-grid microgrid for universal electricity access in the Eastern Cape province demonstrated the feasibility of renewable energy-based microgrids [42]. The proposed microgrid, comprising wind, diesel generator, and battery storage, could supply electricity at \$0.320/kWh with 90.5% renewable fraction, reducing CO₂ emissions and providing a viable option for rural electrification.
- Matjhabeng Solar Power Plant: A 400 MW solar photovoltaic power plant with an 80 MW (320 MWh) battery energy storage system is planned to meet the energy needs of the Matjhabeng municipality [43].
- Limpopo Farm Project: A farm in Lephalale operates a solar PV/BESS hybrid power plant, the BESS capacity being 2.2 MWh/yr, freeing it entirely from the national grid [42], [43].

8.2 Collaboration between local and international researchers

- University of Johannesburg and international partners: Researchers have explored innovative battery solutions, including repurposing EV batteries for grid-scale energy storage [42].

- International Energy Agency (IEA) and African Development Bank: The IEA and African Development Bank have collaborated on reports and projects related to battery storage in South Africa, highlighting the potential for utility-scale battery storage to improve grid stability and integrate variable renewables [43].
- World Bank and Eskom: The World Bank has provided funding for battery storage projects in South Africa, such as the Eskom's JETP, which aims to decommission coal-fired power plants and replace them with renewable energy and battery storage [44].

9. Future directions

South Africa's battery research field is experiencing significant growth, driven by the country's abundant mineral resources and increasing demand for energy storage solutions.

9.1 Key areas of growth

- Vanadium redox flow batteries (VRFBs): South Africa's VRFB value chain currently focuses on raw material output, electrolyte production, and locally manufactured balance of plant components. With the growing need for long-duration storage, VRFBs present a compelling commercial opportunity due to their safety, recyclable electrolytes, and extended cycle life. An important strategy could be vertical integration to localise the manufacturing of the core VRFB technology.
- Li-ion batteries: These dominate the market, and South Africa's government and industry aim to position the local value chain as a key player in the mobility of the future. Research explores opportunities for South Africa to participate in the Li-ion battery value chain, leveraging the country's vibrant automotive manufacturing industry. Researchers are developing new material-based technologies for energy storage systems, improving electrochemical properties, and scaling up cathode material production [16], [45]. Eventually, local cell manufacturing should be part of any long-term national Li-ion battery strategy.

9.2 Roadmap for future directions

To enhance innovation, commercialisation, and global competitiveness in South Africa's battery research, the following roadmap could be considered:

9.2.1 Short-term (2025-2030)

- Improve understanding and awareness: Enhance understanding of grid batteries and their integration into the South African national grid among policymakers, industry stakeholders, and the public.
- Collaborative energy planning: Promote cooperative planning and facilitate battery developers' access to multiple revenue streams and upfront investment.
- Support local value chain opportunities: Identify and support local value chain opportunities, such as mineral processing and battery assembly.

- Develop a clear strategy to enable local cell manufacturing of Li-ion batteries (see mid-term roadmap below) with a strong focus on production of battery-grade chemicals and precursors. While currently lacking refining capacity, the South African Development Community region possesses all the key minerals (lithium, nickel, manganese, cobalt, iron, phosphorus, copper, aluminium, and graphite) required for cell manufacturing. A strategic decision would need to be made in collaboration with the region about which minerals to refine locally in South Africa. Local refining already makes sense for manganese, aluminium and nickel. For example, the Manganese Metal Company is currently constructing a 6,000 tpa Phase 1 plant to manufacture high-purity manganese sulfate monohydrate for battery applications. For lithium (from Zimbabwe and Namibia), cobalt (DRC), copper (Zambia), and graphite (Mozambique and Madagascar), refining at source could be an option. An alternative for graphite is local synthetic graphite production from coal as South Africa has both the raw material and technical capacity if the operation can be run on affordable renewable power.
- Develop local talent: Establish pathways to create a strong talent pool across the battery value chain, especially of high-end skills to deliver research and innovation solutions for the industry's current and future challenges. An important pillar to achieve this is strategic and structured collaborative partnerships involving industry, academia, and research institutions, e.g. through the model of industry-driven PhD programmes.

9.2.2 Mid-term (2030-2035)

- Develop a sustainable VRFB market (for long-duration storage and grid-scale applications) and supply chain in South Africa, integrated with renewable energy generation.
- Localise vanadium battery production through incentive programmes for 50 GWh capacity by 2035 to enhance energy security and reduce costs associated with VRFB systems.
- Build local Li-ion cell manufacturing of at least 10 GWh capacity by 2035, a step that completes all the key stages of the mid-stream segment of the value chain.
- Establish a viable local end-of-life battery management ecosystem that includes second-life pathways and recycling for a circular economy.

9.2.3 Long-term (2035-2050)

- Achieve global competitiveness: Focus on innovation, commercialisation, and global competitiveness in the battery research field, leveraging South Africa's abundant mineral resources and growing demand for energy storage solutions.
- Create jobs and stimulate economic growth: Battery manufacturing could create up to 60,000 new jobs in South Africa, contributing to economic growth and development [18], [45].

10. Conclusions

South Africa is making significant contributions to battery research, driven by its abundant mineral resources and growing demand for energy storage solutions for EVs, the national grid, mining, commercial and industrial, and off grid use cases. Despite challenges, the country has opportunities to leverage its expertise and resources to develop sustainable battery technologies. With its rich mineral resources, growing energy storage market, and innovative research initiatives, South Africa has a promising future in sustainable battery technology. By harnessing its strengths and addressing challenges, the country can become a leader in energy storage solutions, driving economic growth, job creation, and a more sustainable future. South Africa can capitalise on the growing demand for sustainable energy solutions and become a key player in the battery technology industry.

References

- [1] I. Staffell, *et al.*, Drax Electric Insights Quarterly, Q3 (2020), https://www.drax.com/wp-content/uploads/2020/11/201126_Drax_20Q3_005.pdf Accessed: 9 Aug, 2025.
- [2] Ember, 'South Africa' <https://ember-energy.org/countries-and-regions/south-africa> Accessed: 9 Aug, 2025.
- [3] The Africa Report.com. 'South Africa: Wind energy gaining momentum and scaling new heights', <https://www.theafricareport.com/378201/south-africa-wind-energy-gaining-momentum-and-scaling-new-heights/> Accessed: 9 Aug, 2025.
- [4] VUKA Group, 'South Africa's battery storage revolution'. <https://www.esi-africa.com/energy-efficiency/south-africas-battery-storage-revolution/> Accessed: 9 Aug, 2025.
- [5] USGS, '2019 Minerals Yearbook, Manganese'. <https://pubs.usgs.gov/myb/vol1/2019/myb1-2019-manganese.pdf> Accessed: 9 Aug, 2025.
- [6] World Population Review, 'Manganese Production by Country 2025'. <https://worldpopulationreview.com/country-rankings/manganese-production-by-country> Accessed: 9 Aug, 2025.
- [7] M. M. Hasan *et al.*, 'Advancing energy storage: The future trajectory of lithium-ion battery technologies', *J. Energy Storage*, vol. 120, p. 116511, Jun. 2025, doi: 10.1016/j.est.2025.116511.
- [8] O. Tasneem, H. Tasneem, and X. Xian, 'Lithium-ion Battery Technologies for Grid-scale Renewable Energy Storage', *Res.*, vol. 2, no. 2, p. 100297, Jun. 2025, doi: 10.1016/j.nexres.2025.100297.

- [9] Grand View Horizon, 'South Africa Electric Vehicle Market Size & Outlook, 2030'.
<https://www.grandviewresearch.com/horizon/outlook/electric-vehicle-market/south-africa>
Accessed: 9 Aug, 2025.
- [10] Grand View Horizon, 'Africa Electric Scooter Market Size & Share Report, 2030'.
<https://www.grandviewresearch.com/industry-analysis/africa-electric-scooters-market>
Accessed: 9 Aug, 2025.
- [11] MarkWide research, 'South Africa Electric Cars Market 2025-2034'
<https://markwideresearch.com/south-africa-electric-cars-market/> Accessed: 9 Aug, 2025.
- [12] Accounting Insights, 'LCOE Calculation: Methods, Comparisons, and Future Trends',
<https://accountinginsights.org/lcoe-calculation-methods-comparisons-and-future-trends/>
Accessed: 9 Aug, 2025.
- [13] World Bank, Circular Business Model for Vanadium Use in Energy Storage, 2024.
Accessed: 9 Aug, 2025. <https://doi.org/10.1596/41459>
- [14] A. Colthorpe, 'Vanadium producer Bushveld Minerals begins building flow battery electrolyte plant in South Africa', <https://www.energy-storage.news/vanadium-producer-bushveld-minerals-begins-building-flow-battery-electrolyte-plant-in-south-africa/> Accessed: 9 Aug, 2025.
- [15] 'Largo and Stryten Energy to Form Storion Energy for the Manufacture of Vanadium Electrolyte and Battery Components for Long Duration Energy Storage',
<https://www.nacleanenergy.com/energy-storage/largo-and-stryten-energy-to-form-storion-energy-for-the-manufacture-of-vanadium-electrolyte-and-battery-components-for-long-duration-energy-storage> Accessed: 9 Aug, 2025.
- [16] VSUN Energy, 'About VSUN Energy', <https://vsunenergy.com.au/about-vsun-energy/>
Accessed: 9 Aug, 2025.
- [17] S. Creative, 'Pivot Power, Wärtsilä and Habitat Energy activate 50MW Transmission-connected battery in Cowley, Oxfordshire', <https://www.edf-re.uk/news-and-views/pivot-power-wartsila-and-habitat-energy-activate-50mw-transmission-connected-battery-in-cowley-oxfordshire/> Accessed: 9 Aug, 2025.
- [18] First Battery, 'First Battery Factories | Innovation & Quality Production',
<https://www.battery.co.za/about-us/dedicated-factories/> Accessed: 9 Aug, 2025.
- [19] eWASA Team, '5 Types of Batteries and How to Recycle Them', eWASA.
<https://ewasa.org/5-types-of-batteries-and-how-to-recycle-them/> Accessed: 9 Aug, 2025.
- [20] Climate 360 News, 'Lithium: Not as clean as we thought',
<https://climate360news.lmu.edu/lithium-not-as-clean-as-we-thought/> Accessed: 9 Aug, 2025

- [21] eWASA Team, 'New Battery Recycling Plant Opens in Gauteng', <https://ewasa.org/new-battery-recycling-plant-opens-in-gauteng/> Accessed: 9 Aug, 2025.
- [22] UWC, 'UWC and BattCo's home-grown lithium-ion battery'. <https://www.uwc.ac.za/news-and-announcements/news/uwc-and-battcos-home-grown-lithium-ion-battery-948> Accessed: 9 Aug, 2025.
- [23] CSIR, 'The battery research centre: Developing materials-based technologies for energy storage systems'. <https://www.csir.co.za/battery-research-centre-developing-materials-based-technologies-energy-storage-systems> Accessed: 9 Aug, 2025.
- [24] Mintek Annual Report 2024, <https://mintek.co.za/media/annual-report/annual-report-2024.pdf> Accessed: 9 Aug, 2025.
- [25] Top Universities, 'QS World University Rankings for Mineral & Mining Engineering 2025', <https://www.topuniversities.com/university-subject-rankings/mineral-mining-engineering> Accessed: 9 Aug, 2025.
- [26] National Research Foundation, 'About us – National Research Foundation'. <https://www.nrf.ac.za/about-us/> Accessed: 9 Aug, 2025.
- [27] Issuu, 'SA Mining March/April 2025 Edition', https://issuu.com/sundaytimesza/docs/sa_mining_march_april_2025_edition Accessed: 9 Aug, 2025.
- [28] Dept of Mineral & Petroleum Resources, 'Critical Minerals and Metals Strategy South Africa 2025'. https://www.gov.za/sites/default/files/gcis_document/202505/critical-minerals-and-metals-strategy-south-africa-2025.pdf
- [29] National Research Foundation, 'Mintek and NRF Forge Strategic Partnership to Transform South Africa's Mining Innovation Landscape – National Research Foundation'. <https://www.nrf.ac.za/mintek-and-nrf-forge-strategic-partnership-to-transform-south-africas-mining-innovation-landscape/> Accessed: 9 Aug, 2025.
- [30] ECDPM, 'An African battery value chain to kickstart green industrialisation', <https://ecdpm.org/> Accessed: 9 Aug, 2025.
- [31] Afrivolt, 'About Us - Afrivolt', <https://afrivolt.net/about-us/> Accessed: 9 Aug, 2025.
- [32] Solar MD, 'Leading The Future Of Energy Storage Solutions'. <https://www.solarmd.co.za/> Accessed: 9 Aug, 2025.
- [33] International Institute for Sustainable Development, 'How South Africa can Improve Grid Battery Deployment to Unlock Economic and Security Benefits'. <https://www.iisd.org/articles/press-release/south-africa-grid-battery-deployment-economic-security-benefits> Accessed: 9 Aug, 2025.

- [34] World Bank, 'Batteries Can Help Renewables Reach Full Potential in Africa', <https://www.worldbank.org/en/news/feature/2019/02/28/batteries-can-help-renewables-reach-full-potential-in-africa> Accessed: 9 Aug, 2025.
- [35] CIF, 'South Africa Leads in Renewable Energy and Battery Storage', <https://www.cif.org/news/power-moves-south-africa-sets-pace-renewable-energy-battery-storage> Accessed: 9 Aug, 2025.
- [36] SAIIA, 'Renewable Energy Technologies in the Global South: Insights from Africa', <https://saiia.org.za/research/renewable-energy-technologies-in-the-global-south-insights-from-africa/> Accessed: 9 Aug, 2025.
- [37] T. Fundira, The Policy and Regulatory Landscape of Green Technology Transfer in South Africa, Africa Policy Research Institute (2025), <https://afripoli.org/the-policy-and-regulatory-landscape-of-green-technology-transfer-in-south-africa>, Accessed 10 March 2025]
- [38] GreenCo 'Climate Finance Forum PPT Presentation', https://africagreenco.com/pdf/GreenCo%20-%20Climate%20Finance%20Forum%20PPT%20Presentation_compressed.pdf Accessed: 9 Aug, 2025.
- [39] World Bank, 'Accelerating Battery Storage for Development', <https://www.worldbank.org/en/topic/energy/brief/battery-storage-program-brief> Accessed: 9 Aug, 2025.
- [40] APRI, 'Prospects for Development and Integration of African Battery Value Chains', <https://afripoli.org/prospects-for-development-and-integration-of-african-battery-value-chains> Accessed: 9 Aug, 2025.
- [41] H. Kumba and O. A. Olanrewaju, "Towards Sustainable Development: Analyzing the Viability and Integration of Renewable Energy Solutions in South Africa"—A Review', *Energies*, vol. 17, no. 6, p. 1418, Jan. 2024, doi: 10.3390/en17061418.
- [42] O. M. Longe, N. D. Rao, F. Omowole, A. S. Oluwalami, and O. T. Oni, 'A Case Study on Off-grid Microgrid for Universal Electricity Access in the Eastern Cape of South Africa', *Int. J. Energy Eng.*, vol. 7, no. 2, pp. 55–63, 2017.
- [43] Revov, '2nd LiFe EV Batteries for Grid-Scale Energy Storage in South Africa', <https://revov.co.za/news/2nd-life-ev-batteries-for-grid-scale-energy-storage-in-south-africa/> Accessed: 9 Aug, 2025.
- [44] IEA, 'Utility-scale batteries in South Africa: Improving grid stability and renewables integration with dedicated tenders – South Africa Case Study – Analysis', <https://www.iea.org/reports/south-africa-case-study/utility-scale-batteries-in-south-africa-improving-grid-stability-and-renewables-integration-with-dedicated-tenders> Accessed: 9 Aug, 2025.

[45] ESI-Africa.com, 'Turning South Africa into a global battery storage powerhouse', <https://www.esi-africa.com/features-analysis/turning-south-africa-into-a-global-battery-storage-powerhouse/> Accessed: 9 Aug, 2025.

Zambia

This section was written by Dr Enzoh Langi, Lecturer in the Mechanical Engineering Department at the Copperbelt University. His research focuses on the utilisation and recycling of electric vehicle (EV) batteries, including working with the Faraday Institution ReLiB project (Recycling and Reuse of EV Lithium-ion Batteries) on second-life batteries and e-waste.

1. Introduction

1.1 Background

For decades, Zambia's power sector has heavily relied on hydropower, which currently generates 80% of the country's total electricity and accounts for 83% of its on-grid capacity [1] (See Fig. 1). However, a combination of factors, including long-term underinvestment in power generation, rising electricity demand driven by new mining activities, and a recent drought in 2023-2024 exacerbated by climate change in Southern Africa, has led to an electricity supply crisis in the country. This has resulted in widespread load-shedding. Given the adverse impact of power disruptions on productivity and the crucial role of the manufacturing sector in Zambia's economy, it is evident that the country must diversify its energy sources beyond hydropower.

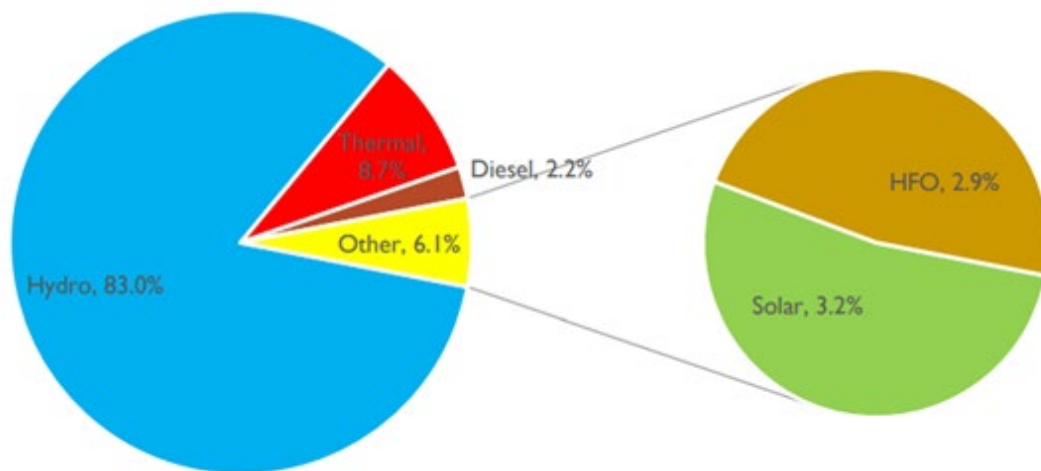


Fig. 1. Zambia installed electricity generation by technology – 2023 [2]

1.2 Importance in Zambia

Zambia's renewable energy potential includes hydropower, solar, wind, biomass, and geothermal. The country has significant opportunities to expand its role in the electric vehicle (EV) battery sector, thanks to its abundant mineral resources critical for EV battery production. Historically, Zambia has been a major exporter of minerals, but now it has the potential to become a key player in the manufacture of EV batteries. Additionally, Zambia's rich renewable energy resources, particularly solar and hydropower, present an ideal

foundation for integrating energy storage systems with solar power plants, especially in off-grid communities where solar-powered mini-grids are deployed.

1.3 Objective

This document provides an overview of battery research in Zambia, highlighting key areas in battery technology, material resources, and manufacturing. It also highlights important research institutions, battery skills development, policy considerations, funding, challenges, and future directions for growth in this sector.

2. Key research areas in battery technologies

Zambia is positioning itself to play a key role in the global transition to renewable energy by leveraging its rich mineral resources, particularly copper and cobalt, which are crucial for battery production. The country is focusing on several key research areas in battery technology to support this shift.

2.1 Battery materials and recycling

Zambia is exploring ways to process locally produced minerals like cobalt and copper into battery-grade chemicals for EV batteries. Research is also underway into recycling technologies to support the growing demand for EVs and renewable energy storage. Copperbelt University, in collaboration with the Faraday Institution's ReLiB project [3] led by the University of Birmingham, is working to advance EV battery recycling, with a focus on lithium-ion (Li-ion) batteries. Zambia and the Democratic Republic of Congo are jointly developing strategies to build local capabilities in battery precursor production and EV battery manufacturing, aiming to retain economic value within Africa and reduce reliance on raw material extraction.

2.2 Energy storage for renewable energy

As Zambia faces ongoing power shortages, off-grid energy solutions are critical, especially in rural areas. The government, through the Rural Electrification Authority (REA), is promoting solar mini-grids, biomass, and other renewable technologies to improve energy access [4]. Research is focused on developing affordable and scalable energy storage systems for off-grid solar solutions. Private companies like Copperbelt Energy Cooperation are also contributing by implementing solar power projects and preparing for a large-scale solar expansion [5].

2.3 Battery manufacturing and industrialisation

Zambia is advancing towards establishing a local battery manufacturing industry, with a battery precursor plant being developed in partnership with the Democratic Republic of Congo. Additionally, Airumi New Energy Zambia is Zambia's first specialised battery manufacturing plant, located in Chibombo. The facility manufactures high-quality lead-acid

batteries, helping make batteries more accessible and affordable for vehicles, households, and businesses across the country.

The plant is operated under the Zambia Jiangxi Multi-Facility Economic Zone. This initiative represents an important milestone in developing a local battery manufacturing value chain, reducing dependence on imported energy storage products, and strengthening Zambia's industrial capacity.

In addition, the setup of this plant is expected to support skills development and research collaboration with local universities and research institutions, particularly in EV battery technology, energy storage systems, and battery recycling. By fostering local expertise and innovation, the initiative will contribute to sustainable industrial growth, green mobility adoption, and the advancement of circular economy practices within Zambia's emerging energy sector.

2.4 Technology transfer and skill development

To foster local expertise, Copperbelt University is developing a master's programme in battery technology and a diploma in renewable energy in partnership with SinoZam College. These programmes aim to equip students and trainees with the necessary skills in electrochemistry, energy storage, battery manufacturing, and recycling to support the growth of Zambia's renewable energy and battery industries.

Together, these efforts are positioning Zambia as a key player in battery production and energy storage solutions, promoting both local innovation and the sustainable development of Africa's energy sector.

3. Material sourcing and local manufacturing

Zambia is rich in mineral resources critical for global battery production. Key minerals include cobalt, copper, nickel, and, to a lesser extent, lithium. Zambia is one of the world's top cobalt producers, a vital material for Li-ion batteries. The country also has significant copper reserves, essential for battery conductors and EV manufacturing. While Zambia's lithium reserves are limited, interest in the mineral is growing as demand for Li-ion batteries rises [6], [7], [8].

Mining is a crucial part of Zambia's economy, contributing significantly to GDP, exports, and government revenue [9]. However, mining activities, particularly in cobalt and copper extraction, have led to environmental damage, such as water and soil contamination, deforestation, land degradation, and health issues for workers and nearby communities. Moreover, mining has displaced local communities and disrupted livelihoods.

Currently, Zambia lacks specialised facilities for recycling Li-ion and EV batteries, though efforts are being made to improve this. Research partnerships, such as those between Copperbelt University and the University of Birmingham, are working on developing

sustainable battery recycling technologies. As Zambia's mineral wealth positions it to play a key role in the green energy transition, the country must balance mining with sustainable practices to reduce environmental impacts and promote long-term resource management.

4. Key research institutions and collaborations

4.1 Leading institutions

Copperbelt University, the University of Zambia, and Mulungushi University are spearheading renewable energy and battery research in Zambia. One notable initiative is a project focused on the beneficiation of local lithium ore and the production of cathode precursors, being led by Copperbelt University and the African Centre of Excellence in Sustainable Mining (CBU-ACESM) [10]. This project is sponsored by the African Centre for Technology Studies (ACTS) in Kenya, in collaboration with the National Science and Technology Council (NSTC) of Zambia. Furthermore, Copperbelt University, the University of Zambia, and the University of Lubumbashi have formed a partnership to foster technology transfer and knowledge exchange in the battery sector. Copperbelt University and the University of Lubumbashi are also researching high-energy-density electric vehicle batteries using nanomaterials.

4.2 Collaborative initiatives

Zambia is actively involved in several international collaborations aimed at advancing battery technology. One such partnership is with China, resulting in the establishment of a battery plant in Chibombo, operated by the Zambia Jiangxi Multi-Facility Economic Zone, which is now producing lead-acid batteries.

Additionally, Copperbelt University is collaborating with the University of Birmingham's ReLiB team to enhance existing research efforts and support the objectives set by the Democratic Republic of Congo (DRC)/Zambian governments, as well as international partners such as the US, UK, and the United Nations (UN). This collaboration focuses on developing efficient methods for extracting, recycling, and reusing critical materials. More recently, Zambia, the DRC, and Morocco have united to establish a regional value chain for electric mobility in Lusaka, aiming to transform Africa's automotive sector [11]. This initiative is being led by the United Nations Economic Commission for Africa (ECA) Office for North Africa, with representatives from Zambia, DRC, and Morocco.

5. Battery skills assessment

5.1 Current state

Zambia is in the early stages of developing technical expertise across the EV battery value chain. While there is growing interest in renewable energy and battery technologies, the country faces a significant skills gap in these areas. Zambia has for many years focused on mining key raw materials for batteries but lacks advanced expertise in battery

manufacturing, design, and recycling. This skills shortage could hinder Zambia's ability to fully capitalise on its mineral wealth for local battery production and recycling.

5.2 Skills development

Government-backed programmes, along with partnerships between universities and technical institutes, are working to address the skills gap in the EV battery sector. Copperbelt University is developing a master's programme in battery technology and collaborating with SinoZam College to offer a diploma in renewable energy. The Copperbelt University, in partnership with the African Centre of Excellence in Sustainable Mining (CBU-ACESM), is also fostering local expertise in battery raw materials processing. International collaborations, such as with the University of Birmingham's ReLiB team, will further contribute to skills development in battery recycling.

5.3 Future plans

To address the skills gap, there is a need to expand education and training programmes at institutions like Copperbelt University and the University of Zambia, focusing on battery manufacturing, recycling, and energy storage. Ongoing international collaborations will continue to promote knowledge transfer.

6. Industry and start-up ecosystem

A growing number of Zambian start-ups are focusing on energy storage, particularly in the off-grid solar market. Companies like Copperbelt Energy have established solar plants with over 90 MW capacity, contributing to the national grid. The government, through the Rural Electrification Authority, is also installing off-grid solar systems to increase electricity access in rural areas. Additionally, Zambia has made progress in establishing a battery manufacturing plant at the Zambia Jiangxi Multi-Facility Economic Zone in Chibombo, which has started producing lead-acid batteries. This plant represents a key public-private partnership, with the government supporting the development of renewable energy and battery technologies by offering incentives and fostering innovation. However, further development is needed to establish a fully operational domestic EV battery manufacturing industry.

7. Policy, funding and challenges

7.1 Policy support

Zambia's commitment to renewable energy is reflected in its Vision 2030 development goals [12], with the government actively supporting renewable energy through policies that promote the development of battery technologies, especially for off-grid and EV applications.

7.2 Funding opportunities

Local and international funding, including grants from organisations like the World Bank and the African Development Bank, are available to support renewable energy research and the commercialisation of EV batteries in Zambia.

7.3 Challenges

Key challenges facing Zambia's battery research and deployment include infrastructure limitations, high technology costs, and a shortage of skilled talent. Additionally, environmental concerns related to mining practices must be addressed to ensure sustainable growth in the sector.

8. Case studies and success stories

8.1 Case study 1

Copperbelt Energy Corporation (CEC) has made significant strides in renewable energy, installing approximately 94 MW of solar capacity, which contributes to the national grid. This project helps meet Zambia's growing energy demand and supports the transition to cleaner, renewable energy sources.

8.2 Case study 2

The Rural Electrification Authority (REA) has been instrumental in providing off-grid solar power solutions to rural communities. In 2021, REA, in collaboration with World Vision, commissioned the Moyo Mini Solar Grid at Moyo Hospital in Pemba District, Southern Province [14]. This \$320,000 investment provides a 45KW power supply to the hospital, primary school, and surrounding areas, benefiting around 34,000 people. REA's efforts play a vital role in addressing the power deficit and promoting sustainable energy access in rural Zambia.

8.3 Case study 3

Airumi New Energy Zambia has commissioned a new battery manufacturing plant in Chibombo that is currently producing lead-acid batteries. In its initial phase, the plant has the capacity to produce 4,800 batteries per day, to be used as both automotive starter batteries and in energy storage systems. This development reflects Zambia's growing commitment to sustainable industrialisation and the advancement of clean energy technologies.

The plant is already supplying energy storage systems to the domestic market, with potential to serve the wider Southern African Development Community region. Importantly, the establishment of this facility marks a significant step toward developing a future EV battery manufacturing industry based on locally available resources, strengthening value addition and regional competitiveness.

8.4 Case study 4

The World Bank and African Development Bank have supported several renewable energy projects in Zambia, including two utility-scale solar plants (54 MW and 34 MW) in Lusaka's South Multi-Facility Economic Zone, part of the World Bank's Scaling Solar initiative [15]. These projects contribute to Zambia's renewable energy capacity and promote energy diversification.

9. Future directions

Zambia is set to explore new technologies, including processing minerals vital for EV batteries while aiming to strengthen its local EV battery manufacturing industry by utilising its rich cobalt and copper resources. Expanding the Chibombo battery plant and focusing on sustainable practices like battery recycling and the circular economy are key priorities. The country plans to invest in renewable energy infrastructure, especially solar power, to meet increasing energy needs. Enhanced research and development, through collaborations with universities and global partners, will drive innovation in energy storage and battery technologies. Public-private partnerships will support sector growth, and workforce development programmes will ensure a skilled labour force. Additionally, Zambia seeks to strengthen regional and global collaborations, such as the Zambia-DRC-Morocco initiative for electric mobility, to boost its renewable energy capacity and attract international investment.

10. Conclusions

Zambia has long been exporting minerals critical for EV batteries, such as cobalt and copper, but now aims to actively participate in the global value chain for EV batteries. Significant progress has been made in the integration of renewable energy, both on- and off-grid. The recent opening of a battery manufacturing plant in Chibombo marks a major step towards Zambia's participation in the global EV battery market. While challenges remain, including infrastructure limitations and the need for specialised skills, opportunities exist in battery recycling, technological innovation, and strategic collaborations.

Zambia is well-positioned to capitalise on its unique advantages as a land-linked, peaceful nation with abundant mineral resources. The country's ongoing efforts in developing its renewable energy and EV battery sectors, including recycling, design, and manufacturing, offer a promising outlook for its future role as a key player in the global transition to clean energy.

References

[1] Ministry of Energy of Zambia, Renewable Energy Strategy and Action Plan, 2022. https://www.moe.gov.zm/wp-content/uploads/2022/08/Renewable-Energy_final-file_for-web.pdf Accessed: 8 August, 2025.

- [2] Energy Regulation Board, Energy Sector Report, 2023. <https://www.erb.org.zm/wp-content/uploads/files/esr2023.pdf> Accessed: 8 August, 2025.
- [3] ReLiB Project, 'Our Technologies'. <https://relib.ac.uk/our-technologies/> Accessed: 8 August, 2025.
- [4] GOGLA, Zambia Country Brief <https://gogla.org/wp-content/uploads/2024/11/Zambia-Country-Brief.pdf> Accessed: 8 August, 2025.
- [5] CEC Renewables Ltd, Audited Results 2024. <https://www.luse.co.zm/wp-content/uploads/2025/03/CEC-RENEWABLES-FY24-ABRIDGED-RESULTS-SENS-11.03.2025.pdf> Accessed: 8 August, 2025.
- [6] O. Nkala, 'Zambia tallies the costs of mining for electric batteries', Oxpeckers, 2024. <https://oxpeckers.org/2024/04/zambia-electric-vehicles/> Accessed: 8 August, 2025.
- [7] African Mining Market, 'Maamba Collieries Ltd. granted exploration licenses for lithium and other minerals in Zambia's Southern Province'. <https://africanminingmarket.com/maamba-collieries-ltd-granted-exploration-licenses-for-lithium-and-other-minerals-in-zambia-southern-province/19018/> Accessed: 8 August, 2025.
- [8] Energy, Capital & Power, 'High-Grade Lithium Discovered at Zambia's Msika Project'. <https://energycapitalpower.com/high-grade-lithium-discovered-at-zambias-msika-project/> Accessed: 8 August, 2025.
- [9] PricewaterhouseCoopers, 'Zambia 2024 Mining Report', PwC. <https://www.pwc.com/zm/en/publications/zambia-mining-report.html> Accessed: 8 August, 2025.
- [10] Copperbelt University Center, 'CBU-ACESM – Centres of Excellence Project'. <https://www.cbu.ac.zm/schoolsAndUnits/centreofexcellence/cbu-acesm/> Accessed: 8 August, 2025.
- [11] Battery Metals Africa, 'Morocco, DRC, and Zambia Collaborate to Revolutionize Africa's Electric Mobility Industry'. <https://batterymetalsafrica.com/morocco-drc-and-zambia-collaborate-to-revolutionize-africas-electric-mobility-industry/> Accessed: 8 August, 2025.
- [12] Ministry of Finance and National Planning, 'The Vision 2030'. <https://www.mofnp.gov.zm/?wpdmpro=the-vision-2030> Accessed: 8 August, 2025.
- [13] Copperbelt Katanga Mining, 'CEC Commissions 34 MW Solar Power Plant in Zambia' <https://copperbeltkatangamining.com/cec-commissions-34-mw-solar-power-plant-in-zambia/> Accessed: 8 August, 2025.
- [14] World Vision International, 'Moyo Mini Hospital receives electricity'. <https://www.wvi.org/stories/zambia/moyo-mini-hospital-receives-electricity> Accessed: 8 August, 2025.

[15] ESI Africa, 'Zambia: 34MW Ngonye solar PV plant comes online'. <https://www.esi-africa.com/renewable-energy/zambia-34mw-ngonye-solar-pv-plant-comes-online/>

Accessed: 8 August, 2025.

Zimbabwe

This section was authored by Eng. Hilton Chingosho, Lecturer and Research Cluster Leader for Energy and Power Systems in the Electrical and Electronics Engineering Department at the University of Zimbabwe. His research focuses on the techno-economic evaluation of locally manufactured battery technologies, including performance testing on energy density, durability, and operational reliability to support the development of a competitive local energy storage industry.

1. Introduction

Zimbabwe, with a population of approximately 16.32 million as of 2022, is characterised by a youthful demographic, with a median age of 18.7 years. Economically, it is classified as a lower-middle-income country with significant growth potential, driven by its rich natural resources and a highly educated workforce. The economy is primarily supported by agriculture, mining, and services, with the informal sector contributing around 64% of GDP.

The country's energy sector is expanding, though it has faced a range of challenges and opportunities. Over the years, Zimbabwe has struggled with an aging energy infrastructure, largely due to prolonged periods of underinvestment amid economic instability, including episodes of inflation and currency volatility since the turn of the millennium. However, recent years have seen notable progress in economic recovery, which has extended to improvements in the energy sector reflected in increased electricity access, now reaching approximately 62% of the population.

The country is undergoing a strategic shift toward renewable energy, driven by its abundant solar resources (with over 300 days of sunshine annually), rising domestic energy demand, and growing regional integration through power-sharing and connectivity initiatives. This transformation is further supported by international investment interest and policy incentives aimed at fostering a decentralised, climate-resilient energy system. As a result, the country's energy market is experiencing significant growth and is increasingly diversified, encompassing hydropower, thermal power, solar, biomass, wind, and geothermal energy, across both on-grid and off-grid systems.

The country's push for widespread adoption of renewable energy is motivated by the need to address persistent power shortages and enhance the reliability of electricity supply across all economic sectors. Recognising its vast potential, particularly in energy minerals and favourable climatic conditions, the country is now prioritising capacity development, innovation, and strategic research partnerships. These efforts aim to deliver cost-effective energy solutions to the broader population. By leveraging its renewable energy potential, tapping into its mineral resource base, improving infrastructure, and attracting investment, Zimbabwe aspires to strengthen its energy security, support sustainable economic growth, and contribute meaningfully to global climate action.

1.1 Strategic energy minerals

Like many African nations, Zimbabwe is richly endowed with mineral resources, including a range of energy minerals that are critical to both its domestic energy ambitions and the global clean energy transition. The country holds significant deposits of coal, including coal-bed methane, primarily located in Hwange and the Zambezi Basin, which continue to play a central role in electricity generation and industrial processes.

Over the past decade, Zimbabwe has begun to tap into its vast lithium reserves, making it the fifth-largest producer globally and the leading producer on the African continent. Lithium has emerged as Zimbabwe's most strategically important energy mineral, with active mining and preliminary processing taking place at the Bikita and Arcadia mines. These operations are positioning Zimbabwe as a key supplier to the global battery and electric vehicle (EV) markets.

In addition to lithium, the country is known to possess other critical battery minerals such as nickel, graphite, and manganese, all essential components in various battery chemistries. Although these resources are not yet as extensively exploited as lithium, they hold significant potential for downstream beneficiation and the development of a local battery manufacturing industry. Zimbabwe also has untapped uranium deposits, which could support future ambitions in nuclear energy. If these energy minerals are effectively harnessed through targeted investment, value addition, and coherent policy alignment, Zimbabwe could transform into a regional hub for energy mineral processing and a vital contributor to the global shift toward low-carbon technologies.

1.2 Zimbabwe's energy potential and battery value chain opportunities

Zimbabwe stands at a strategic crossroads in the global shift toward clean energy, with its vast energy resource potential including critical energy minerals and abundant solar irradiance positioning it as a future clean energy hub. This potential is reinforced by a supportive policy and regulatory environment, a growing renewable energy sector, and strong regional connectivity due to the country's central location in Southern Africa. Together, these factors create a compelling foundation for Zimbabwe to emerge as a key player in the global battery value chain. The emphasis on local beneficiation and value addition further strengthens the case for developing a domestic battery manufacturing industry. The following points highlight the key drivers of this transition:

1.2.1 Renewable energy integration

Zimbabwe has abundant solar resources, making it an ideal candidate for large-scale solar energy deployment. Integrating renewable energy sources such as solar, wind, and hydroelectric power can diversify the energy mix, reduce reliance on non-renewable sources, and decrease greenhouse gas emissions. Investments in renewable energy technologies are crucial for increasing generation capacity and improving access to electricity for both domestic and commercial use. Batteries play a crucial role in Zimbabwe's

renewable energy adoption by enhancing energy storage to influence grid stability, and off-grid applications. Batteries are essential for storing energy generated from renewable sources like solar and wind. This stored energy can be used during periods of low generation, such as at night or on cloudy days, ensuring a consistent and reliable power supply. By integrating battery storage systems, Zimbabwe can maximise the utilisation of its abundant renewable energy resources and reduce reliance on non-renewable sources.

1.2.2 Grid stability

The country's grid infrastructure requires expansion and modernisation to accommodate growing demand and integrate renewable energy sources. Upgrading transmission lines, substations, and distribution networks is essential for ensuring reliable electricity supply and supporting economic growth. Public-private partnerships and investments in renewable energy projects can help bridge the supply-demand gap and enhance grid stability. The integration of batteries into the national grid helps stabilise the electricity supply by providing backup power during peak demand or grid disturbances. Batteries can quickly respond to fluctuations in energy supply and demand, maintaining grid stability and preventing power outages. This is particularly important for Zimbabwe, where the aging grid infrastructure often struggles to meet the growing energy demands.

1.2.3 Off-grid applications

Off-grid solar solutions are gaining traction in Zimbabwe, providing reliable and clean energy to rural and remote areas. These systems, which include solar panels, battery storage, and generators, operate independently from the grid and offer a sustainable alternative to traditional power sources. Off-grid applications provide reliable and clean energy to communities that lack access to electricity and support economic development in underserved communities.

1.2.4 Electromobility applications

Zimbabwe is also exploring electromobility solutions to reduce its carbon footprint and promote sustainable transportation. The National Electric Mobility Policy and Market Readiness Framework was developed with the aim to achieve wide-scale EV deployment by 2030. This includes developing charging infrastructure, providing incentives for EV adoption, and promoting the use of EVs charged mainly from renewable energy powered chargers. These initiatives align with the country's goals of reducing greenhouse gas emissions and enhancing energy security. Zimbabwe's push towards electromobility, including the development of EVs and charging infrastructure, relies heavily on battery technology. The country has substantial lithium resources, which are key components in EV batteries. By developing local manufacturing capabilities for lithium-ion (Li-ion) batteries, Zimbabwe can support the growth of the EV market and reduce its carbon footprint.

Overall, the above discussions highlight how batteries and related technologies are integral to Zimbabwe's energy security ambitions and strategy. They play a crucial role in enabling the country to harness its renewable energy resources more effectively, enhance grid

stability, and expand energy access through off-grid solutions. Additionally, they support the transformation and decarbonisation of the transportation sector by promoting the uptake of electromobility initiatives, including last-mile transportation. By prioritising these strategic applications, Zimbabwe can chart a path toward a more sustainable, inclusive, and resilient energy future.

2. Key research areas in battery technologies

Zimbabwe is making significant strides in battery research, innovations, and development, particularly in the context of its abundant lithium resources. The country is positioning itself as a key player in the global energy transition, driven by the increasing demand for EVs and renewable energy technologies. The government is focused on developing the research capacity needed to lead the local manufacturing of Li-ion batteries to ensure the country fully benefits from its abundant lithium ore. Zimbabwe has the potential to become a significant player in the global lithium battery market. To fully capitalise on this potential, Zimbabwe is focusing on several key research areas in battery technology:

2.1 Prototype development and testing

The government, through the Ministry of Higher and Tertiary Education, has shown particular interest in establishing facilities for prototype development and testing of Li-ion batteries to accelerate the localised manufacturing and commercialisation of new battery technologies. This includes developing pouch cells and other battery formats for various applications. Collaborating with industry partners to scale up production and conduct real-world testing of battery prototypes is crucial for market readiness.

2.2 Advanced materials for anodes and cathodes

Current institutional research at some of the public universities in Zimbabwe such as the National University of Science and Technology and Harare Institute of Technology is focusing on developing advanced materials for anodes and cathodes to improve battery performance. For example, some researchers are exploring silicon-based anodes, which have a higher theoretical capacity than graphite, and can significantly enhance energy density. Investigating cathode materials, such as lithium iron phosphate (LFP) and lithium nickel manganese cobalt oxide (NMC), will assist in improving the battery safety and lifespan of the locally manufactured cells.

2.3 Electrolyte formulation and optimisation

Researchers are also focusing on efforts to develop advanced electrolytes, including solid-state and ionic liquid electrolytes, which can enhance battery safety and performance.

2.4 Battery management systems (BMS)

Researchers in the country are making progress in developing advanced BMS technologies that can monitor and manage battery performance, temperature, and safety, essential for

extending battery lifespan and ensuring reliable operation. Ongoing research efforts include looking into AI and machine learning algorithms for predictive maintenance and optimisation of battery performance.

2.5 Integration with renewable energy systems

Researchers are actively investigating the integration of Li-ion batteries with renewable energy systems, such as solar and wind, to enhance energy storage and grid stability. This includes efforts in developing hybrid energy storage systems that combine batteries with other storage technologies. These research efforts, including investigating the use of Li-ion batteries in off-grid and mini-grid applications, is poised to improve energy access in remote and underserved areas in Zimbabwe.

2.6 Battery recycling and sustainability

There have been some recent efforts in establishing efficient recycling processes for both lead-acid derivatives (flooded, gel and absorbent glass matte batteries (AGMs)) and Li-ion batteries to recover valuable materials and reduce environmental impact. Current research efforts are focusing on developing cost-effective and environmentally friendly recycling methods that fit within the laws governing waste disposal, which are primarily anchored in the Environmental Management Act (Chapter 20:27) and its associated regulations. This research on the use of sustainable and eco-friendly materials in battery production can further enhance the sustainability of the envisioned local lithium battery industry.

Building on the research areas outlined above, researchers aim to generate actionable insights that will enable Zimbabwe to strategically harness its abundant lithium resources. Their goal is to catalyse the development of a robust, sustainable lithium battery industry that not only supports the global transition to clean energy but also drives inclusive economic growth, industrialisation, and technological advancement within the country.

3. Material sourcing and local manufacturing

3.1 Introduction

Zimbabwe is richly endowed with a variety of mineral resources that are critical to the global battery manufacturing industry. Among its most significant assets are vast reserves of lithium, making Zimbabwe the fifth-largest lithium producer globally and the leading producer on the African continent. Major mining and preliminary processing operations at sites such as Bikita and Arcadia have established the country as a growing supplier of lithium to international battery and EV markets. In addition to lithium, Zimbabwe possesses substantial deposits of other critical battery minerals including nickel, graphite, and manganese, which are essential to diverse battery chemistries, such as Li-ion and nickel-metal hydride systems. While these additional resources remain underdeveloped relative to lithium, they present strong potential for value addition through local beneficiation and integration into a domestic battery manufacturing value chain.

Understanding the composition of Li-ion batteries is essential to contextualising Zimbabwe's mineral endowment within the global energy storage value chain. Li-ion batteries rely on a complex interplay of several key minerals, many of which are found within Zimbabwe's borders or its immediate region. These include:

- **Lithium:** The foundational element in Li-ion batteries, lithium is primarily used in the battery's electrolyte and cathode. During charge and discharge cycles, lithium ions migrate between the anode and cathode, enabling energy storage and release. Zimbabwe hosts substantial reserves of lithium-bearing minerals such as spodumene and petalite, particularly in the Bikita and Arcadia regions, reinforcing its emerging status as a major supplier.
- **Graphite:** Serving as the dominant anode material, graphite offers superior conductivity and structural integrity. Both synthetic and natural graphite are utilised, with natural graphite deposits present in Zimbabwe, positioning the country as a prospective source in a market currently dominated by producers such as China and Brazil.
- **Nickel:** A critical element for high-energy cathode chemistries, such as NMC and nickel cobalt aluminium (NCA), nickel enhances energy density and overall battery performance. Zimbabwe possesses notable nickel reserves in areas like Bindura, Makonde, and Shamva, supporting both stainless steel production and battery-grade nickel sulfate refining for cathode materials.
- **Cobalt:** Commonly used to stabilise cathodes and enhance energy density and cycle life, cobalt remains a high-value but ethically complex mineral. While Zimbabwe's cobalt production is less prominent than that of the Democratic Republic of the Congo, the country's nickel deposits often co-occur with cobalt, offering potential for integrated extraction.
- **Manganese:** Utilised in cathode formulations such as NMC and lithium manganese oxide (LMO), manganese improves thermal stability and safety. Although manganese exploitation in Zimbabwe remains limited, its presence holds promise for future diversification of battery chemistries sourced locally.
- **Aluminium:** Employed as a current collector on the cathode side, aluminium is essential for maintaining electrical conductivity and mechanical stability. Its widespread availability globally, including in southern Africa, makes it a readily accessible input for battery component manufacturing.
- **Phosphate:** Central to LFP batteries. These batteries are increasingly favoured in EV and grid storage applications due to their safety profile and cost efficiency. Zimbabwe does not currently produce phosphate at scale, but regional sourcing could be explored.
- **Copper:** Functioning as the anode current collector, copper is critical for electrical conductivity within the battery. While Zimbabwe has modest copper reserves, it

benefits from proximity to major copper mining operations in Zambia's Copperbelt, facilitating regional material integration.

- Iron: A core component of LFP batteries, iron contributes to structural safety and cost-effectiveness. Zimbabwe's iron ore deposits in Kwekwe and Chivhu present opportunities for integration into cathode material production for LFP systems.

Together, these minerals form the backbone of the Li-ion battery ecosystem. Zimbabwe's natural resource base, particularly its lithium, nickel, graphite, and iron, provide a compelling foundation for establishing a vertically integrated battery materials industry. By investing in mineral beneficiation, refining infrastructure, and regional supply chain linkages, Zimbabwe has the potential to move beyond raw material export and into midstream and downstream battery manufacturing processes. Such development would not only support national industrialisation goals but also position the country as a strategic contributor to the global clean energy transition.

3.2 Zimbabwe's lithium value chain

Zimbabwe is emerging as a strategic supplier of battery-grade minerals, particularly lithium, which is central to the global shift toward electrification and renewable energy systems. Among the suite of critical inputs required for Li-ion battery manufacturing, lithium itself holds primacy used in both the electrolyte and cathode components of virtually all Li-ion battery chemistries. Zimbabwe's endowment of lithium-bearing pegmatites, especially those rich in spodumene and petalite, positions the country as one of the most important lithium sources in Africa.

Zimbabwe hosts several major lithium mining operations and exploration projects that form the cornerstone of its contribution to global battery mineral supply.

Bikita Minerals, located in Masvingo Province, is the largest and oldest lithium mine in Zimbabwe, with over a century of operational history. It is estimated to hold around 11 million tonnes of lithium ore, producing both spodumene and petalite, which are key feedstocks for lithium extraction. The mine's established infrastructure and resource base make it a flagship project in Zimbabwe's lithium sector.

Kamativi Lithium Mine, originally developed as a tin mine, has been repurposed for lithium extraction. Preliminary geological assessments have confirmed the presence of high-grade spodumene and petalite, positioning Kamativi as one of the most promising lithium redevelopment projects on the continent.

Arcadia Lithium, situated near Harare, represents one of Zimbabwe's most advanced lithium developments. With proven and probable reserves of 37.4 million tonnes at 1.22% Li₂O, the deposit is hosted within a series of stacked pegmatite dykes. The project gained international attention following its US\$422 million acquisition by Zhejiang Huayou Cobalt, reflecting strong investor confidence in Zimbabwe's lithium potential.

Additional exploration activity is underway at the Zulu Lithium Project in Fort Rixon and the Lutope Lithium Project in the Midlands Province. These prospects demonstrate the broader geographic distribution and scale of lithium resources in Zimbabwe and are expected to contribute to future production capacity as feasibility studies progress.

The distribution and sale of these deposits are particularly significant in light of the increasing global demand for EVs and grid-scale energy storage systems, which are fuelling an unprecedented surge in lithium consumption. Zimbabwe's growing lithium production capability enhances its strategic relevance as part of a diversified and secure global supply chain for battery raw materials. Importantly, lithium is not the only critical mineral found in Zimbabwe. As discussed previously, the country also hosts economically viable deposits of nickel, graphite, manganese, and iron, each of which plays a vital role in the production of Li-ion batteries. The co-occurrence of these minerals within a single jurisdiction offers a unique opportunity for integrated battery material supply, local beneficiation, and eventual development of downstream industries such as precursor material production, battery component manufacturing, and cell assembly.

The country is actively developing its local manufacturing capabilities to fully benefit from its abundant lithium resources. Beginning in December 2022, the government enacted a comprehensive lithium beneficiation policy, banning the export of unprocessed lithium ore and requiring miners to establish local Approved Processing Plants (APPs) for conversion into lithium concentrates and, subsequently, battery-grade lithium compounds (e.g. lithium hydroxide or carbonate).

Chinese companies have been central to these efforts. Sinomine Resource Group, which owns Bikita Minerals, and Zhejiang Huayou Cobalt at Arcadia are investing in local lithium-sulfate refineries, aligning with the export ban scheduled to take effect for concentrates in January 2027. Since 2021, Chinese investors (including Sinomine, Huayou, Chengxin, Yahua, Canmax) have deployed over US\$1 billion in Zimbabwe's lithium sector.

Government policy now mandates that any new lithium mining licence must include a beneficiation plan specifying local refining to at least lithium carbonate and accompanied by export restrictions and incentives. The government is actively supporting midstream initiatives, including investment in local battery manufacturing facilities and R&D partnerships with national universities to advance battery component innovation.

Notably, there have been a significant number of claims (in local press) from some firms and institutions on making progress in Li-ion battery production pilot projects, reflecting the ongoing race to build local value chains that extend from mineral extraction through to finished battery systems. Although still in early stages, these efforts illustrate a broader strategic trend of diversifying the country's mineral revenue away from ore exports toward industrial-scale manufacturing and export of battery-ready materials, stimulating job

creation, technological capacity building, and integration into global clean energy supply networks.

4. Key research institutions and collaborations

Zimbabwe is home to several key universities, each with its own unique mandate and focus areas. These universities are actively involved in research and development, particularly in the field of battery technology, leveraging the country's abundant lithium resources to advance clean energy solutions. The universities play a crucial role in advancing research and innovation in battery technology, contributing to Zimbabwe's development and positioning it as a key player in the global transition to clean energy. The government has tasked universities and other research institutions with developing the research capacity needed to lead the local manufacturing of Li-ion batteries. Researchers have been tasked with finding ways to ensure the country fully benefits from its abundant lithium ore. Universities have been at the forefront of Li-ion battery research as they seek to contribute to the development and commercialisation of Zimbabwe's first fully locally manufactured battery. Some notable research efforts and developments in Zimbabwe are laid out below:

A public university, the National University of Science and Technology (NUST), founded in 1991, is actively involved in battery research, particularly in the development and optimisation of Li-ion batteries. The university's Department of Chemical Engineering has made significant strides in this area with a PhD candidate in the department, having conducted research on the application of microwave heating in graphite preparation for use as an anode component in Li-ion batteries. This research has garnered national recognition and opened doors for collaboration with other institutes and companies. The university's research efforts are focused on producing high-quality, energy-efficient, and environmentally friendly battery components. By using locally available minerals, such as graphite, NUST aims to reduce reliance on imports and save foreign currency. The long-term goal is to establish a Li-ion battery plant in Zimbabwe, utilising locally produced materials to reduce costs and enhance battery performance. Additionally, the university's partnership with Shanghai University of Electric Power focuses on advancing research in renewable energy and battery technologies. These collaborations and partnerships are crucial for NUST's mission to foster knowledge creation, applied research, innovation, and entrepreneurship. By working with local and international partners, NUST is able to address social and economic challenges, contribute to sustainable development, and position itself as a leading institution in science and technology.

Harare Institute of Technology (HIT), which is a publicly owned technical university in Zimbabwe's capital city, has intensified its research focus on energy storage technologies, particularly Li-ion battery systems. According to press releases and local news reports, HIT researchers claim to have successfully purified LFP and developed a prototype battery cell with a nominal voltage of 3.2V and a 60Ah capacity. However, it is important to note that

these claims have not yet been independently peer-reviewed or validated by third-party institutions. These research efforts form part of HIT's broader strategy to enhance battery performance by increasing energy density, extending operational lifecycles, and improving safety key metrics in the development of next-generation EV technologies. If verified and scaled, such innovations could significantly contribute to the competitiveness of Zimbabwe's EV ecosystem and battery manufacturing aspirations.

One of the oldest and largest universities in Zimbabwe, the University of Zimbabwe (UZ) is currently engaged in several research initiatives aimed at enhancing battery efficiency, lifespan, and applicability within Zimbabwe's local context. Notably, UZ received two competitive research grants from the Research Council of Zimbabwe (RCZ). One of them is to evaluate the energy densities and durability of locally assembled Li-ion batteries to verify marketing claims made by domestic battery manufacturers and to provide evidence-based policy recommendations to guide the country's nascent battery manufacturing sector. The second is looking into laboratory scale manufacture of lithium cathode materials for the development of high energy-density Li-ion and lithium-air batteries. Researchers at the university are also exploring the development of a LFP battery prototype using locally available lithium ores. These research efforts aim to enhance battery energy density and operational life, contributing to both local consumption and potential export markets. As part of the Transforming Energy Access Learning Partnership (TEA-LP), some university researchers have started working to develop innovative battery technologies suited for deployment in mini-grid systems, particularly in rural and underserved communities.

Another publicly owned university, Midlands State University (MSU), reports that its researchers are actively investigating the environmental impacts of lithium mining in Zimbabwe and developing strategies to mitigate these effects. This study reportedly explores the environmental consequences of mining activities, including land degradation, water and air pollution, and greenhouse gas emissions. Their work plays a vital role in ensuring that the growth of the lithium battery industry aligns with principles of sustainability and environmental responsibility.

These research and industrial initiatives align closely with Zimbabwe's national thrust toward innovation, industrialisation, and sustainable economic transformation. In particular, they support the government's policy on local beneficiation of lithium and other strategic minerals, as outlined in key strategic documents such as the National Development Strategy 1 (NDS1) and the Zimbabwe National Industrial Development Policy (ZNIDP). By integrating academic research with real-world industrial applications, Zimbabwe is not only fostering homegrown innovation but also positioning itself as a significant player in the global transition to clean and renewable energy.

5. Battery skills assessment

Zimbabwe stands at the threshold of becoming a major contributor to the global Li-ion battery market, leveraging its abundant lithium reserves and strategic industrial policy. Realising this potential hinges significantly on the development of a skilled workforce capable of driving innovation, manufacturing, and advanced research.

Despite growing industry interest, no tertiary institutions in Zimbabwe currently offer dedicated battery technology courses or research programmes. Instead, professionals in the battery sector have largely transitioned from related disciplines such as electrical engineering, chemistry, applied physics, and chemical engineering to fill these roles. Their battery-specific expertise is predominantly acquired through on-the-job training and ongoing professional development.

Technicians and production staff working within Zimbabwe's emerging battery value chain typically hold technical diplomas or degrees in these foundational fields. Formal training in battery science remains minimal, with most skills developed informally through career progression and workplace experience.

There are signs of nascent research activity: the Research Council of Zimbabwe (RCZ) is acknowledged for funding heritage-based research aimed at local battery production. Its portfolio includes projects such as the laboratory-scale manufacture of lithium cathode materials and assessments of locally manufactured batteries as earlier discussed. However, these reported research efforts are mostly documented through press releases, and peer-reviewed confirmation remains elusive. There are also reported partnerships between Zimbabwean universities and Chinese companies to exchange technological and production know-how, reflecting a constructive but limited international collaboration.

To transition from nascent efforts to a fully operational battery manufacturing ecosystem, Zimbabwe must address several critical gaps. Universities and polytechnics (e.g. UZ, HIT, NUST, Harare Polytechnic, Zimbabwe School of Mines) need to integrate specialised programmes in battery technology, materials science, renewable energy, and advanced manufacturing. Strengthened cooperation between industry and academia via co-designed curricula, internships, attachments, and joint research would support practical skills acquisition. Existing frameworks like SAE²Net and Education 5.0 encourage such collaboration within engineering and technical domains. Government and institutional investments are needed to promote battery research and transition laboratory prototypes into peer-reviewed science, validated at scale. One other way will be to establish centres of excellence and prototyping labs, which are essential in supporting both training and industrial readiness for local battery production. In the same spirit to build battery skills along the value chain, the organisation of training workshops, certification programmes, and industry-led seminars will help existing technical professionals to upskill and stay current with fast-evolving battery technologies.

6. Industry and start-up ecosystem

Zimbabwe currently hosts only two local battery manufacturers: the Central African Batteries (duCellier Batteries) and Chloride Zimbabwe. Both specialise in lead-acid technology for automotive, traction, stationary, and renewable energy applications. Despite their output, these firms cannot fully satisfy national demand and face stiff competition from imported brands. Central African Batteries operates at 20,000 units/month while Chloride Zimbabwe reached 35,000 units/month (with plans to increase to 50,000+ per month). However, both remain unable to meet domestic needs and struggle to compete with imported batteries. End users have reported durability and performance issues, including battery failures and incidents of batteries catching fire that have been widely covered in local media (though peer-reviewed data remains limited). Noticeably, neither company has transitioned to lithium-based battery technologies. As a result, Zimbabwe imports all its Li-ion batteries, chiefly from China, India, and South Africa. The importing of batteries falls under Statutory Instrument (SI) 122 of 2017 (previously SI64 of 2016), which requires importers to obtain licenses and pay high duties. This policy was intended to protect local manufacturers from cheaper imports. However, persistent concerns over local product quality, mislabelling, and high failure rates have sustained consumer preference for foreign-made batteries.

The local battery market is primarily segmented by battery chemistry (lead-acid versus Li-ion) and connection type (on-grid versus off-grid). The surge in adoption of energy storage systems is driven by a need to alleviate load-shedding, stabilise the grid, and support renewable energy integration. Key challenges affecting market uptake include high upfront costs, limited technical expertise, and the absence of standardised battery ratings and safety certifications.

6.1 Characteristics of the local battery manufacturing ecosystem

The local battery industry in Zimbabwe is relatively old, characterised by the operation of equipment that is now obsolete, archaic, and often unserviceable. This has resulted in inconsistencies in the outputs from these machines, with varying limits and quality standards. The manufacturing processes in use are outdated and have been overtaken by technological advancements. Many of the machines and equipment used in the manufacturing processes are outdated, leading to inconsistency in product quality. These older machines may not be capable of meeting modern production standards and efficiencies. Technological improvements that could enhance production quality and efficiency have not been widely adopted. There appears to be insufficient quality control at critical stages in the manufacturing process. Some manufacturing plants lack proper process control measures to ensure the quality of the product. This has led to concerns over the reliability and performance of locally manufactured batteries. Most of the battery manufacturing processes are not fully automated, relying heavily on manual labour. This reliance on manual processes introduces the possibility of human errors, whether through

omission or commission, leading to general inefficiencies. Furthermore, this reliance on labour can result in unrestrained overhead costs, reducing the overall competitiveness of the industry. A significant portion of the raw materials (lead, sulfuric acid, ABS and polypropylene resins, lead paste materials) used in the battery manufacturing process are imported until some local production capacity, including new plastic plants, can fully meet demand. This reliance on imported materials exposes the industry to supply chain disruptions and fluctuations in international market prices, adding to the overall production costs.

6.2 Government policy support, funding & strategy

The government has played a strategic role in fostering battery research, especially in response to the global clean energy transition and the country's vast lithium reserves. Its efforts include policy direction, funding mechanisms, capacity building, and facilitating public-private-academic partnerships to position the country in battery innovation.

The National Development Strategy 1 (NDS1) explicitly identifies value addition and beneficiation of minerals, including lithium, as a priority sector for industrialisation and innovation. The government's emphasis on local manufacturing and clean energy has led to support for research and development in lithium battery technology.

In recent years, the Research Council of Zimbabwe (RCZ) has issued calls for proposals under the Heritage-Based Innovation Framework, explicitly targeting local battery manufacturing, energy storage research, and lithium beneficiation. RCZ has funded several public universities for exploratory research into LFP battery cells, energy storage applications, and industrial lithium processing techniques. Further, the government actively encourages collaborations between academia and industry, often brokering partnerships through state institutions and parastatals. To that end, Zimbabwe has explored bilateral cooperation with China, India, and South Africa to facilitate technology transfer in battery manufacturing and materials processing, with some universities having co-signed Memoranda of Understanding with foreign research institutions for capacity building and postgraduate training in battery science.

7. Policy, funding and challenges

7.1 Policies

Zimbabwe has implemented several policies that support the use of batteries, particularly in the context of renewable energy and EVs.

- **National Renewable Energy Policy (NREP):** The NREP, established in 2019, aims to enhance the contribution of renewable energy to Zimbabwe's overall energy supply. The policy sets ambitious targets to increase renewable energy capacity to 1,100 MW (16.5% of electricity supply) by 2025 and 2,100 MW (26.5%) by 2030. It

also includes provisions for energy storage solutions, such as batteries, to ensure a stable and reliable power supply.

- National Energy Policy (NEP): The NEP, established in 2012, recognises the importance of developing a comprehensive renewable energy policy. It aims to promote the use of renewable energy technologies and improve energy access in rural and underserved areas. The policy supports the integration of battery storage systems to enhance grid stability and reliability.
- EV policy: Zimbabwe is crafting a new policy to promote the adoption of EVs. This policy aims to create a conducive environment for the growth of the EV market by addressing infrastructure needs, such as charging stations, and providing incentives for EV manufacturers and users. The policy also emphasises the importance of local battery production to support the EV industry.
- Incentives for renewable energy projects: The government offers various incentives to promote investment in renewable energy projects, including 100% import duty exemption on solar products and Li-ion batteries as SI 13 of 2020 – Customs and Excise (Tariff) (Amendment) Notice, 2020 and SI 78 of 2021 – Customs and Excise (Tariff) Notice. Another incentive is a 100% corporate income tax holiday for the first 5 years, followed by a reduced rate of 15% thereafter for renewable energy projects as according to Finance Act, 2019 (No. 2), which amended the Income Tax Act (Chapter 23:06), reduced licensing fees, and viability gap funding for off-grid community projects. These incentives encourage the development of battery storage solutions to complement renewable energy systems.
- Local manufacturing and value addition: The government mandates that all lithium mining companies beneficiate the mineral domestically, promoting local battery production.

The Zimbabwean government has implemented policies to regulate lithium mining, processing, storage, and export to ensure sustainable development. The laws and regulations governing lithium in Zimbabwe include the Base Minerals Export Control Act, Customs and Excise Act, Mines and Minerals Act, and Value Added Tax Act. Additionally, the Base Minerals Export Control (Unbeneficiated Lithium Bearing Ores) Order, 2022, and the Base Minerals Export Control (Unbeneficiated Base Mineral Ores) Order, 2023, also regulate the mining, storage, transport, sale, and processing of lithium-bearing ores. Combined they make the following provisions:

- Lithium ore policy: The Cabinet approved a new lithium ore policy in April 2023. This policy requires any individual or entity owning a lithium concession to either mine lithium ores for processing at their own approved processing plant or for sale to those with approved processing plants locally. This move aims to encourage the establishment of local processing plants, adding value to lithium resources and boosting the local economy.

- Lithium ore purchase license: Any entity wishing to buy lithium ores from miners must obtain a lithium ore purchase license. A local approved processing plant is a mandatory requirement for obtaining this license.
- Ore movement permits: Ore movement permits for lithium ores are only issued if the ores are destined for a local approved processing plant. This ensures the optimal utilisation of the mineral.
- Storage regulations: Lithium ores can only be stored at the mining site where they were mined or at an approved processing plant.
- Monthly reconciliations: All players in the lithium sector must submit a summary of monthly reconciliations of ore movements to the Ministry of Mines and Mining Development. This requirement is intended to ensure accountability, transparency, and traceability in the lithium supply chain.
- Export regulations: Materials can only qualify as concentrate for export if they meet the minimum technical specifications and set minimum prices by the Minerals Marketing Corporation of Zimbabwe.

7.2 Funding

Securing adequate funding for battery research and manufacturing projects in Zimbabwe is one of the primary challenges faced by the industry. The financial sector in Zimbabwe is constrained by limited access to foreign currency, high interest rates, and economic instability characterised by inflation and currency volatility. These factors make it difficult for researchers and manufacturers to obtain the necessary capital to advance their projects. While the Research Council of Zimbabwe (RCZ) provides essential funding for various research initiatives, there is still a need for more substantial and diverse funding sources. Collaborations with international partners can help bridge this gap by providing financial resources and expertise. Additionally, the government and financial institutions need to work together to create funding mechanisms that support battery manufacturing projects, such as low-interest loans, grants, and incentives for investors. By addressing these funding challenges and leveraging available opportunities, Zimbabwe can enhance its research capabilities, develop a robust battery manufacturing industry, and contribute to the global energy transition.

7.3 Challenges

The funding challenges noted above is a major constraint. Developing the necessary infrastructure for battery research and manufacturing, including production facilities and supply chains, requires substantial investment. The lack of reliable infrastructure can hinder the growth of the industry.

While international partnerships provide access to advanced technologies, there is still a need to develop local technological capabilities. This includes training local engineers and technicians to meet the demands of a growing industry. Navigating the regulatory environment can be challenging for investors. Ensuring that policies are clear, consistent,

and supportive of industry growth is crucial for attracting investment. Establishing a local battery manufacturing industry requires access to both domestic and international markets. Developing effective marketing strategies and building strong distribution networks are essential for the industry's success.

8. Case studies and success stories

There are currently very few validated case studies on successful battery research or production projects in Zimbabwe, largely due to the absence of peer-reviewed publications. Most available accounts are based on press releases that are difficult to verify independently. However, practical efforts toward battery application and deployment are evident, particularly in rural energy systems and last-mile transportation.

For instance, under the UNDP-led Climate Adaptation Water and Energy Programme (CAWEP), a 200-kW solar mini-grid with a 900-kWh battery bank was commissioned in October 2024 at Hakwata Village in Chipinge District, powering over 80 households, a clinic, school, shops, and boreholes. This project, part of a US\$13.6 million programme, demonstrates the real-world application of battery storage to improve energy access and reliability.

Similarly, the Rural Electrification Agency (REA) has implemented green mini-grids in eight provinces, including a 200-kW solar plant in Chipinge that benefits 108 households, a school, a clinic, and a business centre, funded at US\$1.6 million.

Another significant case study is Mobility for Africa (MFA), a women-led enterprise that deploys electric tricycles equipped with swappable Li-ion battery packs and powered by off-grid solar charging stations. MFA's model supports rural communities with last-mile green transport and builds capacity through community-based maintenance and driver training.

9. Future directions

Zimbabwe stands at a pivotal moment in its journey to becoming a significant player in the global battery market. By focusing on strategic initiatives, the country can capitalise on its rich mineral resources and foster a thriving lithium battery manufacturing industry.

The development of a local lithium battery manufacturing industry is poised to create numerous job opportunities across various sectors, including mining, manufacturing, research, and logistics. This industry will stimulate local economies by attracting investment, generating revenue, and fostering the growth of ancillary businesses.

Producing LFP batteries supports the global transition to clean energy, reducing greenhouse gas emissions and promoting sustainable transportation solutions. By focusing on environmentally friendly production processes, Zimbabwe can contribute to global efforts to combat climate change and enhance energy security.

Research and development (R&D) efforts are critical for advancing Zimbabwe's technological capabilities. Future R&D initiatives should focus on:

- **Advanced battery materials:** Developing innovative materials for anodes, cathodes, and electrolytes to improve battery performance and safety.
- **Battery recycling:** Establishing efficient recycling processes to recover valuable materials and minimise environmental impact.
- **BMS:** Developing sophisticated BMS technologies to monitor and optimise battery performance, enhancing safety and longevity.
- **Developing local expertise:** While international partnerships provide access to advanced technologies, it is essential to build local expertise. This can be achieved through establishing training programmes for engineers, technicians, and researchers to develop the skills needed for battery manufacturing and collaborating with international universities and research institutions to exchange knowledge and best practices.

Navigating the regulatory environment can be challenging for investors. To attract investment, Zimbabwe should encourage:

- **Market access and distribution networks:** Establishing a local battery manufacturing industry requires access to both domestic and international markets. Future efforts should focus on effective marketing strategies, such as promoting locally manufactured batteries to a wider audience through targeted marketing campaigns, and developing strong distribution networks to ensure that batteries reach end-users efficiently and cost-effectively.
- **Continued collaboration with international partners:** This is vital for accessing cutting-edge technologies and expertise. Strengthening these partnerships can accelerate the development of local manufacturing capabilities and ensure that Zimbabwe remains competitive in the global market.
- **Innovation and entrepreneurship within the local start-up ecosystem,** which can drive the development of new battery technologies and applications. Supporting start-ups and research projects focused on energy storage solutions can foster a culture of innovation and contribute to the industry's growth.

By focusing on these strategic initiatives, Zimbabwe can harness its rich mineral resources, enhance its technological capabilities, and position itself as a key player in the global lithium battery market. These efforts will contribute to sustainable economic growth, job creation, and environmental sustainability.

10. Conclusions

Zimbabwe is at a critical juncture in its journey to become a strategic hub for battery innovation and manufacturing in Africa. Anchored by vast reserves of critical battery

minerals, particularly lithium, graphite, and nickel, the country holds a natural comparative advantage in the global energy transition. This potential is further bolstered by a growing political will, an improving regulatory landscape, and active engagement by public universities and research institutions. Despite a current lack of validated peer-reviewed battery research, there is mounting evidence of grassroots innovation, applied deployments in rural energy systems, and early-stage pilot development.

Government initiatives such as the National Development Strategy 1 (NDS1), the National Renewable Energy Policy (NREP), and the recently introduced lithium ore policy have created an enabling environment for local beneficiation, research funding, and investment in energy storage technologies. Institutions such as the Research Council of Zimbabwe are helping to direct funding toward heritage-based research that leverages local resources for local solutions, including LFP battery cells and battery cathode material development. Meanwhile, pioneering models like those of Mobility for Africa demonstrate the practical application and socio-economic benefits of battery deployment in transport and energy access.

However, considerable gaps remain particularly in skills development, technical validation, infrastructure, and international-standard production capacity. The country must prioritise formal training in battery science, quality assurance systems, international research collaboration, and full integration across the battery value chain from mining and refining to component manufacturing and recycling. By addressing these gaps and aligning industrial growth with sustainability and innovation, Zimbabwe can transform from a raw mineral exporter to a competitive participant in the global battery economy. With sustained investment, targeted policy support, and strong collaboration between academia, industry, and government, Zimbabwe has the potential to lead Africa's charge toward energy independence and technological leadership in battery storage.

References

- [1] Zimbabwe Reconstruction Fund (ZIMREF). (2022). *Annual report*. World Bank. <https://documents.worldbank.org/>
- [2] African Development Bank, (2025). *Zimbabwe economic outlook*. <https://www.afdb.org/en/countries/southern-africa/zimbabwe/zimbabwe-economic-outlook>
- [3] L. Al-Ghussain, R. Samu, and M. Fahrioglu, 'Techno-Economic Feasibility of PV/Wind-Battery Storage: Case Analysis in Zimbabwe,' in *Proc. 16th Int. Conf. Clean Energy (ICCE-2018)*, 2018.
- [4] B. A. Thango & P. N. Bokoro, 'Battery Energy Storage for Photovoltaic Application in South Africa: A Review,' *Energies*, vol. 15, no.16, pp 5962, 2023.

- [5] O. Sitando, 'Beneficiation of Zimbabwean Petalite: Extraction, Purification, and Compound Synthesis,' Dissertation at University of Pretoria, 2012
<https://repository.up.ac.za/items/f5d8fa3f-4179-4633-8234-9ae79a4d906b>
- [6] G. Mkodzongi, 'Lithium Mining and National Economic Development in Zimbabwe,' Africa Policy Research Institute (APRI), 2024.
https://www.veritaszim.net/sites/veritas_d/files/Lithium%20Mining%20and%20National%20Economic%20Development%20in%20Zimbabwe.pdf
- [8] Research Council of Zimbabwe (RCZ), <https://www.rcz.ac.zw>.
- [9] Research Council of Zimbabwe (RCZ), '2025 Heritage-Based Call For Research Proposals in Energy Production And Delivery; And Energy Storage,' https://grants.rczgrants.org/app/files/25010703RCZ-ZERA_2025_Call_for_Proposals_on_Heritage-based_Research_ogms.pdf
- [10] UNDP Zimbabwe, 'Transforming Lives: Solar Mini-grid Lights Remote Zimbabwe Village,' 2024. <https://www.undp.org/zimbabwe/press-releases/transforming-lives-solar-mini-grid-lights-remote-zimbabwe-village>
- [11] *TellZim News*, 'REA Installs Solar Mini-Grids in Rural Areas', 2024.
<https://tellzim.com/rea-installs-solar-mini-grids-in-rural-areas/>
- [12] F. Mutsaka, 'Electric tricycles are a ticket to respect and prosperity for some rural women in Zimbabwe', AP News, 2025. <https://apnews.com/article/women-zimbabwe-rural-electric-tricycles-9a298da6e5f394bc6394cf61b940b4ed>
- [13] Alliance for Rural Electrification, 'InfraCo Africa invests to scale access to clean transport in rural Zimbabwe', 2022. <https://www.ruralelec.org/infraco-africa-invests-scale-access-clean-transport-rural-zimbabwe/>
- [14] Government of Zimbabwe, Statutory Instrument (SI) 13 of 2020 – Customs and Excise (Tariff) (Amendment) Notice, 2020.
https://www.veritaszim.net/sites/veritas_d/files/SI%202020-013%20Customs%20and%20Excise%20%28Tariff%29%20%28Amendment%29%20Notice%20C%202020%20%28No.%2013%29.pdf
- [15] Government of Zimbabwe, Statutory Instrument (SI) 78 of 2021 – Customs and Excise (Tariff) Notice.
https://media.zambialii.org/media/legislation/20829/source_file/f94128379f9af63e/zm-act-si-2021-78-publication-document.pdf
- [16] Government of Zimbabwe, Statutory Instrument (SI) 122 of 2017 – Import Licensing and Control of Batteries. https://www.veritaszim.net/sites/veritas_d/files/SI%202017-122%20Control%20of%20Goods%20%28Open%20General%20Import%20Licence%29%20%28Amendment%20Notice%20C%20No.5%29.pdf

[17] Government of Zimbabwe. (2019). Finance (No. 2) Act, 2019 (Act No. 7 of 2019). Harare: Government Printer.

[18] Ministry of Energy and Power Development, National Renewable Energy Policy (NREP), 2019. <https://t3n9sm.c2.acecdn.net/wp-content/uploads/2019/08/Zimbabwe-RE-Policy-2019.pdf>

[19] Government of Zimbabwe, Base Minerals Export Control (Unbeneficiated Lithium Bearing Ores) Order, 2022. https://www.veritaszim.net/sites/veritas_d/files/SI%202022-213%20Base%20Minerals%20Export%20Control%20%28Lithium%20Bearing%20Ores%20and%20Unbeneficiated%20Lithium%29%20Order%2C%202022.pdf

[20] Government of Zimbabwe, Base Minerals Export Control (Unbeneficiated Base Mineral Ores) Order, 2023. https://www.veritaszim.net/sites/veritas_d/files/SI%202023-057%20Base%20Minerals%20Export%20Control%20%28Unbeneficiated%20Base%20Mineral%20Ores%29%20%28Amendment%29%20Order%2C%202023%20%28No.%201%29.pdf

Part II: South Asia and Indo-Pacific

Bangladesh

This section was written by Prof Khosru Salim, Professor at the Department of Electrical and Electronic Engineering, School of Engineering, Technology and Sciences, Independent University Bangladesh (IUB). His research focus is energy-efficient battery chargers for small electric vehicles, as well as battery-based energy storage systems for solar energy for food processing activities in off-grid areas.

1. Introduction

1.1 Background

Following its independence in 1971, Bangladesh experienced significant power outages for nearly 25 years. To address electricity shortages, the government implemented energy conservation, load management, and grid/off-grid electrification measures, promoting private sector investment. Despite these efforts, rapid urbanisation and economic growth led to demand outpacing new generation capacity. Rural electrification, however, improved economic conditions. According to the Bangladesh Power Development Board's (BPDB) 2025 annual report, present installed generation capacity is 28,919 MW. Including captive power, off-grid renewable energy generation and off-grid heavy fuel oil generation, the total installed capacity is 32,332 MW. The maximum demand served in a day was 16,794 MW [1].

Bangladesh aims for 4.1 GW of renewables by 2030, with 7% greenhouse gas reduction. The Perspective Plan targets 57 GW grid capacity by 2041, diversifying fuel use and enhancing private investments. The 8th Five-Year Plan (2021-2025) focuses on expanding power capacity and improving investment conditions [2].

Bangladesh is currently facing a significant energy crisis, with the electricity supply struggling to keep up with a rapidly rising demand fueled by urbanisation and industrial growth [1]. Despite a high national electrification rate, the country's power infrastructure is burdened by a heavy reliance on expensive, imported fossil fuels, which leads to frequent load shedding and blackouts [2]. This situation is compounded by the financial strain on the BPDB due to "capacity payments" made to private power plants, even when they are not in use [3]. In response, the government has set ambitious, albeit aspirational, renewable energy targets, aiming for renewables to make up 15% of the energy mix by 2030 and 40% by 2041 [4]. The Institute for Energy Economics and Financial Analysis (IEEFA) has identified three scenarios under which this might be achieved. The least expensive, at an estimated US\$27.5 billion, would involve 15,000 MW of utility scale solar, 4,000 MW of utility scale wind and 6,000 MW of rooftop solar. This strategic shift is crucial for enhancing energy security and meeting international climate commitments [5].

The Bangladesh Council of Scientific and Industrial Research (BCSIR) is an autonomous organisation under the Ministry of Science and Technology. It has three multidisciplinary

regional laboratories and several mono-disciplinary institutes, including the Institute of Mining, Mineralogy and Metallurgy (IMMM).

1.2 Importance of batteries in Bangladesh

The transition to a sustainable energy system in Bangladesh is critically dependent on the widespread adoption of advanced energy storage solutions [6]. Battery technologies are vital for overcoming the inherent intermittency of renewable sources like solar and wind, thereby enhancing grid reliability and stability [6]. Energy storage systems can provide essential backup power during outages and defer costly investments in new transmission infrastructure [7]. At a local level, batteries are the foundation of the country's successful solar home system (SHS) programme, which has provided electricity access to millions in off-grid rural areas [8]. At the national level, utility-scale battery energy storage systems (BESS) offer a clean and efficient alternative to the expensive, diesel-powered generators that are currently used for peak demand and power backup [9]. The Bangladeshi government is making a major push to bring solar power to each and every home in the country.

1.3 Objective

This section provides an in-depth analysis of the battery technology landscape in Bangladesh. It aims to deliver a comprehensive and data-driven overview of the country's market dynamics, key drivers of demand, technological and academic research, and the policy and regulatory frameworks that shape the sector. The following synthesises available information to provide a nuanced understanding of the opportunities, challenges, and strategic pathways for Bangladesh to leverage battery technology to secure its energy future.

2. Key research areas in battery technologies

2.1 Market size and growth projections

The lithium-ion (Li-ion) battery market in Bangladesh is experiencing a period of rapid expansion, fueled by a confluence of economic growth, urbanisation, and a growing awareness of sustainable energy solutions [10]. The market size is projected to grow from an estimated US\$ 297.88 million in 2025 to US\$ 435.06 million by 2030, representing a compound annual growth rate (CAGR) of 7.87% over the forecast period [10]. This growth is not uniform across all sectors, and a detailed examination reveals specific application areas that are acting as the primary engines of this market's expansion.

Table 1: Bangladesh Li-ion Battery Market Drivers and Projections

Market Segment	Primary Demand Driver	Projected Growth & Market Share	Key Characteristics
Telecommunications	Replacement of lead-acid batteries for	Dominant application segment. Market	High reliability, long lifespan, and low

	power backup in base stations due to efficiency and reliability needs.	share driven by operational cost savings and network stability.	maintenance are critical metrics.
Electric mobility	Government's 30% EV penetration target by 2030 and increasing consumer shift to three-wheelers due to high fuel costs.	Nascent but rapidly growing sector. Significant long-term potential; high-growth CAGR.	Demand is highly sensitive to upfront costs and charging infrastructure availability.
Consumer electronics	Rising affluence and increasing adoption of smartphones, tablets, and laptops.	Consistent, stable growth. Foundation of the initial Li-ion market in the country.	Focus on high energy density, compact size, and fast-charging capabilities.
Off-grid/distributed power	Energy security needs in rural areas and off-grid locations; high demand for solar home systems and microgrids.	Established segment with innovative growth models (e.g. peer-to-peer trading).	Reliability and long-term cost of ownership are key decision factors.
Grid-scale BESS	Urgent need for grid stabilisation, peak shaving, and integration of intermittent renewable energy sources.	Emerging and highly strategic segment. Potential for large-scale, transformative projects.	Requires large-scale investment, policy support, and technical expertise.

2.2. Sectoral demand drivers

2.2.1 Telecommunications: the first mover in Li-ion adoption

The telecommunications sector is currently the single largest driver of the Li-ion battery market in Bangladesh [9]. With an extensive network of base transceiver stations (BTS) serving over 180.2 million mobile subscribers as of 2022, a stable and reliable power source is not merely a preference but an absolute necessity for network continuity, especially given the country's unstable power grid [11]. For decades, the industry relied on lead-acid batteries for backup power. However, there has been a decisive and commercially motivated shift toward Li-ion technology in recent years.

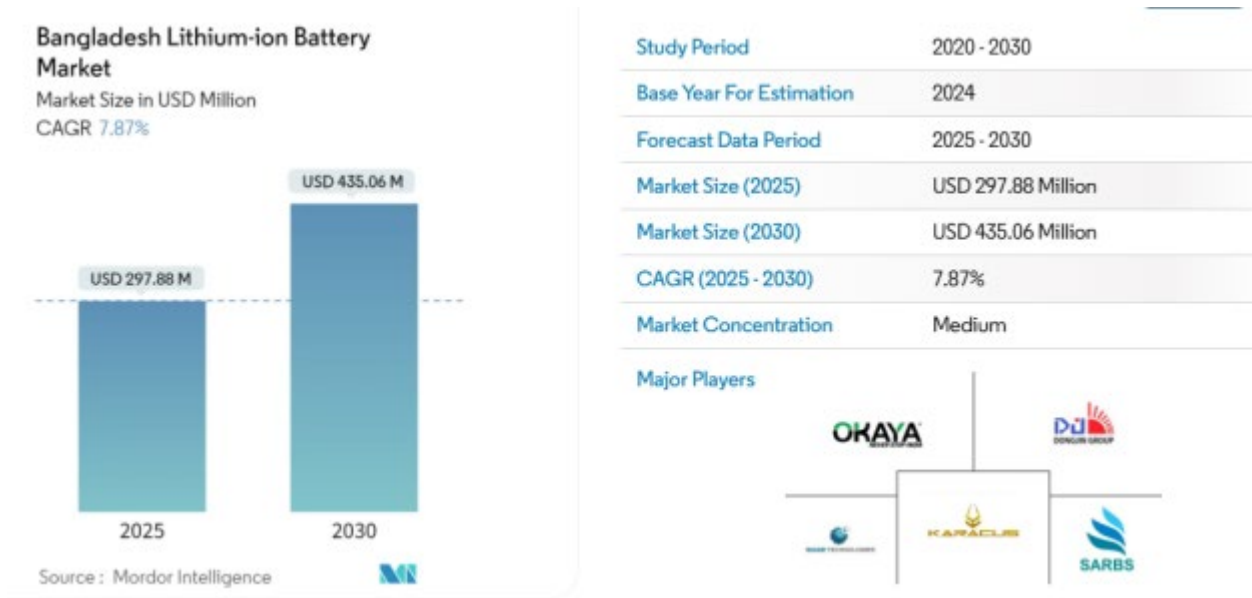


Fig. 1. Li-ion battery market size in Bangladesh (mordorintelligence.com).

The primary catalyst for this shift is not purely environmental but a fundamental business calculation. A comparative analysis reveals that while lead-acid batteries have a lower initial cost, they are less efficient (80-85%), have a shorter lifespan, require frequent maintenance, and produce significant carbon emissions [12]. In contrast, Li-ion batteries boast nearly 100% efficiency, a much longer lifespan, lower maintenance requirements, and are more compact [12]. This translates directly into reduced operational costs, improved network reliability, and a smaller physical footprint for telecom operators. The environmental benefit of lower carbon emissions and reduced lead waste is a valuable positive externality, but the core motivation for this technology adoption is a clear economic return on investment. This illustrates how pragmatic commercial factors are often the most powerful drivers for technological transition in Bangladesh’s private sector.

2.2.2 Electric mobility: a nascent but rapidly growing sector

Since 2017, about 70% of cars imported into Bangladesh have been hybrid electric vehicles (HEVs). Imports of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) remain low. However, electric three-wheelers (ETWs), including “easy bikes” and motorised rickshaws, are widely used. These vehicles, typically fitted with five batteries of varying sizes, are charged overnight, consuming significant electricity. The lack of regulated charging methods has impacted the daily load curve and raised concerns about charger quality, power quality, and environmental effects. The government has introduced charging tariffs for easy bikes, but comprehensive regulations remain absent. Despite challenges like limited charging infrastructure, the adoption of EVs offers environmental, economic, and energy independence benefits.

The EV market in Bangladesh is still in its nascent stages, with electric three-wheelers being the most prevalent form of electric transport. The government has signaled its commitment

to this sector by setting an ambitious target of 30% EV penetration by 2030 and by formulating guidelines for EV charging and registration [5]. This push is motivated by the need to mitigate the economic burden of air pollution and reduce the country's reliance on expensive, imported fossil fuels for transportation [5].

However, the path to widespread EV adoption is fraught with significant hurdles. The high upfront cost of EVs, particularly for cars, is a major barrier for a population with economic constraints [2]. This is compounded by the lack of a robust and accessible charging infrastructure across the country's unreliable power grid [2]. A key regulatory friction point is the 59% import duty on finished and semi-knockdown (SKD) Li-ion batteries, which makes the core technology for EVs prohibitively expensive [9]. To navigate these challenges, innovative business models are emerging. Startups are piloting battery swapping technologies, a "Battery-as-a-Service" (BaaS) model, which aims to reduce the high initial purchase price for consumers and improve the convenience of charging EVs [9].

2.2.3 Off-grid and distributed Power

Bangladesh has a well-established history of decentralised, off-grid power solutions, a model that has served as a global exemplar for rural electrification. Pioneering organisations such as Grameen Shakti have been instrumental in the dissemination of solar home systems (SHS), installing over 1.8 million units and providing electricity access to more than 8 million people in remote and rural areas [8]. These systems have significantly improved the quality of life, enabling extended business hours for rural shops and reduced reliance on harmful kerosene lamps [8].

Despite its success, this model faces a critical challenge: a significant portion of the solar energy generated is wasted because households often produce more electricity than they can consume or store [8]. This "energy waste" problem has given rise to a novel and highly innovative solution. Companies like SOLshare have developed peer-to-peer electricity trading networks, or "nanogrids," which allow households with SHS to sell their surplus electricity to neighbouring homes without solar systems [8]. This model not only addresses energy inefficiency but also transforms households from mere consumers into prosumers, providing them with a new source of income and democratising energy access in a way that is uniquely suited to Bangladesh's context.

2.3 Grid-scale applications: potential for BESS

The instability of Bangladesh's national grid, characterised by high generation costs and frequent load shedding, presents a compelling use case for utility-scale BESS [3]. BESS can be deployed to provide critical grid stabilisation services, manage the intermittency of renewable sources, and perform peak shaving by storing low-cost electricity (e.g. from solar during the day) and discharging it during periods of high demand to alleviate stress on the grid [6].

The deployment of BESS is not merely a technological fix for grid deficiencies; it is a strategic financial and structural solution to the country's energy crisis. The power sector is currently burdened by large capacity payments to fossil fuel-based plants that often sit idle and by the high cost of running expensive, oil-fired peaking power plants [3]. By enabling the storage of inexpensive renewable energy, BESS can directly reduce the reliance on these high-cost generators, thereby lowering the average power generation cost and alleviating the immense subsidy burden on the BPDB [3]. Consequently, the strategic deployment of BESS directly addresses the systemic financial and structural weaknesses of the national power system, moving beyond a temporary solution to a long-term, sustainable one.

2.4. Battery materials and recycling

Bangladesh's battery industry is undergoing a significant transition from a decades-long reliance on lead-acid batteries to the adoption of Li-ion technology [9]. While lead-acid batteries have long been used in automotive and household backup systems, their legacy is marred by a severe public health and environmental crisis [9]. The country recycles only an estimated 59% of its annual lead consumption formally. The remainder is processed in unregulated, informal facilities that use highly polluting methods like open-pit smelting, leading to widespread lead contamination of soil and water [9]. Research by institutions such as Stanford University has highlighted how this poses a pervasive health threat, particularly to children [13]. In contrast, Li-ion batteries are seen as a more sustainable alternative, being significantly safer and more recyclable, with the potential for multiple life cycles through refurbishment before final disposal.

2.5. Energy storage for renewable energy

Energy storage systems are a critical research area for integrating intermittent renewable energy sources like solar and wind into Bangladesh's grid. Research focuses on developing systems that can store excess energy for later use, providing backup power, enhancing grid stability, and deferring costly infrastructure investments [6]. A notable area of innovation is in off-grid solutions. Pioneering organisations have established SHS programmes, which have provided electricity to millions in remote areas [8]. Building on this, companies like SOLshare have developed the world's first peer-to-peer electricity trading networks, or "nanogrids," which allow households with SHS to sell their surplus power to their neighbours [14].

Academic research, such as a techno-economic study using the HOMER Pro programme, has investigated the feasibility of alternative battery chemistries for off-grid hybrid microgrids in rural Bangladesh [15]. The study found that a system with solar, wind, and zinc-bromine (ZnBr) flow batteries consistently outperformed other configurations, including those with Li-ion, achieving the lowest net present cost and cost of energy. The research highlighted the long lifespan (30 years) and low maintenance requirements of ZnBr flow batteries, making them a promising and cost-effective solution for long-duration storage in off-grid applications [15].

2.6. Technology transfer and skill development

The country's research and development (R&D) ecosystem is still developing, with a strong focus on practical applications. The Bangladesh University of Engineering and Technology (BUET) is a leading institution with research in electrical energy and power systems, including the modeling of large-scale power systems, integration of renewable energy sources, and advanced battery technologies [16]. Its Bureau of Research, Testing & Consultation offers expert consultancy services for projects related to EV charging stations and microgrids [17]. The BCSIR also conducts research in energy conservation and new energy sources [18].

Despite these efforts, the country faces a significant skills gap, with quantitative data indicating a low level of preparedness among local graduates for entry-level technical positions [19]. In response, vocational training centers like the Apex Learning Centre are beginning to offer specialised courses for EV mechanics and electricians. These programmes cover a wide range of subjects, from basic battery systems to advanced topics such as high-voltage electrical systems in EVs and computerised vehicle diagnostics [20]. This focus on vocational training is an important step in building the workforce needed for the country's energy transition.

3. Material sourcing and local manufacturing

Bangladesh's battery industry has historically focused on the manufacturing and assembly of lead-acid batteries, a sector in which it has developed end-to-end production capabilities [9]. This legacy industry has prominent players such as Rahimafrooz Batteries, Navana Battery, and Eastern Battery, which have a long history of supplying batteries for automotive applications and electric rickshaws [21]. However, the country is now making a strategic "lithium leap," transitioning to the assembly and integration of Li-ion battery packs [9]. Rahimafrooz exports batteries, mostly under its own brand name.

The battery industry in Bangladesh is undergoing a significant transition, driven by a national push for EVs, renewable energy, and technological advancement. While the country has a long-standing, locally driven lead-acid battery sector, a new focus is emerging on the more advanced Li-ion technology to meet modern energy demands.

3.1. The evolving battery manufacturing landscape

Bangladesh's battery industry, valued at over \$1 billion annually, has historically been centred on lead-acid batteries [22]. 85% of lead-acid battery users are electric three-wheelers [9]. 59% are recycled locally [9]. This sector is highly self-reliant, often cited as a rare example of an industry that handles a product from design to manufacturing and market delivery entirely within the country's borders [23]. These locally produced batteries power a wide range of applications, including electric rickshaws, household UPS units, and telecom base stations. Major local players in this established market include Rahimafrooz Batteries, Saif Powertec Limited, and Panna Battery.

However, the industry is now making a strategic shift toward Li-ion batteries. Several key projects are spearheading this transition:

- **Bangladesh Lithium Battery Limited:** This company is establishing a state-of-the-art plant in Bangabandhu Sheikh Mujib Shilpa Nagar, with a substantial investment of Tk600 crore [24]. The facility is set to have an annual production capacity of 1 GWh and will produce high-quality batteries for EVs and energy storage systems. The company intends for these batteries to replace traditional lead-acid batteries in applications like IPS (Inverter Power Systems) and UPS (Uninterruptible Power Supply) systems and to create a backward linkage for its concurrent EV manufacturing project.
- **Walton-Huawei Partnership:** Local tech company Walton has partnered with Chinese giant Huawei to set up an advanced, fully automated production line with an annual capacity of 80,000 lithium batteries [12]. These batteries are specifically for the telecommunication sector to serve as a more efficient and environmentally friendly backup power source for Base Transceiver Stations (BTS), which have historically relied on lead-acid batteries.
- **Other key players:** Other local firms, including Norban Altilium, BASE Technologies, SARBS Communications, and Tiger New Energy, are also actively engaged in the local assembly of Li-ion battery packs, often targeting specific niches like telecom power solutions [9].
- **Battery swapping:** Startups like Tiger New Energy, GoSwap, and Casetex are piloting battery swapping technologies for electric three-wheelers, a move that could turn local production into a significant growth industry.

Local manufacturing efforts are currently concentrated in the downstream segment of the value chain, focusing on assembly and module integration rather than the complex and capital-intensive process of cell fabrication [23]. This approach is a pragmatic strategy to accelerate market entry and add value to the domestic ecosystem [9]. This reliance on foreign partnerships for technology transfer and localised assembly is a core strategic approach, allowing Bangladeshi firms to mitigate the high-risk and capital-intensive challenges of developing advanced R&D capabilities and access to global supply chains from scratch [23].

3.2. Material sourcing and import dependency

While the traditional lead-acid battery industry has a strong domestic sourcing base, the emerging Li-ion sector is highly dependent on imports [19]. The market's heavy reliance on foreign raw materials and components, such as imported cells, leads to higher costs and makes the industry vulnerable to global supply chain disruptions.

Bangladesh has formulated policies aimed at supporting the shift towards sustainable energy and local manufacturing. The Automobile Industry Development Policy 2021, for

example, provides incentives for local EV manufacturers. Additionally, the government's draft Renewable Energy Policy 2025 proposes significant incentives for BESS, including import duty exemptions and tax holidays for renewable energy components and raw materials.

3.3. Challenges and research efforts

The growth of this sector is not without its challenges. The industry faces a 59% import duty on both finished and semi-knockdown (SKD) lithium batteries. There is also a notable skills gap, particularly in production mid-management, that limits the adoption of modern, automated production processes [25]. Furthermore, the lack of robust infrastructure, including an unreliable power grid, and an inadequate recycling ecosystem for both lead-acid and Li-ion batteries pose significant environmental and operational risks.

To address these issues, local institutions are conducting research to support the industry. The Bangladesh University of Engineering and Technology (BUET) has research centres, including the Green Energy Research Laboratory, that focus on advancing sustainable energy technologies like batteries and microgrids [10]. They also conduct technical and economic feasibility studies for energy management systems and EV charging stations. The Bangladesh Council of Scientific and Industrial Research (BCSIR) also contributes to R&D in fields such as mining, mineralogy, and metallurgy, which are relevant to material sourcing. A recent study demonstrated the techno-economic feasibility of a hybrid system using a specific type of flow battery for rural electrification in off-grid areas.

4. Key research institutions and collaborations

4.1 Leading institutions

4.1.1 Bangladesh University of Engineering and Technology (BUET)

BUET is a leading public technological research university in Bangladesh, considered one of the most prestigious for science and research [16]. Its research activities in battery technology are spread across several departments and centres:

- Department of Electrical and Electronic Engineering (EEE): The EEE department is a key hub for research related to electrical energy and power systems [26]. Researchers focus on modelling and control of large-scale power systems, integrating renewable energy sources, and developing advanced battery technologies. The department also runs the Green Energy Research Laboratory (GERL), which focuses on cutting-edge research in sustainable energy, including batteries and smart grids [26].
- Department of Chemical Engineering: This department has research groups focusing on "Sustainability in Energy and Environment" and "Fuel and Energy Systems". While specific publications on Li-ion batteries are not detailed, the department's work in

related fields like nanomaterial-embedded polymer membranes for water treatment and advances in polymers suggests a foundation for materials-based research.

- Department of Materials and Metallurgical Engineering (MME): The MME department is the sole provider of materials and metallurgical education in the country. It has the facilities and expertise to conduct comprehensive physical and chemical characterisation of materials, which is crucial for battery development.
- Other BUET research: A professor at the Khulna University of Engineering and Technology (KUET) has a research interest in Li-ion battery anode and cathode materials and has published papers on topics such as removing lead and mercury from water using nanoparticles, and a binary solvent system for extracting cathode materials from used Li-ion batteries.
- Consultancy and partnerships: BUET's Bureau of Research, Testing & Consultation (BRTC) offers technical and economic feasibility studies for energy management systems and EV charging stations [17]. The university has also signed an MoU with the Bangladesh Institute of Management (BIM) to strengthen academic and research collaboration.

4.1.2 Bangladesh Council of Scientific and Industrial Research (BCSIR)

The BCSIR is an autonomous organisation under the Ministry of Science and Technology [27]. It has three multidisciplinary regional laboratories and several mono-disciplinary institutes, including the Institute of Mining, Mineralogy and Metallurgy (IMMM).

The BCSIR's research activities cover a broad range of scientific fields, including mining, mineralogy, and metallurgy [27]. It has conducted research on sustainably synthesising zinc-based material from waste dry cell batteries.

The BCSIR actively collaborates with academic institutions. For example, students from the University of Liberal Arts Bangladesh (ULAB)'s EEE department recently visited BCSIR to explore its advanced research facilities, particularly in solar energy and battery technologies, to bridge the gap between academic knowledge and industry-driven innovation [27].

4.1.3 University of Dhaka (DU)

DU is also involved in battery research through its Clean and Sustainable Energy Research Laboratory (CSERL). This lab focuses on cutting-edge research to develop sustainable energy sources, with a specific research area dedicated to next-generation Li-ion batteries. The CSERL also has collaborations with institutions like Guangdong University of Technology to research advanced materials for next-generation lithium-metal batteries.

4.2 Industry and international collaborations

Bangladesh has benefited from international research collaborations that have shed light on critical domestic issues. For example, a study conducted by researchers from Stanford University and other institutions highlighted the pervasive public health threats of unregulated lead-acid battery recycling in Bangladesh [13]. The research demonstrated how

a multi-stakeholder effort is needed to fundamentally shift incentives away from informal recycling and address widespread lead contamination [13]. Based on cost-effectiveness, energy efficiency, and application needs (e.g. EVs, UPS), Bangladesh's battery industry has several leading companies:

- Rahimafrooz Ltd: Established 1954, largest lead-acid battery manufacturer; exports to 44+ countries; multiple ISO and safety certifications; recognised for solar energy projects in 2019.
- Saif Powertec Ltd: Established 1991; diversified into solar, electronics, and lead-acid batteries; multiple ISO certifications; linked to Chittagong Port Authority.
- Navana Battery: Since 2002; focus on automotive, industrial, and solar batteries; part of Navana Group, a major corporate entity in Bangladesh.
- Hamko Group: Since 1978; major isolated power supply (IPS) and automotive battery manufacturer; active in rural electrification and renewable power generation.
- Rangs Power: Since 1996; manufactures lead-acid batteries, IPS systems, and solar products; rigorous quality assurance with eight-step testing.
- BASE Technologies Ltd: Since 2012; specialises in energy storage integration (Li-ion and valve regulated lead acid); partnered with Enzinc for nickel-zinc battery solutions.
- SARBS Communications Ltd: Since 2004; telecom-focused company with ventures in EV batteries and renewable energy products; partnered with several foreign companies.

The companies produce batteries as well as collaborating with other organisations. This collaboration exemplifies how external academic partnerships can provide objective, data-driven analysis to inform the development of more effective and sustainable policies. The private sector in Bangladesh is also initiating collaborations to drive battery technology forward.

- Walton and Huawei: Local tech conglomerate Walton has partnered with Huawei to set up an automated production line for lithium batteries [12]. Huawei provides technical support, design expertise, and raw materials for manufacturing these batteries [16].
- Edotco and Tiger New Energy: Telecommunications infrastructure provider Edotco Bangladesh and clean mobility firm Tiger New Energy are piloting sustainable power systems, including battery backup systems and swapping stations, for both telecom towers and EVs [28]. This partnership aims to reduce reliance on fossil fuels and support the country's sustainability agenda.
- Development Agency Projects: The World Bank's Electricity Distribution Modernization Programme includes a \$15 million grant from the Clean Technology Fund to support BESS. This programme will also help prepare roadmaps for deploying BESS and distributed renewable energy. Another project supported by the

Skills and Training Enhancement Project (SMEP) involves a collaboration between Pure Earth, Georgetown University, and BUET to research business models and policy interventions for the battery manufacturing and recycling industry.

These research and collaboration efforts, spanning fundamental science at universities to industry-led pilot projects, are crucial for developing local expertise, building a robust supply chain, and advancing Bangladesh's energy sector.

5. Battery skills assessment

5.1. Upstream segment: raw material management and sourcing skills

The upstream segment of Bangladesh's battery industry, which primarily deals with raw materials, requires a distinct set of skills depending on the technology. For the established lead-acid battery sector, key manufacturing processes include lead alloying, grid casting, paste mixing, and plate formation. As a result, the necessary skills revolve around managing these processes, safely handling hazardous materials such as lead and sulfuric acid, and operating specialised machinery like ball mills and casting machines. Quality control is also critical at this stage, demanding technicians who can inspect raw materials and test components to ensure they meet the required chemical composition and structural integrity.

In contrast, the nascent Li-ion battery sector is heavily dependent on imports for key materials. Consequently, the initial skill requirements in this segment are less about direct material processing and more focused on sourcing and procurement. However, local companies are actively working to build a domestic R&D base. For example, a job description for a battery R&D chemist at Walton specifies a need for skills in finding suitable material sources and developing new battery chemistries, including for solid-state batteries.

5.2. Midstream segment: manufacturing and technical skills

The midstream segment encompasses the manufacturing and assembly of battery units. The lead-acid sector has a mature, end-to-end production ecosystem that handles everything from design to delivery within the country's borders. The skills needed here are for production operators and technicians who can manage the sequential steps of manufacturing, from pasting plates to assembling the final battery components.

For the emerging Li-ion market, a new set of advanced technical skills is required. Companies like Walton, in partnership with Huawei, are establishing automated production lines with a yearly capacity of 80,000 batteries. A manufacturing technician in this environment is expected to set up, test, and adjust automated machinery using electrical, electronic, and computer technologies. These roles also require a high aptitude for basic data analysis, strong communication skills, and the ability to work in a clean-room environment. The technical expertise extends to R&D chemists who develop systems for

electrode manufacturing and cell assembly and perform physical and chemical analyses of raw materials.

5.3. Downstream segment: maintenance, operation, and recycling

The downstream segment involves the application, servicing, and end-of-life management of batteries. Locally produced batteries power a wide range of applications, including electric rickshaws, telecom base stations, household UPS units, and solar systems.

A key development in this segment is the rise of battery swapping networks for electric three-wheelers, led by startups like Tiger New Energy, GoSwap, and Cassetex [28]. The skills required for a battery swapping station attendant are primarily customer-facing, with a need for basic technical aptitude to manage battery charging, monitor levels, and perform light maintenance.

For electric and hybrid vehicles, formal training programmes are starting to address the technical demands. The Apex Learning Centre, for instance, offers diploma courses that cover advanced automotive electrical systems, high-voltage systems in EVs, and computerised diagnostics. These programmes prepare technicians to diagnose and repair issues in complex vehicle systems, manage high-voltage components, and adhere to safety protocols.

A critical area of concern is battery recycling. The current informal sector for lead-acid batteries is a major health hazard, with workers often operating in unsafe conditions without proper protective gear. Experts and organisations recommend the development of a formal, regulated recycling system with proper occupational health and safety standards. The skills for a formal recycling technician would include an understanding of the circular economy, legal and regulatory requirements, and safe dismantling and processing procedures.

5.4. Existing capabilities and opportunities

Bangladesh's battery industry has several existing strengths and emerging opportunities. The country's long-standing lead-acid battery sector is a successful example of a self-reliant domestic industry. This established base provides a foundation of manufacturing expertise and a domestic supply chain that can be leveraged for future growth. In addition, the shift toward Li-ion technology is a major opportunity. New manufacturing plants and partnerships, such as the Walton-Huawei collaboration, demonstrate a commitment to local production of advanced batteries.

Academic institutions are also playing a vital role. BUET and DU have research labs and projects focused on advanced battery chemistries, sustainable energy systems, and EV integration. BCSIR also conducts research related to mineralogy and metallurgy, including studies on sustainably synthesising zinc from waste batteries, which highlights a commitment to a circular economy.

From a workforce perspective, while a "solar-ready" or "EV-ready" workforce is not yet prevalent, the country has an abundance of human resources. Vocational training institutes are beginning to offer courses that incorporate hybrid and EV technologies, indicating a growing capacity to train a future workforce.

5.5. Challenges and recommendations

Despite its potential, the industry faces significant challenges, particularly in workforce skills and policy coherence. A critical skills gap exists in key areas like production mid-management for modern, automated systems [20]. The existing Technical and Vocational Education and Training (TVET) system needs a comprehensive overhaul to align its curriculum with the demands of the Fourth Industrial Revolution, which emphasises digital literacy and complex problem solving. Inconsistent and unpredictable policies, such as a high 59% import duty on lithium batteries, also pose a significant barrier to the adoption of modern technology.

To address these issues and unlock the industry's full potential, several key recommendations can be made:

- **Revitalise education and training:** A strategic overhaul of the TVET system is essential to bridge the skills gap in advanced manufacturing, with a focus on training engineers and technicians for automated and high-voltage systems.
- **Formalise recycling protocols:** Implement the draft 8-point policy recommendations for electric three-wheelers and their batteries. These recommendations include creating a formal regulatory framework, a battery tagging system for traceability, and a national registry for accountability, all of which are crucial to transitioning the hazardous informal recycling sector into a safe and regulated one.
- **Promote R&D investment:** The government should prioritise increased R&D investment and foster public-private partnerships to build local expertise and reduce technological dependence on imports. This would help local companies move beyond simple assembly and into full-scale, innovative manufacturing.
- **Enforce safety standards:** Establish and enforce strict occupational health and safety standards, particularly in the recycling segment, to protect workers from lead exposure and other industrial hazards.

6. Industry and start-up ecosystem

The battery industry in Bangladesh is experiencing a dynamic transformation, with a well-established, local lead-acid battery sector now coexisting with a rapidly emerging ecosystem for advanced Li-ion batteries. This shift is being driven by a growing demand for EVs and renewable energy storage, sparking innovation from both major corporations and nimble startups. The startup ecosystem, in particular, is proving to be a key driver of new business models, technology adoption, and a push towards a more sustainable and circular economy.

6.1 Established industry leaders and the shift to Li-ion

Bangladesh's traditional battery market, valued at over \$1 billion annually, has long been dominated by manufacturers of lead-acid batteries, such as Rahimafrooz Batteries, Saif Powertec Limited, and Panna Battery. This sector is noted for its self-reliance, with companies handling the entire process—from design to manufacturing and market delivery—within national borders [18]. These batteries are a crucial power source for a variety of applications, including electric rickshaws, household UPS units, and telecom tower backups.

However, these established players are now pivoting to the more efficient and environmentally friendly Li-ion technology. A key example is Walton Digi-Tech, which has partnered with Chinese tech giant Huawei to set up a fully automated production line with an annual capacity of 80,000 lithium batteries. This initiative aims to produce batteries for the telecommunications sector, reducing the country's reliance on imported batteries and aligning with global carbon reduction targets. Similarly, Bangladesh Lithium Battery Limited is establishing a state-of-the-art plant in Bangabandhu Sheikh Mujib Shilpa Nagar with a substantial investment of Tk600 crore, planning to produce high-quality batteries for both EVs and energy storage systems [24]. This facility is intended to serve as a backward linkage for the company's own EV manufacturing project.

6.2 The startup ecosystem: a hub for innovation

Bangladesh's startup ecosystem is growing rapidly, with 343 startups and a global ranking of 79. This ecosystem is actively supported by government initiatives like the IDEA Project and Startup Bangladesh Limited, a government-backed venture capital fund with a capital of Tk500 crores [6]. Several key startups are pioneering innovative solutions in the battery space, particularly in the downstream segment, where they are addressing last-mile mobility and energy access challenges.

- **Tiger New Energy:** Founded by Harvard Business School alumni, this startup has secured \$3.5 million in funding from investors including ADB Ventures and Wavemaker Partners. Tiger New Energy is building a network of battery swapping stations for electric three-wheelers, which are a primary mode of transportation for millions in Bangladesh. Their technology allows drivers to swap a depleted battery for a fully charged one in less than a minute, dramatically reducing downtime and potentially increasing a driver's daily income by 60%. The company's business model is based on "Battery-as-a-Service" (BaaS), which provides an affordable, clean energy solution and also positions their infrastructure to act as a Decentralised Energy Storage System (DESS) for grid stability. Tiger New Energy is also collaborating with telecommunications infrastructure provider Edotco Bangladesh to pilot sustainable power systems for telecom towers and EV charging.
- **Cassetex:** This Bangladeshi cleantech startup, founded in 2020, has raised \$1.6 million to expand its BaaS and swapping solutions. Cassetex's model focuses on

empowering micro-energy entrepreneurs, particularly women, who can manage battery swapping stations from their existing small businesses, creating new income opportunities. The company plans to onboard 50,000 new vehicles by 2026 and integrates its charging devices with renewable energy sources.

- GoSwap: Another local battery swapping startup, GoSwap is headquartered in Rajshahi and focuses on providing swapping solutions for city riders and small fleets. The company was founded in 2023 and is working to build local swap points and partner with ride operators to make EV adoption more convenient and practical.
- SOLshare: This green utility company has pioneered the world's first information and communication technology-enabled peer-to-peer electricity trading network, or "nanogrid," for rural households. The company's technology allows owners of Solar Home Systems (SHS) to sell their excess electricity to neighbours who don't have solar panels, turning their energy generation into an income-generating asset. This model helps to address energy poverty and waste by leveraging the excess capacity from the approximately 6 million SHS installations in the country.

6.3 Challenges and regulatory context

While the startup ecosystem is robust, it faces significant challenges. One of the major hurdles for Li-ion adoption is the 59% import duty on both finished and semi-knockdown (SKD) lithium batteries. This policy, along with other barriers like a lack of standardised batteries and a predictable regulatory framework, can hinder the growth of the EV sector.

In response, there is a push for regulatory reform. A project supported by the Sustainable Manufacturing and Environmental Pollution (SMEP) Programme has developed a draft of eight-point policy recommendations for the electric three-wheeler sector. These recommendations include formalising the sector, implementing a battery tagging system for quality and traceability, and reducing import tariffs for higher-quality lithium batteries to promote responsible manufacturing and recycling. These policy efforts, combined with the innovative solutions from a thriving startup scene, are working to create a more resilient, sustainable, and inclusive energy future for Bangladesh.

7. Policy, funding and challenges

The government of Bangladesh has demonstrated a clear commitment to accelerating the transition to renewable energy. The updated Renewable Energy Policy aims for green sources to generate at least 20% of the national power demand by 2030 [29]. This framework proposes significant incentives to attract private investment, including a 10-year corporate tax exemption for all renewable energy producers and import duty exemptions on components and raw materials for clean energy projects. The government has also stated its intention to promote the adoption of BESS and other storage systems to integrate more renewable energy into the grid [30].

However, this transition is hindered by several significant challenges:

- **Contradictory policy:** A major barrier to the growth of the Li-ion battery sector, particularly for electric mobility, is a 59% import duty on finished and semi-knockdown (SKD) Li-ion batteries [9]. This tariff directly clashes with the government's goals of accelerating EV adoption and clean energy transition by making the core technology prohibitively expensive.
- **Funding and investor confidence:** While the country requires up to US\$980 million annually until 2030 for its renewable energy targets, public finance alone is not enough, necessitating large-scale private investment [31]. Policy uncertainty, such as the sudden shift from non-competitive to competitive bidding for utility-scale projects, has disconcerted investors.
- **Land and grid constraints:** Land acquisition challenges are a significant hurdle for large-scale solar and BESS projects in the densely populated country [4]. Additionally, the grid's limited capacity to absorb intermittent renewable energy sources presents a technical challenge that requires smart grid solutions and energy storage.

8. Case studies and success stories

Bangladesh's battery and renewable energy landscape is home to several pioneering projects that serve as powerful case studies.

8.1 Pioneering rural electrification

The SHS programme, led by organisations like Grameen Shakti, is a globally recognised success story in decentralised electrification. Grameen Shakti has installed over 1.8 million SHS, benefiting more than 8 million people in off-grid rural communities [8]. This model has not only provided basic electricity access but has also had a significant socioeconomic impact, enabling small businesses to operate for longer hours and empowering women entrepreneurs. Building on this foundation, the peer-to-peer trading model developed by SOLshare is a world-first innovation [14]. It addresses the issue of wasted energy from SHS by creating "nanogrids" that allow households to sell their surplus electricity to neighbours, thereby democratising energy trading and generating income for low-income households.

8.2 The telecom tower transformation

A prime example of private-sector innovation is the partnership between telecoms infrastructure provider Edotco Bangladesh and clean energy firm Tiger New Energy [32]. The companies are piloting a dual-purpose system that leverages existing telecom infrastructure. They are deploying a subscription-based battery backup system for telecom towers, which not only ensures uninterrupted network service but also supports the national sustainability agenda by reducing fossil fuel dependency. The partnership is also piloting the use of these tower sites as battery swapping and charging stations for electric two- and three-wheelers [32].

9. Future directions

To unlock the full potential of its battery sector, Bangladesh must adopt a coordinated and multi-faceted strategic approach with a clear roadmap.

- Short-term (2026-2030): The immediate focus should be on creating a favourable regulatory and financial environment. This includes policy reforms to reduce contradictory import duties, streamlining investment processes, and scaling up existing Li-ion assembly and integration capabilities to meet the booming domestic demand from the telecom and off-grid sectors.
- Mid-term (2030-2035): The country should launch a national skills development programme aimed at cultivating high-end battery R&D talent. Concurrently, public and private partnerships should be encouraged to support pilot projects for grid-scale BESS and establish a formal, safe recycling industry for both lead-acid and Li-ion batteries.
- Long-term (2035-2050): With a mature skills base and a predictable regulatory environment, Bangladesh can aspire to move beyond assembly and begin local cell fabrication. This would position the country as a key regional player in the battery value chain, capable of not only serving its domestic market but also exporting its technologies and expertise, thereby driving sustainable economic growth and job creation [9].

10. Conclusions

The analysis of Bangladesh's battery sector reveals a market on the cusp of a major transformation. The country is making a rapid, market-driven "lithium leap," spurred by a systemic energy crisis and booming demand from the telecom, off-grid, and electric mobility sectors. The industry's current strategy is a pragmatic one, focusing on downstream value addition through the assembly and integration of Li-ion battery packs, primarily by leveraging strategic partnerships with foreign technology providers. This approach allows local firms to bypass the complex and capital-intensive stages of cell fabrication, accelerating market entry.

However, this transition is not without significant friction. The policy landscape is a contradictory mix of forward-looking incentives for renewables and high regulatory barriers, such as the 59% import duty on Li-ion batteries, which directly hinders the adoption of clean energy technologies. A critical skills gap exists, particularly at the high-end R&D and engineering levels, which could become a major bottleneck, limiting the country to an assembly-based model rather than fostering genuine innovation. The legacy of lead-acid batteries also poses a severe and unaddressed public health crisis through unregulated recycling, a problem that requires urgent, multi-stakeholder intervention.

To unlock its full potential, Bangladesh must adopt a coordinated and multi-faceted strategic approach. The government should immediately address policy inconsistencies by re-evaluating and reducing import duties on Li-ion batteries and components. It should also invest in high-end human capital through targeted programmes and encourage technological diversification, including pilot projects for alternative battery chemistries like zinc-bromine flow batteries for long-duration rural energy storage. Finally, the government must enforce strict environmental regulations and provide economic incentives to formalise the recycling industry. By addressing these challenges, Bangladesh can leverage its strengths and transition from a technology consumer to a key player in the battery value chain, driving sustainable economic growth and a more resilient energy future.

References

- [1] Centre for Policy Dialogue (CPD, 'Power and energy crisis in Bangladesh'. <https://cpd.org.bd/power-and-energy-crisis-in-bangladesh/> .
- [2] P. Chatterjee, 'Challenges for adopting electric vehicles in Bangladesh', Daily Observer, 2024. <https://www.observerbd.com/news/459228> Accessed 3 September, 2025.
- [3] IEEFA, 'How to make Bangladesh's power sector sustainable', 2024. <https://ieefa.org/resources/how-make-bangladeshs-power-sector-sustainable> Accessed 3 September, 2025.
- [4] International Trade Administration, 'Bangladesh Renewable Energy Sector Opportunities', 2024. <https://www.trade.gov/market-intelligence/bangladesh-renewable-energy-sector-opportunities> Accessed 3 September, 2025.
- [5] IEEFA, 'Faster electric car rollout in Bangladesh demands policy support', 2023. <https://ieefa.org/resources/faster-electric-car-rollout-bangladesh-demands-policy-support> Accessed 3 September, 2025.
- [6] M. Biswas *et al.*, 'Prospects of Renewable Energy and Energy Storage Systems in Bangladesh and Developing Economies', *Global Journal of researches in engineering: J General Engineering*, vol. 11, no. 5, pp. 23-31, 2011. https://globaljournals.org/GJRE_Volume11/5-Prospects-of-Renewable-Energy.pdf
- [7] Siemens Energy, 'Battery energy storage systems' <https://www.siemens-energy.com/global/en/home/products-services/product/battery-energy-storage.html> Accessed 3 September, 2025.
- [8] Grameen Shakti, 'Solar Home System', <https://www.gshakti.org/what-we-do/keyprograms/solarhomesystem> Accessed 3 September, 2025.
- [9] Industry Insider, 'Can Bangladesh become a battery powerhouse?', 2025. <https://industryinsiderbd.com/can-bangladesh-become-a-battery-powerhouse/> Accessed 3 September, 2025.

- [10] Verified Market Research, 'Lithium-Ion Battery In Bangladesh Market Size' <https://www.verifiedmarketresearch.com/product/lithium-ion-battery-in-bangladesh-market/> Accessed 3 September, 2025.
- [11] Mordor Intelligence, 'Lithium-Ion Battery Market in Bangladesh', <https://www.mordorintelligence.com/industry-reports/bangladesh-lithium-ion-battery-market> Accessed 3 September, 2025.
- [12] Bangladesh Sangbad Sangstha, 'Walton, Huawei tie up for lithium battery production', 2024. <https://www.bssnews.net/business/209309> Accessed 3 September, 2025.
- [13] R. Jordan, 'Pervasive health threats of unregulated battery recycling' Stanford Woods Institute for the Environment, 2021. <https://sustainability.stanford.edu/news/pervasive-health-threats-unregulated-battery-recycling> Accessed 3 September, 2025.
- [14] SOLshare <https://solshare.com/> Accessed 3 September, 2025.
- [15] M. F. Ali *et al.*, 'Techno-economic optimization of battery storage technologies for off-grid hybrid microgrids in multiple rural locations of Bangladesh', *Front. Energy Res.*, vol. 13, 2025. Doi: [10.3389/fenrg.2025.1654615](https://doi.org/10.3389/fenrg.2025.1654615)
- [16] Wikipedia, Bangladesh University of Engineering and Technology https://en.wikipedia.org/wiki/Bangladesh_University_of_Engineering_and_Technology Accessed 3 September, 2025.
- [17] BUET, Department of EEE, 'Consultancy', <https://eee.buet.ac.bd/btrc/consultancy> Accessed 3 September, 2025.
- [18] Ministry of Science and Technology, Government of the People's Republic of Bangladesh, 'Pilot Plant and Process Development Centre, BCSIR' <https://pppdc.bcsir.gov.bd/site/page/888f6f57-8b34-4c6c-baed-54f5f9ccfb89/History-&-Functions> Accessed 3 September, 2025.
- [19] T. Abir, 'Bridging the Skills Divide: Addressing Foreign Labor Reliance and Workforce Gaps in Bangladesh's Key Sectors', *ResearchGate*, doi: 10.13140/RG.2.2.21959.61607
- [20] Apex Learning Centre, 'Motor Vehicle Electrician', <https://apexlearningcentre.com.bd/motor-mechanics-department/motor-vehicle-electrician/> Accessed 3 September, 2025.
- [21] BD Trade Info, 'Battery Manufacturers, Assemblers & Distributors in Bangladesh', <https://www.bdtradeinfo.com/yp-data/battery-manufacturers-assemblers-distributors> Accessed 3 September, 2025.
- [22] Rahimafrooz Bangladesh Ltd <https://www.rahimafrooz.com/> Accessed 3 September, 2025.

- [23] Tycorun, 'Top 10 Battery Manufacturers in Bangladesh', <https://www.tycorun.com/blogs/news/top-10-battery-manufacturers-in-bangladesh> Accessed 3 September, 2025.
- [24] S. Rahman, 'Bangladesh ventures into lithium battery production', The Business Standard, 2023. <https://www.tbsnews.net/bangladesh/bangladesh-ventures-lithium-battery-production-653074> Accessed 3 September, 2025.
- [25] The Business Standard, 'Renewable energy to create over 9000 skilled jobs by 2030: CPD study', 2023. <https://www.tbsnews.net/bangladesh/energy/renewable-energy-create-over-9000-skilled-jobs-2030-cpd-study-722590> Accessed 3 September, 2025.
- [26] BUET Department of EEE, 'Electrical Energy and Power Systems (EEPS)', <https://eee.buet.ac.bd/research/research-areas/eeeps> Accessed 3 September, 2025.
- [27] COMSATS Secretariat, 'BCSIR-Bangladesh', <https://comsats.org/bcsir-bangladesh/> Accessed 3 September, 2025.
- [28] J. Tanner, 'Edotco Bangladesh teams with Tiger New Energy for green power', Developing Telecoms, 2025. <https://developingtelecoms.com/telecom-technology/energy-sustainability/18743-edotco-bangladesh-teams-with-tiger-new-energy-for-green-power.html> Accessed 3 September, 2025.
- [29] Cleantech Law Partners, 'Bangladesh Unveils New Renewable Energy Policy' <https://cleantechlaw.com/2025/06/bangladesh-unveils-new-renewable-energy-policy/> Accessed 3 September, 2025.
- [30] JNTech, 'What is the renewable energy policy in Bangladesh?' <https://www.jntechenergy.com/what-is-the-renewable-energy-policy-in-bangladesh/> Accessed 3 September, 2025.
- [31] IEEFA, 'Private investment key to unlocking Bangladesh's renewable energy ambitions', 2025. <https://ieefa.org/articles/private-investment-key-unlocking-bangladeshs-renewable-energy-ambitions> Accessed 3 September, 2025.
- [32] EDOTCO, 'Bangladesh and Tiger New Energy Unite for Greener Connectivity Solutions', 2025. <https://edotcogroup.com/media/news/edotco-bangladesh-tiger-new-energy-unite-greener-connectivity-solutions> Accessed 3 September, 2025

Other references

IDLC, 'Launch of Electric Vehicles in Bangladesh: Hitting the Road to Achieve the Dream of Zero Carbon Footprint' <https://idlc.com/mbr/images/public/Bm4GLDCuQX6a8B7Csvf6PT.pdf> Accessed 3 September, 2025

Markwide Research, 'Bangladesh Lithium-ion Battery Market Analysis'
<https://markwideresearch.com/bangladesh-lithium-ion-battery-market/> Accessed 3
September, 2025

CSIR, 'The battery research centre: Developing materials-based technologies for energy
storage systems' [https://www.csir.co.za/battery-research-centre-developing-materials-
based-technologies-energy-storage-systems](https://www.csir.co.za/battery-research-centre-developing-materials-based-technologies-energy-storage-systems) Accessed 3 September, 2025

Apex Learning Centre, 'Motor Vehicle Mechanics',
[https://apexlearningcentre.com.bd/motor-mechanics-department/motor-vehicle-
mechanics/](https://apexlearningcentre.com.bd/motor-mechanics-department/motor-vehicle-mechanics/) Accessed 3 September, 2025

Mordor Intelligence, 'Bangladesh Lithium-ion Battery Company List'
[https://www.mordorintelligence.com/industry-reports/bangladesh-lithium-ion-battery-
market/companies](https://www.mordorintelligence.com/industry-reports/bangladesh-lithium-ion-battery-market/companies) Accessed 3 September, 2025

UNFCCC, 'ME SOLshare: Peer-to-Peer Smart Village Grids | Bangladesh',
<https://unfccc.int/climate-action/momentum-for-change/ict-solutions/solshare> Accessed 3
September, 2025

Nepal

This section was written by Prof Nawraj Bhattarai, Associate Professor in the Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University. His research focuses on energy and environmental analysis of electric mobility and the promotion of energy storage.

1. Introduction

Nepal is a landlocked country with an area of 147,516 sq. km. Running 885 km from east to west and about 193 km from north to south, it borders China at its north and India everywhere else [1]. It contains three main physiographic regions, the Terai, Hilly, and Himalayan regions, running from south to north respectively. These regions have an altitude ranging from about 60 m above sea level up to the world's highest mountain Sagarmatha (Mount Everest) at 8,848 m. Nepal has three major river basin systems: Koshi, Narayani, and Karnali [1,2,3].

These rivers are the major tributaries of the Ganges in northern India. Nepal lies within the subtropical climate zone, and its climate varies with the seasons, topography, and altitude. Nepal has been administratively divided into seven provinces: Koshi, Madhesh Pradesh, Bagmati, Gandaki, Lumbini, Karnali, and Sudurpashchim Province.

According to the 2021 census, the total population of Nepal is 29.1 million, with a population density of 198 per square kilometre. 66.2% of the country's population lives in an urban area, with 33.8% living in a rural area. The capital city, Kathmandu, is the most densely populated district, housing 7% of the total population [2].

In 2024, the country's Gross Domestic Product (GDP) was US\$42.91 billion, and GDP per capita was \$1,447 [4].

Hydropower is the primary source of electricity in Nepal. The theoretical potential of hydropower in Nepal has been estimated at 83,000 MW. The technical and economically feasible potential is about 45,000 MW and 42,000 MW [5,6]. Electricity demand is fulfilled through internal generation and through imports from India. There are a few large grid-connected solar photovoltaic (PV) plants and the share of PV in the country's national electricity mix has risen in recent years.

The Nepal Electricity Authority (NEA) is responsible for supplying electricity at a utility scale through the national grid. Government organisations under the Ministry of Energy, Water Resources, and Irrigation (MoEWRI), the Department of Electricity Development (DOED) and the Alternative Energy Promotion Center (AEPC), are involved in licensing procedures for different types and sizes of electricity projects across the country [6].

In Nepal, the average solar radiation ranges from 3.6 to 6.2 kWh/m²/day. There are on average 300 sunny days in a year [6]. This is promising for the development of solar power. According to the Solar & Wind Energy Resource Assessment in Nepal (SWERA), the country's commercial potential for grid-connected solar power is estimated to be 2,100 MW [7]. About 1.1 million solar home systems, rated at nearly 30 MWp, have been installed across Nepal. Nepal has good wind resources, mainly located to the northern part of the country in the Himalaya region, but due to its complex landscape, the country's commercially viable wind potential is estimated to be only about 448 MW [6,7].

According to the Alternative Energy Promotion Centre (AEPCC), up to the year 2021/22, the total installed capacity of mini, micro, and pico hydropower projects in various parts of the country amounted to approximately 37.7 MW. These decentralised hydroelectric systems play a significant role in providing electricity to rural communities and meeting energy needs for small-scale applications. Access to electricity in Nepal has shown significant progress over the past few years: 99% of the population had access to electricity in FY 2023/24 [8].

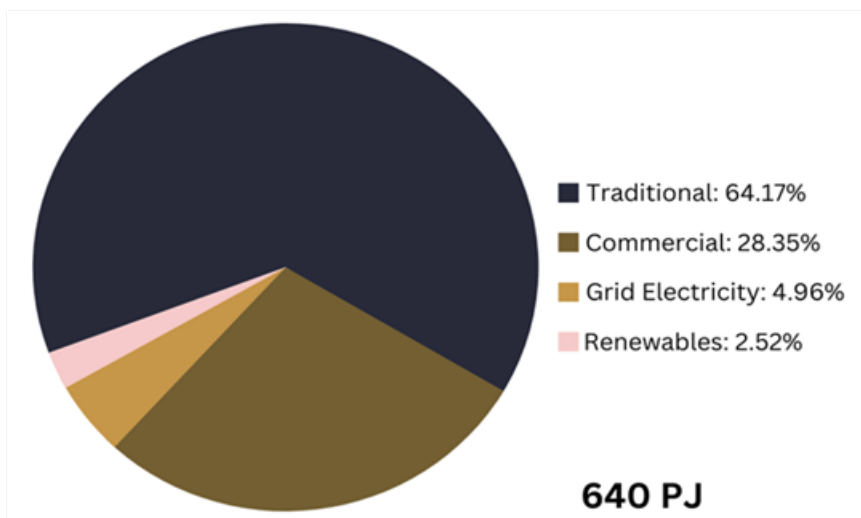


Fig. 1. Nepal's energy consumption via sources in 2022 (fiscal year 2078/79)

In 2022, or Nepali fiscal year 2078/79, total energy consumption reached 640 PJ. As shown in Fig. 1, traditional energy types have dominated the energy mix, accounting for over 69% of total consumption.

The residential sector dominates demand for energy, accounting for 61% of the total consumption. Despite over 60% of the population engaging in agricultural activities, energy consumption in the sector is less than 1% of Nepal's total [6].

In recent years, the share of electric vehicles (EVs) has increased sharply. The number of EVs is projected to rise to over 40,000 by 2025, reflecting a 19% increase year-on-year [9].

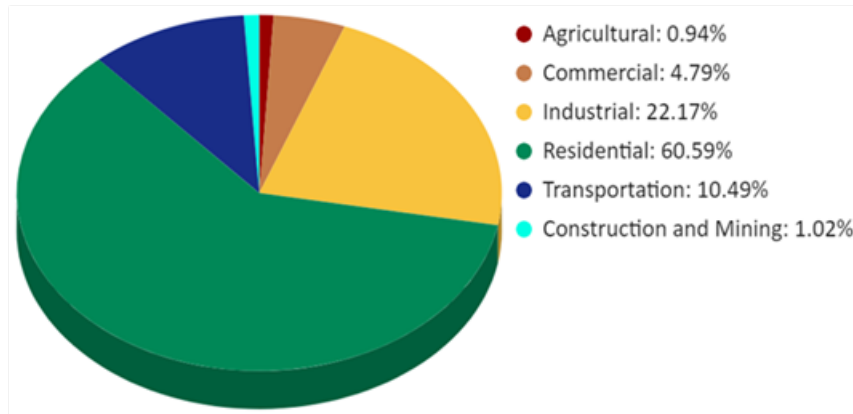


Fig. 2. Nepal's energy consumption by sector

2. Key research areas in battery technologies

Key areas of research in Nepal are:

- the effect on the national grid of the penetration of local decentralised energy resources, especially solar and wind;
- the development of low-cost renewable energy technologies for rural and urban areas;
- and the improvement of energy efficiency and electricity storage systems, based on battery storage, to improve the stability of the national grid.

In terms of EVs, technical and policy research areas are related to enhancing battery capacity, reducing charging times, and improving the overall performance of EV batteries. Battery recycling and reuse through cost effective methods for recycling and the re-use of lithium-ion (Li-ion) batteries is another sector of importance.

3. Material sourcing and local manufacturing

Only lead-acid battery manufacturing industries are available, and most of the materials are imported from India and China.

4. Key research institutions and collaborations

Government- and community-based research institutions include Tribhuvan University, the Nepal Academy of Science and Technology, and Kathmandu University. These institutions are carrying out research in the fields of energy storage, renewable energy and EVs including battery storage.

5. Battery skills assessment

The competency test for Solar PV installation, including battery skill tests, are carried out by the government institution for vocational training certification.

6. Industry and start-up ecosystem

There is little in the way of an industrial or start-up ecosystem for energy storage and battery technologies in Nepal.

7. Policy, funding and challenges

There is a lack of proper policy covering battery technologies for mobility and storage systems. The availability of funding, skilled manpower, battery recycling and waste disposal are the major challenges the country is currently facing, along with a lack of technological innovation, and the need to establish effective institutions. The government has put forward policies to promote the use of EVs in Nepal [10].

8. Future directions

Nepal needs a proper policy to be formulated to guide the use, recycling and disposal of Li-ion batteries in the country. Technology transfer, knowledge transfer and research in collaboration with partner universities and with institutions like the Faraday Institution are needed.

9. Conclusions

Participating in the Faraday Institution Conference 2024 provided opportunities to learn, explore and overcome the challenges in battery technologies in the context of Nepal. The theme of the conference "The Battery Breakthrough: From Research to Scale-up, to Manufacturing" helped to mitigate challenges and boost opportunities for further engagement among stakeholders globally.

Nepal is seeking collaborative efforts for energy security through energy storage and low-cost technologies in the field of electric mobility. This effort helps the country's target to have net zero emissions by the year 2045.

References

- [1] N. Bhattarai, 'National energy demand projections and analysis of Nepal', [Dissertation, Technische Universität Wien], repositUM, 2015. [doi:10.34726/hss.2015.27915](https://repositum.tuwien.at/handle/20.500.12709/10000)
- [2] Government of Nepal, Central Bureau of Statistics, 'Statistical Pocket Book of Nepal', 2014. <https://nsonline.gov.np/content/7777/7777-statistical-pocket-book-of-nep>
- [3] U. Joshi *et al.*, 'Estimation of Solar Insolation and Angstrom–Prescott Coefficients Using Sunshine Hours over Nepal', *Advances in Meteorology*, vol. 2022, no. 1 pp. 3593922, 2022. doi: 10.1155/2022/3593922

[4] World Bank Group data, Nepal
<https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=NP> Accessed 6 February 2026

[5] H.M. Shrestha, 'Facts and Figures about hydropower development in Nepal', *Hydro Nepal: Journal of Water, Energy and Environment*, vol. 20 pp. 1–5, 2017.
doi:[10.3126/hn.v20i0.16480](https://doi.org/10.3126/hn.v20i0.16480)

[6] WECS, Energy Synopsis Report 2023
<http://wecs.gov.np/source/Energy%20Synopsis%20Report%2C%202023.pdf>

[7] UNEP Global Environment Facility, 'Solar and Wind Energy Resource Assessment in Nepal (SWERA)', 2008.
https://policy.asiapacificenergy.org/sites/default/files/Assessment_Solar%20and%20Wind%20Energy%20Resource-%20in%20Nepal%20%282008%29_reduced.pdf

[8] Nepal Electricity Authority, Yearbook 2024/25
https://www.nea.org.np/admin/assets/uploads/annual_publications/NEA_DCSD_Maganize_2082.pdf

[9] A. K. Jha, *et al.*, 'Current State and Energy Policy Roadmap for Sustainable Adoption of Electric Vehicles in Nepal', 2025. *International Journal of Energy Economics and Policy*, vol. 15, no. 4, pp. 272–281. doi: 10.32479/ijeep.18634

[10] Government of Nepal, 'The Sixteenth Plan (Fiscal year 2024/5 – 2028/9)'
<https://npc.gov.np/content/6462/the-sixteenth-plan--fical-year-2024-25-2028-29-/>.

Other references

Ministry of Physical Infrastructure and Transport, National Road Safety Council, 'The comprehensive Management of After-Life Battery Pack Management'
https://giwmscdnone.gov.np/media/pdf_upload/4_ttj3x4j.pdf

iSET Nepal Services, 'Electric Mobility in Nepal', 2024. https://isetnepal.org.np/wp-content/uploads/2024/11/Electric-Mobility_compressed.pdf

UN ESCAP, 'National Strategy for Electrification of Public Transport', 2020.
https://www.unescap.org/sites/default/d8files/event-documents/Report_Strategy_on_electrifying_public_transport_0.pdf

Pakistan

This section was written by Prof Ghulam Ali, Associate Professor at the U.S.-Pakistan Center for Advanced Studies in Energy at the National University of Sciences and Technology (NUST). He leads a team focusing on the development of electrode and electrolyte materials with enhanced performance for lithium-ion (Li-ion) and sodium-ion batteries.

1. Introduction

Applications of battery technology are extremely important for Pakistan. Pakistan is a South Asian nation having India as its eastern neighbour, Afghanistan and Iran as its western neighbours, China as its northern neighbour and the Arabian Sea to its south. It is the fifth-most populous nation in the world, has a great cultural heritage and a variety of landscapes, which include mountain ranges as tall as K2, deserts and fertile plains. Pakistan was founded in 1947 as a Muslim homeland in the Indian subcontinent; its capital is Islamabad and its biggest city is Karachi. The nation boasts of rich culture, historical sites and economic inputs in the agricultural, textile and technological sectors.

Energy demand is increasing in Pakistan, growing by an average 6-7% per year [1], but the costs of importing fuels are putting pressure on the economy. Batteries are, in this sense, a challenge and a prospect. Almost all advanced batteries are imported to Pakistan because lithium, cobalt, and other key components are sourced in foreign countries [2].

Nevertheless, the country has begun to take steps to localise the production and accelerate the uptake of electric vehicles (EVs). For instance, the Electric Vehicle Policy 2020-2025 proposes that by the year 2030, 30% of new vehicles should be electric aided by tax breaks and reduced customs taxes on EV parts [3].

Despite these policy measures, Pakistan's domestic capacity regarding battery research, development and manufacture is still limited. Organisations such as the Pakistan Council of Scientific and Industrial Research (PCSIR) and academic institutions such as the National University of Sciences and Technology (NUST) and the Pakistan Institute of Engineering & Applied Sciences (PIEAS) have started research related to battery recycling, cathode development and hybrid designs, though much remains to be done to take these projects to an industrial level [4]. It is also necessary to align domestic research and development with global developments. Sodium-ion batteries are one such area where Pakistan has a natural advantage due to the abundance of sodium sources compared to the scarcity of cobalt and lithium.

International collaborations and regional partnerships further underscore the strategic importance of this field. Under the China-Pakistan Economic Corridor (CPEC), there is potential for establishing local battery assembly and testing facilities, leveraging China's technological leadership in this domain. Such collaborations can not only accelerate

Pakistan's technological adoption but also provide opportunities for capacity building and integration into global value chains.

It is crucial and timely to research battery technologies and their advancement in Pakistan. It would provide information on how the nation can reduce its reliance on imports, encourage domestic innovation, and establish itself in regional and international technological networks. This report's subsequent sections will examine the main battery technology research areas, the status of local manufacturing and material sourcing, institutional partnerships, regional initiatives, industry and start-up ecosystems, and the funding and policy environment. This report attempts to suggest ways for Pakistan to develop its battery technology industry as part of its larger shift towards a resilient and sustainable energy future by looking at both opportunities and challenges.

2. Key research areas in battery technologies

The global battery landscape is advancing rapidly, with numerous chemistries and technologies under active development. Determining priority research areas is crucial for Pakistan, where the energy transition is intertwined with concerns of affordability, reliance on imports, and growing storage demand. The most important technologies in the field of research today, their significance on a global scale, and their ramifications for Pakistan are described in the following subsections.

2.1 Li-ion batteries

Li-ion batteries continue to be the most widely used storage technology globally, powering everything from electric cars and grid-scale storage to laptops and smartphones. Their long cycle life, high energy density, and steadily falling costs are the main reasons for their success on a global scale [5]. Li-ion batteries are mostly imported into Pakistan, where they are used mainly in electric bikes, telecom towers, uninterruptible power supplies (UPSs), and solar hybrid systems. While businesses like SkyElectric incorporate Li-ion packs into smart energy systems, companies like Jolta Electric depend on imported Li-ion packs for their EVs. Limited but expanding local research is being done by PCSIR and a number of universities on cathode development, battery management systems (BMS), recycling methods, and feasibility studies for Li-ion adaptation for Pakistan's renewable energy sector [6]. However, the absence of domestic lithium and cobalt reserves makes large-scale Li-ion manufacturing challenging, emphasising the need for recycling and second-life use.

2.2 Sodium-ion batteries

Sodium-ion batteries are emerging globally as a low-cost alternative to Li-ion, with China's CATL starting commercial production in 2023 [7]. Their advantage lies in the abundance and affordability of sodium, which makes them particularly relevant for countries like Pakistan. The Khewra Salt Mines and other deposits position Pakistan as a potential supplier of raw sodium resources [8]. Research at NUST (US-Pakistan Center for Advanced Studies in

Energy) and PIEAS has highlighted sodium-ion technology as a strategic opportunity, given Pakistan's lack of lithium but abundance of salt reserves. Although the technology is still in its early stage internationally, Pakistan may be able to jump straight into sodium-ion development with early adoption and research, which would lessen dependency on imports and bring it into line with international innovation trends [9].

2.3 Solid-state batteries

Solid-state batteries offer greater energy densities, quicker charging times, and enhanced safety by substituting solid materials for liquid electrolytes. Though commercialisation is still five to ten years away, companies such as Toyota and QuantumScape are leading this field [10]. Solid-state battery research is very limited in Pakistan, mostly because of a lack of funding and sophisticated labs. However, experimental as well as theoretical research and material simulations are being undertaken by academics [11]. Pakistan could increase its capabilities in this cutting-edge technology without having to pay for the entire R&D infrastructure if partnerships are strategically used.

2.4 Novel battery technologies

Innovative battery technologies like zinc-air, lithium-sulfur, and redox-flow batteries are gaining attention globally in addition to lithium and sodium chemistries. Because zinc is more readily available locally than lithium or cobalt, zinc-air batteries hold particular promise for Pakistan. Initial exploratory research on zinc-based energy storage systems, specifically for telecom backup solutions and rural electrification, has been reported by PCSIR. Flow batteries, which are promising for grid-scale applications, and lithium-sulfur batteries, which have a high theoretical energy density, are still largely missing from Pakistan's R&D pipeline. However, these technologies might become future collaboration priorities as global trends shift towards sustainability and recyclability. Early participation in zinc-air and flow battery research could open doors for Pakistan to develop affordable, locally based storage options that meet the country's energy requirements.

3. Material sourcing and local manufacturing

3.1 Material sources in Pakistan

Pakistan's capacity to engage in the mainstream Li-ion supply chain is restricted due to its lack of commercial-scale lithium and cobalt reserves. Instead, its competitive advantage comes from other minerals:

- Sodium: Pakistan has vast sodium reserves, including the Khewra Salt Mine, which is one of the largest in Asia. This puts the country as a possible raw material supplier for sodium-ion battery technologies, which are gaining attention as viable alternatives to Li-ion [8].

- Graphite: Khyber Pakhtunkhwa and Gilgit-Baltistan have natural graphite reserves, which are currently underexplored. Graphite is an important anode material in Li-ion and other modern batteries.
- Copper: Pakistan can support the electrical and conductive components of batteries due to its substantial copper reserves, especially in Balochistan (e.g. Saindak and Reko Diq).
- Zinc: Zinc mining in Balochistan offers prospects for energy storage technology, such as zinc-air batteries, which PCSIR is studying for use in rural electrification.

While these reserves create potential opportunities, the extraction and refining sectors are underdeveloped, with the majority of raw materials exported without value addition.

3.2 Local manufacturing and assembly

Pakistan currently lacks cell manufacturing facilities. Instead, the industry is concentrated around:

- Lead-acid battery manufacturing: Local businesses such as Atlas Battery (Phoenix), Exide Pakistan, Osaka, and Volta dominate this market, producing the majority of batteries for vehicles, UPS systems, and small-scale solar backup.
- Li-ion assembly and integration: Companies such as Pantera Energy, and SkyElectric import Li-ion cells (mainly from China) and assemble battery packs for solar hybrid systems, telecom towers, and electric mobility.
- EV startups: Jolta Electric imports battery modules but is moving toward limited assembly of packs for electric bikes and rickshaws.
- Government research facilities: PCSIR has initiated pilot projects in battery recycling and cathode development, while NUST is testing materials for Li-ion and sodium-ion batteries.

4. Key research institutions and collaborations

The capabilities of Pakistan's major research institutes, as well as their worldwide relationships, are critical to the evolution of battery technologies. While the country lacks large-scale R&D centres similar to those in China, Korea, or Europe, organisations such as NUST and PCSIR have made significant efforts to develop competence in electrochemical energy storage. International connections, particularly through the US-Pakistan Center for Advanced Studies in Energy (USPCAS-E) and the China-Pakistan Economic Corridor (CPEC), have encouraged this foundation.

NUST is the only university in Pakistan with a dedicated laboratory for Li-ion battery R&D, although the work is limited to coin-type cells rather than pouch or cylindrical prototypes. There is no known R&D for lead-acid batteries in Pakistan's academic sector; lead-acid expertise is concentrated in industry (Atlas, Exide, Volta). NUST signed a Memorandum of Understanding (MoU) with Arizona State University (ASU, USA) under the USPCAS-E

initiative (2014), supported by USAID, enabling faculty exchange, joint publications, and training in energy storage (ASU–NUST Partnership). In 2019, NUST signed an MoU with the Korea Institute of Science & Technology (KIST) to collaborate on Li-ion coin cell research, nanomaterials, and renewable integration (NUST–KIST MoU).

PCSIR functions as the government's applied R&D body, with initiatives in battery recycling, zinc-air prototypes, and cathode development. PCSIR has signed multiple MoUs with Chinese firms under CPEC to explore local battery recycling and assembly (PCSIR, CPEC). It acts as the bridge between academia and local industries.

5. Regional collaboration efforts

Given the high capital requirements and technical difficulties of modern battery technologies, Pakistan's ability to create competitive capabilities will require regional collaboration. While internal organisations have launched research, the country's success is highly reliant on collaboration with regional leaders in Asia and the Middle East.

China is one of the global leaders in battery manufacturing, with companies such as CATL and BYD accounting for more than 70% of total production [5]. Pakistan can make use of the strategic opportunities created by the CPEC to expand its role in regional battery research, manufacturing, and energy storage development. PCSIR and Chinese companies have signed several MoUs to investigate battery recycling, Li-ion assembly, and hybrid energy storage systems [12]. Additionally, Pakistani EV company Jolta Electric has developed supply ties with Chinese Li-ion battery producers, allowing for the production of locally assembled electric motorcycles and rickshaws. Given Pakistan's salt supplies and China's early commercialisation of this technology, potential exists for co-development of sodium-ion research [13].

The Gulf states, particularly Saudi Arabia and the United Arab Emirates (UAE), are making significant investments in renewable energy and energy storage as part of the Vision 2030 and Masdar programmes. Pakistan has taken part in collaborative renewable projects sponsored by Gulf Cooperation Council (GCC)-based investors, which frequently incorporate components for solar energy storage. For example, Masdar in the UAE has worked with Pakistani enterprises on renewable projects that include battery backup [14]. These relationships give Pakistan access to financing, training, and technology transfer, particularly for stationary storage systems related to solar and wind projects.

6. Industry and start-up ecosystem

The battery sector in Pakistan is expanding as part of a larger landscape of industrial and entrepreneurial activities. With frequent power outages, increased renewable energy use, and the rise of electric mobility, batteries have emerged as a vital enabler in both old and emergent industries. Unlike consolidated worldwide markets dominated by a few giant multinational corporations, Pakistan's market is highly fragmented, with established lead-

acid battery producers, Li-ion assemblers, overseas suppliers, and a growing number of startups.

Pakistan's industrial environment is varied, with significant contributions from the energy, textile, mechanical, and general manufacturing sectors. These sectors lay the groundwork for applied breakthroughs that benefit the battery ecosystem, particularly through supply chains for metals, chemicals, and engineering services.

To boost prosperity, the Pakistani government has constructed Special Economic Zones (SEZs) along the CPEC. These zones provide tax and duty exemptions, encouraging both domestic and foreign enterprises to establish manufacturing and assembly operations. Similarly, science and technology parks affiliated with universities, such as the National Science and Technology Park (NSTP) at NUST, help companies by offering incubation, R&D facilities, and access to venture funding [15]. These structures indirectly benefit the battery industry by providing opportunities for businesses focused on sustainable energy, materials research, and EV technology.

The local battery market is highly fragmented, with old lead-acid manufacturers dominating mass markets and newer companies advancing in advanced storage and EVs. Established organisations including Atlas Battery Limited (Phoenix), Exide Pakistan Limited, Osaka Batteries, and Volta dominate the automobile and UPS markets. Meanwhile, foreign businesses such as Zhejiang Narada Power Source Co., Ltd. have entered the market to provide innovative storage solutions for telecom and renewable energy.

Pakistan's industry and startup environment is constantly expanding, with increasing contributions from areas such as technology, energy, and manufacturing. Pakistan's important sectors include the energy sector, textiles and manufacturing, and mechanical manufacturing. Pakistan's government maintains certain economic zones to encourage business, as well as science and technology parks to help institutions get started.

7. Startups and innovations

Pakistan's startup ecosystem has emerged as a key source of innovation in the clean energy and battery industries. Despite the country's lack of industrial-scale cell production, local entrepreneurs and spin-offs have brought novel solutions by focusing on battery integration, renewable energy applications, and electric transportation. The existence of Special Economic Zones (SEZs) and university-linked scientific and technology parks, notably the National Scientific and Technology Park (NSTP) at NUST, provide an ideal environment for energy-centred entrepreneurship.

7.1 Jolta Electric: Electric mobility pioneer

Jolta Electric is Pakistan's first EV startup, producing electric bikes, scooters, and rickshaws. It assembles imported Li-ion battery packs locally, utilising the EV Policy 2020–2025. While

Jolta is not involved in cutting edge battery chemistry, its innovation is in making EV adoption affordable to middle-income consumers.

7.2 SkyElectric: Smart solar-storage integration

SkyElectric's Smart Energy System combines solar PV, Li-ion storage, and AI-driven energy management software to improve residential and industrial energy systems. Its originality is in the digitisation of energy storage, which allows users to monitor and manage their usage.

7.3 Tesla Industries Pakistan – localised Li-ion assembly

Tesla Industries Pakistan (not affiliated with Tesla in the United States) assembles Li-ion battery packs for UPS systems, telecom towers, and solar applications. Customising imported Li-ion cells for local demands provides alternatives to traditional lead-acid batteries.

7.4 University spin-offs and research innovations

The National Science & Technology Park (NSTP) at NUST is home to a number of energy-focused firms, including those developing BMS, solar-storage hybrids, and IoT-enabled energy monitoring. Spin-offs like ModulusTech (building cheap modular houses with integrated solar storage) show how cross-disciplinary innovation intersects with battery solutions.

National Incubation Centres in Islamabad and Lahore have helped entrepreneurs in clean tech, renewable integration, and smart energy solutions, all of which overlap with battery storage.

8. Policy, funding and challenges

The policy environment for battery technologies in Pakistan is still in its early stages, but it is gradually improving, particularly in light of the national energy transformation and renewable energy integration. While the government has implemented regulations to promote EVs and renewable energy, obstacles in implementation, funding, and infrastructure continue to impede development.

8.1 Policy landscape

The Electric Vehicle Policy 2020-2025 has ambitious objectives: EVs should be 30% of all new vehicle sales by 2030 and 90% by 2040. The policy provides incentives such as reduced cost of import on Li-ion batteries and EV components, cheaper customs charges (as low as 1%) on CKD (completely knocked down) kits for EV assembly, and tax breaks for local assembly companies. These steps indirectly promote battery manufacturing and integration, as batteries are the most crucial and expensive component of EVs. The regulation has already inspired businesses like Jolta Electric to construct two- and three-wheel EVs domestically, as well as drawing the interest of Chinese battery and EV providers.

The government of Pakistan approved the Alternative and Renewable Energy Policy 2019 to guarantee that renewable energy accounts for 30% of total power output by 2030. This strategy emphasises the relevance of energy storage systems in stabilising the grid, integrating intermittent renewables, and providing backup in off-grid areas. While ambitious, the programme lacks a defined structure for growing battery storage systems, resulting in a mismatch between renewable ambitions and storage preparedness.

8.2 Funding landscape

Government funding: the Higher Education Commission (HEC) supports small-scale R&D initiatives at institutions like NUST. The Ignite National Technology Fund encourages renewable energy businesses, especially those that combine solar and storage technologies. PCSIR gets federal financing for pilot studies in zinc-air batteries and recycling, but at a restricted scale.

International support: USAID's USPCAS-E programme has given infrastructure and training in energy storage and renewable energy. KIST collaborated with USPCAS-E to co-fund research on Li-ion coin cell development, nanomaterials, and renewable integration. UNDP Pakistan has sponsored the Pakistan Electric Vehicle Roadmap (2021) and is providing technical help to increase adoption. The China-Pakistan Economic Corridor provides a setting for knowledge transfer and possible battery assembly initiatives via MoUs with Chinese enterprises.

8.3 Key challenges

- **Import dependence:** Pakistan relies largely on imported lithium and cobalt due to a lack of economic deposits.
- **Limited manufacturing:** Lead-acid manufacturing and Li-ion pack assembly are the only activities, as there are no gigafactories or mid-scale cell facilities.
- **Infrastructure deficit:** EV charging facilities are few, with few standards.
- **Weak R&D ecosystem:** University research focuses on coin-cell prototypes (NUST) and materials research (PIEAS), with no pilot-to-industry pipeline.
- **Policy gaps:** While policies encourage adoption, they do not fully address battery production, recycling, and supply chain development.
- **Financial barriers:** Limited access to venture financing and cautious financial backing limit startup growth.
- **Sustainability concerns:** Informal lead-acid recycling is popular, but there is no recognised infrastructure for Li-ion recycling.

9. Case studies and success stories

Although battery technology R&D and manufacturing is at a nascent stage in Pakistan, the country has seen some developments driven by academic research, industrial innovation, and renewable energy integration. These case studies demonstrate how institutional

support, entrepreneurial vision, and legislative incentives may all work together to produce significant advancements.

Jolta Electric is Pakistan's first local EV effort, focusing on electric bikes, scooters, and rickshaws. Jolta assembles packs locally and imports Li-ion modules from China, building on the EV Policy 2020–2025. The business has spearheaded local EV assembly and developed cost-effective mobility choices catered to Pakistan's urban transit market, while not yet pursuing sophisticated cell chemistries.

SkyElectric, a company founded by Pakistani-American businessman Ashar Aziz, has unveiled smart solar and storage solutions that integrate solar photovoltaic cells, Li-ion battery packs, and artificial intelligence (AI)-powered monitoring software. Its "Smart Energy System" lessens reliance on the grid while offering dependable, round-the-clock electricity to homes and businesses.

10. Future directions

Pakistan is planning to establish local production of both Li-ion and sodium-ion batteries, but this has not yet been funded; nor have the necessary infrastructural clearances been made to facilitate development. Plans to build a lithium cylindrical and pouch cell lab, have been suggested but not funded yet, which demonstrates the greater challenge of aligning policy ambitions with financial investment. The set-up of such a facility is essential to enable Pakistan to move beyond small scale coin-cell experiments and produce commercially viable prototypes.

Sodium-ion batteries, however, are an entirely different strategic opportunity, as Pakistan is well endowed with sodium reserves and the global trend towards this chemistry.

Cooperation with universities, such as KIST, and partnerships within the frame of the China-Pakistan Economic Corridor can accelerate the transfer of technologies and the development of talents. It is also important to create a formalised recycling economy and second-life applications to be sustainable and less reliant on imported goods.

Finally, the future of battery technology in Pakistan will rest on how to translate government ambitions into funded research. The country can become more than a technology importer and become an active participant in the global battery economy with consistent investment in manufacturing facilities, recycling structures and university-industry collaboration.

11. Conclusions

A sustainable battery ecosystem initiative in Pakistan is in its infancy, yet it is already gaining momentum due to institutional research, startup activity, and regional alliances. Limited funding, lack of large-scale production and recycling systems are still pressing issues, but government promotion of EVs, renewable energy adoption and Li-ion and sodium-ion

chemistry research demonstrate a clear intention to move forward. Pakistan can tap into the growing renewable energy sector and align its regulation with those of other countries around the world to become a regional leader in battery technology.

To attain this objective, it will be necessary to focus on R&D, building infrastructure and integrating sustainability into all growth processes. By investing more selectively, building better academia-industry relationships and international cooperation, Pakistan can move from dependence on imported technologies to increased energy autonomy and sustainable economic growth through clean energy and new storage options.

References

- [1] Hydrocarbon Development Institute of Pakistan (HDIP), 'Pakistan Energy Yearbook 2023'. Government of Pakistan, Ministry of Energy. <http://www.hdip.gov.pk/>
- [2] United Nations Development Programme (UNDP) Pakistan, 'Pakistan Electric Vehicle Roadmap', 2021. https://www.pk.undp.org/content/pakistan/en/home/library/environment_energy/pakistan-electric-vehicle-roadmap.html
- [3] Government of Pakistan, 'Electric Vehicle Policy 2020–2025', Ministry of Climate Change, Islamabad, 2023. <https://www.invest.gov.pk/sites/default/files/inline-files/EV%20Policy.pdf>
- [4] Institute for Energy Economics and Financial Analysis (IEEFA), 'Battery Storage and the Future of Pakistan's Electricity Grid', IEEFA, Lakewood, 2025. <https://ieefa.org/resources/battery-storage-and-future-pakistans-electricity-grid>
- [5] International Energy Agency (IEA), 'Global EV Outlook 2024: Scaling up the transition to electric mobility', Paris: IEA, 2024. <https://www.iea.org/reports/global-ev-outlook-2024>
- [6] G. Ali, 'Development of high voltage phosphate-based cathodes for li-ion batteries', 2021, NUST. <https://researchblog.nust.edu.pk/development-of-high-voltage-phosphate-based-cathodes-for-li-ion-batteries/>
- [7] BloombergNEF (BNEF), 'Electric Vehicle Outlook 2024', 2024. <https://about.bnef.com/electric-vehicle-outlook/>
- [8] Sustainable Development Policy Institute (SDPI), 'Energy Transition Worth its Salt: Sodium-ion Batteries and Pakistan's Industrial Future', SDPI, Islamabad, 2025. <https://sdpi.org/resources/energy-transition-worth-its-salt>
- [9] M. N. Akhtar, N. A. Shah & R. Raza 'Current status and future potential of renewable energy in Pakistan with special focus on storage technologies', *Renewable Energy*, 142, 278–289, 2019.
- [10] J. Janek & W. G. Zeier, 'A solid future for battery development', *Nature Energy*, vol. 1, no. 9, pp. 16141, 2016. [doi:10.1038/nenergy.2016.141](https://doi.org/10.1038/nenergy.2016.141)

- [11] G. Ali, 'Solid-State Electrolytes: A Safer Future for Energy Storage Systems', NUST, 2025. <https://researchblog.nust.edu.pk/solid-state-electrolytes-a-safer-future-for-energy-storage-systems/>
- [12] China–Pakistan Economic Corridor, Science & Technology and Industrial Collaboration Initiatives. <https://cpec.gov.pk/>
- [13] Contemporary Amperex Technology Limited (CATL), 'CATL Debuts Sodium-Ion Batteries' Ningde, China, 2023. <https://www.catl.com/en/news/665.html>
- [14] Masdar (Abu Dhabi Future Energy Company) <https://masdar.ae/en/masdar-clean-energy>
- [15] NUST National Science & Technology Park (NSTP) <https://nstp.nust.edu.pk/>

Malaysia

This section was written by Dr Mohd Najib Mohd Hussain, Associate Professor in the School of Electrical Engineering and College of Engineering Universiti Teknologi Mara (UiTM). He focuses on microgrid battery energy storage systems.

1. Introduction

1.1 Background

Malaysia has been focusing on enhancing its battery energy storage systems (BESS) since the early 2020s, when the Sustainable Energy Development Authority (SEDA) introduced a Net Energy Metering scheme, which credits photovoltaic (PV) system owners for electricity they add to the grid [1]. This focus is driven by the need to stabilise the grid and efficiently manage the intermittent nature of renewable energy sources, especially for solar PV systems, and the potential impact of high penetration of solar PV systems on the electricity grid system, known as the duck-curve phenomenon [2].

Malaysia is also undergoing a significant transformation in its energy sector, with BESS emerging as a cornerstone of its strategy to achieve a low-carbon, resilient, and sustainable energy future as the country accelerates its adoption of renewable energy (RE). Solar PV systems were encouraged as early as 2004 through the Malaysia Building Integrated Photovoltaic (MBIPBV) project supported by the United Nations Development Programme (UNDP)'s Global Environment Facility (GEF) [1]. The installation of solar PV continued as the first introduction of the Feed-in Tariff (FiT) scheme was launched in December 2011 [3], [4], administered by the SEDA, making the need for reliable energy storage solutions increasingly critical.

The revolution of BESS technology towards the green energy industry, with its potential to harness and utilise renewable energy sources, especially solar PV, offers not only environmental benefits but also lucrative investment opportunities for Malaysian solar PV players and users. As Malaysia works towards reducing its carbon footprint and meeting green energy targets, BESS provides a reliable, efficient solution to current and future local energy solutions for distribution of renewable energy sources.

1.2 Importance in Malaysia

The Malaysian government, through initiatives such as the Malaysia Renewable Energy Roadmap (MyRER), aims to increase renewable energy capacity and reduce carbon emissions. In September 2024, the government launched the Corporate Renewable Energy Supply Scheme (CRESS) [5], [6], which allows firms to buy green electricity from RE developers, delivered through the national grid.

RE developers are encouraged to install battery storage systems to deliver the electricity by the incentive of cheaper charges to access the grid if they have such systems installed (with storage capacity of at least 50% of the renewable energy plant's capacity).

The global battery research landscape is rapidly advancing due to the increasing demand for efficient and sustainable energy storage solutions. This trend is primarily driven by the growing adoption of electric vehicles (EVs) and the integration of renewable energy sources into power grids. In Malaysia, significant developments in battery technology include the exploration of advanced materials such as lithium-ion (Li-ion) batteries [7], silicon anode batteries, and sodium-sulfur (NaS) batteries [8]. These innovations promise higher energy densities, longer lifespans, and enhanced safety.

As the demand for batteries surges, the extraction and refining of critical raw materials like lithium, cobalt, and nickel has also intensified. Additionally, there is a strong focus on innovations in battery recycling and reuse to mitigate environmental impacts, which will be further explored in terms of research and application in Malaysia.

1.3 Incentives for BESS in Malaysia

Malaysia's battery market is predicted to grow at a CAGR of 5.28% from 2025 to 2033 [9]. Key motivations and incentives for BESS technology in Malaysia include:

1.3.1 Enhancing grid stability and renewable integration

Malaysia aims to use BESS to mitigate the intermittency of renewable energy sources, such as solar PV systems, through the Net Energy Metering (NEM) scheme [10]. With the latest NEM scheme allowing users to sell energy for a period of only ten years, BESS serve as a solution to store surplus energy generated by users. Additionally, demand management strategies can be implemented by storing energy during peak generation periods and releasing it during times of low output. This approach ensures grid reliability and maximises the use of renewable energy. The NEM scheme aligns well with the government's recent tariff system, known as the Time-of-Use (TOU) scheme. This tariff offers lower rates during off-peak hours and higher rates during peak hours, facilitating the integration of BESS facilities into the energy market.

1.3.2 Supporting national energy transition goals

Under the National Energy Transition Roadmap (NETR) [11] and MyRER, BESS is identified as a critical enabler to reduce fossil fuel dependence from 96% in 2023 to 77% by 2050, and is expected to increase the renewable energy share from 4% to 22% by 2050, following Malaysia's Net Zero Carbon Emission Target [12].

Fig. 1 illustrates a scenario of likely investments required if renewable energy were to make up 100% of the energy mix by 2050, according to modelling. Fig. 2 shows how the balance of electricity generation by source might change under a National Energy Transition Roadmap Scenario (NETRS), which targets 70% renewable energy in the national energy mix.

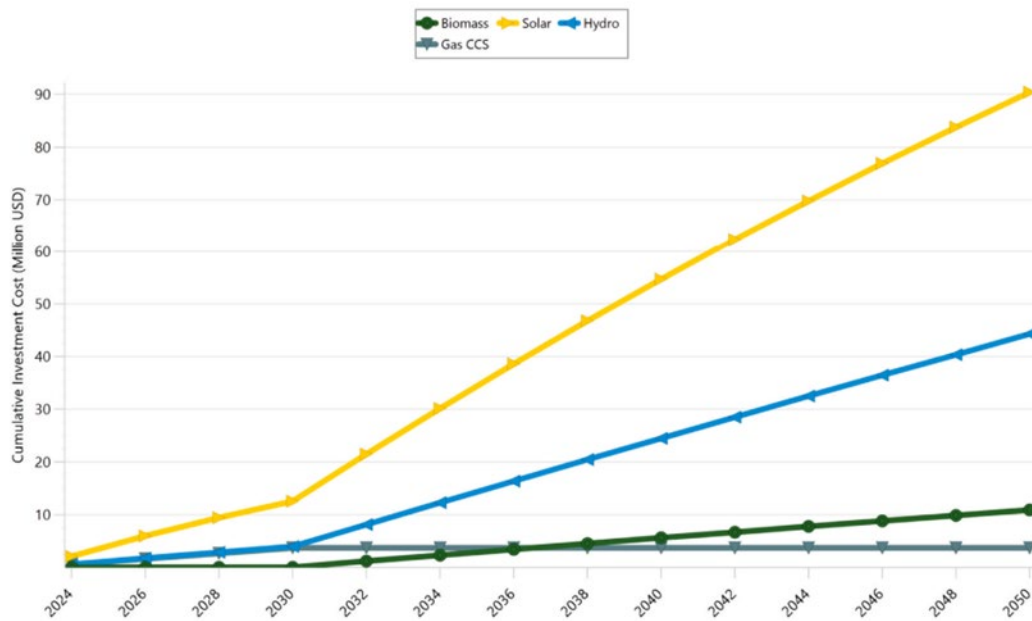


Fig. 1: Investments needed for 100% renewable energy scenario

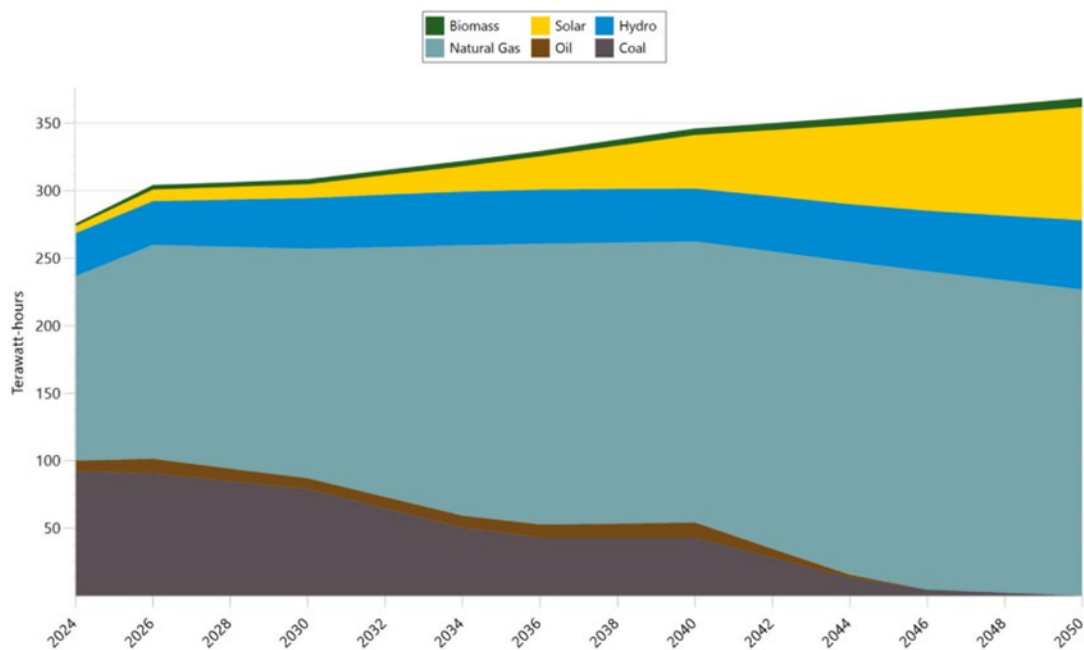


Fig. 2: Energy sources in electricity generation under NETRS

1.3.3 Driving economic growth and investment

Malaysia plans to position BESS as a lucrative investment opportunity for both domestic and international players. For this reason, the government of Malaysia promotes BESS through several schemes such as:

- A Green Investment Tax Allowance (GITA) introduced in 2014 [13], which has catalysed RM2.1 billion in green investments since 2023.

- Strategic partnerships, such as the Citaglobal–Genetec collaboration to manufacture BESS systems locally [14].
- The CRESS.
- Supporting BASF Malaysia to develop a project around production manufacturing for stationary energy storage using sodium-sulfur battery technology.

1.3.4 Enabling energy cost optimisation and business resilience

The Malaysian government recognises that energy cost volatility and grid reliability are significant concerns for businesses, particularly in the commercial and industrial sectors where energy consumption is high. To address these challenges, the government is promoting BESS as a strategic tool to help businesses effectively manage energy costs and enhance operational resilience. BESS offers several advantages such as:

- Energy arbitrage (charging during off-peak hours and discharging during peak hours) via TOU tariff expansion.
- BESS allows businesses to reduce peak demand, which is often the basis for the maximum demand (MD) charge. By discharging stored energy during peak periods, companies and users can lower their MD profile, resulting in significant savings.
- During outages or periods of instability, BESS provides essential backup power. This feature is especially crucial for industries such as manufacturing, healthcare, military, and data centres, as downtime can result in significant losses.
- Supporting Environmental, Social, and Governance (ESG) frameworks by reducing carbon footprint activities encouraged by BESS technologies.

Overall, BESS technology in Malaysia will serve as a valuable solution for managing energy demands while supporting broader environmental goals such as expanding access to clean energy. Through initiatives such as the Ministry of Energy Transition and Water Transformation (PETRA)'s RM500 million grant programme, Malaysia continuously supports rural microgrid development using BESS, helping expand access to sustainable power in underserved areas [15].

Malaysia is also actively exploring advanced optimisation strategies to enhance the performance and cost-effectiveness of BESS in renewable energy systems, especially on the development of directed search-based, probabilistic, and rule-based strategies to optimise BESS operations. These methods are tailored to meet financial, technical, and hybrid objectives, ensuring that BESS can support grid stability, reduce curtailment, and extend battery lifespan [16-18].

Malaysia's energy transition, as outlined in the MyRER 2022–2035 [1], emphasises the need to modernise and restructure electricity markets to accommodate high penetration of variable renewable energy (VRE) sources, especially on solar PV systems. BESS is the solution to this transformation, which enables grid flexibility, reliability, and economic efficiency. Post-2025 strategies under MyRER include:

- Creating structured markets for grid balancing services.
- Encouraging innovative grid management solutions.
- Exploring new economic activities linked to energy storage.

2. Key research areas in battery technologies

Key areas of research innovation in Malaysia relate to stabilising the grid and ensuring a reliable supply of renewable energy to improve the efficiency, lifespan, and cost-effectiveness of BESS for renewable energy interconnections.

In terms of EVs, research efforts are needed to enhance battery capacity, reduce charging times, and improve the overall performance of EV batteries. This includes exploring new materials and technologies for better energy density and sustainability. Battery recycling and re-use are other research areas, especially around sustainable methods for recycling and re-use of Li-ion batteries. These are being developed to address environmental concerns and reduce dependency on raw materials.

The prospects of battery technologies in Malaysia can be encouraged by undertaking more BESS systems as utility-scale projects, providing relevant government incentives including policies to attract investments in BESS, and developing schemes around small-scale recycling and re-use of batteries to become a global hub for sustainable energy solutions in Southeast Asia and achieving Malaysia's goal of becoming a net-zero emission nation by 2050 [11].

Universiti Teknologi MARA (UiTM), and partner institutions have conducted research on developing a Virtual Power Plant (VPP) platform as a cloud-based decentralised network of distributed energy resources (DERs). The system consists of solar PV systems and 200 kWh battery storage energy systems for side demand response systems through an artificial intelligence (AI)-based optimisation engine for microgrid energy management. It has been installed at UiTM Pulau Pinang Branch Campus. This development was successfully commissioned at the end of 2023 and enables the system to deploy methods for automated charging and discharging instructions via the Application Programming Interface (API) to be executed from the VPP to the BESS system.

The deployment of AI grid and VPP optimisation and machine learning models within a cloud infrastructure enables optimum energy dispatch based on the energy mix from the grid, distributed energy resources (DERs), load, and battery energy storage systems (BESS) across multiple physical locations, with the objective to minimise energy cost and maximise energy surplus of the campus. The implementation of an Energy Management System (EMS) is also adapted to utilise the monitoring and control capabilities of the VPP to efficiently regulate the load, including the installation of energy-efficient devices such as sensors and timers, which respond to remote or automated commands from the VPP control centre.

UiTM also focuses on research on the sustainability of Li-ion batteries in Malaysia as the preferred technology for energy storage devices. Li-ion has quickly dominated the global

electrical consumer market due to its relatively high energy density, advanced operating voltage, and lack of a memory effect. The battery market in Malaysia is projected to reach a CAGR of about 5.28% between 2022 and 2027 according to a recent report, and in general demand for lithium will increase in the future. However, the amount of lithium in the world is depleting and there is a need to develop or improve the current established method to recycle lithium from waste Li-ion batteries.

UiTM will focus on analysing the circularity of Li-ion battery resources and carry out proof-of-concept testing of the most feasible Li-ion battery green recycling process. An analysis of the regional prospect of Li-ion battery recycling from a life cycle assessment (LCA) perspective will be conducted. At the end of the project, the suitability of upscaling the recycling of lithium and other potential elements like nickel, cobalt, or cadmium from the lab to bench scale using uncommercialised methods will be determined from the ongoing research.

Malaysia has been actively fostering technological innovation in battery energy storage systems to support its energy transition and sustainability goals. The country is a regional hub for Li-ion battery manufacturing, with companies such as EVE Energy and Samsung SDI investing in advanced production facilities that focus on improving energy density, lifecycle, and safety.

To diversify beyond lithium, Malaysia needs to collaborate with international partners to develop sodium-ion batteries, which offer a cost-effective and scalable alternative for solar energy storage [19]. Solid-state batteries are also gaining traction, with early-stage research under NanoMalaysia's NESTI programme [20] exploring graphene-based solid electrolytes and leveraging artificial intelligence for material screening and performance prediction.

For large-scale renewable integration, Malaysia is investigating vanadium redox flow batteries, which provide long lifespans and modular scalability, although commercial deployment remains limited [21], [22]. Additionally, novel technologies like sodium-sulfur and aluminium-ion batteries are being developed locally [23], with research highlighting their potential for safer, longer-lasting, and more recyclable energy storage solutions. These efforts reflect Malaysia's strategic commitment to becoming a regional leader in sustainable and innovative energy storage technologies.

3. Material sourcing and local manufacturing

The government of Malaysia's strategic plan has prioritised developing a domestic ecosystem for rare earth elements, over lithium exploration. Malaysia does have some rare mineral deposits and is developing its recycling infrastructure, but there is a lack of significant lithium production, and it is hard to compete with the prices of Chinese manufacturers. Therefore, Malaysia focuses on strengthening its capacity in battery recycling and e-waste processing, which are considered significant growth areas for the country. Local battery manufacturing will become increasingly important to meet the rising

demands for energy and transportation [24] and more could be done to promote local manufacturing. The country should also take measures to manage resources in batteries at end-of-life for potential use in re-manufacture.

Nevertheless, to ease the barriers to growth, the industry requires more support from various government departments and private stakeholders to accelerate its development.

3.1 Recycling and circular economy

Malaysia projects 870,000 EV batteries will need recycling by 2050 [25] as Li-ion batteries power more new EVs and hybrid cars. Due to this, Malaysia is taking significant steps to establish a sustainable ecosystem for handling end-of-life (EOL) electric and hybrid vehicle batteries. A circular economy for BESS covers:

- Recycling batteries to recover valuable materials like lithium, cobalt, and nickel.
- Repairing or refurbishing batteries to extend their lifespan.
- Responsible disposal of batteries when no longer usable.

3.1.1 Existing recycling practices in Malaysia

In Malaysia, Li-ion battery recycling is still in its early stages. However, in late December 2024, the Energy Commission (EC) of Malaysia invited companies or consortiums to apply to build a landmark BESS. This project could kick start Malaysian researchers and manufacturers to work on Li-ion battery recycling.

Furthermore, other elements of government renewable energy programmes such as the Solar Energy Self Consumption (SelCo) programme, the New Enhanced Despatch Arrangement (NEDA), the Corporate Green Power Program (CGPP) and the CRESS should drive more players for the recycling process to meet the demand for energy storage systems.

One government initiative was a collaboration with the company Ni Hsin EV Tech Sdn Bhd and SIRIM Berhad (an agency under the purview of the Ministry of Investment, Trade and Industry) to establish a Li-ion battery recycling plant in Malaysia. This strategic collaboration is expected to recycle up to 550 tonnes of Li-ion batteries annually. The plant aims to recover precious metals such as lithium and cobalt so that Li-ion battery manufacturing can commence in 2025.

The Malaysia Investment Development Authority (MIDA) also launched an Electric Vehicles and Battery Management Guideline (EVBM Guideline) in October 2024 as a framework to cover the entire lifecycle of EV batteries, from acquisition and usage to final disposal and recycling, ensuring safety and environmental responsibility.

EVE Energy, a China-based energy firm, has a Malaysian subsidiary that has established an advanced manufacturing facility in Malaysia located at Kulim, Kedah. It will serve as a hub

for producing cutting-edge cylindrical Li-ion batteries, specifically designed for power tools and electric two-wheelers.

Malaysia is well poised to become a major producer of EVs in Southeast Asia with the government's proactive initiatives to foster a favourable EV ecosystem.

The Malaysia government, through the MyRER, supports the development and integration of BESS to meet the ambitious target of sourcing 70% of energy from renewables by 2050. With a clear roadmap and supportive policies, Malaysia's BESS landscape is poised for a significant expansion for clean and sustainable energy future. Key players in this sector include Ditrolic Energy, which offers versatile BESS solutions, and Plus Xnergy that has designed battery storage solutions to be customised, scalable, and cost-effective, focusing on reducing energy bills, providing backup power, improving microgrids and offering potential tax allowances through the GITA [13].

Other stakeholders include regulatory bodies, industry leaders, and international partners, all working together to foster a robust and sustainable energy ecosystem, thus providing more opportunities for recycling practices in Malaysia [11].

4. Key research institutions and collaborations

Universiti Teknologi Mara (UiTM) and its Solar Research Institute (SRI) have created a flagship centre for renewable energy and BESS innovation. The two worked together at UiTM's Penang campus to install the first 200kWh BESS into a government building. The development focuses on:

- Hybrid PV-BESS and AC coupled BESS system design and optimisation.
- Energy management systems using AI.
- Grid demand reduction and resilience strategies.

Using software from RatedPower (a part of Enverus) for PV and BESS design, researchers aim to optimise hybrid PV-BESS and AC coupled BESS systems for UiTM's Pusat Islam and Facility building, achieving high performance ratios and demonstrating the viability of using lithium iron phosphate battery storage for commercial buildings.

4.1 Strategic collaborations

In 2023, UiTM's Penang campus established a strategic partnership with GoodWE Technologies through a Memorandum of Understanding (MoU). This collaboration aims to advance BESS. The agreement includes the installation of a 200 kWh BESS at UiTM's Solar PV campus, joint research initiatives focused on cloud-based energy management systems for Virtual Power Plants (VPP), and academic exchange programmes that promote researcher and student mobility. Additionally, both institutions will co-host a webinar to encourage innovation and knowledge sharing.

As part of its ongoing commitment to advancing sustainable energy solutions, UiTM Penang's collaboration with the UK-funded Transforming Energy Access – Learning Partnership (TEA-LP) network also serves to strengthen Malaysia's PV and battery storage landscape by cultivating local expertise and innovation. This is a fantastic milestone, not only for Malaysia but for the broader Southeast Asian region as Malaysia is the sole representative from Southeast Asia in the TEA-LP network. Through targeted coursework and research embedded in UiTM's master's programme, Master of Science in Electrical and Electronics Engineering with Management, the partnership empowers students to design and deploy decentralised energy systems that integrate solar PV and battery technologies—critical components for enhancing energy access in remote and underserved communities. This initiative not only supports national energy goals but also positions UiTM as a regional leader in clean energy education and capacity building towards providing local solutions for energy access in Malaysia.

5. Battery skills assessment

Malaysia has made significant strides in promoting solar energy through the implementation of grid-connected photovoltaic (GCPV) and off-grid photovoltaic (OCPV) certification programmes [26]. These certifications help ensure that solar PV systems are installed safely and efficiently by qualified personnel. However, as the energy landscape continues to evolve, BESS are becoming increasingly crucial for grid stability, renewable energy integration, and overall energy resilience.

Despite their growing importance, Malaysia currently lacks a dedicated certification framework for BESS, which poses risks to safety and reliability. To address the gap in knowledge and skills, the country could begin by developing a national certification for BESS that aligns with international standards. Additionally, initiatives like industry-academic partnerships and national battery research programmes can help bridge these gaps by fostering the necessary skills and knowledge. This framework should include tiered qualifications for technicians, inspectors, and designers, enabling them to provide reliable and comprehensive design reports for BESS plants and PV-BESS integration.

The training programmes can be undertaken through institutions such as Tenaga Nasional Berhad (TNB) and its training programme TNB Integrated Learning Solution (ILSAS), the SEDA, or the related Human Resource Development Centre (HRDC) in Malaysia. All these can equip professionals with hands-on experience in battery technologies, energy management systems, and grid integration. Additionally, incorporating Continuing Professional Development (CPD) requirements will ensure ongoing competency in the field. Collaboration with industry partners and the establishment of apprenticeships can provide valuable real-world exposure to utility-scale BESS projects. Moreover, establishing clear safety protocols and licensing requirements for installation and maintenance will strengthen accountability and technical rigour. Finally, public awareness campaigns and supportive

government policies such as grants, incentives, and pilot programmes can accelerate the adoption of BESS technology and encourage more professionals to enter the field. This approach will help ensure that Malaysia remains at the forefront of clean energy innovation.

6. Industry and start-up ecosystem

Malaysia's industry and start-up ecosystem for EVs and BESS is gaining momentum, driven by a blend of innovation, manufacturing capability, and strategic public-private collaboration. The transportation sector in Malaysia is the second worst for carbon emission, primarily due to the extensive use of fossil fuels in vehicles. This issue is exacerbated by the fact that many Malaysians rely heavily on personal vehicles because of an inadequate public transportation system. EVs, which produce zero emissions, present a viable alternative to fossil fuel-powered vehicles. However, charging EVs from low-voltage (residential) power lines creates challenges for the electricity distribution network [27]. Strategic partnerships between the public and private sectors, along with strong government support and targeted incentives, are essential to address the challenges of EV adoption. By aligning industry innovation with policy frameworks, these partnerships can expedite the development of infrastructure, promote local manufacturing, and encourage consumer adoption, ultimately fostering a more sustainable and competitive EV ecosystem across the country.

6.1 Public-private partnerships

Malaysia's shift towards green mobility and energy storage is supported by strategic partnerships among government agencies, universities (academia), and industry players. Agencies and authorities have strengthened these partnerships as follows:

- Agencies such as MIDA (Malaysian Investment Development Authority) and MARii (Malaysia Automotive, Robotics and IoT Institute), which both sit within the Ministry of International Trade and Industry, can facilitate investment, and offer grants for R&D and infrastructure development.
- The Ministry of Investment, Trade and Industry (MITI) has launched initiatives such as the National EV Task Force (NEVTF) and the National EV Steering Committee (NEVSC) to coordinate policy and industry efforts.
- Collaborative efforts with universities and research institutions help develop talent pipelines and foster innovation in battery lifecycle management, recycling, and repurposing through multinational companies like Petronas, TNB and Sime Darby Berhad.

6.2 Government support & incentives

Malaysia's government is promoting EV and BESS adoption through:

- Adopting incentives for battery manufacturing and electric vehicle production, including tax exemptions, grants, and related green certificates, which are necessary to ensure greater participation and involvement from industries.
- Ambitious goals outlined in the NETR and the Low Carbon Mobility Blueprint (LCMB), which include the installation of 10,000 electric vehicle charging stations by 2025.
- Reforms of regulatory and standard guidelines to streamline approval processes for infrastructure projects. This involves authorities like the Energy Commission (EC) and stakeholders such as Tenaga Nasional Berhad (TNB), the Malaysia Productivity Corporation, Vendors, Manufacturers and local councils.

Together, these efforts are fostering a dynamic and resilient ecosystem, establishing Malaysia as a rising leader in Southeast Asia's clean energy sector with the support of BESS technology.

7. Policy, funding and challenges

Malaysia is actively promoting BESS through national policies and government support, aiming to enhance its renewable energy objectives. Agencies such as PETRA and MIDA are leading efforts in investment and development, while new programmes such as the CRESS allow private companies to construct and operate BESS under concession agreements. Funding opportunities are stimulated through competitive bidding; however, challenges persist such as unclear regulations, dependence on imported raw materials, and unpredictable grid usage.

Without faster deployment and clearer regulatory frameworks, Malaysia risks falling short of its renewable energy targets, despite having strong momentum in policy and planning.

7.1 Regulatory framework

A robust regulatory framework is essential. A circular economic framework covering the battery lifecycle is shown in Fig. 3 [28]. This framework helps industry manage and promote proper access to recycling processes.

Clearer regulations are required to address Malaysian challenges such as stringent safety standards to prevent fires and explosions, environmental regulations for mitigating the impact of raw material extraction, and supply chain transparency to ensure ethical sourcing of materials. Moreover, there are opportunities through government-related authorities to offer incentives or tax exemptions, harmonise existing standards and guidelines, and support sustainable practices and green technologies to better meet the demand for Li-ion battery production.

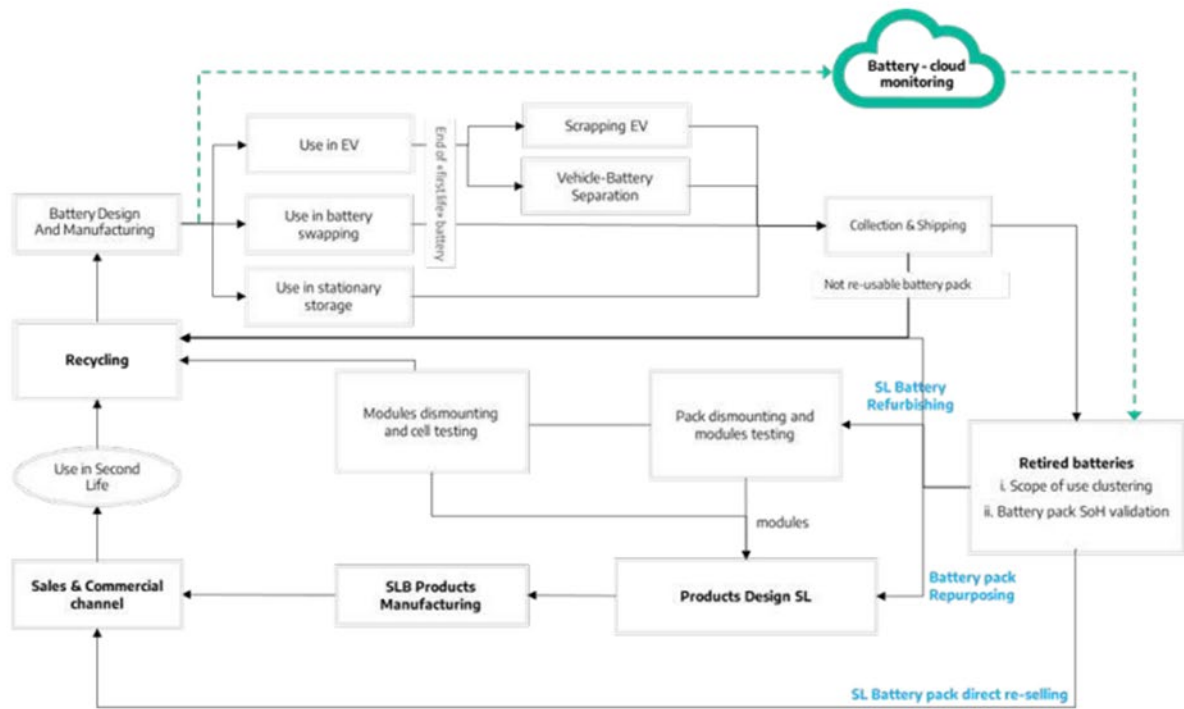


Fig. 3: Economic framework for a battery lifecycle [28]

These regulations should drive innovation, promote recycling and ethical sourcing extraction, and expand the market for Li-ion batteries, particularly in electric mobility and energy storage systems, to ultimately support Malaysia toward sustainable development and a transition to cleaner energy solutions.

8. Case studies and success stories

Malaysia's progress in BESS highlights a developing ecosystem of innovation, policy support, and industrial collaboration. As renewable energy targets increase and grid modernisation efforts advance, BESS installations have become essential for balancing supply and demand in Malaysia. Early success stories, such as the MYBESS prototype, which is a locally developed 1 MW system by Citaglobal and Genetec [29], have demonstrated Malaysia's capacity to engineer and manufacture advanced energy storage solutions domestically. Also, the collaboration between UiTM and Petronas Berhad in developing a microgrid testbed using AI, at UiTM Permatang Pauh, illustrates the commitment of both academia and industry to enhance the resilience of government buildings in support of sustainability efforts through BESS technology.

8.1 MYBESS prototype

By successfully developing a 1MW battery energy storage system with local engineering talent and manufacturing capabilities, MYBESS has demonstrated that Malaysia can reduce its dependence on imported technologies and establish its own clean energy infrastructure. This initiative also highlighted the importance of strategic partnerships, such as the collaboration between Citaglobal and Genetec Technology, in accelerating technical

advancements. Most importantly, MYBESS served as a launchpad for larger national projects, showcasing how small-scale prototypes can evolve into grid-level solutions when supported by appropriate policies and industry collaboration.

8.2 UiTM microgrid testbed using 200kWh BESS

UiTM made a significant advancement in Malaysia's energy innovation sector by developing a 200 kWh microgrid testbed as part of the overall project known as the Virtual Power Plant (VPP) platform via a cloud-based decentralised network of distributed energy resources (DERs). This installation aims to improve energy resilience and demand-side management for government buildings. It features a hybrid and AC-coupled BESS, which facilitates seamless integration between renewable energy sources and the conventional grid supply.

Located at UiTM's Pulau Pinang Campus, the testbed functions as a real-time side demand management for a virtual power plant system. It combines solar PV systems, programmable loads, and advanced control systems to replicate real-world energy scenarios. By enabling autonomous operation and interaction with the grid, the system supports critical infrastructure during power outages and peak demand periods. Additionally, it contributes to Malaysia's goals for sustainable and secure energy systems.

UiTM used an AC-coupled BESS and a hybrid BESS system, installed at a UiTM facility building and at a mosque (Pusat Islam) to establish the microgrid project for the campus. The BESS installation at UiTM operates mainly in demand-side management mode, emphasising self-consumption, peak shaving, and load shifting, instead of functioning solely as a backup power source for the building.

As a result of the BESS installation at UiTM, the university has achieved up to a ~10% reduction in its electricity bill. This cost saving stems from strategic demand-side management practices such as peak shaving, load shifting, and maximising self-consumption of solar energy. By optimising energy usage and reducing reliance on grid power during high-tariff periods, the system not only enhances operational efficiency but also contributes to long-term financial and environmental sustainability for the campus.

9. Future directions

Malaysia's BESS sector is entering a transformative phase, driven by emerging trends and a clear national roadmap. As outlined in the NETR, Malaysia aims to reduce its reliance on fossil fuels and increase the share of renewable energy in its energy supply from 4% in 2023 to 22% by 2050. BESS plays a crucial role in this transition by addressing intermittency, especially for solar PV systems, while enhancing grid reliability and preventing the duck curve phenomenon. Key trends include the emergence of sodium-sulfur batteries, which offer improved safety, lower costs, and higher energy density, making them particularly suitable for Malaysia's tropical climate.

The government is also encouraging third-party participation through concession models, similar to power purchase agreements, allowing private developers to invest in and operate BESS assets. Post-2025 strategies under the MyRER emphasise the development of structured markets for grid balancing services. This allows BESS operators to monetise stored energy through dynamic pricing and service contracts. With supportive policies such as the GITA and the CRESS, Malaysia is well-positioned to become a regional leader in energy storage innovation and deployment.

10. Conclusions

In conclusion, Malaysia's progress in battery energy storage system (BESS) technology reflects a strategic blend of innovation, policy, and sustainability. The country has showcased its ability to design and implement energy storage solutions that cater to local needs, starting from early prototypes like MYBESS to university-led microgrid testbeds. Ongoing research into battery technologies, especially the family of lithium and sodium-sulfur batteries, has indicated a strong potential for developing safer and more cost-effective systems tailored to Malaysia's climate and energy requirements.

Key focus areas such as grid stabilisation, commercial peak shaving, and renewable energy integration are driving adoption across various sectors. However, challenges still exist in material sourcing, recycling infrastructure, secondary batteries and scaling up domestic manufacturing. Policies outlined in the NETR and the MyRER are establishing a foundation for structured markets and encouraging private sector participation. Additionally, incentives like the GITA and the CRESS are boosting the uptake of these technologies. Collectively, these initiatives position Malaysia not only as a consumer of clean energy technologies but also as a regional leader in battery innovation, deployment, and circular economy practices.

References

- [1] Sustainable Energy Development Authority (SEDA) Malaysia website, Malaysia Renewable Energy Roadmap (MYRER) <https://www.seda.gov.my/reportal/myrer/>.
- [2] L. A. Wong *et al.*, '[Optimal Placement and Sizing of Battery Energy Storage System Considering the Duck Curve Phenomenon](#)', *Special Section on Evolving Technologies in Energy Storage Systems for Energy Systems Applications*, IEEE vol. 8, pp. 197236-197248, 2020.
- [3] F. Muhammad-Sukki *et al.*, 'Progress of feed-in tariff in Malaysia: A year after', *Energy Policy*, vol. 67, pp. 68-625, 2014.
- [4] Business Times, 'Feed-in-Tariff Scheme Fits in Well with Gading Kencana', 2012. https://dev.seda.gov.my/seda_dev/?y=45&s=1839
- [5] Single Buyer website, 'Corporate Renewable Energy Supply Scheme (CRESS)' <https://www.singlebuyer.com.my/>.

- [6] Energy Commission of Malaysia, 'Guidelines for Corporate Renewable Energy Supply Scheme (CRESS) (First Edition Sept 2024)', 2024. <https://www.st.gov.my/>.
- [7] S. M. Abu *et al.*, 'State of the art of lithium-ion battery material potentials: An analytical evaluations, issues and future research directions', *Journal of Cleaner Production*, vol. 394, pp. 136246, 2023.
- [8] Energy Storage News, 'Leader Energy and BASF to deploy NGK's sodium-sulfur batteries in SE Asia', 2023. <https://www.energy-storage.news/leader-energy-and-basf-to-deploy-ngks-sodium-sulfur-batteries-in-se-asia/>.
- [9] 'Malaysia Battery Market 5.28 CAGR Growth Outlook 2025-2033', December 25, 2024.
- [10] SEDA, Net Energy Metering (NEM) 3.0, <https://www.seda.gov.my/reportal/nem/>.
- [11] Ministry of Economy, 'National Energy Transition Roadmap, Energising the Nation', 2023. <https://ekonomi.gov.my/>.
- [12] I. Farouk, Y. L. Go & M. Fernandez, 'Evaluation of energy scenarios for Malaysia for energy transition in meeting net-zero target 2050', *Next Energy*, vol. 7, pp. 100295, 2025.
- [13] Malaysian Green Technology and Climate Change Corporation, 'Green Investment Tax Allowance (GITA) & Green Income Tax (GITE)' <https://www.mgtc.gov.my/what-we-do/green-incentives/green-investment-tax-incentives-gita-gite/>.
- [14] The Edge Malaysia, 'Citaglobal-Genetec JV unveils Malaysia's first locally produced battery energy storage system', 2023. <https://theedgemalaysia.com/node/662928>
- [15] Nabalunews, 'Powering The Future: The Role of BESS In Renewable Energy Integration', 2025. <https://www.nabalunews.com/post/powering-the-future-the-role-of-bess-in-renewable-energy-integration>.
- [16] I. B. N. Anwar *et al.*, 'Micro-Grid of Batteray Energy Storage System (BESS) Design for Malaysia's Net Energy Metering (NEM)', *The 3rd International Conference on Renewable Energy (I-CORE 2023)*, vol. 473, p. 02001, 2023.
- [17] V. Saxena, N. Kumar & U. Nangia, 'Computation and Optimization of BESS in the Modeling of Renewable Energy Based Framework', *Arch Computat. Methods Eng* vol. 31, pp. 2385–2416 (2024).
- [18] S. S. M. Isa *et al.*, 'A Review on Deep Learning and Hybrid Model for Forecasting Residential and Commercial Buildings Energy Consumption', *5th International Conference on Artificial Intelligence and Data Sciences*, 2024.
- [19] K. Deshmukh *et al.*, 'Sodium-ion batteries: state-of-the-art technologies and future prospects', *Journal of Materials Science*, vol. 60 pp. 3609-3633, 2025.

- [20] NMB, 'NanoMalaysia Energy Storage Technology Initiative (NESTI)' <https://nanomalaysia.com.my/nesti>
- [21] Energy Storage News, 'Vanadium flow batteries considered for integration into green hydrogen project in Malaysia', 2021. <https://www.energy-storage.news/vanadium-flow-batteries-considered-for-integration-into-green-hydrogen-project-in-malaysia/>.
- [22] M.R. Mohamed, P.K. Leung & M.H. Sulaiman, 'Performance characterization of a vanadium redox flow battery at different operating parameters under a standardized test-bed system', *Applied Energy*, vol. 137, pp. 402-412, 2015.
- [23] Verified Market Reports, 'Malaysia Aluminum Foil for Battery Cathode Market Size, Trends, Major Competitors | Forecast Challenges 2033', 2025.
- [24] Mohamad Azreen Firdaus Abd Aziz, Mahallil Amin Abdul Malek, Norsam Tasli Mohd & Ir. Mohd Qaharuddin, 'Outlook of Malaysia's battery industry ecosystem', Malaysian Foresight Institute, 2019. <https://www.myforesight.my/outlook-of-malysias-battery-industry-ecosystem/>
- [25] MGTC News, 'By 2050, 870,000 EV batteries will need recycling: How is Malaysia tackling the challenge?', 2025. <https://www.mgtc.gov.my/2025/03/by-2050-870000-ev-batteries-will-need-recycling-how-is-malaysia-tackling-the-challenge/>
- [26] SEDA, 'GCPV Systems Design Course', <https://www.seda.gov.my/seda-event/trainings/gcpv-systems-design-course/>.
- [27] C. W. Siang, A. S. B. Shamsuddin & L. K. Boon, 'Investigation of Electric Vehicle (EV) and Renewable Energy Sources (RES) for Low Voltage Distribution Network in Malaysia', *International Conference on Green Energy, Computing and Intelligent Technology Proceedings*, vol. 2023, no. 11, 2023.
- [28] P. Eleftheriadis *et al.*, 'Second Life Batteries: Current Regulatory Framework, Evaluation Methods, and Economic Assessment', IEEE Industrial and Commercial Power System Europe Conference, 2022.
- [29] Energy Storage News, 'Malaysia government minister welcomes country's first 'homegrown' BESS solution', <https://www.energy-storage.news/malaysia-government-minister-welcomes-countrys-first-homegrown-bess-solution>

Fiji

This section was written by Dr Sekove Vodo, Lecturer in Chemistry at the University of Fiji. He researches sustainable energy and waste management, with a particular emphasis on second-life batteries and e-waste.

1. Introduction

Fiji is a Small Island Developing State (SIDS) with a growing economy and population. The availability, accessibility, and reliability of energy services are essential for Fiji's economy and to the well-being of all Fijians. Fiji's economy and energy sector face many challenges and will continue to be shaped by various local, regional, and global trends. Fiji's National Energy Policy 2023-2030 is the blueprint towards a highly sustainable, inclusive and affordable energy services sector by the close of the decade [1]. It sets a strong policy foundation for the transformational investments that are urgently needed to revolutionise Fiji's energy sector for the better. Fiji aims to derive close to 90% of its electricity services from renewable energy (RE) sources by 2035 [2]. This will require systemic transitions for Fiji's energy sector, including the integration of variable renewable energy (VRE) capacity into the country's electricity grids, the development of mini-grids, and the linkage between renewable electricity production and the use of electric vehicles (EVs).

2. Key research areas in battery technologies

Research into large-scale energy storage solutions for solar power is a priority [3]. This involves improving the efficiency, lifespan, and affordability of batteries to store solar energy and ensure a stable supply for off-grid communities and businesses [4]. Given the environmental impact of battery disposal, companies like Pacific Batteries have made significant progress in developing solutions for recycling lead-acid batteries. Research into sustainable methods of recycling batteries, particularly for use in off-grid applications, is ongoing.

In both solar and vehicles, lead-acid batteries are still widely used in Fiji. Research efforts are focused on improving efficiency and recyclability within the local context [5]. Although not as prevalent as lead-acid, lithium-ion (Li-ion) batteries are an emerging area of interest, and Li-ion battery recycling would be important. As an alternative to Li-ion batteries, sodium-ion batteries could be an area of future exploration in Fiji but there are no current large-scale research initiatives on sodium-ion, solid-state, or flow batteries. This Faraday Institution Ambassadorship could eventually influence Pacific SIDS to delve into battery technology research.

3. Material sourcing and local manufacturing

Fiji does not have significant reserves of critical raw materials used in battery production, such as lithium, cobalt, manganese, or nickel [5]. The country is largely dependent on imports of battery materials, which are required for manufacturing lead-acid batteries. Fiji's mining industry primarily focuses on mineral extraction such as gold and bauxite, with no substantial production of the raw materials critical for battery manufacturing [6].

Mining activities in Fiji, such as bauxite mining, have raised concerns over environmental degradation. Deforestation, water contamination, and habitat disruption have been reported in areas near active mining sites [7]. Mining operations need to adhere to strict environmental regulations to mitigate these effects, but enforcement can sometimes be a challenge. While mining provides employment opportunities, especially in rural areas, there are concerns over labour conditions and displacement of communities. Mining contributes to Fiji's economy, though its role is comparatively small when compared to sectors like tourism or agriculture [6].

Fiji has made some strides in establishing local battery recycling programmes, especially for lead-acid batteries. The country's recycling industry is limited, and efforts to develop sustainable solutions for the disposal of hybrid car batteries are still in the early stages [5]. The primary recycler of lead-acid batteries in Fiji is Pacific Batteries, located in Lami, Fiji. Pacific Batteries is a leading player in the Pacific region, handling the recycling of both local and imported used lead-acid batteries. This includes batteries from hybrid vehicles, which use lead-acid cells for starting, lighting, and ignition purposes. The company processes approximately 200,000 tonnes of used lead-acid batteries monthly [8]. These are sourced from Fiji and other Pacific Island countries, following the Waigani Convention, which mandates the shipment of hazardous waste to the nearest recycling facility. The recycling process at Pacific Batteries involves cutting open the batteries, neutralising the acid in a treatment plant, and then melting the lead at high temperatures to refine it. The plastic casings of the batteries are also recycled and sold as chips to Spain [8]. This process helps mitigate the environmental risks associated with improper disposal of lead-acid batteries. Although hybrid vehicles are increasingly common on Fijian roads, the recycling of Li-ion and nickel-metal hydride batteries is not yet widespread. Pacific Batteries currently processes only about 5% of the used hybrid vehicle batteries [8]. The technology and infrastructure to effectively recycle these types of batteries locally are lacking, and it is not economically viable for Fiji to set up such facilities due to high investment costs and limited demand.

The Department of Environment in Fiji works closely with Pacific Batteries to monitor environmental standards, especially the emissions from battery recycling processes. The company regularly tests its water samples to ensure that they meet environmental standards, especially in the treatment of acidic waste. There are also discussions within the government about strengthening policies related to the recycling of hybrid and electric

vehicle batteries. The Department of Environment is working on introducing appropriate technologies for the management of waste at the Naboro Landfill, which could play a role in the future handling of automotive batteries and related waste.

The Pacific Islands Forum has been instrumental in encouraging collaboration between Pacific Island countries, and Pacific Batteries' recycling efforts are also supported by regional conventions such as the Waigani Convention. This has facilitated the export of hazardous waste from neighbouring countries like Papua New Guinea to Fiji's recycling facilities. While Fiji is not a major player in the global battery production supply chain due to a lack of raw materials, the country has made significant strides in recycling lead-acid batteries. The recycling of hybrid vehicle batteries, however, remains a challenge due to the lack of local infrastructure and economic feasibility. Efforts are underway to improve battery disposal and recycling methods, with a particular focus on creating a more circular economy for the automotive sector. Further investment in technology and research, as well as international partnerships, will be critical to scaling up these efforts in the future.

4. Key research institutions and collaborations

The Fiji Department of Environment (DoE) plays a pivotal role in promoting environmental sustainability and managing waste. In collaboration with local universities and international partners, the DoE is actively involved in research and initiatives related to the recycling of lead-acid batteries, a significant environmental concern in many Pacific Island nations. The DoE works closely with local and regional stakeholders to develop policies and solutions that support battery recycling, reduce hazardous waste, and promote circular economy practices.

Fiji's local town councils, alongside the national government, are key players in ensuring that proper waste management systems are in place, particularly for hazardous materials like lead-acid batteries. These councils have been instrumental in fostering public-private partnerships to establish collection points and recycling programmes. Their efforts are supported by ongoing research in battery management and recycling to ensure that Fijian communities are better equipped to handle the growing waste challenges in a sustainable manner.

Pacific Waste Recyclers is a private-sector collaborator focused on lead-acid battery recycling in Fiji and other Pacific Island countries. The company has worked to develop local solutions for the safe disposal and recycling of lead-acid batteries, which are commonly used in vehicles and solar photovoltaics (PV). By partnering with academic institutions and government bodies, Pacific Waste Recyclers is making strides in creating a more sustainable and closed-loop system for battery disposal and recycling in the Pacific region.

The Asian Development Bank (ADB) has been instrumental in funding renewable energy projects and infrastructure development across the Pacific Islands. ADB's ongoing efforts in energy storage systems, particularly for renewable energy integration, could potentially

extend to collaborative research on energy storage solutions like lithium batteries [9]. ADB could also play a key role in funding initiatives that support Fiji's capacity-building efforts in this area.

The EU has been at the forefront of developing sustainable energy solutions, including battery technology for clean energy. Through various funding mechanisms like the Horizon Europe programme, Fiji could potentially engage in EU-funded research projects focused on advanced battery technologies, recycling, and sustainable energy storage solutions, particularly for off-grid communities in the Pacific Islands.

The International Union for Conservation of Nature and SPREP (Secretariat of the Pacific Regional Environment Programme) play critical roles in promoting environmental sustainability and supporting the Pacific region's efforts to mitigate the impacts of waste and pollution. While their primary focus has been on broader environmental concerns, they have increasingly included topics related to waste management, which could include recycling and safe disposal of batteries. Collaborating with these bodies could strengthen Fiji's capacity to develop environmentally sustainable approaches for battery waste management, aligning with regional environmental goals.

The University of Fiji has taken a pioneering role in the region by initiating research focused specifically on Li-ion battery systems. This effort marks an important step in developing localised solutions for battery storage and disposal. UniFiji's commitment to conducting research on battery technologies, including the environmental impacts of battery use and disposal, is crucial for Fiji's future energy sustainability.

5. Battery skills assessment

In recycling lead-acid batteries, companies like Pacific Batteries operate a lead recycling plant and engage in activities like battery cutting, neutralising acid, and refining lead to create new products. Technical skills in both environmental management and battery production are available, but there is no specific mention of skills across other segments of the value chain, such as battery design, manufacturing, or advanced energy storage solutions.

In terms of skills development programmes, Pacific Batteries invests in upgrading its machinery and technology, which may indirectly imply efforts to maintain and develop a skilled workforce. The company works closely with the DoE to meet environmental standards, indicating that there may be training and skill development to ensure compliance with these regulations [8].

6. Policy, funding and challenges

Regarding national policies supporting battery research, the government has incentives for the use of fuel-efficient hybrid cars and EVs to reduce fuel imports and protect the

environment [1]. This could indirectly support the use of batteries, especially for hybrid and EVs. The government of Fiji is committed to promoting the use of environmentally friendly vehicles that would require the integration of battery technology. The key challenge for the battery sector in Fiji is the lack of capacity to recycle Li-ion and nickel-metal-hydrate batteries. While Pacific Batteries is actively recycling lead-acid batteries, the company does not yet have the infrastructure to handle newer types of batteries like those used in hybrid and EVs. Also, the high cost of setting up a local recycling plant for these advanced batteries as well as the insufficient end-of-life battery supply makes it unfeasible in the current economic climate. There is also a challenge in balancing cost with the need to maintain environmental standards and expand capacity.

References

- [1] Government of Fiji, Ministry of Public Works, Meteorological Services and Transport, 'Fiji National Energy Policy 2023-2030', Suva, Fiji.
https://prdrse4all.spc.int/sites/default/files/nep-report_final_2023_2030.pdf
- [2] Energy Fiji Limited, 'Annual Report 2024', Suva, Fiji. <https://www.parliament.gov.fj/wp-content/uploads/2025/07/75Energy-Fiji-Limited-Annual-Report-2024.pdf>
- [3] World Bank, 'Fiji: Accelerating Renewable Energy Integration', 2021.
- [4] International Renewable Energy Agency (IRENA), 'Fiji Energy Sector Overview', 2021.
- [5] R. D. Prasad & A. Raturi, 'Energy Storage Technologies for Small and Mini Grid Systems in Fiji', The University of the South Pacific, 2019.
- [6] Fiji Bureau of Statistics, 'Mining and Quarrying 2023', Suva, Fiji.
<https://www.statsfiji.gov.fj/mining-and-quarrying-2023/>
- [7] N. Tuilevuka, 'Soil degradation due to bauxite mining activities', The Fiji Times, 2024.
<https://www.fijitimes.com.fj/soil-degradation-due-to-bauxite-mining-activities/> Accessed 6 December, 2024.
- [8] I. Nataro-Tunidau, 'The challenges of importing hybrid cars', Fiji Sun, 2021.
<https://fijisun.com.fj/news/investigations/the-challenges-of-importing-hybrid-cars>
- [9] Asian Development Bank, 'Rural Electrification Support Project (Project No. 57056-001)'
<https://www.adb.org/projects/57056-001/main> Accessed 3 September, 2025.

Summary and other Initiatives

This report “Charging Ahead: Battery Ecosystems, Energy Transitions and Electrification in Emerging Economies” maps the battery ecosystem landscape in 12 emerging economies, to document the progress of the electrification transition in those nations, and to lay out the opportunities and challenges in battery research, technology integration and policy regulation. The paper also sets out to signpost ongoing needs to meet electrification targets, including in fundamental research, demonstrator projects, training and skills, and national and international collaborations.

Twelve individual country perspectives have been provided by the Battery Ambassadors: from Sub-Saharan Africa: Ghana, Kenya, Malawi, Nigeria, South Africa, Zambia, and Zimbabwe; from South Asia: Bangladesh, Nepal, and Pakistan; and Malaysia and Fiji from the Indo-Pacific region.

It is important to note that this report does not attempt to benchmark opportunities in one country or region against another, or against Western nations or, indeed, China. The report [“Minerals to Manufacturing: Africa’s Competitiveness in Global Battery Supply Chains”](#) published in November 2024, goes some way towards benchmarking these opportunities across Africa, revealing cost-competitive investment opportunities in the battery supply chain in Africa. Key findings indicate that, with the right investment and policy environment, refining locally extracted lithium, nickel, manganese and copper in Africa could be up to 40% more competitive than the rest of the world by 2030. Beyond mineral refining, initial analysis suggests that countries like Tanzania and Morocco could produce batteries that are cost-competitive with Europe under certain conditions.

This lack of benchmarking across nations in the current report makes it difficult to draw together conclusions that apply universally across all 12 nations included in the study. Indeed, caution should be exercised before attempting to draw conclusions that apply in a single region considered, for example, Sub-Saharan Africa. Each country’s minerals wealth, geography, political stability, energy policy framework, strength of its academic and industry sectors, and many other factors all contribute to influencing the current status of access to clean energy in the nations and the opportunities that batteries will play in each in the energy transition.

That said, certain general themes can be drawn:

1. Power mix and the key role of batteries

The electricity generation per capita in the 12 Ambassador countries ranges from a high of about 5,500 kWh for Fiji to a low of 100 kWh for Malawi. Furthermore, the generation mix varies considerably from fossil fuel-intensive systems such as South Africa (80% coal), Nigeria (80% natural gas), Bangladesh (> 85% natural gas + coal + oil), and Malaysia (80%

coal + natural gas) to considerably cleaner power grids, such as Nepal (98% renewable), Kenya (nearly 85%), and Zambia (85%). These vast differences in the existing power generation mix leads to fundamentally different drivers for battery adoption - including the specific battery technologies likely to be adopted, in which sectors and their adoption rates.

Having stated this, batteries will play multiple key roles in all the nations considered in the report and in so doing will support the move towards achieving Sustainable Development Goals (SDGs), particularly progress on Affordable and Clean Energy (SDG7) and Climate Action (SDG13). These roles include:

- Increasing the penetration of renewable energy sources on the grid
- Improving grid stability
- Replacing fossil fuel generators
- Improving energy access in off-grid communities via deployment of mini-grids
- Driving the electrification of transport – particularly in two- and three-wheelers.

2. Challenges with battery deployment

Despite early demonstrations of use of battery technologies in many emerging economies, the battery sectors of many of the countries are limited by several recurring challenges:

- High dependency on imports (exacerbated by local currency fluctuations).
- Undeveloped infrastructure across the battery value chain, including energy and utilities, supply chain logistics, specialised manufacturing equipment, R&D centres, and battery testing facilities.
- A lack of clear battery quality and safety standards leading to performance and safety issues associated with use of cheap cells, with imports very much driven by price.
- Limited technical expertise.
- Environmental and health concerns associated with a lack recycling facilities for the growing volumes of lithium-ion batteries at end of life.
- (In some cases) a lack of coherent and stable policy environment that would anchor investor confidence that is needed to facilitate growth of the sector, encourage battery adoption and supply chain development.
- Financial barriers: limited government financing and foreign direct investment.

3. Battery chemistries

In general, lead-acid batteries are ubiquitous in Ambassador countries and command existing local manufacturing, usually in the form of a full end-to-end self-reliant domestic industry. Given this capability it is likely that the use of lead-acid batteries will persist for longer in many emerging economies than in high-income countries, The transition from lead-acid to lithium-ion varies greatly among the Ambassador countries from more

advanced (e.g., Malaysia) to nascent (e.g., Fiji). Furthermore, Ambassador countries vary considerably in which subsector leads lithium-ion battery adoption.

For example, stationary applications are leading in South Africa (residential, commercial, industrial and grid) and Bangladesh (telecommunications) while mobile applications are leading in Kenya (two- and three-wheelers). In Nepal where existing electricity generation is 98% hydro, there is limited scope for grid-connected BESS. On the other hand, with one of the highest EV adoption rates in the world (estimated to be second only to Norway as of 2025), the four-wheeler EV subsector leads lithium-ion battery adoption in Nepal.

The mix of battery chemistries in use in emerging economies is likely to be different to that used in high income countries. Flow batteries may find significant use cases in some countries featured in this report. This is particularly true for South Africa, which is a globally significant producer of vanadium (and vanadium redox flow batteries – VRFBs – being the most advanced commercially). An assessment of the suitability of flow batteries for use and manufacture in emerging economies in comparison to lithium-ion and lead-acid batteries can be found in the report [“Market and Technology Assessment of Flow Batteries for Developing Economies.”](#)

A number of countries covered in this report have significant reserves of sodium and are interested in the development and use of sodium-ion batteries. More broadly, some sodium-ion technologies have a number of advantages (high-temperature operation and the ability to discharge to zero Volts, easing issues of transportation relative to Li-ion) that make the technology attractive in certain emerging economies.

There is limited battery research in many Ambassador nations. National research priorities are focused on where countries see strategic opportunities that are underpinned by the availability of resources and market demand. Of the nations studied, South Africa has the broadest battery research programme that is both academic- and industry-driven through its universities and research institutes and spans the entire value chain from mineral processing and refining to recycling of end-of-life batteries.

4. Policy

4.1 Vertical integration of supply chains

Most, though not all, of the nations considered in the report have considerable mineral wealth in battery minerals. Several battery minerals are already being mined at scale in some Ambassador countries, e.g., manganese (South Africa, Ghana, Kenya), lithium (Zimbabwe), cobalt (Zambia), copper (Zambia, Zimbabwe), fluorspar (Kenya), and rock salt and zinc (Pakistan). Advanced efforts are also underway to develop mine deposits, e.g., Ewoyaa Lithium Project (Ghana), Reko Diq Project (Pakistan – copper and gold), and Kasiya Rutile-Graphite Project (Malawi). Some Ambassador countries have known battery mineral

deposits that require further geological exploration work before they could be developed such as Nigeria (e.g., manganese, lithium, graphite, and cobalt), and Pakistan (graphite).

However, most of the minerals that are mined are exported and refined elsewhere, limiting the economic impact to the originating nation. The exception is South Africa, which produces some battery-grade mineral products: electrolytic manganese metal and pilot scale high-purity manganese sulfate monohydrate for use in lithium-ion batteries and vanadium electrolyte for use in VRFBs.

By attracting investment in mineral beneficiation, refining infrastructure, and regional supply chain linkages, many of the 12 countries featured here have the potential to capture more value and move beyond raw material export and into other upstream battery manufacturing processes. Indeed there is a growing move by countries to mandate such processing in-country before export licenses are granted. In doing so, there are considerable opportunities for wealth generation and further involvement in the battery materials supply chain, enabling such nations to become true participants in the global battery economy. The report [“Minerals to Manufacturing: Africa’s Competitiveness in Global Battery Supply Chains”](#) outlines some of these opportunities. Additionally, the African Green Minerals Strategy (2025) proposes several policy interventions to stimulate local advanced processing of energy minerals.

Further country-specific research, such as the British Geological Survey’s “Critical minerals potential of Zambia,” the first critical minerals guide that supports the country’s potential in global clean energy transition and Manufacturing Africa’s “Tanzania-Minerals-Value-Addition-Perspective” outline additional support for furthering the ambitions of countries with significant mineral resources. Partnering with organisations like these offers opportunities to obtain data and evidence to further support policy and other interventions that could help drive local participation in global critical mineral and battery value chains.

Cross-border partnerships will be key to capturing value in battery supply chains. For example, Zambia is part of the ambitious Zambia-DRC-Morocco strategic tripartite partnership which, if successful, could see the country establishing local battery precursor and cell manufacturing capacity.

4.2 Mandating energy storage systems

To ensure grid stability while increasing the penetration of renewable energy generation, more countries are requiring independent power producers to include a battery energy storage system in new developments as a prerequisite for award of a power purchase agreement. More nations could explore such mechanisms, for example, to require the integration of a battery energy storage system equivalent to a certain percentage of a new solar module’s AC capacity.

4.3 Supporting the start-up ecosystem

Many sections of this report recognise the significant role that entrepreneurship and start-ups are playing in the energy transitions of emerging economies. For example, in Kenya, electric mobility, predominantly two-wheelers, has driven a thriving start-up ecosystem across battery pack design, battery-as-a-service (BaaS) models, and battery swapping infrastructure.

In South Africa, Giga Africa 1 and Afrivolt are two start-ups attempting to develop local lithium iron phosphate cell manufacturing. Other start-ups are manufacturing battery packs, predominantly LFP for residential, commercial, industrial and utility-scale applications. Pack development for use in fully off-grid renewable energy EV charging infrastructure is an emerging segment.

With its ambition to become the ASEAN regional EV industry hub, Malaysia is building an end-to-end EV ecosystem, making it unique among Ambassador countries. Its ecosystem includes a mix of start-ups and established companies with existing or planned operations in cathode production, cell manufacturing, pack assembly and system integration, second-life batteries, and recycling, including the metallurgical refining of black mass. This ecosystem also includes a growing number of actors in BESS for renewable energy integration to the power grid and microgrids.

For most Ambassador countries, public-private partnerships are seen as playing a key role in promoting investment across the battery value chain. Development finance institutions and donor agencies are also actively involved in battery value chains either through capacity building or direct investment in start-ups in many Ambassador countries. These partnerships, alongside policies that encourage innovation and entrepreneurship within the local start-up ecosystem, will be critical to nations achieving their potential.

4.4 Dependence on imports and performance standards

Most authors noted the considerable challenge of aligning policy ambitions with financial investment. Across all nations considered in this report continued government support as well as investment and strategic collaborations are needed to help the battery industry bridge the energy gap and meet the continent's growing demand for reliable, sustainable energy solutions.

Most of the countries included in this report recognise the need to minimise dependence on imports. Effective and coherent policy direction is key – including to support use and assembly of batteries locally, while not implementing prohibitive import tariffs that stifle the whole sector. As outlined in “Minerals to Manufacturing: Africa’s Competitiveness in Global Battery Supply Chains” one of the most immediate opportunities for nations to engage in the battery supply chain is to import cells and assemble them into packs for use in, for example, battery energy storage systems suited to the local context. Consideration needs to be given to ensure that performance and safety standards are set (supported by in-

country skills and test facilities) for cells exported to emerging economies. This is needed to ensure that BESS systems do not fail due to import and use of substandard cells – as has been noted in several places in this report. The Faraday Institution Seed project, [MaxBatt](#) explored the performance of cheaper Li-ion cells in applications in the Global South, noting that storing cells at a high ambient temperature can negatively affect their performance.

The World Bank Energy Storage Partnership has highlighted the safety concerns associated with BESS systems and will be publishing a BESS Safety Live Wire later this year entitled “Enhancing Safety in Battery Energy Storage Systems: Global Lessons and Best Practices.” The report will provide its client countries in the early stages of BESS adoption with information on current standards and industry practices.

5. Circularity and recycling

While Li-ion battery recycling plants are already operational in Malaysia and pilot projects exist in South Africa, Nigeria, and Kenya, a lack of battery recycling capacity remains a growing challenge across many Ambassador countries (as is the case with many high-income countries). As battery use grows and increasing volumes of batteries reach their end of life this must be addressed.

Recycling Li-ion batteries offers several benefits, including reducing environmental damage and opening up significant economic opportunities. It offers the opportunity to recover high-value metals such as lithium, manganese, copper, aluminium, cobalt and nickel for reuse, thereby reducing the need for primary metal extraction, conserving natural resources and supporting a circular economy. For those countries that succeed in attracting investment in cell manufacture the creation of a formalised recycling economy would reduce reliance on imports of those materials that cannot be sourced locally.

As high-income countries develop their own battery reuse and recycling industries measures and mechanisms should be put into place to enable knowledge sharing and collaboration with emerging economies in reuse and recycling methods that are suitable for that context, including demonstrator projects. Mechanisms should be investigated to encourage neighbouring countries to share recycling facilities, especially while recycling volumes are small.

In 2021, the Faraday Institution, working with partners the Global Battery Alliance and the World Bank Energy Storage Partnership, published “[Closing the Loop on Energy Access in Africa](#),” which proposed several immediate steps that could be taken to establish circular economy principles in countries in Africa.

The Faraday Institution is working with entities such as the Ellen MacArthur Foundation that is proposing a [system-level approach](#) to EV battery life and critical mineral management. This is a shift from previous thinking on a circular economy for EV batteries, which has been fragmented and not presented in a coherent manner.

[Recently announced](#), a battery recycling pilot plant is being established in Nigeria, with support from the UK Government-funded Accelerate-to-Demonstrate facility, managed by the United Nations Industrial Development Organization. The pilot, led by Hinckley Recycling, in partnership with the University of Birmingham and the Federal University of Technology Owerri (FUTO), will demonstrate the recycling of around 5,000 tons of lithium-ion batteries per year using innovative solutions that recover valuable minerals. In doing so nearly 100 jobs will be created. Pilot demonstration projects of this type are needed if circular economy ambitions are to be realised.

6. Capacity building, training and skills development

Successfully deploying batteries in emerging economies will require overcoming skills challenges. The skills required by the workforce, and at which time, will depend on the rate of progression towards electrification in each country, the type of batteries deployed, and the activities being carried out in-country across the value chain (minerals refining, development of mini-grids, build out of battery swap out stations, production of battery packs, and eventually recycling of batteries at end-of-life).

Research collaborations and funding towards technical skills development for sustainable battery management practices are vital factors to produce a trained workforce across the entire battery value chain. Addressing the gaps will require coordinated efforts between governments, educational institutions, industry, and international partners to develop curricula aligned with emerging market and regulatory needs.

It is likely that universities and polytechnics will need to integrate specialised programmes in battery technology, materials science, renewable energy, and advanced manufacturing. Strengthened cooperation between industry and academia via co-designed curricula, internships, attachments, and joint research are likely to be impactful ways to support practical skills acquisition.

The Transforming Energy Access Learning Partnership (TEA-LP), which includes many of the Battery Ambassador's host organisations, will play a key role in skills development and knowledge sharing. It is a global partnership of universities and stakeholders across Africa, South Asia, and the Indo-Pacific, driving the transition to sustainable energy access for all. Through innovative Master's programmes, continuing professional development courses, and a growing network of expertise from emerging economies, TEA-LP is equipping the next generation of energy leaders and supporting professionals already shaping the sector.

The Faraday Institution's Battery Ambassador Network could play a key role in the establishment of battery-specific skills development in emerging economies. By partnering with UK academic institutions and exploiting the electrification skills and training frameworks being developed in the UK, together they could explore visiting researcher and knowledge exchange programmes focusing on battery operation, safety and end of life.

Other organisations will also play an important role. The United Nations Institute for Training and Research (UNITAR) is establishing a Global Battery (Waste) Monitor, which will be a global and interdisciplinary report for sustainable battery waste management. Part of the programme will include capacity building initiatives such as battery waste academies and bootcamps for senior decision makers.

7. Collaboration across nations

An array of success stories have been described in the various sections of this report on use of energy storage systems on mini-grids. In addition [six concept-to-demonstrator projects are ongoing as part of the Ayrton Challenge on Energy Storage](#). It is evident that there would be considerable benefits for the sharing of learnings from these demonstrators across nations. This could be the focus of a future series of Battery Network webinars.

The structure of this report, which considers each nation's battery ecosystem individually, means that the value of collaboration between regional neighbours and into Western countries has been largely overlooked here. There are some exceptions. For example, it has been mentioned that Zambia and the Democratic Republic of Congo are jointly developing strategies to build local capabilities in battery precursor production. Other authors have reflected on opportunities open to members of the Southern African Development Community, whose nation states, between them, possess reserves of almost every battery mineral.

Readers of this report, particularly from Sub-Saharan Africa, are encouraged to read sections not just about their own countries, but on others from their region to identify common themes and opportunities for collaboration.

Continued collaboration with international partners will remain vital for accessing technologies and expertise and catalysing growth in the sector. Initiatives such as the Ayrton Challenge on Energy Storage (specifically the Battery Ambassadors), and the Transforming Energy Access Learning Partnership will be key in linking up battery researchers, innovators and practitioners in different countries – links that can be developed into collaborative partnerships that can deliver impact.

Complimentary government programmes and initiatives can also play a part. For example, the UK's Foreign, Commonwealth & Development Office-funded, Climate Compatible Growth programme recently published a policy brief "[Beyond Extraction: Simulating Increased Battery Mineral Value Addition in Southern Africa](#)" in which simulations identify significant potential to increase net export revenues by diversifying mining activities and moving up the value chain into processing, particularly where there is regional cooperation. The report does note that "a regional processing approach would heighten demand for transport and energy infrastructure in order to realise the resulting increased potential for mineral and metal processing in Southern Africa. Delivering a regional approach would also require overcoming political challenges to crossborder trade and benefit sharing."

Another example of an international partnership in critical minerals linked to the battery value chain comes from India, where partners from India and the University of Cambridge have developed the [UK–India Critical Mineral Supply Chain Observatory](#). Funded by the UK-India Technology Security Initiative, this tool has been used to track global movements of cobalt and lithium to the UK and India. Further development of the tool, to include geographies in the Global South, may be possible with the right partnerships.

8. Future perspectives

Virtually every Ambassador country has published targets for renewable energy integration into the generation mix as well as, in some cases, EV adoption targets. While some of these are aspirational rather than realistic, they represent a clear direction of travel – that battery adoption will continue in multiple sectors of the economies of the nations covered in this report.

The report’s authors predominantly relied on desktop research, and as such the report should be understood as only the first step in developing visibility of battery activity in Ambassador countries – and more broadly, emerging economies – on a global stage. More needs to be done, not only to build a fuller picture through gathering direct evidence from local stakeholders, but to also expand this type of research to other emerging economy countries.

To continue the momentum, the Battery Ambassadors from Ghana, Zambia and Nepal plan to conduct in-person validation workshops with key stakeholders from government, the private sector and research to dive deeper into the battery value chain opportunities within their countries and propose actions to guide policy, research, and investment in their battery and energy storage sectors.

There are opportunities for the Battery Ambassadors to deliver further impact by informing routes to penetration of new battery technologies across their nations. For example, to help inform investment priorities for the next phase of the TEA programme, individuals will carry out country-level energy storage context studies exploring opportunities for market growth potential of a new pack technology in several key African countries. They will seek to understand wider ecosystem challenges (such as manufacturing bases, transportation, training, and cost) of deploying a small, simple, low cost and scalable soft-case sodium-ion battery pack that can be assembled locally, transported safely, and used in a variety of applications in Sub-Saharan Africa.