Faraday Report – October 2025

THE FARADAY INSTITUTION

with

and

FORESIGHT TRANSITIONS

Swanbarton

University of Southampton

Market and Technology Assessment of Flow Batteries for Developing Economies

UKaid from the British people

AYRTON FUND

This report was commissioned by the Faraday Institution and written by [1]Foresight Transitions Ltd, with [2]Swanbarton Limited and the [3]University of Southampton. Authors were Diarmid Roberts[1], James Hancock[2], Ewan Fraser[3], Anthony Price[2], Alastair Stevens[2], Solomon Brown[1] and Richard Wills[3].

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: Invinity VS3 vanadium flow battery at the Spencer Energy project, South Australia. A 2 MW / 8 MWh VFB collocated with a 6 MWp PV array.

Contents

Glossary

ASEAN	Association of Southeast Asian Nations
BESS	Battery energy storage system
BMS	Battery management system
CIP	Competitive Industrial Performance
CMP	[African] Continental Master Plan
DE	Developing economies
EMS	Energy management system
FB	Flow battery
GDP	Gross domestic product
HVAC	Heating, Ventilation and Air Conditioning – equipment required to keep a battery system at the required temperature
IEA	International Energy Agency
LCE	Levelised Cost of Electricity
LDES	Long duration energy storage. Broadly speaking this refers to energy storage suitable for time shifting of bulk electricity consumption as opposed to ancillary services like frequency response. In the UK the lower threshold definition has increased from 4 h (LODES tender in 2022) to 6 h then 8 h for the Cap and Floor support policy mechanism. The latest change was made partly to achieve consistency with "various international definitions at eight hours or longer"[1]. In a developing economy context, this definition broadly aligns with the duration of storage required to improve stability of grids using solar power.
LFP	Lithium iron phosphate – a type of lithium-ion battery
LIB	Lithium-ion battery, referring to the LFP chemistry – which is becoming prevalent in stationary storage applications - unless otherwise stated
MCI	Mining Contribution Index

[1]Long Duration Electricity Storage: Technical Decision Document https://www.ofgem.gov.uk/sites/default/files/2025-03/Long Duration Electricity Storage Technical Decision Document.pdf

NGCP	National Grid Corporation of the Philippines
ODA	Official development assistance
OECD	Organisation for Economic Co-operation and Development
PbAB	Lead acid battery
PFAS	Polyfluoroalkyl substances
PNG	Papua New Guinea
PPA	Power purchase agreement
PV	Photovoltaics, shorthand for solar panels produced from polycrystalline silicon solar panels.
RTE	Round-trip efficiency – percentage of energy used to charge an energy store that may be recovered.
SOC	State of charge of a battery
SCADA	Supervisory Control and Data Acquisition – the components of a battery system that allow it to safely run autonomously and necessary maintenance to be triggered.
SSA	Sub-Saharan Africa
TRL	Technology readiness level
TEMPO	2,2,6,6-tetramethyl-1-piperidinyloxy, a stable free radical compound
TRL	Technology readiness level
UNIDO	United Nations Industrial Development Organization
UPS	Uninterruptible power supply
VRE	Variable renewable energy, primarily wind and solar, where the output varies in an uncertain way
V(R)FB	Vanadium (redox) flow battery – note that the 'redox' designation is now considered superfluous
WHO	World Health Organisation

Executive Summary

Flow batteries (FBs) are a form of long duration energy storage, a set of technologies crucial for the provision of reliable zero-emission electricity from variable renewable energy sources. In this report, the suitability of FBs for use and manufacture in developing economies (DE) is assessed with comparison to lithium-ion (LIB, specifically the lithium iron phosphate variant) and lead-acid batteries (PbABs).

There are two main classes of FBs. The first is all-liquid systems, in which electrolyte solutions stored in two tanks are pumped through electrodes to generate or store electrical power. A key feature of all-liquid FBs when compared to other battery types is the separation of power and energy capacity, which can be scaled independently of one another, providing increased system design flexibility. The second type is hybrid FBs, where energy and power capacity are no longer independent. In these systems, either a metal is plated on the negative electrode, or a gas such as hydrogen is generated and consumed during charge/discharge.

The targeted discharge duration of FB technologies under development varies, reflecting the balance between energy capacity and power capacity costs. Most FB companies are targeting 4-12 h durations, placing their systems in direct competition with LIBs. However, some are aiming for durations of up to 100 h. Additionally, products are moving away from traditional chemical plant designs toward a shipping container format, to capture cost efficiencies through economies of standardisation.

The performance characteristics of flow batteries vary greatly, highlighting the need for further prototyping of promising chemistries. Some general observations apply to the FB subclasses. The energy density of the best-known FB, the vanadium flow battery (VFB), falls in the middle of the range. Other, all-solution (all-liquid) FBs, have much lower energy densities, while hybrid FBs tend to have higher values, in some cases approaching those of LIBs. Conversely, hybrid FBs employing metal plating generally exhibit lower current density than all-solution FBs, meaning that the cost of power capacity is higher. An advantage often cited for FBs is long lifetime. However, this has been best demonstrated in VFBs, where manufacturers advertise 20,000+ cycles, supported by real-world demonstrations. Some hybrid systems like zinc bromine and iron/iron FBs, also show promising longevity. In contrast, lifetimes of other FBs remain largely unproven beyond a few hundred cycles due to limited large-scale demonstrations.

Performance gaps exist between each FB type and LIBs, but none of these are critical. The impact of efficiency – typically 70-90% for hybrid FBs and VFBs compared to 90+% for LIBs – depends largely on the cost of the electricity used for charging. Analysis of deployed systems suggests that the large energy density gap between VFBs and LIBs at the cell level almost closes at the MW-scale system level. This is due to current safety practices for LIB, which require large spacing and single level container stacking[2].

[2] CATL have announced a double-stacked BESS product in May 2025 https://www.catl.com/en/news/6410.html

Temperature tolerance is another area where FBs could gain an advantage over LIB, which are subject to accelerated degradation and fire risk at elevated temperatures.

Successfully deploying batteries in developing economies requires overcoming both logistics and skills challenges. Some of these are more pronounced for FBs than for LIBs, while in other cases, FBs may offer advantages. For example, the electrolytes can be removed from the system, allowing transportation of a discharged battery, something that is not possible with LIBs. The primary logistical challenge for FBs comes from their low energy density, which makes transport challenging, and may necessitate supply chain innovation and localised electrolyte production. In areas with poor infrastructure, it may be necessary to deploy smaller modules, though these regions are not the primary target markets for FBs.

FBs may also require more frequent interaction with a local workforce compared to LIBs, as some chemistries involve routine maintenance. However, this varies by FB type and could be automated in some cases. The exact skills required for successful FB operation (over and above the electrician and control and data acquisition (SCADA) skills that LIB systems are known to require) constitutes an important knowledge gap. FBs with water-based electrolytes offer a notable advantage in terms of intrinsic fire safety, making them well-suited for operation in regions with less developed safety regulations.

South Africa, Indonesia, Thailand and India were found to be the most promising developing economy markets for flow batteries. This finding followed an analysis of key metrics, including population size, political stability, grid reliability and the prevalence of key use-case sectors such as mining, industry and data centres. Most of these applications suit the 4-12h discharge durations targeted by VFBs and hybrid metal plating FB types, particularly when combined with low-cost solar power.

For smaller-scale community and residential applications, FB opportunities appear more limited. However, a key exception is regions with many "island" communities that remain disconnected from the main grid but rely on costly fossil fuel generators to maintain a stable power supply. Such scenarios are common across Southeast Asia, where FBs could offer a viable alternative.

The manufacture of FBs is well suited to developing economies as it is possible to begin assembly and production of simple components -- such as injection moulded flow frames -- and gradually scale up to higher value-added components like extruded composites for bipolar electrodes or even thin film membranes. Since flow frames and bipolar electrodes are common across almost all FB types, economies of scale could be achieved more quickly, reducing the risk associated with selecting specific technologies. Hybrid metal-plating FBs are an especially promising class for local manufacture in developing economies, as they can be designed without ionic membranes and porous separators, which are challenging to manufacture.

FBs are assembled from a diverse set of stack components, electrolytes and balance-of-plant items, such as pumps, tanks and control systems. Each item has a unique supply chain, and the prevalence of mineral resources (notably for electrolytes) and basic or advanced manufacturing capabilities affects local production potential in developing economies.

By analysing the status of selected industries such as chemicals, electronics, advanced manufacturing, and existing FB activities, one can see strong near-term potential in India, Thailand, Malaysia and South Africa, with other countries potentially following, as markets evolve.

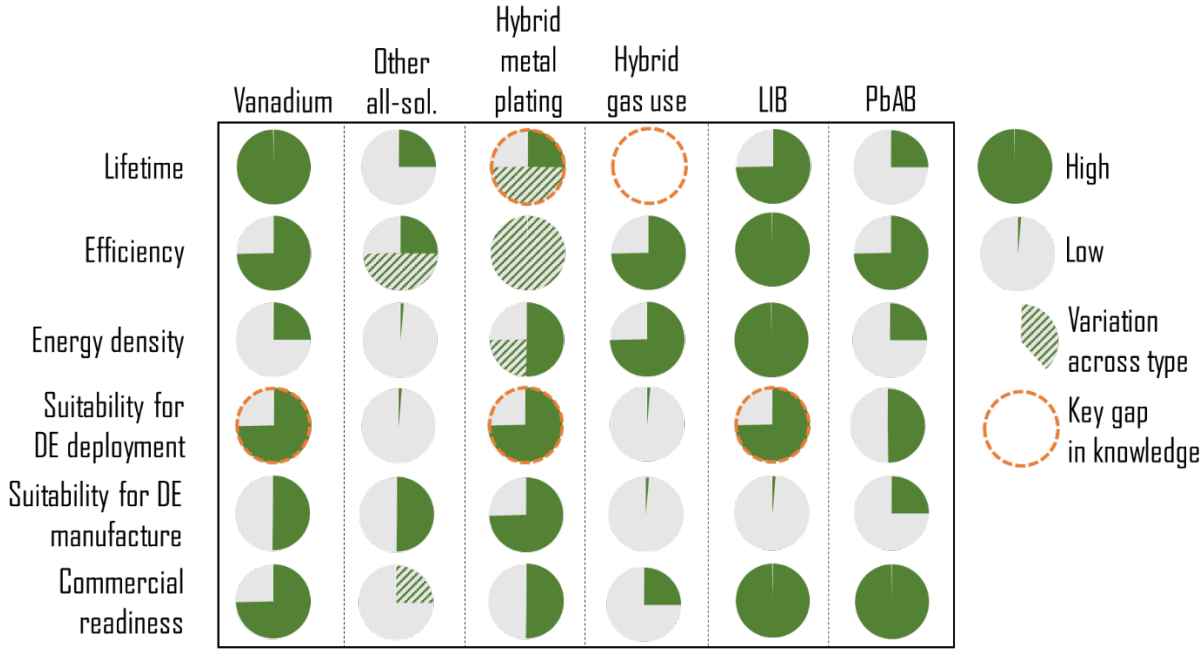
South Africa's strongest potential is in vanadium and iron electrolyte manufacture, where value could be added to domestically mined ore. Meanwhile, Malaysia and Thailand could follow India in building stack components. Even countries with less-developed high-tech manufacturing can still contribute by producing balance-of-plant items. If quality controls are maintained, local manufacture of electrolytes in developing economies could address the issue of transporting large volumes of water-based solutions.

Investing in FB production is financially accessible, with capital costs per MWh of annual production ($/MWh.p.a.) similar to LIBs but at much smaller scales. FB manufacturing facilities have been built at scales two orders of magnitude smaller than what is typical for LIB. This makes investment in manufacturing facilities far less risky for investors in developing economies. Unlike LIB manufacturing, which is characterised by sophisticated facilities with stringent humidity control, and advanced capabilities in powder processing and coating, FB production is generally simpler. The few complex components could be purchased for assembly if the FB in question requires them, further lowering barriers to entry.

Notable research gaps in FB development include the need for demonstrator projects to validate reliability in challenging environments and to showcase the advantage in temperature tolerance of FBs of over LIBs. For pre-commercial and low-TRL FB systems, long-term lifetime data is lacking. However, focusing on this single metric may result in wasted resources. Techno-economic analysis is also required to provide a holistic measure of viability.

Given the universality of bipolar electrodes, and the intermediate complexity of manufacturing them, there is a need for research to find better ways of making these at low cost. Additionally, optimising bipolar electrodes for reliable metal deposition would be particularly valuable for various hybrid metal FB systems.

Key findings on the performance of FB classes, and their suitability for manufacture and deployment in developing economies (DE) are summarised in the dashboard below. Hybrid metal plating FB offer many advantages, with the key technical challenge being the demonstration of adequate lifetime.



1. Scope, Aims and Structure of Report

The overall objective of this report is to evaluate the potential of FBs as long duration energy storage solutions in the context of developing economies. This potential is assessed both in terms of suitability for end use in these regions and as a route to value creation through local manufacture.

It is important to note that this report is **not** intended as a detailed technical review of FBs, as existing literature already covers this topic[3,4]. Nor does it aim to provide detailed analyses of FB costs or end-use economics. That said, it is important to note that upfront cost presently acts as a barrier to FB commercialisation. Some cost challenges are intrinsic (e.g., cost of raw materials such as vanadium), but others may be overcome by economies of scale. FBs have not so far benefited from adjacent higher-value industries that have driven scaling, as seen for LIBs[5].

This study will support the delivery of the ACES/Ayrton Challenge programme and subsequent deployment of technologies in the field and is targeted at in-country installers or integrators of battery systems. It will also be of interest to energy storage professionals who have an interest in alternative battery technologies and who are considering alternatives to lead-acid and lithium-ion, but are unsure of the different technologies available, the performance that one might expect to be achieved, the potential of the technology to deliver reliable energy and the improvements that may be needed.

The study will also be of interest to battery manufacturers and raw material producers who are considering developing their own local battery products but are unsure of the material flows and local supply chains.

Chapter 2 gives an introduction to FBs. The remainder of the report is structured around four key areas of analysis, each covered in a dedicated chapter:

- Chapter 3: A comparison of FB performance metrics with lithium-ion and lead-acid batteries, followed by a review of performance gaps – evaluating their significance and potential solutions.
- Chapter 4: An assessment of the practical challenges associated with deploying battery energy storage in developing economies, alongside specific challenges and opportunities specific to FBs.
- Chapter 5: An evaluation of the market potential for FBs in developing economies, highlighting promising regions and use-cases, and assessing the suitability of different FB types for these applications.
- Chapter 6: An analysis of the potential for FB manufacture in developing countries, identifying regions with the strongest prospects and determining which components should be prioritised for local production.

Research priorities emerging from these analyses are explored in Chapter 7, while conclusions and recommendations are made in Chapter 8.

---

[3] Redox flow batteries: Status and perspective towards sustainable stationary energy storage. https://doi.org/10.1016/j.jpowsour.2020.228804

[4] A comprehensive review of metal-based redox flow batteries: progress and perspectives. https://doi.org/10.1080/17518253.2024.2302834

[5] https://www.lazard.com/media/42dnsswd/lazards-levelized-cost-of-storage-version-70-vf.pdf

2. An Introduction to Flow Batteries

Flow batteries (FB) are electrochemical devices that can be used at a range of scales (kW to GW) to repeatedly store electricity and discharge it later. In a FB, energy is stored in solutions or suspensions of chemicals known as electrolytes. This contrasts with closed-cell batteries such as lithium-ion batteries (LIB), lead-acid (PbAB) or zinc-alkaline, where the energy is stored in the electrodes and where the electrolyte is purely a conductive medium.

In the traditional FB configuration, exemplified by the VFB and even earlier iron-chromium FBs, there is one electrolyte that is reduced (receives electrons) during charging (named the anolyte (like the anode in a LIB) or "negolyte") and one that is oxidised (loses electrons, "catholyte/posolyte"). For charging to occur, both electrolytes must be pumped through a "stack" of flow cells, where electrical current supplied to the electrodes drives this reduction/oxidation (redox) reaction. On discharge, the reverse occurs, and the stack produces power. A schematic of such an all-liquid FB is shown in **Figure 1**.

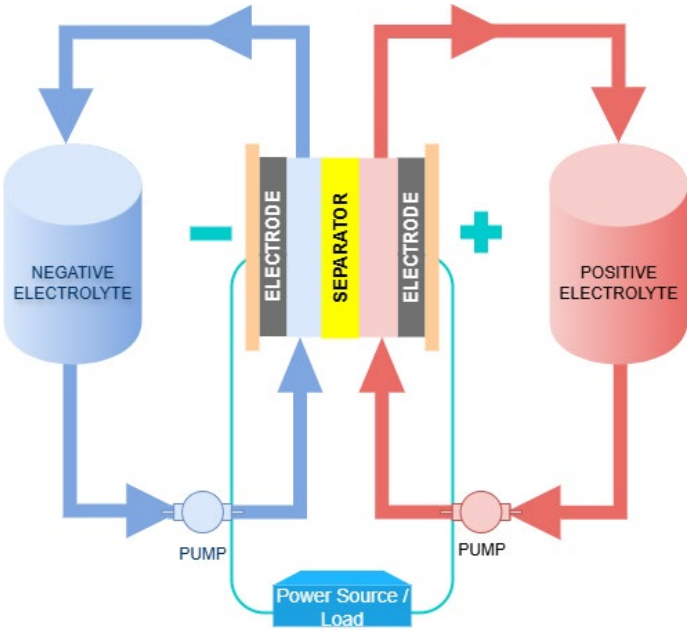


Figure 1: Flow cell schematic for the traditional all-liquid flow cell, where energy stored as electro-chemical potential in the positive and negative electrolyte tanks is converted to electrical power in the flow cell. Here, only a single flow cell is shown for clarity. In reality, multiple cells are connected in electrical series (supplied by parallel electrolyte flow from a manifold) to reach a useful voltage, e.g., 24 V or higher.

It is clear from the schematic that the energy capacity may be increased independently from the power capacity by making the tanks larger (power can be increased through increasing the size/number of cells), and that there is no practical limitation to how many hours of storage could be provided.

The primary motivation for the development of FBs has been the potential to utilise a wide range of low-cost materials. The electrolyte, most typically comprising a solution of metal ions in an acidic or alkaline solution of water, is potentially far cheaper than the structured materials used in closed-cell batteries such as LIBs.

2.1 Important Subclasses of Flow Batteries and their Commercial Status

There are many distinct FBs reported in the academic literature, and detailing every combination of electrolytes is not feasible in this report. The interested reader should look at the reviews on the subject referenced in Chapter 1. Here the objective is to identify important subclasses to understand the impact of any differences on performance characteristics and manufacturability.

2.1.1 All-liquid FBs

The schematic in **Figure 1**introduces the concept of an all-liquid FB. The defining feature of this architecture is the separation of power and energy capacity. In addition to VFBs, several other metals have been tested in various combinations, including chromium, iron, cerium and even uranium. There is also a system based on vanadium and iron that is being investigated in a partnership between Saudi Aramco and Rongke Power[6] (discussed further in 4.3.1. There are also several aqueous organic FB systems, in which relatively complex organic compounds, such as quinones, are used either alone or in combination with metal ions.

An interesting subclass of the all-liquid FB is the semi-solid type, in which at least one of the chemicals is not dissolved in the electrolyte[3]. The primary benefit of this type is an increase in energy density by overcoming the solubility limitation and it also offers the added advantage of a reduced risk of cross-contamination between the two electrolytes[7]. There are systems in which small particles suspended in a non-aqueous solvent are pumped through the cell, as well as systems where the solid remains in the reservoir but dissolves into the electrolyte as the charge/discharge process progresses. In this report, the analysis is confined to the suspended particle systems, as it is strongly distinct from the all-solution RFB and is being commercialised by at least one company. Another variant on the all-liquid FB is one using a micro-emulsion electrolyte, where an organic solvent is finely dispersed within water allowing enhanced solubility of an iron complex, and a wider voltage range[8].

2.1.2 Hybrid FBs

The all-liquid FB architecture, introduced through **Figure 1**, represents one branch of FB technology. While its association with the VFB may make it seem like the archetype, a similar number of hybrid flow batteries (hybrid FB) are under development. Unlike in the all-liquid FB, a phase change takes place during cycling in the hybrid FB. The most common form of phase change is deposition of a metal from solution onto the negative electrode. A schematic of a metal plating hybrid flow cell is shown in **Figure 2(a).** This innovation allows the use of metals such as lithium, lead and zinc, which do not have sufficient soluble oxidation states to be used in an all-liquid FB.

Hybrid FBs can also achieve higher energy densities compared to all-liquid FBs. This is partly because taking the metal all the way to the metallic (most reduced) state during charging creates a higher cell voltage. Additionally, some types of hybrid FBs, such as the soluble lead and lithium-polysulfide systems, developed by StorTera, require only one

[6] https://www.aramco.com/en/news-media/news/2025/renewable-energy-storage-system-for-gas-operations

[7] All-polymer particulate slurry batteries. https://doi.org/10.1038/s41467-019-10607-0

[8] https://flowbatteryforum.com/wp-content/uploads/2025/06/7.-Fraser-Hughson.pdf

electrolyte. This not only improves energy density but also reduces the cost of components (for example, only one pump is required instead of two).

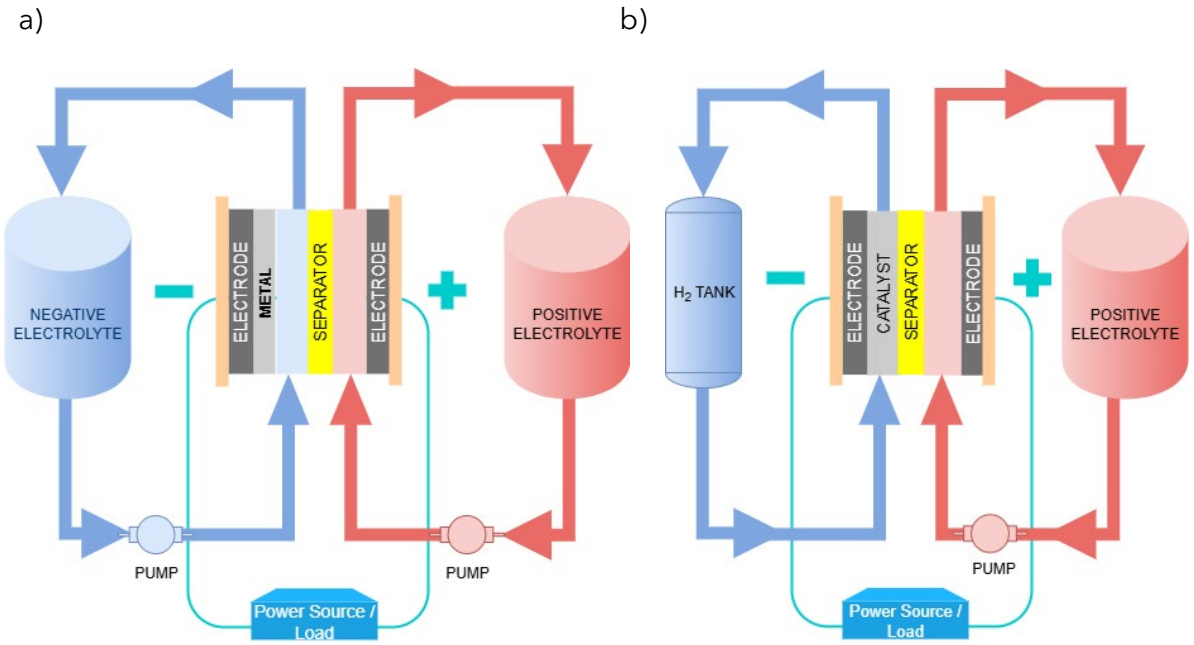


Figure 2: Flow cell schematics for (a) a hybrid single metal plating electrode flow cell, and (b) and a hybrid hydrogen-liquid flow cell. Here, only a single flow cell is shown for clarity.

However, the metal plating requirement introduces additional challenges. Firstly, the energy capacity of the battery becomes tied to the electrode area, meaning it is no longer decoupled from the power capacity. Secondly, achieving a uniform deposit repeatedly while operating at a high current density (approximately 50 $mAcm^{-2}$) is technically challenging. Much of the research on this FB type has focused on addressing this issue, which is discussed further in Section 3.2.

A second type of hybrid FB uses a gas for energy storage at one of the electrodes. A schematic of this hybrid hydrogen flow battery is shown in **Figure 2(b).** There are two well-studied systems that employ hydrogen at the negative electrode. The hydrogen-bromine system, being developed by Elestor[9] and others, claims benefits such as low material costs, global material abundance and high energy density. The hydrogen/ manganese FB being developed by RFC Power combines the use of hydrogen with a posolyte based on manganese[10]. Its development is primarily motivated by the very low cost of manganese compared to other metals, although the electrolyte also employs titanium as a stabilising agent, which may negatively impact the cost.

Almost all FBs use aqueous (water-based) electrolytes, including the "aqueous organic" FB shown in **Figure 3**, where the electrolytes contain organic materials dissolved or suspended in water. Aqueous electrolytes offer several practical benefits compared to the organic electrolytes used in LIBs, notably low toxicity, non-flammability and high

[9] https://elestor.com/

[10] https://www.rfcpower.com/

conductivity. Exceptions in the examples above are the lithium/polysulfide system, which uses an organic electrolyte to be compatible with metallic lithium, and the semi-solid FB being developed by CMBlu[11].

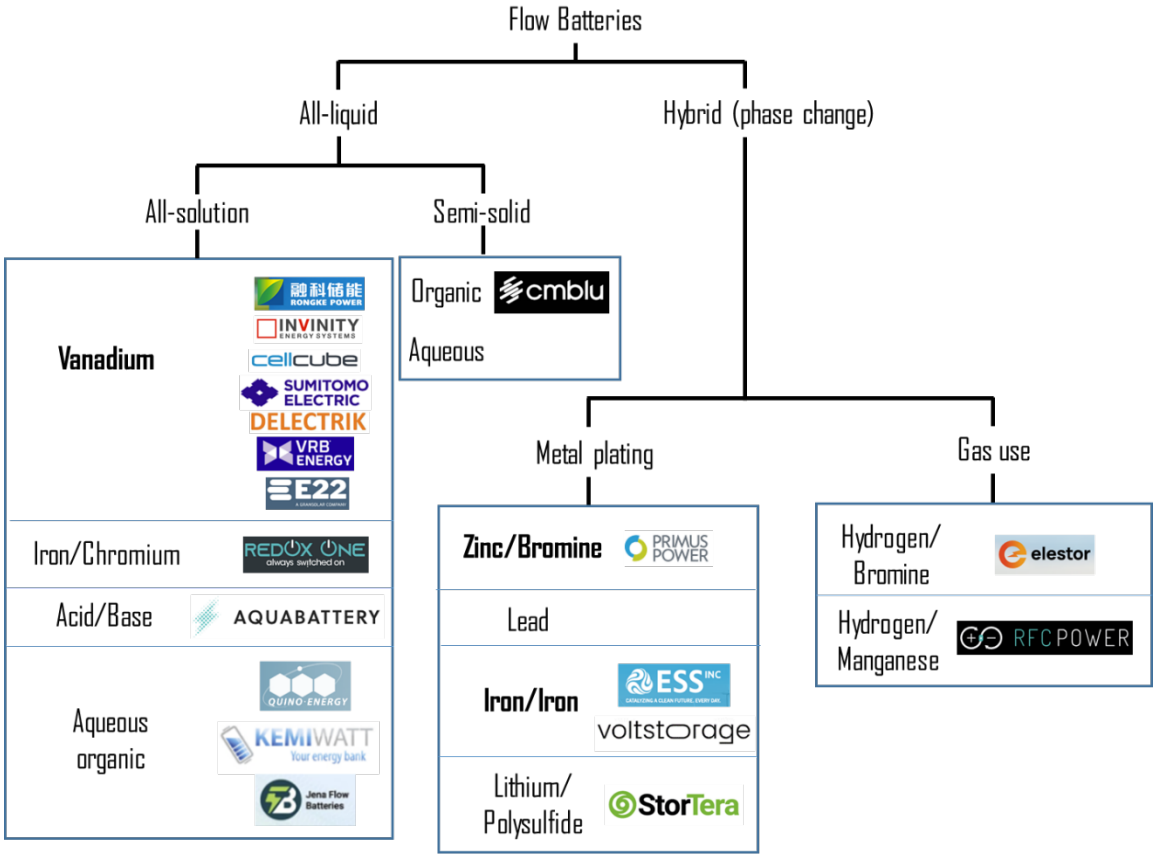


Figure 3: The FB family tree, showing notable systems grouped in subclasses. Where a system is in the process of commercialisation, the responsible company has been indicated. The list is non-exhaustive. Bold font denotes the existence of a clearly defined product with a data-sheet.

2.2 Duration Targeted by Flow Batteries

The ability to independently scale the power rating and energy rating of FBs is highlighted in many academic articles and commercial materials. In practice, however, the duration of a deployed system is constrained by economic considerations – adding duration incurs additional costs, and the marginal revenue opportunities currently decrease as duration increases. LIB or PbAB systems may also be specified at any duration simply by adding more modules behind the inverter. The dominance of FBs with 1-2 h duration seen so far for large-scale deployed systems is thus driven by economics rather than technical limitations.

Rather than perform an in-depth techno-economic analysis for the different FB types, a survey of commercial offerings was made, effectively using the judgement of manufacturers to determine the present economically optimal duration. The results of this exercise are shown in **Figure 4**.

[11] https://www.cmblu.com/

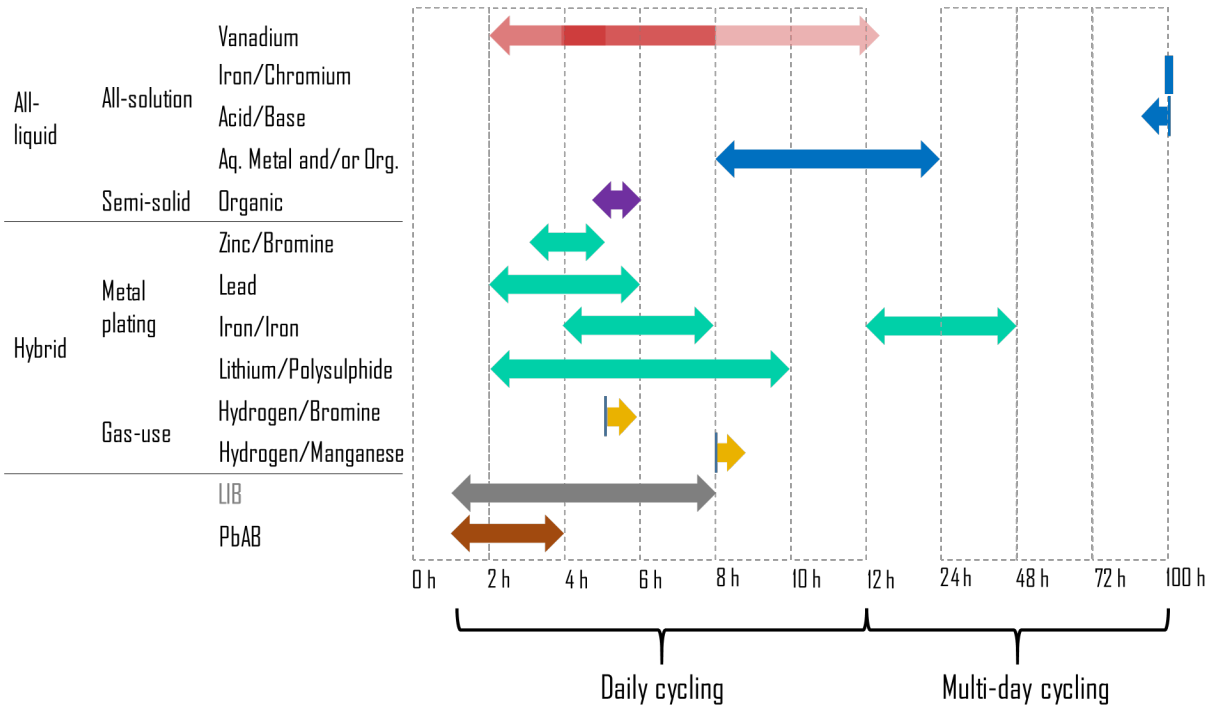


Figure 4: Data on duration for commercial FB products or reference systems. Darker shades for a given colour indicate overlap in duration offered by multiple examples of the same FB type. The focus is on designed-for duration. Although it is possible to achieve a longer duration by operating at low power, this would not be economical as the power components would be under-used.

VFB products cover a range of durations from 2-18 h, with Delectrik[12] targeting shorter durations (2-5h), CellCube[13] offering 14.4 h, and Invinity offering the longest duration defined product, Endurium, at 18 h. However, most offerings are concentrated in the 4-8 h range. VRB Energy, using the chemical plant format, does not specify a defined duration but state that 4-8 h is typical[14]. Iron/chromium[15] and acid/base[16] all-liquid offerings are targeting much longer durations, around 100 h, which reflects the low cost of energy capacity afforded by the chemicals used. However, their poor power performance makes short durations non-competitive. Quino Energy[17], which is developing an aqueous organic solution FB, state that they are targeting an 8-24 h duration.

Hybrid FBs using metal plating are primarily represented in the 4-6 h range. This may reflect a combination of market status with limitations around metal plating. To increase duration in this type either a) the deposit thickness or b) the electrode area must be increased. Approach a) may be problematic, as large changes in deposit thickness during operation can impact the flow of electrolyte and round-trip efficiency. Approach b) is

[12] https://delectrik.com

[13] http://www.cellcubeenergystorage.com/

[14] https://vrbenergy.com

[15] https://redoxone.com/

[16] https://aquabattery.com/

[17] https://quinoenergy.com

problematic from a cost perspective[18]. Despite this, the iron/iron hybrid FB manufacturers are targeting relatively long durations. ESS has defined products in the 5-8 h range but states that durations up to 12 h are achievable. The VoltStorage product is something of an outlier within this class, targeting durations of 12-48 h, which implies that the technical challenge of plating metal at sufficient thickness may be overcome[19].

It is also worth noting the non-flow technology developed by Form Energy, which employs a solid-state reaction to reduce and oxidise large balls of iron without ever dissolving them, thus removing the need to plate on an electrode[20]. This is an innovative method of achieving long durations, and the company is targeting a 100 h duration. This technology is considered out of scope for further analysis, as it is not technically a FB.

Several FB technologies are currently under commercial development, but it has not been possible to determine the targeted duration. Although the companies behind the hybrid FB using hydrogen do not yet have concrete products, RFC Power indicates that their product is suitable for "multiple hours to days". Given the complexity of the power production equipment in these systems, they are unlikely to compete in the 2-8 h range that LIBs currently cover. The company's marketing materials emphasises pairing with wind power, suggesting that a longer duration is required.

Elestor, manufacturers of a hydrogen/bromine FB, have worked on a 5-h pilot project, which has been interpreted here as an indication of the minimum economically viable duration[21]. The company CMBlu, which has already deployed its "Organic SolidFlow" product and is in the process of validating it at USDOE, does not publish a datasheet but provides the capacities of their installations in MWh terms. The 5-h duration in **Figure 4** is based on presentations made at the IFBF conference in 2024.

In summary, the data in **Figure 4** show that different types of FBs are targeting varying durations, meaning some are more likely to compete with technologies like hydrogen storage, rather than with LIB/PbAB.

2.3 Flow Battery Formats - Chemical Plant or Shipping Container?

An interesting aspect of FB commercialisation is the format and scale that manufacturers are targeting. For stationary applications, LIBs appear to be splitting into small residential systems with custom containment, and larger modular systems based on shipping containers, particularly those around 5 MWh in a 20ft container[22]. A similar trend is emerging in the FB industry.

[18] Predicting the cost of a 24 V soluble lead flow battery optimised for PV applications. https://doi.org/10.1016/j.jpowsour.2023.233058

[19] Personal correspondence with Michael Peither of VoltStorage Gmbh 8th November 2024.

[20] The iron-energy nexus: A new paradigm for long-duration energy storage at scale and clean steelmaking. https://doi.org/10.1016/j.oneear.2022.03.003

[21] https://elestor.com/projects

[22] https://www.energy-storage.news/bess-commoditising-industry-converges-20-foot-5mwh-products/

VFBs are being sold both in custom domestic formats (e.g., Prolux Solutions[23], StorEn[24], SMT Energy AG[25]) and as containerised offerings (e.g., Invinity[26], CellCube[13], Sumitomo Power[27]). Invinity's Endurium VFB product, for instance, is based on a 20ft container with an energy capacity of 0.3 MWh. Even amongst containerised VFB offerings, there is a decision to be made on the degree of modularity. The Invinity product appears the most modular, with both energy and power components (excluding inverters) housed in the same container, whereas Sumitomo Power and CellCube have separate containers for each (which appear to include inverters).

The containerisation trend is a move away from the earlier "chemical plant" format, previously used by Sumitomo Power. In this format, electrolyte is stored in large cylindrical tanks, as seen in the world's largest FB (200 MW/800 MWh), developed in Dalian, China by Rongke Power[28]. It is likely that this move toward containerisation prioritises the reduction in costs attainable by use of standardised components, rather than optimising for performance (e.g., energy density comparison in Section 3.3.3). VRB Energy appears to be using the containerised format for MW-scale systems, while opting for the chemical plant format for GW scale systems, suggesting that the chemical plant approach requires substantial economies of scale to be economically viable[29].

In the hybrid FB class, Redflow offered a small zinc-bromine module (3 kW/10 kWh) without containment, as well as a larger system with a custom enclosure based on 20 modules. However, as this report was being written, Redflow entered administration. The company cited challenges in raising capital, high costs of producing components at small volumes and reliability issues leading to high repair costs under warranty[30]. These problems do not appear linked to the format of the batteries. Primus Power also offers a zinc-bromine system with a custom enclosure (25 kW/125 kWh)[31]. The iron system offered by ESS is based on ISO shipping containers[32], whereas the VoltStorage system appears to feature a combination of containers and large tanks[33].

2.4 Flow Batteries and the Circular Economy

Recently, the recyclability of FBs has become an additional selling point, as the electrolyte may be easily recovered or reused at end-of-life, and individual components may be replaced on a rolling basis. One example of electrolyte recovery comes from the Regenesys bromine/polysulfide FB demonstration plant in the UK. When the project was

[23] https://www.prolux-solutions.com/de/de/

[24] https://www.storen.tech/

[25] https://www.smt-energy.ch/

[26] https://invinity.com/

[27] https://sumitomoelectric.com/products/redox

[28] World's largest flow battery connected to the grid in China (newatlas.com)

[29] https://wp-vrbenergy-2023.s3.ca-central-1.amazonaws.com/media/2024/02/Gen-3-Brochure-VRB-2022-1000kW.pdf

[30] https://amp.abc.net.au/article/104650074

[31] https://primuspower.com/en/product/

[32] https://essinc.com/energy-warehouse/

[33] https://voltstorage.com/en/solutions/the-voltstorage-iron-salt-battery

discontinued, the electrolytes were sold back to the original supplier[34]. The VFB also has a highly recyclable electrolyte. US Vanadium has demonstrated both the recycling of electrolyte and the economically viable recovery of vanadium oxide, which can be sold into the broader vanadium market[35].

The soluble lead FB may benefit from synergies with the well-developed PbAB supply chain, where, in the US at least, 100% of PbAB batteries are recycled, with 80% of the material recovered[36]. The electrolyte for the soluble lead FB can even be prepared from spent PbAB cells[37]. Beyond this system and VFBs, there is little publicly available material on FB recycling, though some companies such as CMBlu[11] and VoltStorage[38] highlight recyclability in their commercial material. StorTera has also recently received funding to develop a route to recondition the catholyte of their FB system[39].

Although FBs generally offer superior recyclability compared to LIB in principle (some issues still exist around the used of PFAS-based membranes), recycling has not been a research priority to date. Further work is needed to demonstrate the recycling processes at pilot or commercial scale. A key consideration for future FB (also LIB) research will be increasing the recycled content to satisfy upcoming EU directives and initiatives such as the battery passport[40].

2.5 Global Scale of FB Deployment and Examples from Developing Economies

A survey of global FB deployments, commissioned by the International Flow Battery Forum in 2020[41], listed 168 MW of FB projects either deployed or announced. Of this, 74% were VFBs, 22% were zinc/bromine hybrid FBs, 1.7% were zinc/iron hybrid FBs and 1.0% were hydrogen/bromine hybrid FBs. However, there is little evidence that the zinc/iron FBs were ever built, and ViZn, the company responsible for them, does not appear to be a going concern.

A VFB database compiled by Vanitec[42] listed 207 MW in operation, 3,060 MW under construction and 5,800 MW announced as of 2023, showing rapid growth in this particular FB sector. The average duration of the pipeline (weighted by power capacity) was 3.4 h.

In the Vanitec dataset, 98% of VFB power capacity, whether operational or under construction, is located in China, which appears to have a strategic interest in this technology. Of the remaining projects, 64% are in Japan. The remainder are spread across the globe, including in developing economies, which are within the scope of this

[34] Personal correspondence with Anthony Price of Swanbarton, 7th November 2024.

[35] https://usvanadium.com/solving-the-technical-and-economic-challenges-to-reprocessing-vrfb-electrolyte/

[36] https://batterycouncil.org/recycling-sustainability/battery-recycling/

[37] Developing electrolyte for a soluble lead redox flow battery by reprocessing spent lead acid battery electrodes. https://doi.org/10.3390/batteries3020015

[38] https://voltstorage.com/

[39] https://www.faraday.ac.uk/five-research-projects-initiated-to-advance-batteries-for-emerging-economies

[40] https://www.globalbattery.org/battery-passport

[41] https://flowbatteryforum.com/where-are-flow-batteries/

[42] https://vanitec.org/

report (see Chapter 1). A selection of VFB and other FB projects in developing economies is given in **Table 1**.

Table 1: Selected examples of FB deployments in developing economies, grouped by use case. These were taken from the survey commisioned in 2020 by the International Flow Battery Forum, and company announcements/publicity.

Use-case	Region	Country	Details	FB type	Scale	FB company
Commercial & industrial (peak management, backup power, and/or PV firming)	Africa	South Africa	Manufacturing plant, Johannesburg	Vanadium	10 kW / 130 kWh	CellCube
	South Asia	India	Office building, Bhopal[43]	Vanadium	30 kW / 300 kWh	CellCube
			Bharat Heavy Electricals Ltd[44]	Vanadium	50 kW / 200 kWh	E22
Firming PV to power off-grid telecoms sites	Africa	Botswana	14 sites	Vanadium	40 kWh per site	Invinity
		South Africa	Kalahari Desert	Vanadium	20 kW/ 200 kWh	CellCube
		Various	20 sites[45]	Zinc /bromine	-	Redflow
Firming PV in island micro-grid	Africa	Uganda	Kitobo Island		60 kW / 480 kWh	CellCube
	Southeast Asia	Vietnam	Con Dao Island	Vanadium	10 kW / 40 kWh	CellCube
		Indonesia	Sumba Island	Vanadium	400 kW / 500 kWh	VRB Energy
EV charging	South Asia	India	Bangalore		10 kW / 190 kWh	Not recorded

The selection of projects in **Table 1** demonstrates that FBs are being used for a wide range of use cases across developing economies, albeit at relatively small overall scale. The deployed FBs are almost exclusively VFBs. The most common application is storage and discharge of surplus PV power to improve reliability (PV "firming").

It is also noticeable that the durations of some systems in **Table 1** are around 10 h, which is more than double the aforementioned average of 3.4 h for the global VFB pipeline. This is likely because the developing economy projects have tended to focus on firming PV power, which requires longer durations when compared to batteries operating in industrialised economies. In the latter the focus is more on daily peak shaving.

[43] https://asiacleanenergyforum.adb.org/wp-content/uploads/2015/06/Chih-TingLo_CanadianDeepDive.pdf

[44] https://energystoragesolutions.com/e22-commissioning-flow-battery-bhel-india/

[45] https://www.energy-storage.news/flow-batteries-offer-low-carbon-alternative-for-south-africa-telecoms-provider/

2.6 Conclusions

There are several subclasses of FB, with the main distinction being between those that have liquids on both sides of the cell (allowing energy and power to be decoupled) and the hybrid FB where metal is plated on the negative electrode. There are double figure numbers of companies in the process of commercialising FB, but only three types show concrete products with datasheets: VFBs, zinc/bromine hybrid FBs, and iron/iron hybrid metal plating FBs.

VFB and hybrid metal plating FB commercialisation primarily target sub-12 h durations, while some all-solution FBs are aiming for much longer duration, up to 100 h.

Deployment of FBs to date has been dominated by VFBs, which has seen substantial growth in the last four years. There are a small number (10 well-evidenced examples) of FB deployments in developing economies, mostly for remote micro-grids, telecom infrastructure, and commercial and industrial applications.

Lastly, the trend in FB deployment is shifting away from a chemical plant format with large tanks to systems based on ISO containers.

3. Performance Characteristics of Flow Batteries with Comparison to LIBs and PbABs

This section compares the performance characteristics of the key FB classes with those of LIBs and PbABs, as these are expected to be the primary competition for long duration energy storage (LDES) in developing economy use-cases.

3.1 Important Metrics for LDES

Round-trip efficiency (RTE): RTE is the fraction of energy used to charge the battery energy storage system (BESS) that can be recovered later. A higher RTE is preferable, as it indicates more efficient energy storage and retrieval. An important use case for LDES is peak shaving, where energy is purchased during off-peak hours and sold during peak hours. Losses in storage reduce the sellable energy volume and, consequently, the revenue. If the asset is used to provide firm power from PV or other variable renewable energy (VRE) sources, then lower efficiency generally means that the size of the PV array must be increased, which raises the total levelised cost of electricity. In this report, the RTE is defined at the DC boundary, i.e., it does not include inverter losses. For lab-scale and pilot FB systems, the RTE does not account for pumping losses (around 5%), which increase as electrolyte concentration drops. It should also be noted that the LIB efficiency values given do not account for parasitic losses such as cooling power.

Power density: Power density is an important metric for FBs, as the cost of producing power is inversely related to this metric via the area of the electrodes and other stack components. Power density is the product of working cell voltage and current density. As most FBs use water-based electrolytes, they benefit from high ionic conductivity, supporting a high current density when compared to organic solvents. The downside of this is that the cell voltage is limited by the need to avoid water splitting, which would reduce the efficiency of the battery and potentially corrode the electrodes. Typically, high power density is required for FBs to be economically viable at shorter durations. It is possible to increase the power density at the expense of RTE by sizing the components to run at a higher current density, which results in greater voltage drop and hence reduced round trip efficiency. Therefore, for FBs, RTEs should be evaluated in relation to power density.

Maximum temperature: Given that many developing economies are located in hotter regions (as illustrated in 8.Appendix A), the tolerance of high temperatures is an important metric for LDES. This issue is explored in more detail in Section 4.2.1.

Energy density: Volumetric energy density is an important metric as it determines both the cost of space required for the BESS and the associated delivery costs. For each technology, energy density is measured based on the electrolyte (for FBs), or the cell (for LIBs). A more detailed discussion of system-level energy density can be found in Section 3.3.3.

Lifetime: For this analysis, lifetime is calculated as the lower of cycle life (assuming 1 cycle per day) and calendar life. A cycle rate of 1 per day is considered typical for a LDES system with a duration of 4-8 h paired with a PV system, though in practice, the cycle rate may be lower[46]. Defining the lifetime of FBs is a more complex matter than in closed-cell

[46] The economics of firm solar power from Li-ion and vanadium flow batteries in California. https://doi.org/10.1557/s43581-022-00028-w

chemistries. Using the VFB as an example: while the electrolyte itself does not degrade, the stack will eventually need replacing due to factors like electrode corrosion or membrane degradation. In many FBs, chemical species may cross the membrane and contaminate the opposite electrolyte, reducing capacity. While this process is continuously reversible for VFBs and some other variants, it may be irreversible for aqueous organic FBs. This complexity means that the cycle lives provided should be taken as indicative. For LIBs, cycle life is heavily dependent on depth of discharge, while calendar life is strongly influenced by the temperature at which the batteries are operated and stored. For this reason, several cases are presented in this analysis.

3.2 Analysis of FB Performance in Comparison to LIB and PbAB

A review of publicly available material was conducted to gather recent performance data for FBs and to assess where performance gaps or advantages exist with reference to LIBs and PbABs. This assessment incorporated data from a mix of academic studies, commercial product specifications and real-world deployments. The results are summarised in a trade-off plot presented in **Figure 5**.

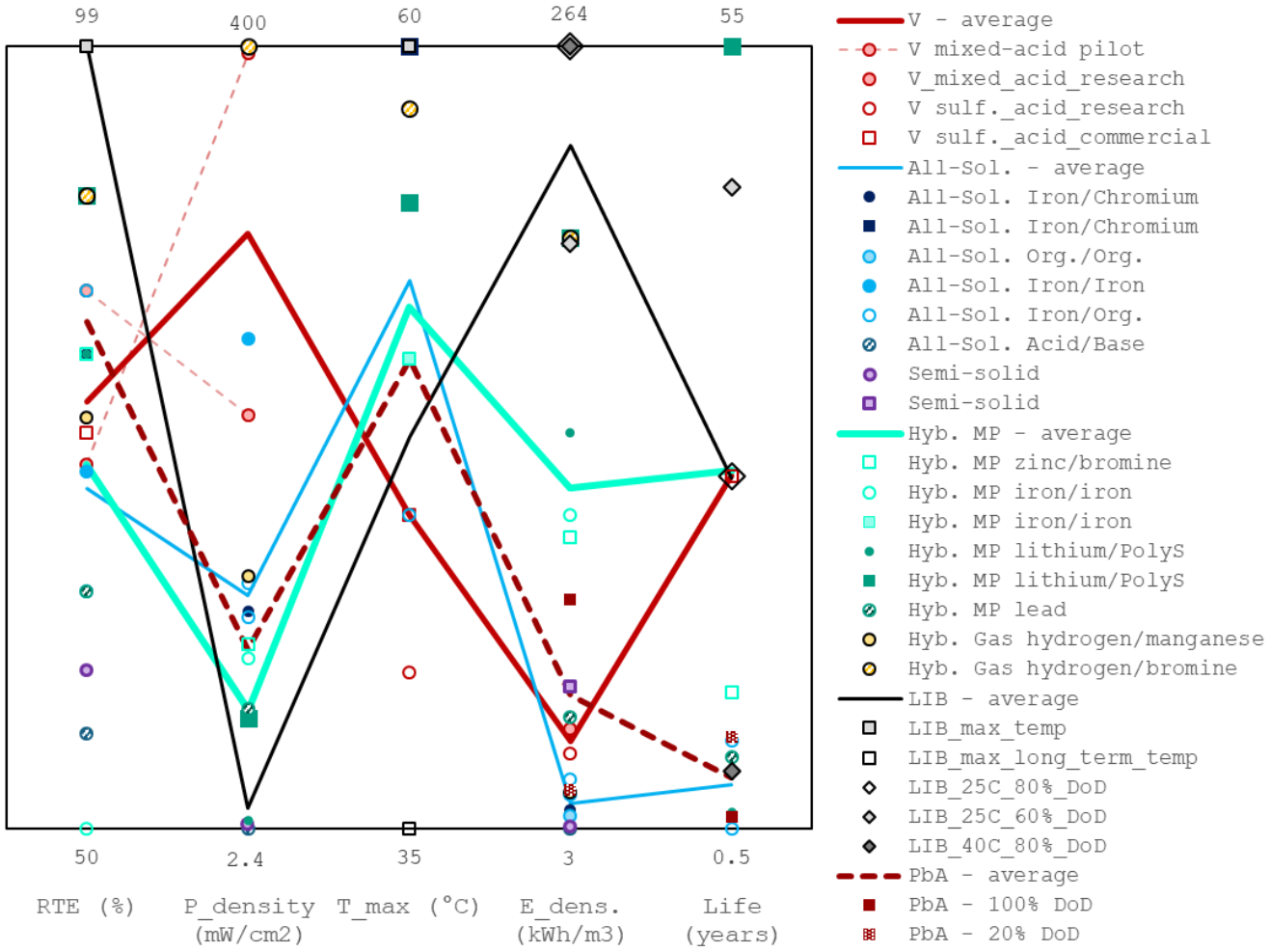


Figure 5: A comparison of performance data for FBs, LIBs and PbABs . Lines represent the average metric value for the class, whereas markers represent individual embodiments. Circles represent lab-scale or pilot data, squares commercial claims, and diamonds independent test-data from commercial products.

The first observation from **Figure 5** is that the performance properties of different FB classes vary significantly. This variation is so pronounced that treating FBs as a single technology class is not useful from an end-use perspective.

From a strict performance metric standpoint, the hydrogen/bromine FB is the best performing in four out of five metrics (with the exception of lifetime), and offers energy density and power capability comparable to LIBs. The question arises – why are hydrogen/bromine FBs not dominating the current stationary storage market? The likely answer lies in the challenges associated with the handling of hydrogen and bromine. Hydrogen is highly flammable, while bromine is toxic, both of which increases system cost. There are also serious issues with lifetime, particularly with seal corrosion caused by bromine exposure.

Among FB systems, the lithium/polysulfide variant stands out for its excellent round-trip efficiency, reaching approximately 90%. The next best FBs for RTE include the vanadium, iron/chromium and iron/organic systems, followed by the zinc/bromine system.

Linked to RTE, the highest power density of the FB systems (after hydrogen/bromine) is found with VFBs. Broadly speaking, hybrid FBs exhibit lower power density due to the need for reliable deposit formation and removal. It is notable that LIBs have very low power density at the electrode level. However, as there is no need to flow electrolyte between the electrodes, a large surface area is packed in a small cell, resulting in a high volumetric power density at cell level at a low cost.

Apart from the hydrogen/bromine and lithium/polysulfide systems, there is a large gap between the cell/electrolyte energy density of LIBs and FBs generally, as well as among different types of FBs. Hybrid metal plating FBs exhibit an average electrolyte energy density of 111 kWh/m^3, which is three to four times higher than that of VFBs. The wide overall range in energy density in **Figure 5** compresses the range for low energy density systems, obscuring the fact that the energy density of the vanadium system (~30 kWh/m^3) is around four times higher than that of the organic FB developed by brine4power[47] (7 kWh/m^3) and ten times higher than that of the acid/base (neutralisation) system (3 kWh/m^3).

Lifetime and temperature tolerance are particularly interesting from a developing economy perspective. High cycle life is a key selling point of VFBs and other types of FBs, but recent developments in the LFP variant of LIBs have somewhat diminished this advantage. LFP cells can now achieve 9,000 cycles at 80% depth of discharge, equating to 25 years of operation at one cycle per day. VFBs and possibly iron/iron hybrid FBs (assuming commercial claims hold true) can match or even exceed this cycle life. However, such performance has not been demonstrated for other FB types. Unlike LIBs, where a single LIB cell can be tested in isolation, testing of some types of FBs require continuous operation of an entire system demanding extended use of lab space. These practical hurdles have limited the availability of long-term performance data for many FB chemistries.

FBs can operate at higher temperatures than LIBs; at 40 °C cell temperature, a LIB will be limited by calendar ageing and reach 80% state of health (the traditional end-of-life

[47] https://newatlas.com/brine4power-largest-redox-flow-battery/50405/

threshold) after only 4.5 years[48]. This is why the maximum recommended storage temperature for LIB cells is given as 35 °C. In addition to VFBs, lithium/polysulfide and iron/iron hybrid FBs, this lifetime is exceeded by the commercial claims made for the zinc/bromine hybrid FBs (although issues highlighted previously with the Redflow system call these into question).

The maximum temperature tolerance of the VFB electrolyte is 40-50 °C depending on whether a sulfuric or mixed acid electrolyte is used. Although not included in **Figure 5**, the iron/vanadium variant being developed by Saudi Aramco and Rongke Power is specifically being developed for higher temperature tolerance, with limited testing showing stability over 100 cycles at 60 °C ambient temperature[49]. Overall this variant has similar performance to the VFB, except for increased risk of decreasing lifetime due to crossover risk between the iron and vanadium sides of the FB[50]. The iron/chromium FBs developed by RedoxOne has a claimed maximum operating temperature of 60 °C, although it is not clear what ambient temperature this would correspond to. The lithium/ polysulfide hybrid FB system of StorTera and the iron hybrid FB from ESS have claimed maximum ambient temperatures of 55 °C and 50 °C respectively. The zinc/bromine system from PrimusPower has a claimed maximum ambient temperature of 40 °C, increasing to 50 °C with a hot weather package. There is further discussion of this subject in Section 4.3.1.

3.3 Significance of Performance Gaps and Routes to Overcoming Them

A key objective of this report is to identify the existing performance gaps between FBs and LIBs / PbABs and identify routes to overcome them. Observed performance gaps are discussed below.

3.3.1 **Efficiency**

The importance of efficiency depends on the cost of charging, and the frequency of cycling. Generally, lower efficiency is more tolerable in longer-duration systems that cycle less frequently, as these systems are designed to capture longer-term surpluses in VRE output that would otherwise have little value[51]. For this reason, the gap in efficiency between LIBs and the acid/base FBs is irrelevant, as the latter is intended for much longer durations.

Among the FBs that are targeting the same daily cycling duration as LIBs, the all-solution VFBs, aqueous organic FBs, hybrid zinc/bromine and lithium/polysulfide FBs can all reach 80%. However, the iron/iron hybrid being marketed by ESS[52] for daily cycling may struggle, as the literature reports an RTE of only 50% for this chemistry. This may explain why VoltStorage[38] is targeting longer-duration applications.

Research and development efforts at Pacific Northwest National Laboratory (PNNL) improved the RTE of a 1 kW VFB stack from 73% to 84% just by redesigning the flow

[48] The Degradation Behavior of LiFePO4/C Batteries during Long-Term Calendar Aging. https://doi.org/10.3390/en14061732

[49] https://flowbatteryforum.com/wp-content/uploads/2023/07/Thursday-11.30-23103-Ahmad-Hammad-Slides.pdf

[50] A comparative study of iron-vanadium and all-vanadium flow battery for large scale energy storage https://doi.org/10.1016/j.cej.2021.132403

[51] https://assets.publishing.service.gov.uk/media/670660eb366f494ab2e7b57a/LDES-consultation-government-response.pdf

[52] https://essinc.com/energy-warehouse/

channels on the electrodes[53]. Closing gaps between lab-scale performance and optimised performance, however, can be expensive. This highlights both the role for physical modelling to guide design improvements, and economic modelling to determine the value of enhanced performance.

3.3.2 **Lifetime**

While the high cycle life of the VFB is well established, it is often incorrectly attributed to other FB types (unsurprisingly, given the dominance of VFB deployment shown in **Table1**). However, several FB chemistries do not presently show evidence of longer lifetimes than LIBs, though they do comfortably outperform PbABs. Some FB systems perform very well in other metrics, but not on lifetime. For example, hybrid metal plating FBs are likely limited by issues with the gradual loss of metal during plating/dissolution. The cycle life of one type of zinc/bromine FB is given as 3,650[54] or 10 years at one cycle per day -- only half the lifespan for LIBs under favourable conditions. While the business case for zinc/bromine FBs may be improved by investing in further R&D to lengthen the lifetime, this is not a given, as 10 years is already beyond the planning horizon of many entities. Additionally, the high cost of capital in developing economies necessitates shorter payback periods. For the zinc/bromine FB, funds may be better allocated on pilot projects and demonstrators, particularly to validate temperature tolerance relative to LIB and to drive down manufacturing costs.

Other hybrid FBs, such as the soluble lead system, may achieve improved lifetimes (beyond the current 2,000 cycles observed at lab-scale[55]) through further research into the mechanisms of plating/dissolution, and design of more suitable electrodes and flow architecture.

3.3.3 **Energy Density**

The importance of energy density depends on land availability and supply chain constraints. While improvements at the system scale are likely through innovation, fundamental advancements in energy density remain limited. It is also important to note that the energy density of LIBs decreases dramatically when scaling from the cell to the system level due to mounting, control systems, access ways, and measures needed to meet safety regulations.

A 2023 study by Reber et al. reviewed the energy density on a per-meter-squared basis for existing VFBs and LIBs and found average values of 15 kWh/m^2 and 34 kWh/m^2 respectively[56]. However, a limitation of this study was the difference in average system durations -- 2.6 h for VFBs and 4.3 h for LIBs. For this reason, additional LIB systems were included in the dataset presented in **Figure 6** by reviewing longer duration projects under planning application. New South Wales in Australia is at the forefront of long-duration storage, with systems of up to 8 h duration under planning. Increasing the duration of the LIB system is seen to increase the energy density, as the land required for

---

[53] Stack Developments in a kW Class All Vanadium Mixed Acid Redox Flow Battery at the Pacific Northwest National Laboratory. https://doi.org/10.1149/2.0281601jes

[54] As an aside, many FB being commercialised have advertised cycle lives that hit round numbers e.g., 10,000, or 20,000.

[55] Achieving high efficiency and cyclability in inexpensive soluble lead flow batteries. https://doi.org/10.1039/C3EE40631H

[56] Beyond energy density: flow battery design driven by safety and location - Energy Advances (RSC Publishing). https://doi.org/10.1039/D3YA00208J

cabling and power conversion does not increase linearly with energy capacity. However, the smallest system shown, at 98 MW, exhibits a poorer energy density due to fixed requirements for perimeter spacing.

The 50 MW/50 MWh LIB system at the Energy Superhub Oxford[57], included in **Figure 6** and which also features an Invinity Energy Systems manufactured VS3 2 MW/5 MWh VFB, is unusual in that the containers are stacked two high using a custom frame, which approximately doubles the energy density. Reber et al. noted that of the 21 LIB installations surveyed, only 2 were configured in this way. The layout of containerised LIB projects appears to be primarily guided by insurance requirements, with a minimum spacing of 4.5 m being specified to limit losses to a single container in case of fire[58]. The only mention of stacking found during this review was guidance from the National Fire Chiefs Council, stating that they do not support stacking (they also suggest a minimum spacing of 6 m)[59]. Recently CATL announced a 9 MWh LIB product based on two 20 ft ISO containers stacked, showing that footprint is becoming a focus for LIB manufacturers[60].

For VFBs, the energy density of the 200MW/800 MWh system in Dalian in China, which is based on a chemical plant format, is expected to reach an energy density of 50 kWh/m^2 (once the second phase of construction is completed) -- exceeding that of the 4 h LIB system. Also, Invinity's progress in stacking 20 ft containers two-high suggests that if three-high stacking were possible, the energy density gap between VFBs and 4 h duration LIBs would be closed.

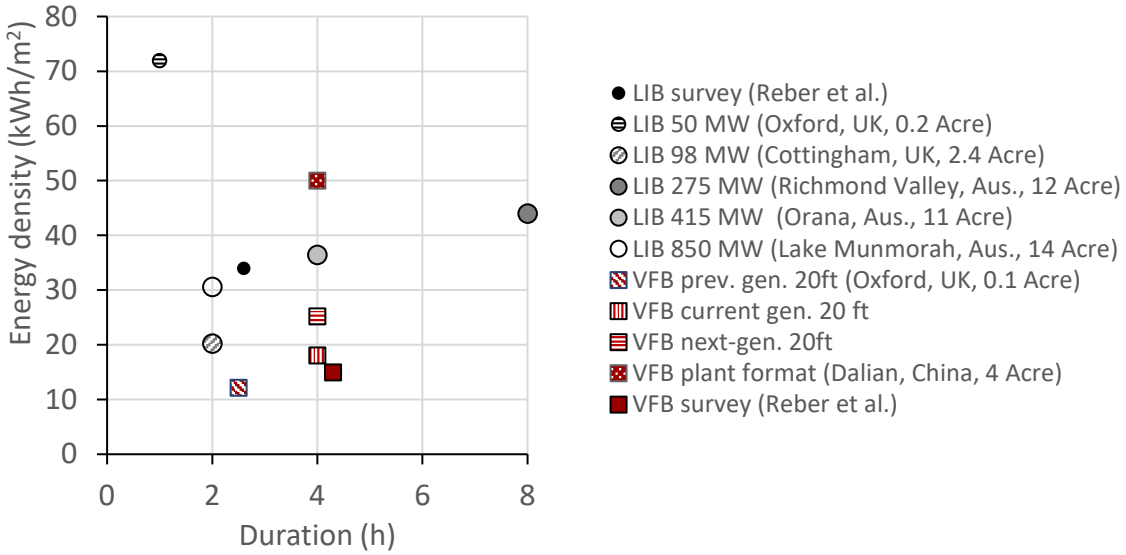


Figure 6: Energy footprints of vanadium FB projects and large-scale LIB installations taken from Reber et al. or judged from photography or planning drawings. The "current generation VFB" product shown is the Invinity VS3 containerised modules stacked 2 high with manways at the sides and ends, as deployed at the Viejas Project in California.[61] The next generation VFB product shown is Invinity Endurium, which

[57] https://www.apse.org.uk/sites/apse/assets/File/Renewables Oct23 combined.pdf

[58] https://www.wtwco.com/en-gb/insights/2023/02/battery-energy-storage-systems-key-risk-factors

[59] https://nfcc.org.uk/wp-content/uploads/2023/10/Grid-Scale-Battery-Energy-Storage-System-planning-Guidance-for-FRS.pdf

[60] CATL Launches World's First 9MWh Ultra-Large Capacity TENER Stack Energy Storage System Solution https://www.catl.com/en/news/6410.html

61 https://www.sandiegouniontribune.com/2024/09/13/a-microgrid-project-at-viejas-gets-a-macro-boost/

removes the requirement for side access to containers and can achieve an energy density of up to 100 MWh / acre in double-stacked configuration.

It is probable that, given the higher electrolyte energy density of the hybrid lithium/polysulfide, zinc/bromine and iron/iron hybrid FBs, these technologies will be able to achieve even greater system-level energy densities than VFBs.

It is unlikely that further research will markedly improve the electrolyte energy densities of FBs, as their limitations are primarily dictated by the solubility of the active chemicals in the electrolyte.

3.4 Conclusions

The analysis of key performance metrics across the different FB types reinforces the point that that FBs are too diverse to be considered a single class from an applications perspective.

The widest range in performance is related to energy density. Hybrid metal plating FBs tend to have the highest energy density, with electrolyte energy density ranging from15% to 76% of LIBs. In contrast, well-established VFBs have an electrolyte energy density of approximately 10% that of LIBs. Most other all-solution FBs have energy densities as low as 10% of VFBs. The gap between VFBs and LIBs at the electrolyte level is mostly closed on a square–meter basis at the system level, implying that hybrid metal plating FBs could surpass LIBs in this metric. Transport challenges will remain, and these are discussed further in Section 4.3.2.

RTE also varies across FB technologies, though most fall within the 70-80% range. While lower than the cell efficiency of LIBs, this may not be crucial if the cost saving from use of FBs across the project lifetime outweigh the increase in charging costs.

Regarding lifetime, VFB systems are expected to exceed those of the latest LIB systems. However, other FB types have yet to demonstrate comparable longevity or may require further research and development to be able to do so. Hybrid metal plating FBs tend to have shorter lifetimes than VFBs, making research into flow path and electrode design critical to improving their ability to support repeated plating and dissolution.

4. Practical Challenges and Opportunities Around Deployment of Flow Batteries in Developing Economies

4.1 Introduction

The deployment of FBs in developing economies presents a unique set of challenges and opportunities. These regions, characterised by diverse climates, logistical hurdles, and varying levels of workforce expertise, require tailored solutions to effectively integrate FB technology. This section first explores the critical issues that impact the deployment of all LDES, including climate considerations and logistical constraints. The challenges and opportunities associated with FBs are then analysed in comparison to LIBs and PbABs.

Consideration of the availability of skilled labour is out of scope of the report.

4.2 General Challenges for Deployment of LDES in Developing Economies

4.2.1 **Climate**

The countries and regions covered in this report span a wide array of climates. However, broad climate definitions can be used to group areas with similar climate conditions. Within these climate zones, factors such as temperature, humidity and dust can be assessed for impact.

These climate zones are discussed in 8.Appendix A. Climates in the areas of interest include regions of high and low temperature as well as humid and wet conditions with seasonal storms a further consideration.

Battery systems operating in these environments must therefore be capable of functioning at high temperatures and, depending on the location, must also perform effectively in both very dry and highly humid conditions. While higher environmental temperatures are favourable for some battery chemistries, they can be detrimental to others. Increased humidity raises the risk of condensation inside battery installations, which can lead to corrosion and safety issues.

4.2.2 **Logistics**

In developing economies, particularly in rural SSA, logistics present a significant challenge.

Road transport in SAA is hindered by inadequate and underdeveloped infrastructure. Many roads, especially outside major urban areas, are unpaved, poorly maintained, and prone to damage from seasonal weather conditions. During the rainy season, flooding and mud can render roads impassable, severely disrupting transport routes.

Limited road network coverage further complicates logistics. With vast distances between major cities and industrial hubs, many rural areas remain disconnected from main road systems, as shown in **Figure 7**. This makes accessing many regions difficult and costly.

The poor condition of vehicles adds to the difficulty. In many parts of the region, trucking fleets are aging and poorly maintained, leading to frequent breakdowns. This not only slows down deliveries but increases costs for repairs and replacement parts, which are not always readily available. The lack of reliable roadside assistance or repair services in remote areas compounds this issue.

Border crossings present additional logistical barriers. Cross-border road transport can be delayed by inconsistent regulations, lengthy customs procedures and corruption. Similar inefficiencies are present at ports. Major ports such as those in Lagos, Mombasa,

and Dar es Salaam often experience congestion, with lengthy clearance processes and outdated infrastructure. This can result in significant delays, increasing the cost of imports and exports. Additionally, many smaller ports lack the capacity to handle large container ships, forcing reliance on trans-shipment through other regional hubs.

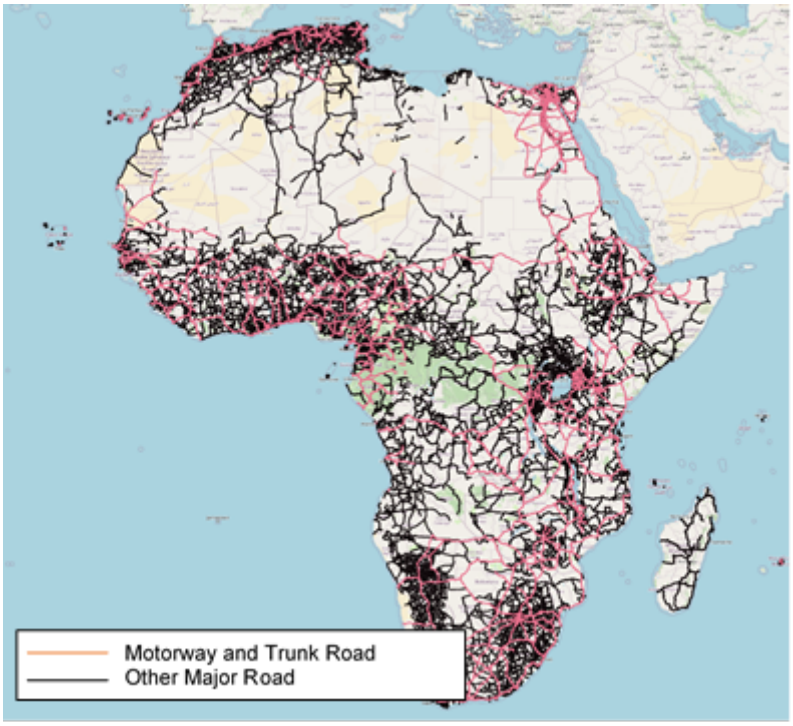


Figure 7: Road network in Africa, using data from Open Street Map from November 2024[62].

Logistics in South Asia is characterised by both opportunities and challenges due to the region's diverse geography, growing economies, and infrastructural limitations. South Asia - India, Pakistan, Bangladesh, Nepal, and Sri Lanka - presents a dynamic logistics landscape shaped by a combination of increasing trade activity and infrastructural bottlenecks.

One of the biggest challenges in deploying FBs is the region's infrastructure. Although countries such as India have made significant investments in improving roads, ports, and railways, many areas still suffer from poor connectivity, particularly in rural regions. Roads are often congested and in poor condition, slowing down the movement of goods. In mountainous regions in Nepal and parts of northern India, rugged terrain further complicates road transport. Rail networks, while extensive in India, remain outdated in parts. Port congestion, particularly in major hubs such as Mumbai, Karachi, and Chittagong, adds to the logistical burden by slowing down the import and export processes.

Cross-border logistics also face challenges due to complex customs regulations, border delays, and inconsistent policies between countries. For instance, trade between India and Pakistan has historically been hampered by political tensions, while movement between India, Nepal, and Bangladesh is often slowed by bureaucracy and outdated border infrastructure.

[62] Data from Open Street Map, https://www.openstreetmap.org/, Data accessed Nov 2024

4.3 Flow Battery-specific Challenges and Opportunities

While the preceding discussion highlighted the general challenges of deployment of LDES in developing economies, there are specific challenges and opportunities unique to FBs that contrast to those of LIBs and PbABs.

4.3.1 **Climate**

It was shown in Section 3.2 that the lifetime of LIBs is significantly reduced at 40 °C, and prolonged storage at even 35 °C is not recommended. High temperatures lead to faster degradation by accelerating side reactions such as electrolyte decomposition and solid electrolyte interphase layer growth. These reactions lead to loss of active lithium and increased internal resistance, ultimately reducing battery capacity and lifespan. Additionally, thermal decomposition of the electrolyte can increase the risk of gas formation and swelling within the battery cell, further accelerating wear and tear.

By contrast, the maximum operating temperatures for FBs range from 40-60 °C, implying that FBs should have better chance of outcompeting LIBs in hot climates. However, the comparison becomes more complex at the system level and in real world applications.

Heating, ventilation & air conditioning (HVAC) systems can be installed to regulate LIB temperature, also helping to maintain humidity levels, preventing corrosion of metal parts. While HVAC will improve LIB lifetime, it introduces parasitic losses that reduce efficiency, likely closing some of the performance gap between LIBs and FBs.

An intrinsic advantage of FBs in thermal management is the generally high thermal mass of water-based electrolytes, which leads to them having a degree of passive thermal regulation. Maintaining the electrolyte at the correct temperature is also straightforward, as a heat exchanger can be used. This contrasts with the LIBs where the HVAC must be designed to cool thousands of individual cells uniformly.

It is however important to note that operating at high ambient temperatures does place a constraint on VFB operation. This is because losses during cycling are converted to heat, which is transferred to the electrolyte. VFB Manufacturer CellCube includes a cooling system in its product line[63]. In principle, it is easier to cool a system operating at 40 °C than one that must operate at 30 °C (for example to manage LIB degradation) as passive cooling through air circulation may suffice, reducing the need for active HVAC. This appears to be the case with the "forced air" cooling employed by Invinity in its Endurium VFB product[64]. Other FB chemistries have higher claimed temperature tolerance than VFB (see Section 3.2), and should hence require less cooling equipment. The development of the iron/vanadium flow battery by Saudi Aramco and Rongke Power (see Section 3.2) implies that there is room for improvement on the VFB temperature tolerance with regard to extreme heat environments.

Detailed modelling or pilot studies would greatly benefit the comparison of FB and LIB operation in hot climates. The impact of temperature is also use-case specific; FBs with longer durations are generally easier to manage due to the larger thermal mass of the electrolyte.

[63] https://www.cellcube.com/wp-content/uploads/R4.2_Product-Data-Sheet_external_CellCube_V01.02.pdf

[64] https://invinity.com/wp-content/uploads/2025/03/Invinity-Endurium%E2%84%A2-Data-Sheet-MAR0020-2025-04b.pdf

In general, higher temperatures lead to increased conductivity due to the increasing mobility of the ions in solution. Increasing temperature can also increase the dissociation of ions, further increasing the conductivity due to the increased number of ions available for charge transfer. However, at lower temperatures, the viscosity of the electrolyte increases, increasing pressure drop through the flow circuit; this is typically up to a 10% drop in efficiency for a VFB. This increased viscosity also can lead to higher pumping losses, reduced mass transfer, side reactions and an overall decline in system efficiency. Simultaneously, lower temperatures decrease the conductivity of the electrolyte, reducing the speed of ion transport and slowing the redox reactions, which negatively impacts power output.

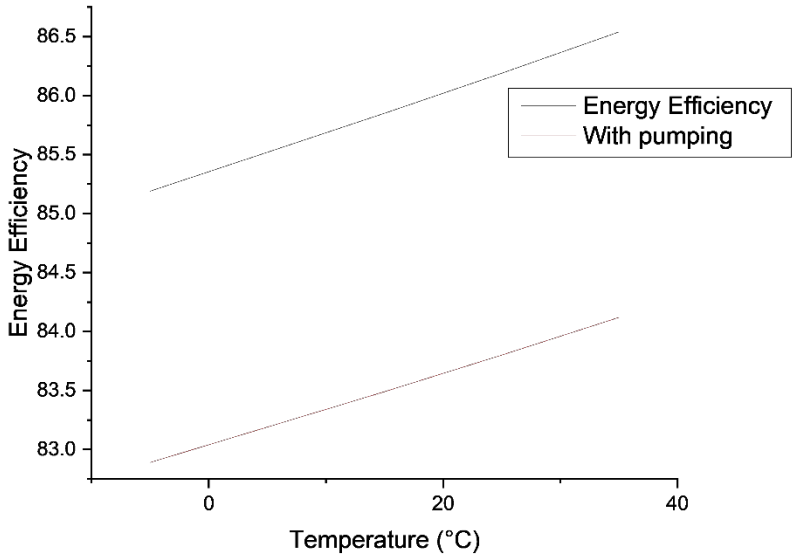


Figure 8: VFB efficiency (with and without pumping losses) over a range of temperatures[65].

Conversely, at higher temperatures, electrolyte conductivity typically improves, enhancing ion transport and reaction rates, which can boost power density and efficiency. An example of the efficiency-temperature relationship for VFBs is shown in **Figure 8**. However, excessively high temperatures can lead to thermal degradation of the electrolyte, potentially causing precipitation of dissolved metals or breakdown of other components, reducing the battery's lifespan.

Long-term exposure to high temperatures can also degrade other components of FBs, including membranes, electrodes and pumps. Membranes, which are crucial for ion exchange between the battery's compartments, become less selective at higher temperatures, leading to crossover of ions and reduced system efficiency. Similarly, high temperatures can accelerate corrosion of electrodes, particularly in acidic or highly oxidative environments, affecting the battery's durability. However, the impact of these effects has not been studied in depth. High temperatures can also increase the degradation of plastics and pumps, which are common to all FBs.

[65] Thermal hydraulic behavior and efficiency analysis of an all-vanadium redox flow battery. https://doi.org/10.1016/j.jpowsour.2013.05.092

In some cases, the electrolyte may precipitate or decompose at elevated temperatures. For example, in VFBs using the common sulfuric acid-based electrolyte, vanadium species can precipitate out of solution above 40 °C reducing the capacity and forming solids that clog the system's channels[66]. It is important to note that precipitation occurs from the most oxidised state of vanadium in the posolyte, hence the problem is not observed when the VFB is discharged, allowing safe transport of the electrolyte, and may be mitigated during operation by avoiding high states of charge.

A mixed-acid electrolyte has been developed to improve solubility, increase temperature tolerance, and reduce viscosity. This electrolyte has been demonstrated to be stable in operation at 50 °C and 5 °C[67], but is under patent protection, which is the subject of some controversy[68].

4.3.2 **Logistics**

As discussed in Section 3.3.3 the lower energy density of FBs at a container level is unlikely to be a major concern for installations - except perhaps for the lowest energy density systems as noted in Section 3.2 - with the closing of the areal energy density difference between FBs and LIBs. However, when it comes to transporting these systems, the lower energy density per container still necessitates the transport of a larger number of containers for the same energy. In a 20 ft container, future LIB products have been announced with capacities of up to 8 MWh[69], though most installations are converging at around 5 MWh[22]. In contrast, FBs are usually <500 kWh in a 20 ft container. However, as discussed in Section 2.3, some FBs have been configured with multiple smaller modules within each container. Each module can usually run independently with minimal linking of control systems required to integrate each module. This may offer an advantage in that multiple smaller modules can be transported without the same need for system HVAC and fire mitigation, which is more difficult with LIBs. This could be a key advantage for FBs when transported via underdeveloped road networks.

There are other advantages: flow batteries can be shipped fully discharged unlike LIBs. The components of a FB system, e.g., the electrolytes and stack/balance of plant, can also be transported separately as commodities, further easing transport limitations.

Transport challenges may impact LIB viability, particularly relating to temperature aggravated degradation. As noted in Section 3.2, the maximum recommended storage temperature for a commercial LIB cell is 35 °C. However, containers in transit can reach temperatures up to 50 °C at sea and 57 °C on land[70]. Such high temperatures have been identified as a potential cause of recent fires on container ships[71] and may significantly reduce LIB lifetime before installation. This would apply to both cells being transported, and to containerised LIB systems, where the HVAC is not powered.

---

[66] 1 kW/1 kWh advanced vanadium redox flow battery utilizing mixed acid electrolytes. https://doi.org/10.1016/j.jpowsour.2013.02.045

[67] Chloride supporting electrolytes for all-vanadium redox flow batteries. https://doi.org/10.1039/C1CP22638J

[68] https://www.npr.org/2022/08/03/1114964240/new-battery-technology-china-vanadium

[69] https://etn.news/energy-storage/envision-8-mwh-containerized-battery-storage-system-details

[70] https://epgna.com/how-hot-do-shipping-containers-get/

[71] https://www.reuters.com/world/europe/one-dead-cargo-ship-fire-electric-car-suspected-source-dutch-coastguard-2023-07-26/

4.3.3 **Maintenance**

There are notable differences between the installation and operation of FBs and LIBs that can impact project success when utilising workforces in developing economies.

FBs are inherently multidisciplinary in nature, requiring expertise in engineering, chemistry, safety and electronics during their design. However, compared to LIBs, their installation is generally simpler and does not require the same level of safety-critical site design and fire mitigation strategies. Fire safety standards for BESS are still evolving globally and are tending to become more stringent. Given the lower fire risk, FBs have less complex fire mitigation and HVAC requirements, reducing the need for highly specialised, safety-critical roles during installations. While LFP batteries are known for their inherent thermal stability and lower risk of thermal runaway compared to other lithium-ion chemistries, they are still susceptible to high-temperature-induced safety issues. If temperatures exceed 60 °C, the likelihood of thermal runaway -- a chain reaction of exothermic processes that can cause fire or explosions -- increases.

Local workforce availability may also impact the success of FB deployment, particularly in terms of ongoing maintenance requirements.

Some FBs require rebalancing, and therefore maintenance (likely at the skilled manual worker level), when the concentrations of each electrolyte differ from what is expected at a given state of charge[72]. There are three main mechanisms that cause these imbalances:

1. **Side reactions**: Processes such as hydrogen and oxygen evolution in aqueous systems reduce coulombic efficiency and can cause a reduction in capacity by consuming active materials or by causing an imbalance in electrolyte state of charge. If these reactions occur at different rates at the positive and negative electrode, this causes an imbalance. The SoC of one electrolyte would reach 100% before the second electrolyte, while the other electrolyte would reach 0% SoC prematurely.
2. **Crossover**. The movement of species or solvents between the positive electrolyte to the negative electrolyte or vice versa, affecting system performance.
3. **Electrolyte-air reactions**. Exposure to air can trigger chemical reactions that further disrupt electrolyte composition.

Hybrid metal plating FBs require periodic electrode stripping to maintain performance. In real systems, deposited material can be uneven or dendritic, leading to deposits that cannot be effectively removed during discharge. In some cases, these deposits may grow across the cell causing a short circuit. To prevent this, after a certain number of charge/discharge cycles, these technologies need to undergo a maintenance or stripping cycle, during which the system is discharged to 0 V to completely remove material from the electrodes[73,74]. These maintenance cycles can reduce overall efficiency and restrict the

[72] Vanadium redox flow battery with slotted porous electrodes and automatic rebalancing demonstrated on a 1 kW system level. https://doi.org/10.1016/j.apenergy.2018.12.001

[73] Innovative zinc-based batteries. https://doi.org/10.1016/j.jpowsour.2020.229309

[74] All-Lead-Flow-Batteries as Promising Candidates for Energy Storage Solutions. https://doi.org/10.13044/j.sdewes.d6.0256

operational freedom of the FB as they must be fully discharged intermittently, although it has been shown that this can be scheduled to minimise the impact[75].

When designing an FB, it is possible to automate at least some of the maintenance processes, but it is not clear to what extent manual interventions will remain necessary. In a developing economy context, it may make more sense to design a lower-cost and easier-to-manufacture system that requires some manual intervention, given the lower cost of labour, and the potential for job creation.

FBs are not unique in requiring maintenance. Lead-acid batteries, for example, need to be regularly fully charged or overcharged to maintain optimal performance and extend their lifespan. Care must also be taken to operate them within the recommended state-of-charge envelope. Flooded lead-acid cells require maintenance and re-watering, while valve-regulated and gel-type versions have lower maintenance requirements. Nevertheless, many lead acid systems have been used in applications such as uninterruptible power supplies (UPS), and traction (including submarines) for lifetimes of 10 to 15 years or more. LIBs, on the other hand, do not require (or allow) intervention at the cell/battery level. However, maintenance is still necessary for the balance-of-system components, such as cooling fans.

4.4 Deployment Challenges Matrix

There are several issues common across many FB technologies that are not specific to developing economies. However, they are still relevant in these environments.

Table 2 describes several common issues with FB, grouped into VFB, all-liquid and hybrid systems. LIB is included for comparison. Green signifies that the issue has a low impact on the technology group. Amber has some effect, but it can be mitigated. Red signifies a significant issue that is detrimental to the performance of the technology, while black signifies a substantial issue that also leads to safety concerns.

Hybrid FBs are given a mixed scored for electrolyte balancing; hybrid FB based on a single electrolyte like the lithium/polysulfide and soluble lead systems are intrinsically resistant to crossover, but for other types this must be designed for.

As many FB technologies require an ion exchange membrane or separator, these components must remain stable in their environment. At higher temperatures, many membranes degrade at an increased rate, affecting performance and longevity.

Security is another claimed advantage of FBs. They are often installed in large modules that are very difficult to remove. Any precious materials are dissolved in a liquid electrolyte that must undergo chemical reaction to recover. Because they are arranged as a bipolar stack there is a reduced requirement for copper wiring and bus bars, which, as they contain valuable metals, may be subject to theft.

[75] Overcoming the performance limitations of hybrid redox flow batteries with modular operation. https://doi.org/10.1016/j.est.2023.110280

Table 2: Common FB issues with prevalence by FB type. Colour indicates impact on technology, green signifies low impact, amber some impact that can be mitigated, red is a significant issue and black also signifies safety concerns.

		VFB	All-liquid	Hybrid	LIB
Electrolyte rebalancing					
Electrode stripping					
Air sensitivity					
Temperature °C	20				
	30				
	40				
	50				
	>60				
Membrane/separator stability					N/A
Security					
Dust					

Key	Low	Can be mitigated	Significant	Safety concerns

Many electrolytes, particularly those that are highly acidic or alkaline, are subject to reaction with the air. Typically, in acidic electrolytes, exposure to oxygen causes oxidation of species, leading to capacity loss or an imbalance between electrolytes. These side reactions also lead to the formation of unwanted by-products, such as solid precipitates that may clog flow channels and damage separators.

Because FBs rely on a flowing electrolyte, they must have good ingress protection to prevent electrolyte evaporation and contamination from dust, which could lead to blockages in the flow circuit. A sealed system helps mitigate these risks by preventing exposure to air and oxidation of the electrolyte.

4.5 Safety Concerns & Toxicity

FBs that use aqueous electrolytes -- the vast majority, as discussed in Section 2.1 -- have a major advantage over LIBs as they do not suffer from thermal runaway and hence have a significantly reduced fire risk. However, they are not without hazards, as many electrolytes are highly acidic or alkaline and may contain toxic substances.

Table 3 summarises the primary electrolytes of commercially explored FBs, listing their constituents and their Globally Harmonized System of Classification and Labelling of Chemicals (GHS) toxicity classification in a range of areas. The GHS system classifies

substances on a scale from 1-4, with lower numbers indicating a higher toxicity. A ranking of 5 is assigned to chemicals that are not classified as toxic in any of the following categories: toxic via oral exposure, toxic via inhalation, mutagenicity, carcinogenicity, reproductive toxicity, toxic with effects of or via lactation, specific target organ toxicity – single exposure (STOT SE), specific target organ toxicity – repeated exposure (STOT RE) and hazardous to the aquatic environment[76].

Table 3: Toxicity of different compounds found in different FB electrolytes. 1 is highest toxicity (marked in red), 5 lowest (green).

Battery		Compound	Toxicity classification									
			Oral	Inhalation	Mutagenicity	Carcinogenicity	Reproductive	Lactation	STOT SE	STOT RE	Aquatic	Total
All-liquid	VFB	V_2O_5	3	1	2	1	2	5	3	1	2	2.2
		Electrolyte	4	5	5	5	2	5	1	1	1	3.2
	Fe/Cr	Cr(III)Cl	4	5	5	5	5	5	5	5	5	4.9
		Cr(II)Cl	4	5	5	5	5	5	5	5	5	4.9
		$FeCl_2$ (Soln)	5	5	5	5	5	5	5	5	5	5.0
		$FeCl_3$ (Soln)	4	5	5	5	5	5	5	5	5	4.9
		HCl	5	5	5	5	5	5	3	5	5	4.8
	Aqueous Organic	Anthraquinone	5	5	5	1	5	5	5	5	5	4.6
		Ferrocyanide	5	5	5	5	5	5	5	5	5	5.0
		TEMPO	5	5	5	5	5	5	5	5	3	4.8
		Fremy's salt	4	5	5	5	5	5	5	5	5	4.9
		Porphyrexide	5	5	5	5	5	5	5	5	5	5.0
	Acid/Base	NaOH	5	5	5	5	5	5	5	5	5	5.0
		HCl	5	5	5	5	5	5	3	5	5	4.8
		NaCl	5	5	5	5	5	5	5	5	5	5.0
Hybrid (metal plating)	Zinc/ bromine	ZnBr	4	5	5	5	5	5	5	5	2	4.6
		MEP (complexing agent)	5	5	2	5	5	5	5	5	5	4.7
		MEM (complexing agent)	5	5	5	5	5	5	5	5	5	5.0
		Bromine	5	1	5	5	5	5	5	5	1	4.1
		Zinc	5	5	5	5	5	5	5	5	5	5.0
	Lead	Pb	4	4	5	1	1	5	5	2	1	3.1
		PbO_2	4	4	5	5	1	5	5	2	1	3.6
		PbO	4	4	5	2	1	5	5	5	1	3.6
		Pb (MSA)	4	5	5	5	1	5	5	2	5	4.1
		MSA	4	5	5	5	5	5	3	5	5	4.7
	Iron/iron	$FeCl_2$	4	5	5	5	5	5	5	5	5	4.9
		$FeCl_2$ (Soln)	5	5	5	5	5	5	5	5	5	5.0
		$FeCl_3$ (Soln)	4	5	5	5	5	5	5	5	5	4.9
Hybrid (gas-use)	Hydrogen/ manganese	$MnCl_2$	3	5	5	5	5	5	5	2	5	4.4
		$TiCl_2$	5	5	5	5	5	5	5	5	5	5.0
		MnO_2	4	5	5	5	5	5	5	2	5	4.6
		H_2SO_4	5	5	5	5	5	5	5	5	5	5.0
	Hydrogen/ bromine	HBr	5	5	5	5	5	5	3	5	5	4.8
		HBr/Br_2 (aq)	5	2	5	5	5	5	3	5	1	4.0
		Bromine	5	1	5	5	5	5	5	5	1	4.1

While the substances listed in **Table 3** are those most frequently found under normal operating conditions, additional hazardous substances may form during failure or non-standard conditions. Bromine gas, for example, can be released under adverse conditions

[76] https://www.legislation.gov.uk/eur/2008/1272/pdfs/eur_20081272_2020-11-14_en.pdf

from zinc/bromine FBs[77]. Similarly, while ferrocyanide is stable under alkaline conditions and is not classified as a toxic substance, if the pH is allowed to drop too low it degrades to the highly toxic hydrogen cyanide [78]. Currently no comprehensive review of substances produced under adverse conditions exists in the FB literature.

4.6 Conclusions

Proposed opportunities for FB deployment in developing economies come from their relative temperature tolerance when compared to LIBs during transit, storage and operation. However, the extent of this advantage at the full system level – where LIBs can be cooled with HVAC albeit at the cost of efficiency – has not been publicly documented. While FBs may also see accelerated degradation at temperatures over 40 °C, this has not been studied in depth.

A significant challenge for FBs in developing economies, particularly in regions with under-developed road networks, is the low energy density of their electrolytes. In this context, containerisation may not always be the best approach, as smaller modules could be more easily transported. This approach may not be suitable for LIBs used for BESS, where the container itself is part of the climate control system. As noted in Chapter 3, some FB chemistries offer considerably higher electrolyte energy densities than VFBs. Local manufacture of FB electrolytes, therefore, could help address logistical challenges associated with import and in-country transport.

Fire safety risks are lower for FBs that use water-based electrolytes, and this is particularly relevant in developing economies where the workforce may have limited fire safety training. Maintenance poses another challenge as FBs may require specialised servicing. However, it is not clear to what extent maintenance operations can be automated. maintenance presents an opportunity for local employment.

[77] Thermodynamic study of bromine evaporation from solid Bi(III) polybromides. https://doi.org/10.1016/j.jct.2019.105958

[78] Long-Term Stability of Ferri-/Ferrocyanide as an Electroactive Component for Redox Flow Battery Applications: On the Origin of Apparent Capacity Fade. https://iopscience.iop.org/article/10.1149/1945-7111/ace936

5. Market Potential for Flow Batteries in Developing Economy Use-cases

5.1 Introduction

FBs are positioned as a leading solution for long duration energy storage (LDES), particularly in developing economies. For this analysis, LDES is defined as storage systems with a minimum duration of four hours, though the increasing share of renewable energy will likely push demand toward longer durations—up to 10 or 24 hours, or even longer. According to IDTechEx[79], storage durations of around 6 hours become economically viable once renewable energy penetration reaches 45%, matching the durations being targeted by several FB products, (see **Figure 4**). Several OECD countries and developing economies have already surpassed this threshold.

Understanding the potential market for FB requires an analysis of electricity market structures, regulations, and targets within key developing regions. A detailed evaluation of demand sectors will also help identify the most suitable applications for FBs.

5.1.1 Flow Battery Scale

Discussions with multiple manufacturers at the 2024 International Flow Battery Forum indicate that the lower threshold for economically viable FBs is approximately 200 kW / 1 MWh, though this can vary depending on the manufacturer and chemistry. In this report, we focus on systems with a minimum output of 200 kW and durations of at least 5 hours, as economies of scale favour FBs in larger deployments, while lithium-ion batteries dominate the smaller-scale market.

For context, a 200 kW / 1 MWh FB could power a small factory, a medium-sized workshop deploying multiple heavy-duty machines, or a large commercial building for 5 hours. In a community, it could power 400-500 homes for the same duration.

5.1.2 Geographical Scope

The focus of this report is on three regions and the most relevant economies within each. These were selected based on data availability and comprise a mix of countries broadly representative of their region, along with outliers to capture the areas of greatest challenge. Countries with the largest economy and/or population are each included.

[79] https://www.idtechex.com/en/research-report/long-duration-energy-storage-market-2024-2044-technologies-players-forecasts/983#:~:text=Global%20lon

Figure 9: Geographic location of developing economies covered within this report.

- **South Asia:** focusing on India and Nepal
- **Southeast Asia:** including Vietnam, Thailand, Malaysia, Indonesia, the Philippines and Papua New Guinea (PNG)
- **Africa:** including South Africa, Nigeria and Kenya

While Singapore is not a developing economy, its role as a major trading hub within ASEAN makes it relevant. Singapore's relatively recent electricity market liberalisation, the first in Asia, could serve as a model for neighbouring countries. Hence it could be an important proving ground for LDES.

Other regions are excluded from this report, but many insights may also be relevant to developing economies in Polynesia, Central Asia, and South America. These regions, among others, aim to significantly expand renewable energy deployment, making LDES an essential component to achieve this goal.

5.1.3 **Overview of Potential Market Drivers**

The following are potential drivers for LDES in developing economies, with a particular focus on systems that can support durations of 4–12 hours, where FBs offer the greatest benefits:

1. **Unreliable power grids**: LDES can enhance the integration of renewable energy into weaker grids, which are common in developing economies, improving both grid stability and reliability[80].
2. **Remote and off-grid locations**: FB can deliver reliable long-duration energy storage, making them ideal for applications such as isolated or off-grid services, telecoms infrastructure, and remote communities[81].

[80] https://www.atlanticcouncil.org/blogs/energysource/developing-countries-offer-enormous-market-potential-for-long-duration-energy-storage/

[81] https://www.ldescouncil.com/

3. **Critical infrastructure**: FBs can enhance resilience for hospitals, data centres (see Section 5.3.4), and water treatment facilities, all of which require uninterrupted, high-quality power—often a significant challenge[80].
4. **Replacement for fossil fuel generators**: FBs offer a more sustainable and cost-effective alternative to generators, commonly used for backup power[80].
5. **Renewable energy integration**: As developing countries increase their share of solar and wind power, FBs can stabilise the grid and ensure a reliable electricity supply for both on- and off-grid applications[80].
6. **Areas with limited flexibility options**: In regions where flexibility options (e.g., gas-fired generation and cross-border interconnections) are limited, FBs can provide essential power balancing[80].

Figure 10 summarises the breakdown of fossil (coal and gas), nuclear and renewable generation across the target regions. While fossil fuels still dominate in most countries, the increasing deployment of renewable energy sources will expand the opportunities for FBs.

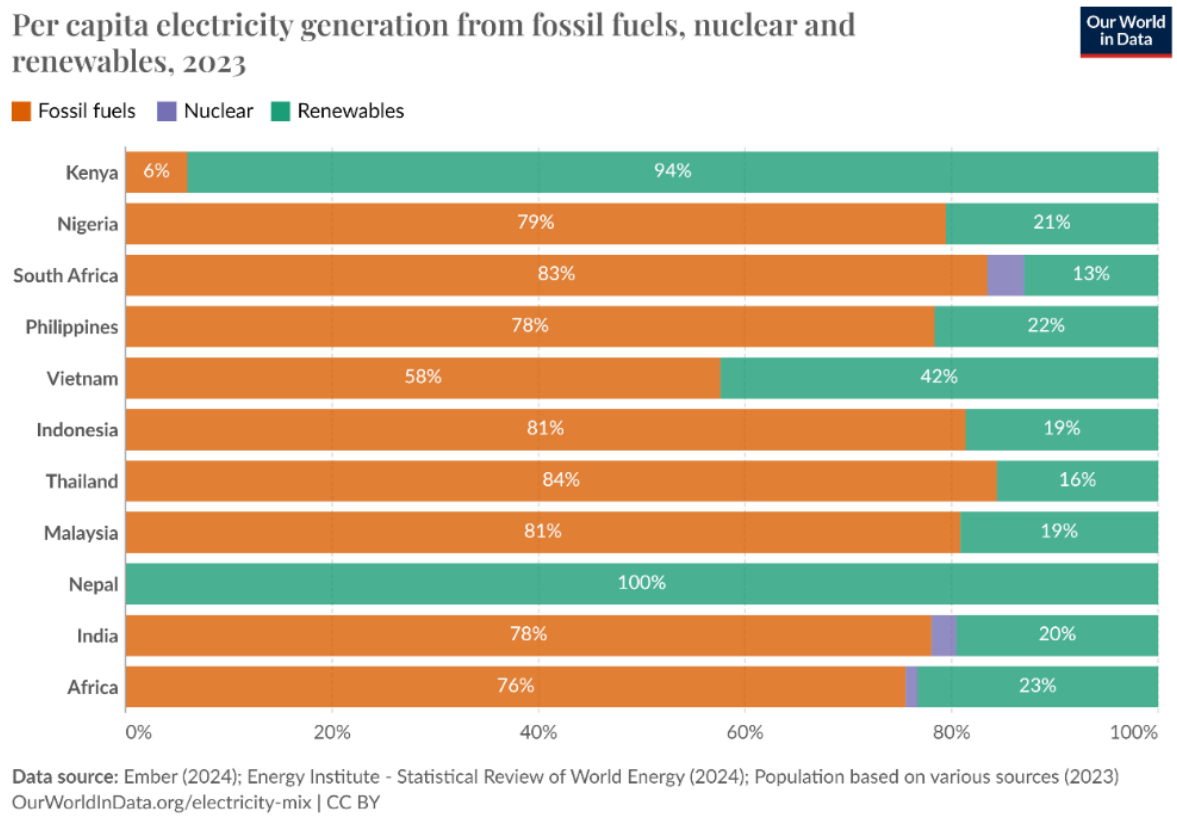


Figure 10: Generation split of renewables, nuclear, fossil (coal and gas) in the target countries/regions[82].

5.2 Electricity Sector Analysis

The progress of the energy transition varies significantly by region, influenced by diverse regulatory structures, market maturity, and energy generation mixes. To assess the market

[82] Hannah Ritchie and Pablo Rosado (2020) - "Electricity Mix" Published online at https://ourworldindata.org/electricity-mix

potential of FBs, it is important to understand these regional differences in the electricity sector.

Despite the growing focus on renewable energy and the acknowledged need for storage, there are no specific initiatives promoting FBs, and awareness of their potential and unique benefits remains generally low. This is one challenge that this report aims to address.

A more detailed analysis of the electricity sector in each country is presented in Appendix B.

5.2.1 **Overview of Grid Reliability**

Many developing economies suffer from unreliable electricity grids with all the negative consequences this entails. **Figure 11** illustrates the issue:

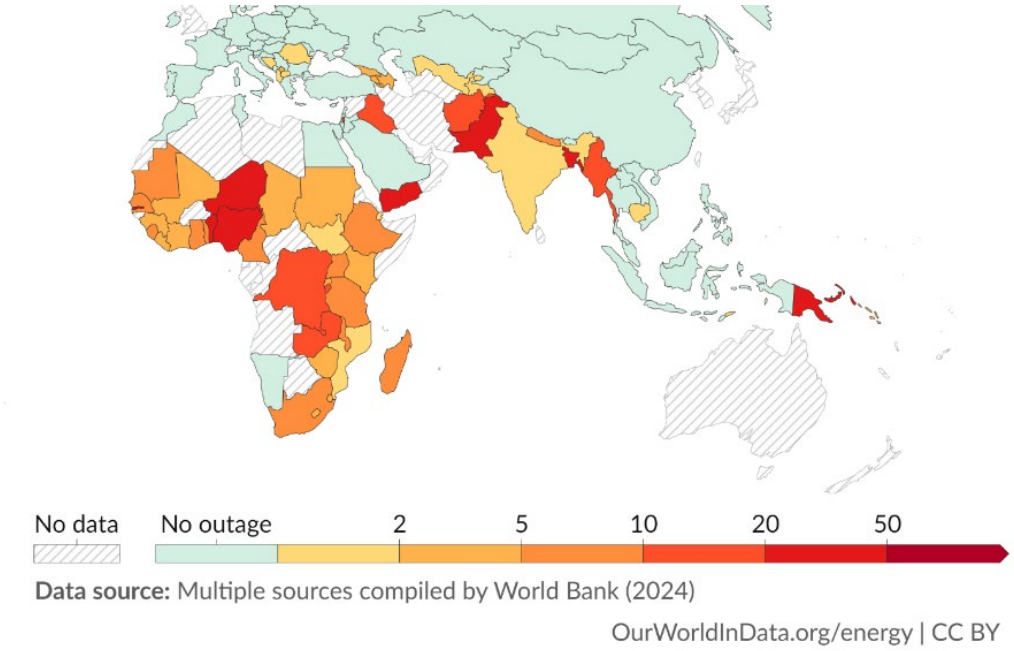


Figure 11: Monthly grid outages experienced by country across Africa and Asia. Source: Our World in Data (2024)

In Africa and parts of Asia several countries continue to experience frequent outages due to longstanding shortages in generation capacity and grid penetration.

5.2.2 **Small-Scale Generators**

Standby fossil fuel generators are widely deployed in such countries, leading to more pollution, greater energy costs and a higher fossil fuel dependency. **Figure 12** illustrates the scale of the challenge with India, Nigeria and Indonesia standing out in their regions:

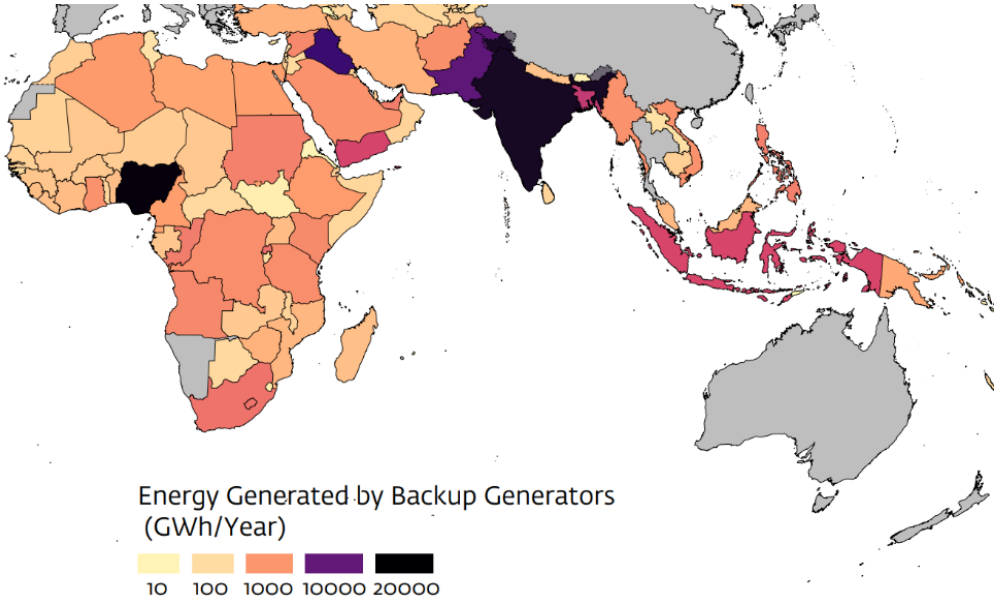


Figure 12: Backup generators, total output. Source: IFC report, 'The Dirty Footprint of the Broken Grid', 2019

5.3 Key Demand Sectors

In this section, the ability of FBs to solve the unique energy challenges of specific sectors is assessed. These sectors where chosen following correspondence with experts in the energy industry in developing economies and analysis of the sectors where LDES is being using in developed markets.

5.3.1 **Mining**

FBs can be well-suited for mining operations in developing economies, offering several advantages that address the unique challenges faced by mines, such as scalability, long lifespan, tolerance to harsh climates, and integration with renewable energy sources. VSUN in Australia is already trialling a VFB for its remote operations[83], as is idemitsu[84].

Although a large potential market, the mining industry is known to be cautious in adopting new technology, and so initial adoption rates may be slow.

Mining Breakdown by Region

The ICMM has conducted a recent analysis of mining's significance to national economies via its Mining Contribution Index. The ranking is based on a composite measure, with a full explanation of the methodology provided in their report[85].

[83] https://www.pv-magazine.com/2021/11/16/australian-miner-tests-vanadium-redox-flow-battery-technology/

[84] https://flowbatteryforum.com/wp-content/uploads/2025/06/1.-Shaun-Vagne.pdf

[85] https://www.icmm.com/en-gb/research/social-performance/2022/role-of-mining-in-national-economies

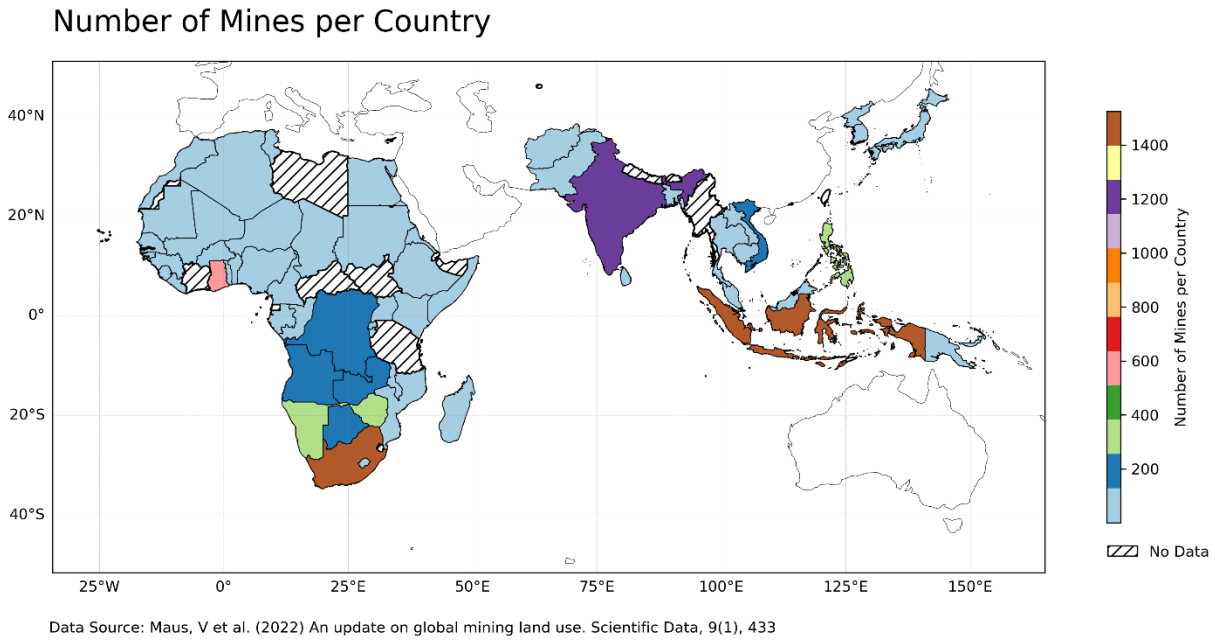


Figure 13: Overview of mining density by country across Africa, S Asia, SE Asia

In Asia, the top-ranked mining countries are Mongolia, Kyrgyzstan (focused on gold and many other metals[86]), Uzbekistan, Papua New Guinea (PNG) and Tajikistan. No other South or Southeast Asian countries feature in the top 25 list.

Mining remains a significant industry in India, with over 1,200 sites operational and a GDP share of up to 2.5%[87]. Mining is widely diversified across a range of minerals, as well as traditional energy sources such as coal, on which India and ASEAN remain reliant.

The most important ASEAN mining country is Indonesia, where the sector accounts for 6.2% of its GDP[88]. Activities span many key minerals, and Indonesia is also a major coal producer, both for self-consumption and export. Additionally, it is also an important supplier of nickel and tin.

In Africa, the top-ranked mining countries according to ICMM are Burkina Faso, Liberia, Mauritania, Mali, Zambia, Zimbabwe and the Democratic Republic of Congo (DRC). This ranking is based on the Mining Contribution Index (MCI), a measure of the significance of mining to a nation's overall economy.

South Africa is recognised as an important supplier of the vanadium required for VFBs and several other relevant minerals including manganese, iron and chromium (see Section 3.2). Mining and other industries are greatly affected by the unreliability of the grid and regular load-shedding events[89]. The need for backup power or firmed solar

[86] https://www.trade.gov/country-commercial-guides/kyrgyz-republic-mining

[87] https://economictimes.indiatimes.com/markets/stocks/news/harnessing-indias-mineral-riches-a-blueprint-for-mining-sector-growth/articleshow/106717456.cms

[88] https://eiti.org/countries/indonesia

[89] https://www.bushveldminerals.com/wp-content/uploads/2023/07/Record-production-achieved-in-trying-circumstances.pdf

power combined with the local availability of minerals make South Africa a very promising market.

5.3.2 **Commercial & Industrial**

Heavy industries with high energy costs and unreliable power supply can benefit significantly from installing behind-the-meter storage. FBs are particularly advantageous for energy-intensive operations that require a high cycle rate.

In India, where rapid manufacturing growth depends on grid reliability and reduced industrial power costs, localised generation with LDES solutions such as FBs could be crucial.

Similarly, African nations with strong manufacturing bases as defined by UNIDO, such as South Africa, Morocco, and Egypt, could also benefit from these solutions to enhance energy stability and reduce costs.

5.3.3 **National Infrastructure**

Utilities and grid operators need to incorporate LDES into their plans from the outset. Whilst experience from developed markets around short duration storage (i.e., LIB systems) is now plentiful, the situation for LDES is very different.

The diversity of electricity markets across the studied regions was outlined in Section 5.2., but there are some common threads. Almost all the countries have near- or medium-term renewable generation targets. Moving away from fossil fuels makes grids less stable and harder to balance; LDES connected 'front of meter' to utility grids can directly ameliorate this.

Grids that are still heavily reliant on dispatchable coal or gas generation may see less need for storage in the short term, but smaller island grids -- common in Indonesia and the Philippines -- can benefit from the balancing capability of FBs.

These solutions can enhance the resilience of critical infrastructure -- such as hospitals, emergency services, data centres, transport hubs and water treatment facilities -- by providing uninterrupted, high-quality power. This is an essential but challenging need, particularly in developing countries[90].

A notable example from a Native American community in the USA is a 500 kWh VFB paired with PV to ensure power resilience for a fire station in an area prone to grid disruptions from California's wildfires[91].

5.3.4 **Data Centres**

The expanding data centre market in developing countries, particularly in Southeast Asia, could be decarbonised from the outset via on-site or nearby VRE sources (particularly solar) firmed by LDES. Data centres are very large and steady electricity consumers and need 24/7 reliable power. In 2022, they consumed 2% (460 TWh) of the world's electricity[92], with some estimates suggesting the figure is even higher. Sites may have

[90] https://www.atlanticcouncil.org/blogs/energysource/developing-countries-offer-enormous-market-potential-for-long-duration-energy-storage/

[91] https://invinity.com/vanadium-flow-battery-resilience-cec-california/

[92] https://www.datacenterdynamics.com/en/news/global-data-center-electricity-use-to-double-by-2026-report/

multiple levels of supply redundancy, including dual grid connection points and banks of backup generators (diesel or open-cycle gas turbine).

FBs have excellent potential as a reliable, long-duration backup solution, although they face competition from LIBs, sodium-ion batteries[93] and cheaper but shorter-lived PbABs. For short duration, rarely-cycled backup utilisation, the latter is perfectly suitable; but for more advanced scenarios involving solar-supported firming, FBs, with proven high-cycle life, can yield additional value.

Additional regional analysis of data centre market potential is provided in 8.Appendix C.

5.3.5 **Electric Vehicle Charging**

The global shift to electric vehicles is extending to developing economies, with a focus on smaller 2/3-wheeled personal transport rather than passenger vehicles. Africa's electric 2-wheeler market is projected to grow at nearly 25% annually, potentially reaching $2.6 billion by 2031[94].

Kenya is spearheading this shift with policies to deploy electric motorbikes to tackle pollution and fuel costs. Indian manufacturer One Electric has begun producing 3.65 kWh battery-powered bikes in Africa, targeting major markets such as Nigeria, Kenya, Egypt, and South Africa. These growing fleets will require reliable charging infrastructure, where FBs could play a key role by serving as hubs that store solar power, enabling all-day charging access. At a notional 7 kW charging rate (which allows a 30-minute charging duration for the vehicle above), a 30-bike charging station would incur a peak load of over 200 kW, a sufficient scale to make a FB relevant.

5.3.6 **Community & Residential**

Reliable electricity access can greatly improve lives and boost economic potential in communities with weak grid connections or off-grid communities, including many island communities in Indonesia, the Philippines, and the South Pacific. Micro-grids with FBs and decentralised renewable generation could form a solution. However, residential-scale FB systems are rare (some examples are given in Section 2.3) and have so far aimed only at the wealthy DACH region (Germany, Austria, and Switzerland) where higher costs are palatable, and the sustainability aspect is emphasised. Companies that previously targeted this scale, including VoltStorage[38], have shifted their focus to larger-capacity systems.

A recent report from the Faraday Institution estimated a latent demand for energy storage in micro-grids for developing economies of 149 GW by 2035, with around 90% of this demand expected to come from SSA[95]. While some spatial mapping of micro-grid potential has been undertaken for SSA[96], there does not appear to be any analysis of the associated scale of energy storage required. For this reason, this sector has not been included in the per-country analysis below. Addressing this knowledge gap through further mapping analysis remains an important objective for future research.

---

[93] https://www.economist.com/business/2024/09/01/clean-energys-next-trillion-dollar-business

[94] https://www.giiresearch.com/report/mx1453697-africa-electric-two-wheeler-market-assessment-by.html

[95] https://www.faraday.ac.uk/wp-content/uploads/2024/03/Battery-Storage-in-Developing-Countries.pdf

[96] https://blogs.lse.ac.uk/africaatlse/2023/12/14/how-microgrids-can-electrify-rural-africa/

5.4 Market Potential Matrix

A matrix has been generated to assess the market potential for FB deployment across selected countries. This high-level overview considers factors such as population size, the presence of relevant industries, grid reliability (particularly in remote areas), and the evolution of electrified transport. However, this remains a preliminary assessment, and deeper, region-specific analyses are required to understand the nuances of each country's market potential. While the matrix offers a foundation for further investigation it does not account for all variables, such as regulatory environments or long-term electricity market trends, which could significantly impact the evolution of FB deployments.

The following metrics were used to quantify potential in each sector:

- **Population:** the total population of the country, reflecting the overall addressable market.
- **Political stability**: using the Political Stability and Absence of Violence/Terrorism Index from the World Bank. This index measures the likelihood of political instability or politically motivated violence, including terrorism, within a country.
- **Mining**: The Mining Contribution Index (MCI), which synthesises the significance of the mining sector's contribution to national economies into a single number and an associated ranking, indicating the relative importance of mining to a country's economic life.
- **Industry**: Industry as a % of GDP, reflecting the strength and scale of existing manufacturing and thus potential for behind-the-meter FBs.
- **National infrastructure**: A metric generated from research using data from the IEA, World Bank, and US Department of Commerce to assess the current and future state of energy distribution. Countries with the higher quality of national infrastructure receive *lower* scores.
- **Data centres**: the number of data centres per million population, reflecting the relative penetration of this sector.
- **EV charging**: a quantitative mechanism reflecting both the current and potential adoption of EVs (including 2 and 3-wheeled vehicles) and their associated charging infrastructure. Due to limited EV penetration in Africa (e.g., South Africa has ~1,000 EVs in a total fleet of 12 million vehicles) and low motorisation rates (73 vehicles per 1,000 people on average), this metric was particularly challenging to generate. South and Southeast Asian data were gathered from reports such as the ERIA Study Team's 'EV Policies in ASEAN Countries' (2023).

All scores in the matrix are normalised between 0 and 5. Malaysia has been excluded from the data centre metric due to its dominance relative to its population and grid reliability. Additionally, no weighting factors have been applied to the matrix, so each element carries equal weight.

Table 4: Developing world FB market potential matrix.

Sector	Country											
	IN	NE	MY	ID	PH	TH	VN	ZA	NG	KE	EG	CD
Population	5.0	0.1	0.1	1.0	0.4	0.2	0.3	0.2	0.7	0.2	0.3	0.3
Political Stability	1.3	1.8	2.8	2.1	1.8	1.9	2.7	2.1	0.3	1.4	1.3	0.2
Mining	2.7	0.7	1.3	3.7	3.5	2.3	1.9	4.3	1.5	2.9	2.6	4.5
Industry	2.4	0.1	5.0	5.0	3.3	3.8	4.0	2.4	2.8	0.6	3.7	0.0
National Infra.	2.0	3.0	0.5	2.0	2.5	1.0	1.5	3.0	3.5	2.5	1.5	4.0
Data Centres	1.3	1.5	N/A	2.0	1.5	3.6	2.3	5.0	0.5	1.9	1.0	0.3
EV Charging	1.5	1.0	1.0	1.5	1.0	3.0	1.5	1.0	0.5	1.0	1.0	0.5
Total	**16**	**8**	**11**	**17**	**14**	**16**	**14**	**18**	**10**	**10**	**11**	**10**

Key: Green: higher market potential. Red: lower market potential

Key to ISO 3166 country codes: IN = India, NE = Nepal, MY = Malaysia, ID = Indonesia, PH = Philippines, TH = Thailand, VN = Vietnam, ZA = South Africa, NG = Nigeria, KE = Kenya, EG = Egypt, CD = DR Congo

The matrix highlights Indonesia as the most promising market in Southeast Asia for FB deployment, with several neighbouring countries showing strong potential. Outside of Southeast Asia, South Africa and India also stand out as excellent opportunities for FB deployments, while the rest of Africa presents more significant market-entry challenges.

South Africa's potential is driven by its large mining industry and strong and growing data centre industry, set against its relatively poor grid reliability that drives the need for resilient storage systems. Indonesia's strengths lie in its mining and industrial sectors, both of which have substantial growth potential. Although not captured in the table, there is also additional potential in the community sector due to the country's large and scattered population, with many communities on remote islands not benefiting from the same grid reliability as in the major centres.

Elsewhere in Asia, India presents immense market potential due to its vast population, broad spectrum of mining, industrial and high-tech sectors, and the need to expand the grid to keep pace with economic growth. While India's data centre market is relatively small on a per-capita basis, it remains large in absolute terms. In India, Thailand, and other ASEAN nations, electric vehicle growth – initially dominated by two- and three-wheelers -- is expected to be rapid in future years and power grids could struggle to accommodate the expansion of required charging stations.

At the other end of the spectrum, countries including Nepal, Malaysia, Egypt and Kenya have lower market potential at present, but often for different reasons. Malaysia benefits from a high level of economic development and a reliable power grid, and the absence of

market reforms mean ancillary services[97] are not yet in evidence. Nepal has a relatively small mining and industrial footprint and a high penetration of hydro power, which has a seasonal rather than daily deficit/surplus cycle. Although there are many remote communities that would benefit from PV based microgrids[98], the small size of these projects may not be suited to FB as mentioned previously.

5.5 Suitability of Flow Batteries for Identified Use-cases

As shown in Section 2.1, there are a variety of FB classes, with differing performance characteristics, with commercial products designed for a wide range of discharge durations. In this section, the suitability of each FB type is assessed by use case requirements.

First, it is important to note the general prevalence of high solar irradiation in the developing economies covered in this report, although there is some regional variation[99]. In contrast to Northern Europe and the US, PV power output varies little across the year, making near 24/7 energy by firming with LDES much easier to achieve.

Providing firm PV power to support key sectors will be a defining feature of LDES markets in developing economies. This is particularly relevant in the least developed economies, where PV-powered grids may allow a leapfrogging effect, bypassing the traditional model of large, centralised electricity generators. To effectively firm PV, with its primarily daily cycle, FBs with high lifetime, efficiency and low cost at durations of 6-12 h will be best suited in the short term, although 6-8 h may be most viable option[100].

In intermediate economies such as India and Indonesia, where thermal generation like coal, gas or nuclear is present, a daily cycle will also be the dominant frequency required of LDES when replacing peak power plant, with shorter cycles required for frequency management if that market is accessible.

While it is important not to rule out low technology readiness level (TRL) FB technologies that may see performance improvements, the targeted duration data in **Figure 4** suggests that some FB types are better suited to daily cycling than others. For example, iron/chromium and acid/base FBs are being commercialised with target durations of 100 h. These FBs are likely to become commercially viable first in regions where wind power -- characterised by surplus/deficit cycle spanning days to weeks[101]-- is becoming dominant, such as the UK. However, these durations are not necessary for solar firming. The hybrid FBs incorporating hydrogen may fall into the same category, though potential commercial products remain less well defined. The iron/iron hybrid FB is promising from a sustainability perspective, but currently, only one company is targeting durations relevant to daily cycling, while another focuses on longer durations.

While energy density is not necessarily crucial for most applications, FBs that perform well in this area -- along with the key metrics efficiency, temperature tolerance and lifetime --

---

[97] In many countries operating a market for electricity, in addition to wholesale trading of electricity, batteries can bid to provide ancillary services that facilitate grid stability.

[98] https://gridalternatives.org/news/power-nepal-solar-micro-grids-rural-electrification

[99] https://www.iea.org/reports/solar-energy-mapping-the-road-ahead

[100] The economics of firm solar power from Li-ion and vanadium flow batteries in California. https://link.springer.com/article/10.1557/s43581-022-00028-w

[101] https://www.electricinsights.co.uk/#/dashboard?_k=1ais8w

will have an advantage. For this reason, the hybrid metal-plating FBs are promising if they can achieve and demonstrate long lifetimes in the field.

5.6 Conclusion

FBs represent a small and relatively immature market with enormous growth potential in many developing economies. Their potential performance benefits -- such as temperature tolerance and long cycle life (albeit not demonstrated for all types as discussed in Section 3.2) -- offer considerable advantages for stakeholders in the power system. These benefits extend to grid stabilisation, micro-grid support, and the long-term expansion of solar and wind generation.

As a LDES technology, FBs can support owners, operators and developers of power systems looking to expand solar and wind energy on less reliable grids. They offer a lower-cost energy storage solution for mining operations, large industrial facilities, and data centres that require reliable power. FBs can support remote communities in places not connected to centralised grids. Given that much of the world's future growth will be driven by today's developing economies, the adoption of FB in these regions will help to enable new economic opportunities.

There are other countries beyond the scope of this report to which these principles can also apply. For example, several African nations as well as countries in South and Southeast Asia with similar characteristics with the countries named in this report, also have significant FB market potential as they work to decarbonise their power grids, develop new industries, and electrify transport.

Certain FB technologies are better suited to these use-cases than others. In the near-term, particularly when solar power is ascendant, FBs with durations of 6-12 h shown in **Figure 4** are likely to penetrate the market first.

All of this points to new market opportunities for FBs, include the potential for local assembly. Establishing local assembly and manufacturing capabilities would enable LDES technologies to better serve local markets. The next chapter explores the feasibility of manufacturing FBs and their components in developing economies.

6. Opportunities for Manufacturing Flow Batteries in Developing Economies

6.1 Introduction

Many developing economies aim to move up the value chain into higher-margin sectors by developing advanced manufacturing capabilities. This trend is particularly evident in countries such as India and Vietnam, where Western manufacturers are increasingly investing to diversify beyond China due to rising labour costs, demographic shifts, a relative economic slowdown, and geopolitical tensions. In the LDES sector, a concrete example of policy to stimulate local manufacture is the addition of a local content metric to recent tenders for battery energy storage in South Africa[102].

FBs, which require a range of mechanical and electrical components, could be manufactured in regions with existing industrial bases, via plants pivoting from their current product mix to building the specific components needed. In-country manufacturing can further boost local market potential.

This chapter explores opportunities for FB component manufacturing in various regions. It focuses on FB-specific technology, while excluding generic downstream electrical infrastructure components.

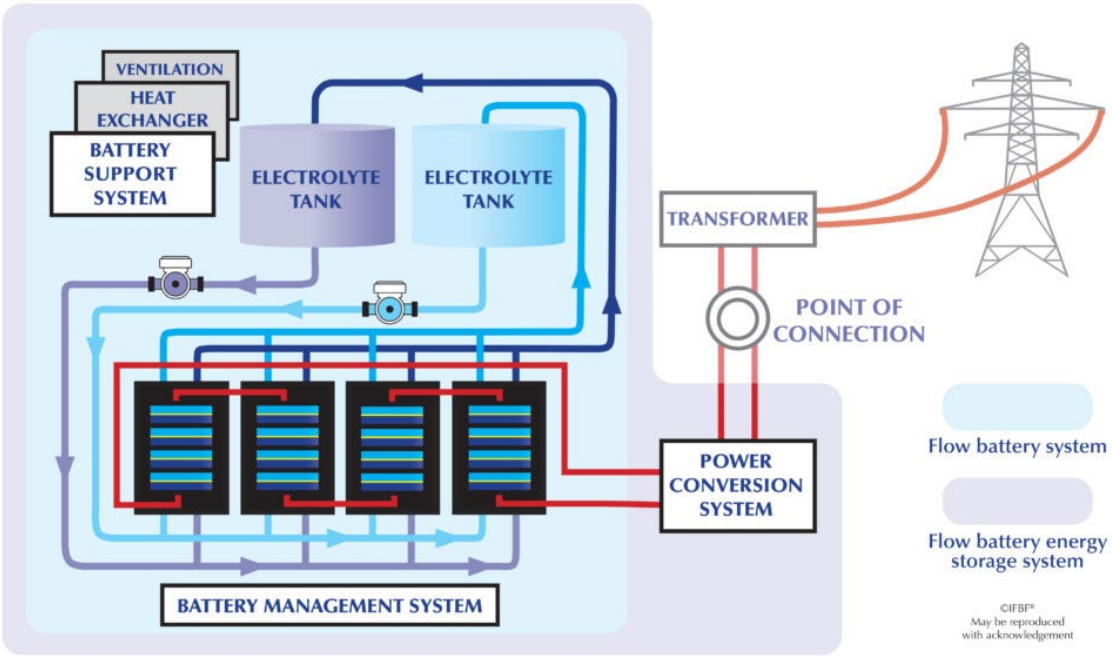


Figure 14: Generic FB schematic, highlighting major components. The components that fall within the scope of this analysis are highlighted in "Flow battery system" box. Source: IFBF.

[102] https://allafrica.com/stories/202411190429.html

The main components of FB are:

- Power generating stack
- Electrolytes
- Balance of plant
- Control system and power conversion system (outside the scope of the report)

While these categories are generic, there are variations between chemistries, as discussed in Chapters 2 and 3. Key differences are in the electrolyte composition (including the electroactive species, solute, concentration, and any additives), and the stack (particularly which separator is used). The balance of plant including tanks, pumps and controls is mostly common to all FB types and chemistries.

6.2 Stack Components

The most complex part of the FB is the power producing stack. A schematic of a stack is shown in **Figure 16**, and photos of real examples in **Figure 17**. The stack is formed of repeating cell units, as shown in **Figure 15**, that are sandwiched together, with the plastic flow frame forming the structural backbone. End electrodes with metal current collectors are then fitted and compression applied – by either bolts or straps. The stack is connected to the electrolyte pipework via a manifold, and the end electrodes to the external circuitry. Additional instrumentation is then added. More detailed technical information on key stack sub-components is given in 8.Appendix D.

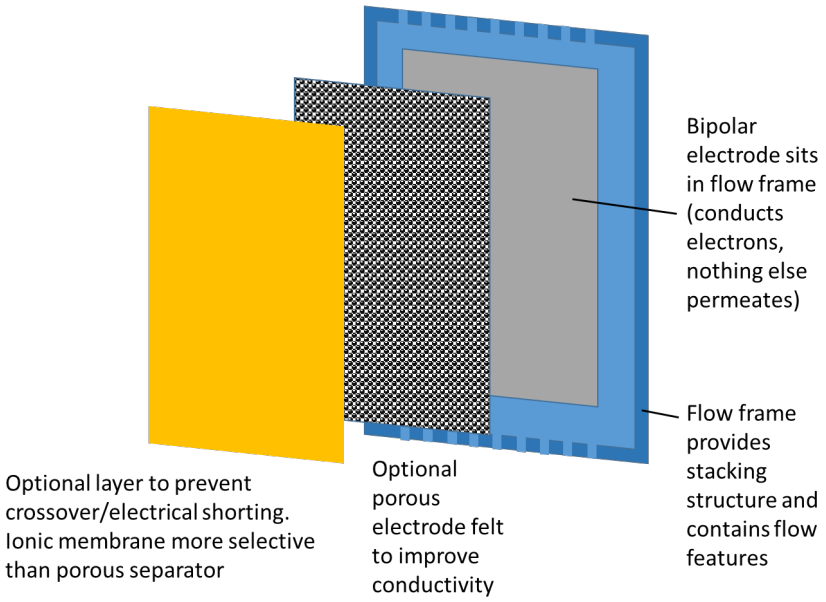


Figure 15: Explanation of a flow frame and connected components that make up the repeating cell unit in a FB stack. Source – Foresight Transitions.

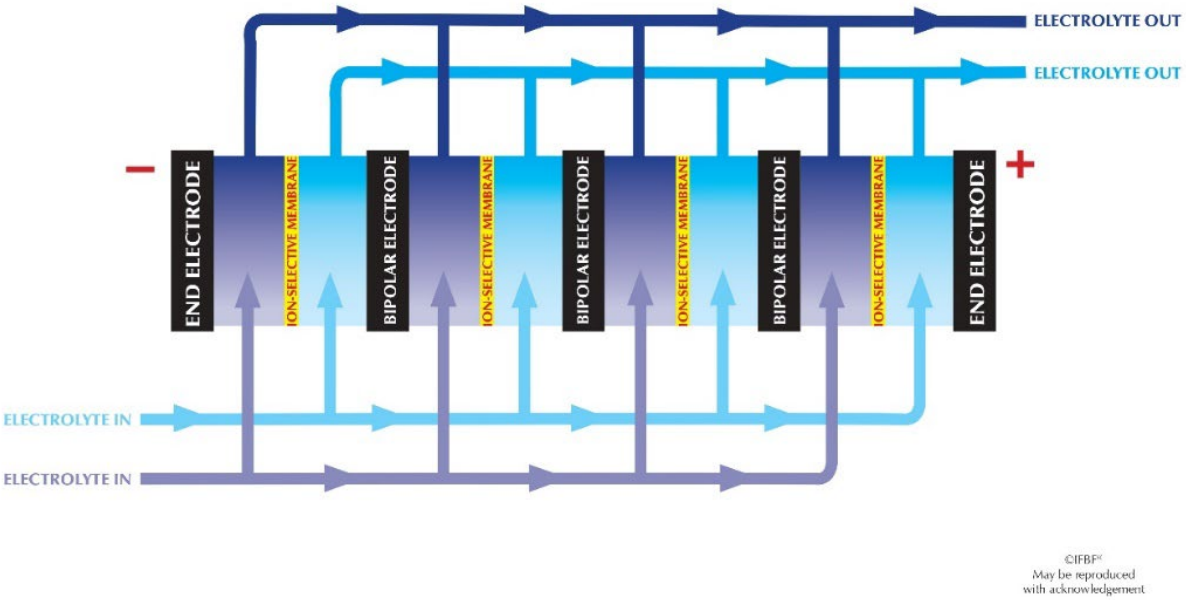


Figure 16: Schematic of electrode stack assembly. Source: IFBF

Stack design is usually highly proprietary and specific to individual manufacturers, although more recently some manufacturers, for example Pinflow[103] and Volterion[104] have entered the market selling stacks to other FB developers.

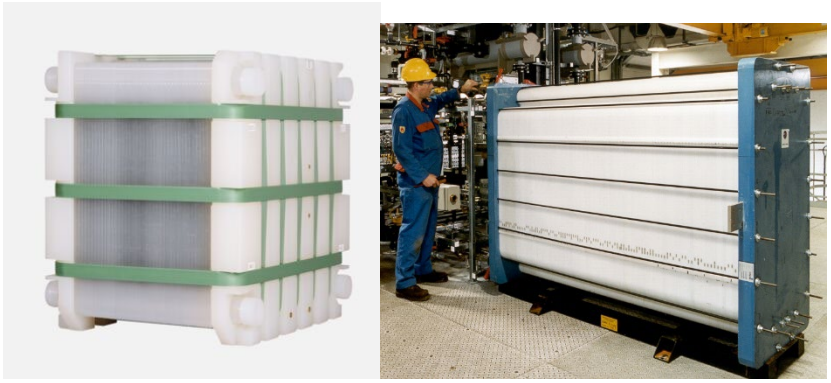


Figure 17: Photographs of examples of FB power generating stacks. Left: Volterion 5 kW stack. Right: Regenesys 100 kW stack.

The technical difficulty of manufacturing each of the stack sub-components differs greatly.

The manufacture of ionic membranes requires advanced material science capabilities, specialised facilities and skilled personnel, and these can be limited in some (not all) developing regions. Some membranes use polyfluoroalkyl compounds (PFAS), which are

[103] http://pinflowes.com/

[104] https://www.volterion.com/home.html

subject to restrictions on materials considered harmful and hazardous, and may be additionally regulated as "forever chemicals" in the future[105]. Patent restrictions may limit production to some specific manufacturers, for example Asahi Glass, Chemours or Gore. It may be financially impractical to set up manufacture for relatively small production runs, and hence purchasing from third parties is a better choice. Quality control also depends on advanced industrial equipment as well as reliable access to high-quality raw materials. Porous separators are slightly simpler than ionic membranes to manufacture but still require stringent manufacturing tolerances and quality control.

Carbon bipolar electrodes are less technically challenging to manufacture as they are thicker and may be moulded or extruded. They are also manufactured from relatively cheap raw materials[18], so present a good opportunity for value addition. Continuous manufacturing such as roll-to-roll processing at high volumes would be economically beneficial, and this may require a level of centralisation and standardisation.

Flow frames are simple to manufacture as they require injection moulding and machining of plastics such as polypropylene.

Hand-assembly of the stacks is feasible at low volume or automated once higher volumes are required. It is feasible to set up assembly facilities in many regions, and relatively low labour costs in developing economies should make this an attractive proposition. By importing critical components and focusing on final assembly, FB manufacturing hubs might be established in the areas of interest. Local manufacture would also reduce the costs associated with transporting fully assembled systems.

Although assembly of FB stacks does *not* require overpressure and filtered clean room and dry room facilities, such as that required for LIB manufacture, it is still necessary to have high levels of cleanliness to avoid any dust or other debris entering the stacks. Discussions with several manufacturers in Europe have emphasised the need for clean assembly to achieve long term reliability of the stack modules.

In summary, the combination of assembly and manufacturing of varying complexity could provide an accessible route into high-value manufacturing.

6.3 Balance of Plant

Other FB components, such as pumps, tanks, and valves, are not unique to FBs. As such, the ability of local supply chains to produce or supply these components is highly relevant to the overall feasibility of manufacturing and assembling FB systems in developing regions.

6.3.1 **Pumps**

The pumps, which circulate electrolytes, need to be highly reliable and have a long service life. Care should be taken in selection of the pumps, considering the acidic or alkali environments, as pump failure and lack of efficiency has a detrimental effect on both performance and reputation of the FB.

Many established pump manufacturers can provide pumps in commercial quantities. Although pump manufacturing has traditionally been dominated by North America,

[105] https://flowbatterieseurope.eu/wp-content/uploads/2023/09/FBE_PFAS-Position-paper_September-2023.pdf

Europe, and East Asia, there is established capacity in Africa[106] and India[107], with multiple facilities already in operation, most notably in South Africa[108]. These operations are well-placed to serve these regions' emerging FB market.

6.3.2 **Tanks**

Storage tanks and bunds are either made from plastics or lined with a plastic or similar material to provide chemical resistance, although stainless steel tanks have been used. VFlowTech, headquartered in Singapore, is examining the feasibility of reusing petroleum fuel storage tanks[109]. Plastic tanks are less prone to acid attack than metals, are lightweight and can be made in a wide range of shapes and sizes. Tanks are low-tech and can be readily manufactured anywhere with an established plastics manufacturing capability.

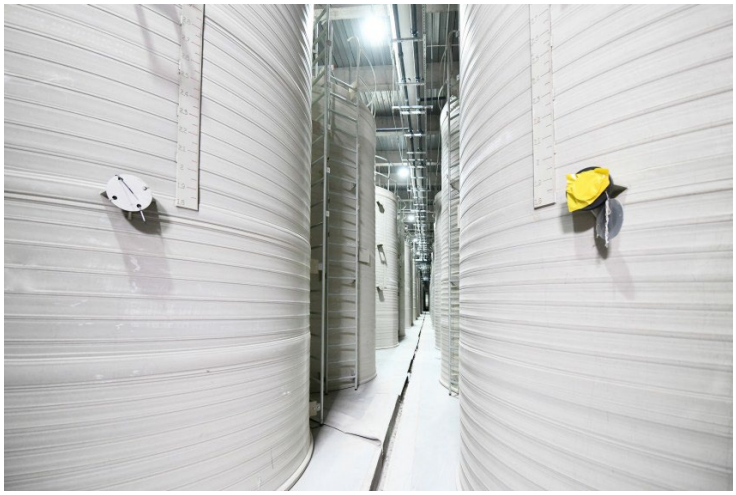


Figure 18: Electrolyte tanks for 100MW Dalian flow battery. Source: DICP

6.3.3 **Gaskets & Sealants and Other Fittings**

In common with many chemical industries there is a reliance on gaskets and sealants and other fittings, both electrical and mechanical. Some of these might be sourced locally, others will be imported. This report does not cover these specific items as they will be highly specific to the type of FB and method of manufacture. Early FBs used gaskets and O-rings. Recent developments in manufacturing have trended towards clip together seals. Most FB manufacturers are investing heavily in engineering to reduce the number of components on the bill of materials.

[106] https://cbeuptime.com/largest-industrial-pump-manufacturers/

[107] https://www.kirloskarpumps.com/discover-us/manufacturing-facilities/

[108] https://pumps-africa.com/top-7-pump-manufacturers-in-africa-2/

[109] https://vflowtech.com/

6.3.4 **Containers and System Packaging**

The trend for larger installations to assemble FB systems within multimodal shipping containers in ISO 20' or 40' lengths was noted in Section 2.3, although some larger applications may favour the traditional chemical plant format. 20' containers are widely used because their lower weight makes for ease of shipping. These are available worldwide, can be readily manufactured anywhere with an existing steel industry and are effectively a commodity.

Some manufacturers such as Redflow (now in administration) had packaged their units as kW size modules, which is sufficient for a household or group of residential units. As noted in Section 4.3.2 there may be advantages to working with smaller formats in areas with poor road networks. Developing custom enclosures should be within the capability of many developing economies, as metal fabrication and plastic forming are the main techniques used.

6.4 Raw Materials

While vanadium is the basis of the most commercially mature FB technology, other important electrolyte precursors include iron, chromium, zinc, manganese, lead, and bromine. Recovered or recycled lead is clearly an important resource for soluble lead chemistries, and this is widely available because of the very high use of lead acid batteries in the automotive industry.

Many FBs use sulfuric acid as the base for the electrolyte. This is widely available (and is also used in PbABs). Other systems use alkaline solutions of hydroxide salts and in a few cases organic solvents (e.g., the StorTera FB, Kemiwatt, Jena Batteries offerings referenced in **Figure 3**).

For aqueous organic FBs, the key compounds include anthraquinone, ferrocyanide, TEMPO[110] and porphyrexides (see **Table 3**). These are derived from a variety of input feedstocks and complex chemical processes. For example anthraquinone is synthesised by modifying either anthracene or benzene, fossil-fuel based feedstocks. This class of FB may be suited to regions with developed chemical industries but lacking metal resources.

6.5 Supply Chain

There are large vanadium reserves in China, Australia, Russia and South Africa[111]. Whilst the latter has the fourth largest reserves, it is the third largest producer, responsible for around 16% of global output [112].

Vanadium is predominantly derived as a byproduct of steelmaking (75%) or as a secondary component of various mined ores[113], with direct mining of vanadium-containing ores being the smallest source. The most common product form is vanadium pentoxide (V_2O_5).

---

[110] https://www.acs.org/molecule-of-the-week/archive/t/tempo.html

[111] https://vanitec.org/vanadium/making-vanadium/

[112] https://www.ga.gov.au/scientific-topics/minerals/mineral-resources-and-advice/australian-resource-reviews/vanadium

[113] https://chemrxiv.org/engage/api-gateway/chemrxiv/assets/orp/resource/item/62a76b9f8f92d915724f9f90/original/materials-availability-and-supply-chain-considerations-for-vanadium-in-grid-scale-redox-flow-batteries.pdf

There are significant manganese and chromium reserves in Africa, with new manganese refining projects planned in South Africa. South Africa is also a leading producer of chromium (important in Fe-Cr batteries), with India also being in the top five[114].

Iron ore reserves are widely distributed globally. Within the regions under consideration, India and South Africa are the principal suppliers. For lead, used in some FBs as well as traditional lead-acid batteries, India is ranked as the 6th largest producer with a 2022 output of 240,000 MT[115, 116]. Zinc is also extracted in many SE Asian nations.

No notable producers of bromine have been identified among the target regions. The largest concentrations and lowest-cost production facilities are instead found in the Dead Sea region[117].

An established chemical industry is expected to be a prerequisite for setting up production of organic electrolytes. This would be an obstacle to manufacture in some developing economies. Further in-depth research is required to understand the evolving supply chains in this specialised area.

Correspondence with various electrolyte and battery manufacturers highlighted that the industry is keen to manufacture finished electrolytes close to market to reduce supply chain complexity and final system costs.

6.6 Commonality and Economic Importance of FB Components

Given that a variety of FB classes and sub-types exist (see **Figure 3**), from a manufacturing policy perspective it is important to understand which components are common to multiple potential products. A summary of the component applicability is given in **Table 5**.

[114] https://investingnews.com/daily/resource-investing/industrial-metals-investing/chromium-investing/top-chromium-producing-countries/

[115] https://investingnews.com/daily/resource-investing/base-metals-investing/lead-investing/lead-producing-countries/

[116] https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-zinc.pdf

[117] https://www.albemarle.com/global/en/what-we-offer/reliable-supply/bromine-resources-processing

Table 5: Dashboard showing which components are used in which FBs.

The economic importance of the components will vary according to the class of FB and the specific performance metrics of the individual system. For example, bipolar plate electrodes are used in all FBs but will be a more important cost component in hybrid FBs, where they may act as an energy storage component in addition to being a power generating one. Ionic membranes are the most expensive component of the stack per square metre (in the FB systems that require them as shown in **Table 5**) but in systems with high power density a smaller area is required (e.g., VFB and hydrogen/bromine). Pumps and tanks become more significant cost components when the electrolyte concentration is low as larger volumes of liquid must be stored/circulated. The pump cost impact is given as medium for the semi-solid FB system as pumping a slurry may require non-standard specification pumps.

Flow frames, bipolar plate electrodes, tanks and pumps are the components that are most common across the FB classes. ISO containers may potentially be used in all FBs except systems with very low energy density, such as the acid/base and other all-solution FBs like aqueous-organic types.

Hybrid metal plating FBs are more likely to use a simple porous separator (or no separator) than the other FB types. This may make them more suitable for local manufacture in developing economies due to simpler manufacturing methods (see Section 6.2). Simple porous ionic membrane separators are a critical cost and performance component for many all-liquid FBs, particularly the organic solution type, where cross contamination of electrolytes is a life-limiting issue.

6.7 Manufacturing Potential Matrix

A detailed breakdown of manufacturing potential by geography is presented in Appendix E. A summary of this information is presented in the matrix below, which has been generated to highlight the viability of local FB manufacturing. This matrix was developed to provide a high-level overview of the suitability of selected countries based on factors such as industrial capacity, access to raw materials, workforce skills, and infrastructure. However, this remains a preliminary assessment, and deeper, region-specific analyses are necessary to understand the nuances of each country's

manufacturing potential. The matrix offers a foundation for further investigation but does not account for all variables, such as local regulatory environments or long-term market trends, which could significantly impact the feasibility of establishing FB production in these regions.

The following metrics were used to quantify the potential in each sector:

- **Mineral Resources**: The number of relevant mineral resources present (comprising V, Fe, Cr, Mn, and graphite)[118]
- **Industrial Capacity**: The country's Competitive Industrial Performance score (2021 data)[119]
- **Chemical Industry**: Chemicals industry by %GDP value add in manufacturing (UNIDO data published by the World Bank)[120]
- **Advanced Manufacturing**: The Manufacturing Performance Index as a metric for higher value-add capabilities[121]
- **Industrial Strategy**: Global Trade Alert interventions tracker, as a metric for proactive industrial strategy[122]
- **Investment Climate**: World Bank 'Doing Business' rankings (2020) as a reflection of the investment climate[123, 124]
- **R&D Structure**: World Bank data on R&D share by %GDP rankings[123]
- **Quality Control/Labs**: the WHO list of Prequalified Quality Control Laboratories as a metric for assessing quality control capabilities, for example, for testing electrolytes[125]

Within the matrix, all scores are normalised between 0–5. Note that some data, such as recent information on Nigeria's chemicals industry, is missing, which has impacted Nigeria's overall score. The lack of available data itself highlights the challenges in assessing and leveraging the country's manufacturing potential. No weighting factors have been applied to this matrix, meaning that each category carries equal importance, regardless of its relative significance to FB manufacturing.

[118] https://data.worldbank.org/indicator/NV.MNF.CHEM.ZS.UN?utm

[119] https://stat.unido.org/data/table?dataset=cip#data-browser

[120] https://data.worldbank.org/indicator/NV.MNF.CHEM.ZS.UN?utm

[121] https://blog.falcony.io/en/basics-of-manufacturing-performance-index-and-kpis?utm

[122] https://globaltradealert.org/?utm

[123] https://documents1.worldbank.org/curated/en/688761571934946384/pdf/Doing-Business-2020-Comparing-Business-Regulation-in-190-Economies.pdf?utm

[124] https://archive.doingbusiness.org/en/doingbusiness?utm

[125] https://extranet.who.int/prequal/medicines/prequalified/quality-control-labs

Table 6: Developing world manufacturing potential matrix.

Sector	Country										
	IN	MY	ID	PH	TH	VN	ZA	NG	KE	EG	CD
Mineral Resources	4	2	4	3	3	3	5	4	3	1	5
Industrial Capacity	2.1	5.0	2.5	1.8	3.9	3.6	1.4	0.0	0.0	0.7	0.0
Chemical Industry	3.9	1.7	2.3	0.9	1.5	0.8	1.3	N/A	1.9	2.4	0.0
Advanced Manuf.	1.7	1.7	1.4	0.9	1.1	1.0	1.1	N/A	N/A	0.8	0.0
Industrial Strategy	2.6	0.2	0.3	0.1	0.1	0.1	0.2	0.0	0.1	0.0	0
Investment Climate	3.3	4.7	3.1	2.5	4.4	3.2	2.8	1.6	3.5	2.0	0.2
R&D Structure	2.1	3.6	1.1	5.0	4.3	1.4	2.1	1.1	1.4	3.6	1.4
Quality Control/Labs	5.0	0.0	1.3	0.0	2.5	2.5	3.8	0.0	2.5	0.0	0.0
Total	**25**	**19**	**16**	**14**	**21**	**16**	**18**	**7**	**13**	**11**	**7**

Key: Green: higher manufacturing potential. Red: lower manufacturing potential

Key to ISO 3166 country codes: IN = India, MY = Malaysia, ID = Indonesia, TH = Thailand, VN = Vietnam, PH = Philippines, ZA = South Africa, NG = Nigeria, KE = Kenya, EG = Egypt, CD = DR Congo

The matrix highlights that India and Thailand are the most viable locations for FB manufacturing, which is accurate considering both have current or recent production activities. Their strong industrial bases, skilled workforces, and supportive policies make them well-positioned for growth in this sector.

The DRC, despite its rich raw material resources, highlights the importance of manufacturing capacity as an enabler for battery production, as its lack of manufacturing infrastructure limits its potential for local FB production. This highlights the need for more than just resource availability.

Asian countries, such as India, Thailand, and Malaysia, have an advantage due to established domestic manufacturing and skilled labour resources, allowing them to be early adopters of FB technologies.

In Africa, significant development is required to enable FB manufacturing. However, the continent's growing, youthful population and rising educational standards provide optimism for future potential as a key growth area. Investments in infrastructure and education will be crucial for Africa to capitalise on its resources.

6.8 Viable Manufacturing Scale for Flow Batteries

LIB manufacturing is characterised by sophisticated facilities with stringent humidity control, and advanced capabilities in powder processing and coating[126]. For this reason,

[126] https://volta.foundation/battery-report-2023

manufacturing facilities are built large to realise economies of scale. Recent data on US LIB manufacturing capacity were analysed for this report; the median scale of planned projects was 35 GWh/annum, and the median cost $3bn [127]. Such a high minimum up-front investment is likely to pose an obstacle to manufacture of LIBs in developing economies, especially those with higher perceived financial risk.

The manufacture of FBs, as detailed above, is generally simpler, and the few complex components could be purchased for assembly if the FB in question requires them. An example of a VFB manufacturing plant in Thailand serves as an example; in 2023 VFlowTech obtained $10M funding to set up a plant to manufacture its 250 kW modules, with a capacity of 200 MWh.p.a [128]. The cost of manufacturing capacity may be slightly cheaper for the VFB facility, at $50k/MWh.p.a versus $55k/MWh.p.a for LIB in Asia [129] but the most important difference is the two orders of magnitude in investment scale, making the VFB facility far less risky for developing economy investors looking to enter the sector.

6.9 Conclusion

This section has assessed the opportunities and barriers associated with manufacturing FB components in developing economies. The analysis highlights the varying complexity of manufacture for the key FB components. An approximate ordering by decreasing complexity (excluding more generic balance of plant items) is: ionic membranes > porous separators > electrolytes ≈ electrodes > FB assembly > flow frames.

FB assembly could be a possible starting point for developing economies with less existing manufacturing capacity to participate in the FB value chain as they are labour intensive at small scale. Local assembly could reduce costs associated with importing fully assembled components while building domestic capabilities over time.

Electrode manufacture could be an accessible route into higher value manufacturing for intermediate economies. Electrodes are of particular interest as they are common to all FB types and are of particular importance in hybrid metal plating FBs, where they serve as the energy store as well as being one of the power components. Countries such as India, Thailand and Malaysia, with established industrial bases and emerging advanced manufacturing sectors, are well-positioned to potentially engage in the partial production or assembly of these components. With strategic investments, these and other countries could become regional hubs for FB production, particularly as demand for long-duration energy storage grows across Asia.

Manufacturing FB electrolytes, particularly for VFBs, requires high-purity materials and stringent quality control processes. While some countries in developing regions, such as South Africa and India, possess substantial raw materials such as vanadium, iron and chromium, the capability to process these materials into high-purity electrolytes is presently limited. However, these nations could supply raw materials, which are then refined and processed further for use further up the value chain in other countries. Alternatively, investment in local refining and processing facilities could enable countries such as South Africa to capture more value, particularly given the global demand for sustainable energy solutions.

---

[127] https://techcrunch.com/2024/07/20/tracking-the-ev-battery-factory-construction-boom-across-north-america/

[128] https://vflowtech.com/2023/02/07/vflowtech-raises-us10m-in-series-a-funding-to-expand-global-reach-of-vanadium-based-renewable-energy-storage-solutions/

[129] https://volta.foundation/battery-report-2023

Local manufacturing potential depends to a certain extent on the complexity of the FB class being manufactured. For example, hybrid metal plating FB could potentially be easier to manufacture in developing economies, as the class is less reliant on complex components, such as ionic membranes, and some have no separator at all.

The balance of plant components, such as pumps, tanks, and gaskets, are less technically demanding and more easily sourced or manufactured in developing regions. These items are often generic industrial components, meaning many developing nations, particularly those with existing manufacturing industries, could easily produce or assemble them. Countries such as Kenya, Nigeria, and the Philippines may not yet have the capacity for manufacturing some of the more complex components, however, they could contribute meaningfully by producing balance of plant items, possibly in collaboration with international companies.

India stands out as a key player due to its large industrial base, access to skilled labour, and growing focus on renewable energy. Existing manufacturing infrastructure could be expanded to produce certain FB components, while local assembly could provide a more immediate opportunity.

Partnerships with international companies could help developing economies overcome hurdles associated with investment and regulations, allowing these countries to localise assembly and capture emerging market opportunities as demand for sustainable energy storage grows.

7. Research Gaps

Several important research gaps have been identified during the course of this report. The following summary is not intended to be exhaustive and focuses on gaps that are most relevant to the deployment and manufacture of FBs in developing economies. For example, ionic membrane research is an important strand of FB research, but this component is unlikely to be manufactured in a developing economy at present.

Lifetime data: A key finding of the analysis in Chapter 3 was that the long lifetimes associated with VFBs have not yet been demonstrated for other FBs. The demonstration of a long lifetime is the most important technical hurdle for hybrid metal plating FBs to overcome, which otherwise have very promising properties. At the same time, it is important to avoid metric chasing; for example, increasing the lifetime of a FB from 10 years to 20 years may not impact the investment case, particularly in higher risk areas where faster returns are required. Spending research money on long-term testing must be justified by a holistic economic analysis.

Real-world performance in hot climates: While the potential of FBs to operate at higher temperatures than LIBs (>35 °C) has been highlighted, the constraints on operation of some VFB products, and the pursuit of vanadium/iron as a specific high-temperature solution show that the actual benefit in deployed systems is an open question. There is also very little published data to back up the claims of higher operating temperature for other FB types.

To answer this question a combination of pilots and modelling is required. Standardised testing based on expected use cases, particularly PV firming, would be more beneficial than simple repeated cycling tests typically carried out in a laboratory. Given the high costs, logistical challenges and specific nature of any pilot studies, modelling should be completed first to identify the most promising FB, location, and use-case candidates.

Lab scale testing of different electrolytes would also be beneficial in helping to understand the potential they have to operate in elevated temperatures.

FB maintenance requirements in developing economies: while the analysis in Section 4.3.3**.** describes the maintenance requirements of some FBs, it is unclear to what degree the protocols can be automated versus requiring manual intervention. The economic benefit of each approach requires specific assessment for developing economies as the ratio of capital cost to labour cost is higher than that seen in developed nations.

Recyclability: This claimed benefit of FBs is intuitive from the basic architecture and, as shown in Section 2.4, some feasibility studies have been completed on the VFB electrolyte. However, very little research exists on the recycling of other FB systems, and the cost of transporting electrolyte for recycling has not been studied. Such research should be informed by the commonality of components shown in **Table 5**., allowing a focus on electrolytes.

Supply chain economics of electrolyte: While the analysis in Section 3.3.3 showed that lower FB energy density (compared to LIBs) at the electrolyte level became less of a drawback at the system level, concerns remain about logistical challenges of electrolyte transport. This subject is lacking in publicly available research, and a reference supply chain model is needed.

Design of stacks and electrodes for hybrid FB with metal plating: Although this class of FBs includes some of the highest energy densities of FBs, the requirement for metal plating presently leads to lower power density and poses a challenge to lifetime as metal

may fall off the electrode and sink rather than re-dissolving. There is potential for research into the design of novel electrode and stack architectures for hybrid FBs, which would help to solve some of these challenges.

Materials, design and manufacture for bipolar electrodes and separators: Bipolar electrodes emerged from Chapter 6 as a component that could allow developing economies to contribute to the FB manufacturing value chain, as they are of intermediate complexity, are used in almost all FB types, and are particularly important in hybrid metal plating FBs. There is relatively little academic research on this component (when compared to research on electrolytes and ionic membranes), however there are important fundamental challenges to be solved such as corrosion resistance of the electrodes and the suitability for metal adherence. Similar arguments apply to porous separators, which can be used in some hybrid FBs (notably zinc/bromine and iron/iron). These are cheaper and simpler to manufacture than ionic membranes, which make them possibly suitable for manufacture in developing economies due to the less complex manufacturing processes. These porous separators appear to be standard, readily available products, which have been developed for other applications, therefore it may be possible to improve their performance for use in FBs or reduce their cost with further research.

Safety and toxicity of FBs: The analysis in Section 4.5 covered the fire risk of FBs versus LIBs and the toxicity of the chemicals present at installation. What is lacking for FBs, but exists for the LIB, is research and analysis of the potential chemical hazards that may be produced under adverse conditions e.g., fire or containment failure.

Opportunity for FB in community micro-grids: It was noted in Section 5.3.6 that while the potential demand for energy storage in micro-grids has been estimated for developing nations, this has not been done to a high level of spatial resolution, that would allow focus regions to be identified. Additionally, some micro-grids may be too small for FBs to be suitable, given the minimum economic scale discussed in Section 5.1.1. There is therefore a requirement to combine mapping studies of micro-grid potential, with energy storage sizing estimation, in order to better quantify the opportunity in this sector. Although the majority of future demand has been attributed to SSA, other regions, particularly Indonesia should be studied also.

8. Conclusions & Recommendations

Classification of FB by targeted duration and performance

A key objective of this report was to make a comparison of the technical characteristics of FBs with LIBs and PbABs. The data in Chapters 2 and 3 show that the characteristics of FBs vary to the extent that it is not particularly useful to talk about them as a group. Broadly speaking there are systems that have the potential to compete with LIBs (and out-compete PbABs) in the 4-12h range associated with daily cycling operations, and systems that are more likely to be competing with hydrogen or other longer duration ESS from 12 h to 100 h and beyond.

Most all-liquid FBs fall into the second category, with low energy density, low proven cycle life and moderate round-trip efficiency (RTE). These properties make it unlikely that this category will be suitable for near-term deployment for daily cycling in developing economies, but it is possible that they will find a market for longer duration storage (>12h) in the future, where low cost of electrolyte becomes the most important factor.

The VFB is a notable exception, which have high RTE, moderate energy density, and excellent lifetime. Hybrid FBs employing metal plating generally have lower power performance, lower proven lifetime but higher energy density.

The key performance gaps between the 4-12 h FB types and LIBs are round trip efficiency and energy density. VFBs reach around 80% of the LIB efficiency and hybrid FB 65-90%, which may be acceptable if the cost of charging is not high (e.g., from cheap PV) and the difference is offset by other cost benefits. Although the energy density of the VFB electrolyte is about 1/8th that of the LIB at the chemistry level, at the system level, it reaches about 2/3rd, due to the efficiency of the format and the reduced fire risk. Hybrid metal plating FB should be able to exceed the energy density of LIB at the system level.

Deployment challenges and opportunities

The key technical benefit of FBs is the potential for longer lifetime, particularly for the VFB. It is important to note that the lifetime of LFP-based LIBs is potentially excellent at moderate temperature but drops markedly when the cell temperature increases from 30 °C to 40 °C. This is an issue during transportation as well as in operation. Developing economies should therefore be seen as a critical market for FBs given the prevalence of high ambient temperatures. However, further modelling and piloting are required to make the economic case at the system level (e.g., including cooling equipment).

Logistics pose significant hurdles for all battery systems in developing economies, including LIBs, particularly in SSA, where inadequate infrastructure, poor road conditions, and seasonal weather disruptions complicate transportation. Ports and border crossings can add delays. The lower energy density of some FBs will make transport more difficult, due to the larger size of the installation. However, this does provide an impetus for local manufacturing of electrolyte and in supply chain innovations.

In most developing economies development of a skills base at both higher education and vocational training is required, with a focus on practical electrician-type skills applicable to all LDES types. Some FBs require regular maintenance activities during routine operation, though further work is required to understand the balance of automated protocols and manual intervention, and how best to maintain the system whilst engaging the local workforce.

FBs, in general, have a lower fire risk compared to LIBs but are not without hazards. These include either highly acidic or alkaline electrolytes and use of toxic substances,

necessitating careful handling of components, robust safety measures and adequate training of local operatives.

Developing Economy Market Potential

The market potential of flow batteries in specific developing economies covering SSA, South Asia and Southeast Asia was assessed. These regions encompass significant diversity, including countries with poor grid reliability and coverage. Their electricity markets are at widely varying stages of privatisation, liberalisation, and maturity, but almost all seek to grow the penetration of renewables. Grid integration projects within ASEAN and across Africa paint a picture of rapidly evolving opportunities for storage systems including FBs.

Mining and other heavy industries comprise a significant GDP fraction in several African and Asian nations and offer a strong point for potential entry market. Flow batteries also have a role in the utilities sector itself, in some areas of critical infrastructure, and in supporting reliable power provision in fast-growing digital industries such as data centres. Larger-scale community micro-grids are a suitable application for FBs, and VFBs have already been deployed in combination with PV as shown in **Table 1**. However, the scale of the sector is limited by relatively low population of these areas, except in countries with many island communities remote from main grids, such as Indonesia and the Philippines. Areas with weak grids are likely to be a larger scale market, as highly populated regions such as South Africa and India fall into this category.

Most of the above applications suit the 4-12 h duration targeted by vanadium and hybrid metal plating FB types, particularly when combined with low-cost solar power.

Developing Economy Manufacturing Potential

FBs are assembled from a diverse set of components. Each of these has a unique supply chain, and the prevalence of mineral resources (notably for electrolytes) and basic or advanced manufacturing capabilities affects local production potential in developing economies.

The level of manufacturing sophistication required for each component varies hugely, making them suitable for countries looking to progress to higher value manufacturing. Also, some components are common to all flow batteries, so technology risk could be minimised. A suitable strategy would be to start with assembly and manufacture of basic components like flow frames, then move on to intermediate components like bipolar electrodes. This stands in contrast to the manufacture of closed cell batteries, for example, LIBs, where a large and complex production line is required from the start, and where the scale of investment may be two orders of magnitude greater. There is hence a far lower barrier to entry for developing economies with FBs.

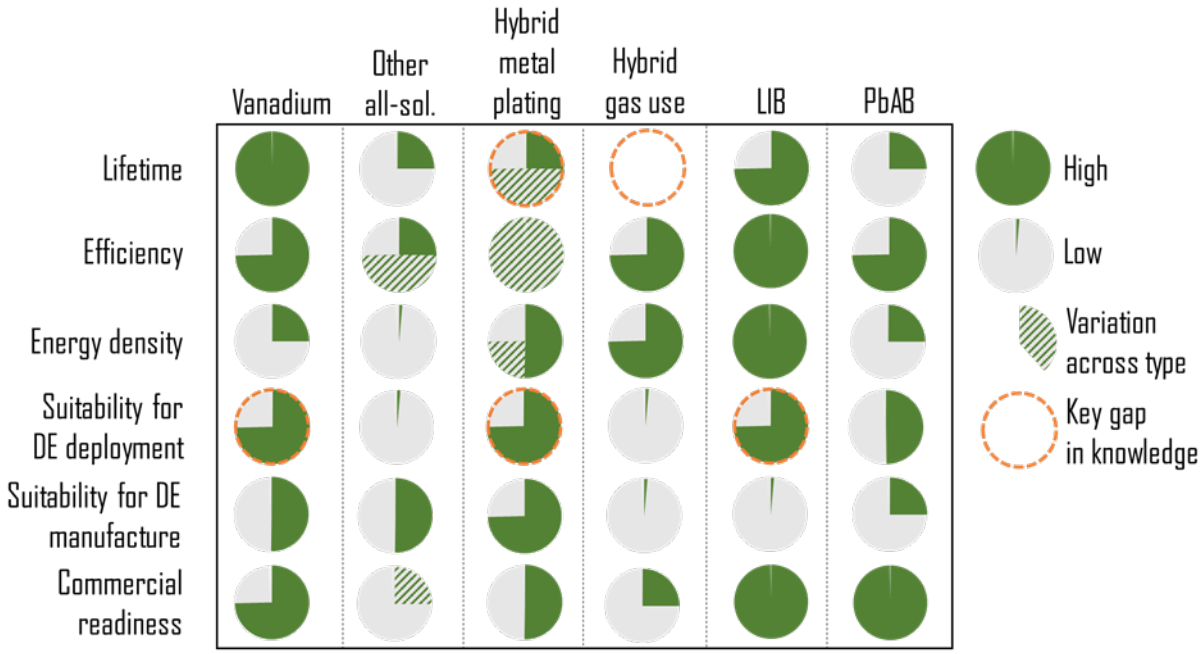
By analysing the status of selected industries such as chemicals, electronics, advanced manufacturing, and existing FB activities, some high-level conclusions can be drawn. There is strong near-term potential in India, Thailand, Malaysia and South Africa, with other countries like Vietnam, Indonesia, the Philippines, Kenya and Egypt potentially following later as markets evolve.

South Africa's strongest potential is in electrolyte manufacture, where value could be added locally to raw materials such as vanadium and iron; Malaysia and Thailand could follow India in building stack components. Countries with less-developed high-tech manufacturing can still contribute through balance of plant items that are required for a full battery assembly.

Summary of FB Suitability for Developing Economies

A high-level summary of the performance of the FB sub-types and their suitability for developing economies deployment and manufacture is given in **Table 7**. Hybrid metal plating FBs show promising overall technical performance, although further demonstration is required to give confidence in the lifetime claims. The high energy densities of some electrolytes in this class are attractive from a developing economy deployment perspective as transport may be more challenging. The claims of high temperature tolerance are also of interest to many developing economy contexts. This FB class is also promising for developing economy manufacture as some examples do not require ionic membranes, and others require no thin film separator at all.

Table 7: Summary of findings on technical performance and suitability of FB types for deployment and manufacture in developing economies (DE).



Recommendations

This report has shown that some (not all) FBs are well suited to the provision of reliable electricity in partnership with the abundant solar power available in many developing economies. To overcome the challenges mentioned above, the following actions are recommended:

- Techno-economic analysis of promising FBs in developing economy use cases. This report shows that while hybrid metal plating FBs show promising energy density and temperature tolerance, the cycle life and round-trip efficiency of some are lower than that of VFBs. To prioritise research and development efforts in these FBs, techno-economic analysis should be used as a screen to avoid improving metrics that do not impact the end-use economics. These should focus on the developing economy use cases highlighted within this report.
- Increase technology confidence. While several FB types have commercially claimed lifetimes of 10,000+ cycles, there is little data outside of the vanadium system to back this up and some FBs have suffered from reliability issues. There is hence a need for demonstrations and standardised testing to increase confidence in the technology. This testing may differ from previous developing economy projects, where the focus has been on getting a system operational in collaboration with local operatives. High TRL FB systems (vanadium and metal plating hybrid FBs) would ideally be tested

alongside LIBs in representative developing economy use-cases, particularly PV firming. Carrying out this testing in a hot climate is important to test the claimed FB benefit of reduced cooling requirements and longer lifetime at high temperatures. Such a study should also quantify any costs associated with maintenance.
- Understand logistical challenges: deployment of FBs in developing economies presents challenges and opportunities. To truly make the case for FBs in these regions, detailed supply chain mappings should be carried out for the most promising FB types. The manufacture and transport of electrolyte is a particularly important subject that requires immediate attention. This task would be best undertaken in combination with a study on manufacturing, focusing on the countries highlighted in this report as having strong potential for both manufacture and end-use; India, Thailand, and South Africa.

It has also been shown that FBs present a more accessible opportunity for local manufacture in developing economies than LIBs. This is an important benefit which in national policy setting may compensate for the present cost advantage of LIBs. Achieving the goal of local value creation will be accelerated by:
- Mapping supply chains for all components in FB types found to be most promising for developing economies in this report. Several manufacturing models should be compared, including assembly only, full local manufacture (if feasible) and a mixed approach.
- Detailed modelling of manufacture/assembly plant requirements and costs.
- Establishing priority components for local manufacture to maximise feasibility/value addition, using the findings of Chapter 6 as a starting point.
- Surveying intellectual property status of promising FBs types.
- Identifying possible partnerships between FB manufacturers, NGOs, local industry and academic/technical institutes.

Lastly, awareness of FBs as an enabling technology for low carbon electricity supply lags that of LIBs by a long way, a challenge that this report will hopefully help to address. Although bodies such as Flow Batteries Europe[130] are tackling this problem, there is scope for other organisations to leverage existing relationships within the international development community.

[130] https://flowbatterieseurope.eu/

Appendix A. Climate in Developing Economies

A.1 Africa

While Sub-Saharan Africa (SSA) encompasses a wide range of climate zones, the region is predominantly characterised by tropical climates. According to *Encyclopaedia Britannica* the major climate regions in SSA include Rainforest, Grasslands, Semiarid, Desert (tropical/subtropical), Humid subtropical and Highland, see **Figure 19**.

Rainforest climates experience consistently high temperatures and heavy rainfall, leading to high humidity. Grasslands and the African Savanna, which dominate Central Africa, are characterised by hot, seasonally dry-then-wet conditions. Moving further north and south, the climate remains hot but becomes increasingly arid, moving through semi-arid into desert regions.

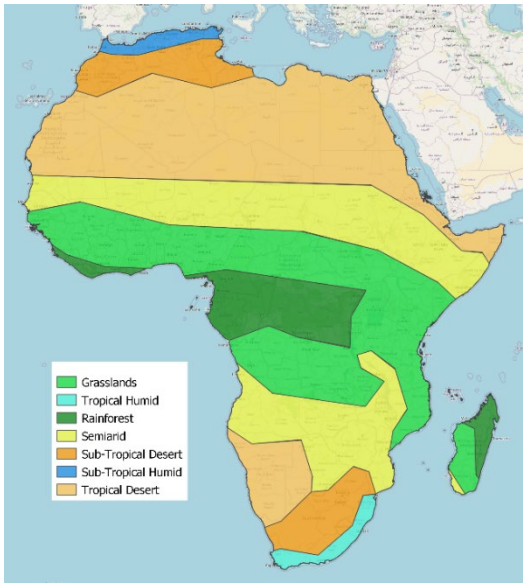


Figure 19: Major climate regions of Africa[131].

A.2 Indo-Pacific

Similarly, the Indo-Pacific region contains a diverse range of climates. However, the countries in Asia that are the focus of this report are primarily characterised by rainforest and grassland climates, as shown in **Figure 20**.

Pacific islands generally experience a tropical climate that is relatively stable year round. Average temperatures can range between 15 °C and 28 °C. Many of these islands also have high humidity, particularly during the rainy season. Relative humidity can often exceed 80%, especially in island groups for example Fiji, Samoa, and Tonga.

Much of the Indo-Pacific region is prone to tropical cyclones, which bring high winds, flooding and storm surges in coastal areas. Coastal areas are also exposed to saltwater aerosols from ocean spray, increasing the risk of corrosion.

[131] https://www.britannica.com/place/Africa/Climate

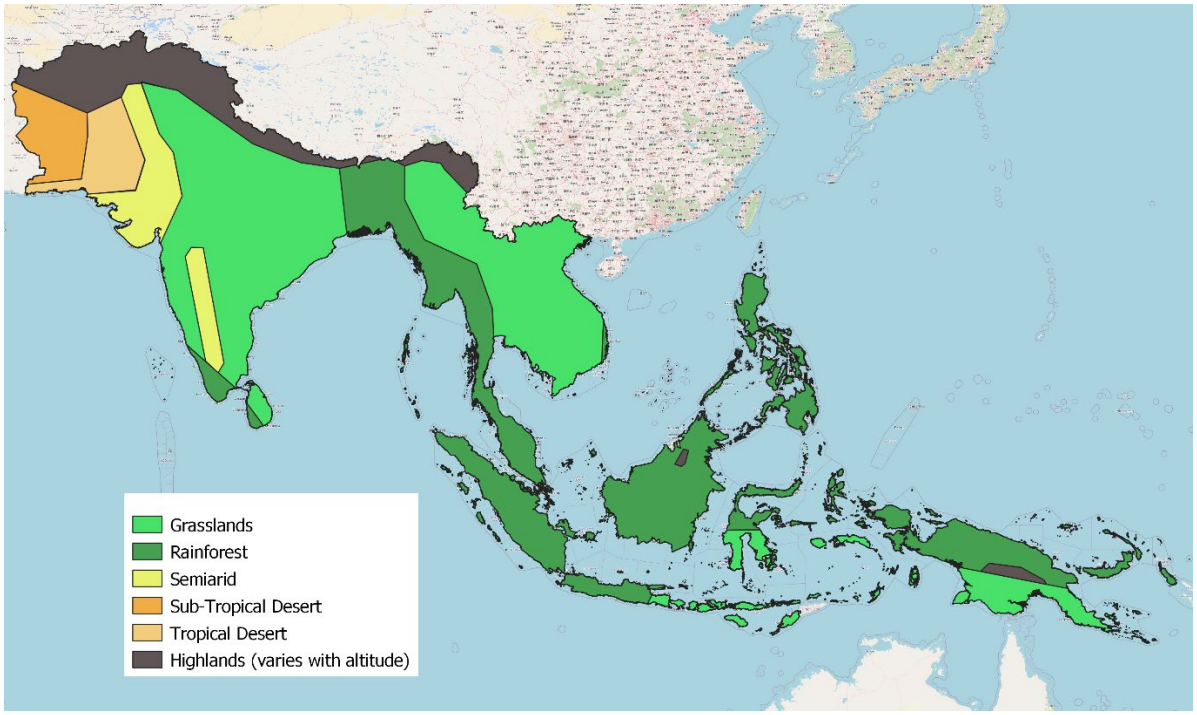


Figure 20: Major climate regions of Asia[132]

[132] https://www.britannica.com/place/Asia/Climate

Appendix B. Electricity Sector Analysis by Country

B.1 South Asia

B.1.1 Interconnections

Interconnection capacity plays a crucial role in supporting renewable generation growth, alongside storage technologies such as FBs. Cross-border transmission capacity has reached 6.4 GW[133], with interconnections between India, Bangladesh, Nepal, and Bhutan. However, further market integration is needed to fully realise the potential shared benefits.

B.1.2 India

As the world's most populous nation and fifth largest economy, India has achieved rapid electrification. Starting from around 60% at the turn of the century, India now has almost 100% coverage[134] and generates over twice as much electricity (1,967 TWh) as the whole of Africa (881 TWh)[135]. However, most of this derives from coal (see **Figure 21**).

India still experiences outages and load-shedding events (i.e., planned disconnections of certain areas in a rota) in more remote areas, and this has led to widespread use of small and medium UPS systems based on short duration lead-acid batteries and fossil fuel generator sets. Reconnections can take considerable time, ironically, in part, because of these systems: reconnected areas cause demand spikes due to the compound effects of batteries attempting to recharge alongside the actual restored loads. Longer-duration FBs could be more intelligently managed to use adaptive recharging, reducing this effect.

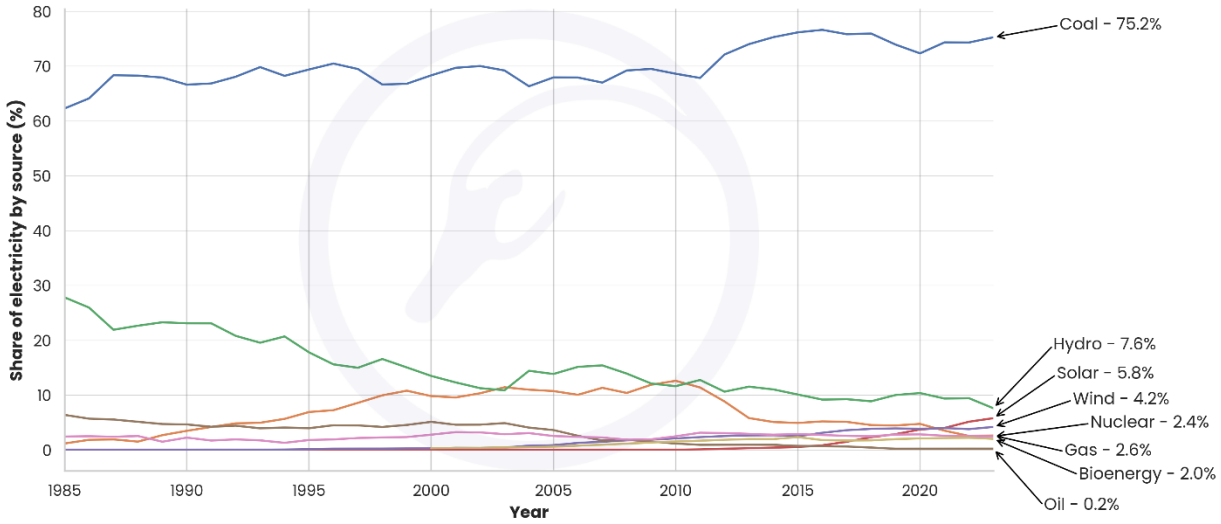


Figure 21: Generation breakdown for India, 1985-2023. Source: Our World in Data

The electricity market has experienced major changes since the 2003 Electricity Act, which launched the liberalisation process and led to the dismantling of the old State Electricity Boards.

[133] https://blogs.worldbank.org/en/endpovertyinsouthasia/integrated-electricity-market-south-asia-key-energy-security

[134] https://ourworldindata.org/grapher/share-of-the-population-with-access-to-electricity?tab=chart&country=~IND

[135] https://ourworldindata.org/energy-production-consumption

A sophisticated market structure with multiple power exchanges (operating since 2008) and trading mechanisms now exists[136]. IEX (90% share), PXIL, and HPX are the main power exchanges, and there is an active Spot Market (since 2020), a Day-Ahead Market (DAM), a Term-Ahead Market (TAM) and Bilateral Contracts (essentially long-term PPAs).

Further market reforms are on the way, albeit with unclear timescales. These include a Capacity Market (modelled on European instances, and particularly favourable for LDES such as FBs). An ancillary services market has been developing since 2017[137] and this can create new beneficial revenue opportunities for LDES, including FBs.

B.1.3 Nepal

Grid coverage has risen from just 30% in 2000 to around 90%[138] but rural electrification remains a challenge. Domestic generation is almost entirely supplied by run-of-river hydropower, with surplus demand in the dry season being provided by interconnectors from India.

Market liberalisation remains at an early stage. The Nepal Electricity Authority is state-owned and covers generation, transmission, and distribution, retaining a monopoly over the latter two. Independent power producers can also generate and sell power[139].

Nepal has been able to participate in India's DAM and TAM markets since 2021. As well as the historical reliance on dry season imports from India, Nepal already takes advantage of its wet season power *surplus* and is thus already an exporter at times.

Regarding storage, note that there are high tariffs (34-35%) on importing batteries into Nepal[140], currently applicable to all types. This could negatively impact FB deployment.

B.2 Southeast Asia

Most countries in the Southeast Asia region achieved 100% grid coverage (not to be confused with reliability, especially in more remote areas) by the 2020s[141], with the exception of Myanmar, Cambodia and PNG. With heavy grid reliance on coal and gas, the transition to non-hydro renewable generation remains at an early stage. The ten countries of the ASEAN bloc have a population of almost 700 million, with very rapidly growing energy demand, expected to triple by 2050 compared to 2020 levels[142].

---

[136] https://www.studyiq.com/articles/power-markets-in-india/

[137] https://bridgetoindia.com/an-essential-step-towards-deepening-ancillary-services-market/

[138] https://ourworldindata.org/grapher/share-of-the-population-with-access-to-electricity?tab=chart&country=~NPL

[139] Journal of Physics – Tech Investigation of Nepalese electricity market (2020) https://iopscience.iop.org/article/10.1088/1742-6596/1608/1/012005/pdf

[140] https://nepaltradeportal.gov.np/major-commodity?_commodityportlet_WAR_tepc_param=getByHscode&hscode=85076000&id=11129&p_p_id=commodityportlet_WAR_tepc&p_p_lifecycle=0&p_p_mode=view&p_p_state=normal

[141] https://ourworldindata.org/energy-access

[142] https://www.eco-business.com/news/how-a-flexible-cross-border-power-grid-can-help-decarbonise-asean/

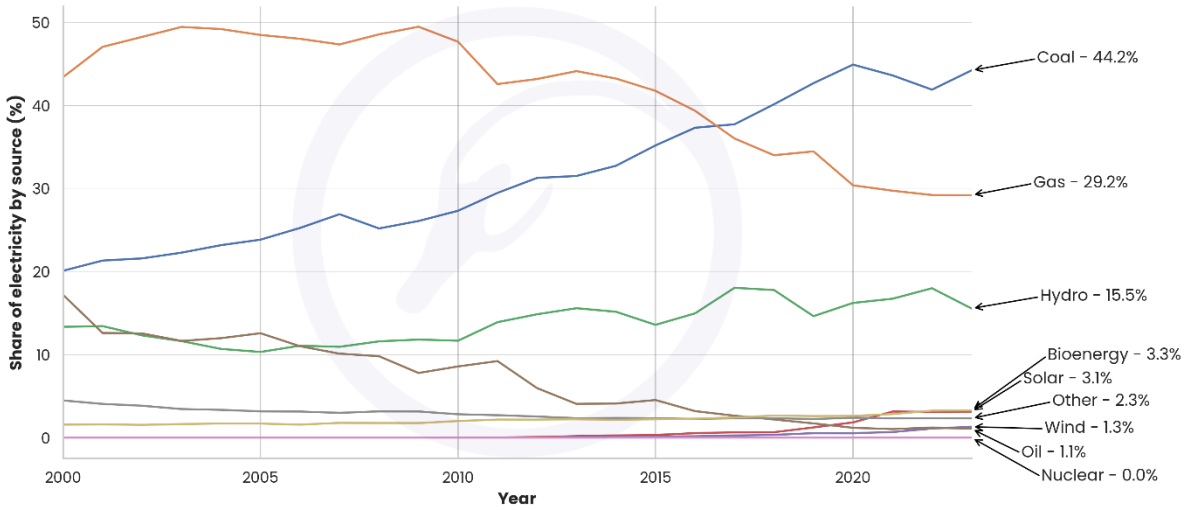


Figure 22: Generation breakdown for overall ASEAN nations, 1985-2023. Source: Our World in Data

B.2.1 Interconnections

Energy policies across the bloc differ significantly, with market integration still in progress. The development of the ASEAN Power Grid is advancing as new interconnection projects are proposed. This is crucial for increasing renewable energy use and will boost demand for storage systems. The work focuses on two main areas: building physical interconnections and strengthening grids in various countries and creating regulatory and trading frameworks for cross-border power exchange. However, the status of these efforts remains unclear.

B.2.2 Singapore

While Singapore is not a developing economy, its role as a major trading hub within ASEAN makes it relevant to this report. Singapore's relatively recent electricity market liberalisation, the first in Asia, could serve as a model for neighbouring countries.

The Energy Market Authority serves as both regulator and system operator, with the wholesale market adopting a half-hourly trading system. Multiple legal entities are responsible for different aspects of the overall system.

B.2.3 Indonesia

By 2021, the country achieved 99% electricity access[143], despite the challenge of operating across 6,000 inhabited islands without a centralised grid. The archipelago has multiple grids with varying connectivity levels, including major ones such as the Java-Madura-Bali System and the Sumatra System, with plans to connect these by 2028.

The electricity market remains highly centralised and is controlled by Perusahaan Listrik Negara (PLN), which handles transmission, distribution, and supply. Independent power producers generate about 26% of the total electricity[144], supplying it to PLN. The sector is heavily regulated with limited competition. There is a target to increase renewable energy

[143] https://ourworldindata.org/grapher/share-of-the-population-with-access-to-electricity?tab=chart&country=~IDN

[144] https://www.lexology.com/library/detail.aspx?g=6add9e46-1b23-4c18-963c-c5399f940f89

integration to 23% by 2025, up from 14% in 2021[145], alongside policies to promote energy storage and battery production through incentives for the EV and battery industries[146].

Figure 23: Transmission lines in the Java, Bali and Sumatra system. Source: IEA. This map included is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

B.2.4 Malaysia

Tenaga Nasional (TNB) is the main operator for all grid aspects on the Malay peninsula, functioning as a government-owned private company since 1990[147]. TNB Genco holds a 51% market share of generation. TNB's Grid Division manages the transmission network, including connections to Thailand and Singapore. TNB also runs its own technical university, UNITEN, to develop engineering talent. Energy storage is still emerging, with 500 MW planned on the peninsula[148]. In East Malaysia (Borneo), the electricity market is managed by separate, vertically integrated companies, Sarawak Energy and Sabah Electricity.

[145] https://iea.blob.core.windows.net/assets/247b5328-2cd7-4fbb-a800-dd1c71f6e562/EnhancingIndonesiasPowerSystem.pdf

[146] https://www.csis.org/analysis/indonesias-battery-industrial-strategy

[147] https://www.tnb.com.my/about-tnb/our-business/

[148] https://owcltd.com/media/blog/the-challenges-and-outlook-for-bess-developments-in-malaysia/

Malaysia has yet to undergo market liberalisation, and advanced ancillary market services are not yet present. However, significant grid flexibility will be required to maximise the country's substantial solar potential.

B.2.5 Philippines

The Philippines, as an archipelagic nation, faces challenges in providing reliable grid access across its many islands. The country operates three separate grids for its northern (Luzon), central (Visayas), and southern (Mindanao) regions. The Energy Regulatory Commission oversees market liberalisation, while the National Electrification Administration focuses on rural electrification.

The generation sector is largely privatised, with incentives in place to promote renewable energy, aiming for 35% by 2030[149]. The transmission network is operated by NGCP, which is 40% Chinese-owned, raising national security concerns. The Wholesale Electricity Spot Market facilitates near real-time trading based on supply and demand, and a new restricted peer-to-peer energy trading market is available for solar PV owners in specific areas.

B.3 Africa

Some of Africa's largest economies, particularly Nigeria, face significant grid reliability issues, with Nigeria's grid capacity far below its needs. Notably, Egypt and South Africa each produce and distribute about 15 times more electricity than Nigeria, despite having populations less than one-third of Nigeria's. This shortfall has led to widespread reliance on small-scale fossil fuel generators.

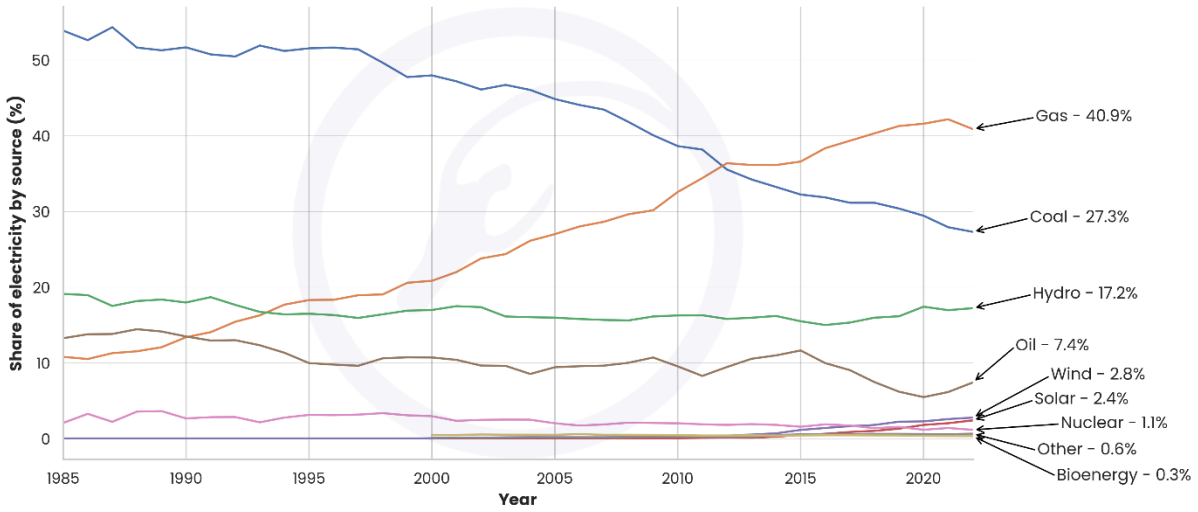


Figure 24: Generation breakdown for the continent of Africa, 1985-2023. Source: Our World in Data

Nearly one-third of the world's "unconnected" population lives in just three African countries: Nigeria, DR Congo, and Ethiopia[150]. In several central African countries,

[149] https://climateanalytics.org/publications/a-15c-future-is-possible-getting-fossil-fuels-out-of-the-philippine-power-sector

[150] https://knowledge.energyinst.org/new-energy-world/article?id=138984

electricity access remains below 20%, making this region the last in the world to face such widespread lack of access to electricity [151].

B.3.1 Interconnections

Africa is currently divided into five multinational power pools:

- COMELEC - North
- SAPP – Southern
- WAPP - West
- EAPP - Eastern
- CAPP – Central

The four Sub-Saharan pools were established between 1995 and 2005. SAPP is the oldest of these and considered the most advanced; COMELEC is the oldest overall, being originally created in 1974 [152].

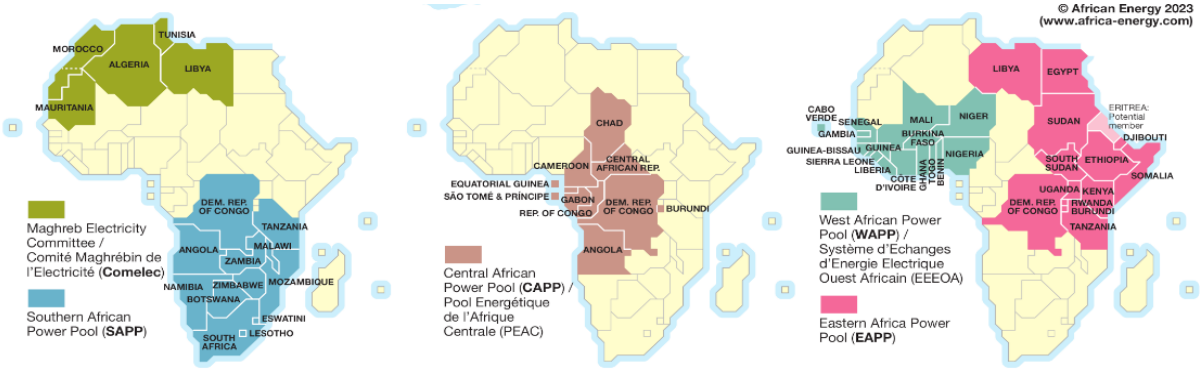


Figure 25: Overview of current African power pools (map source: African Energy, 2023)

There exist some obvious overlaps, with countries connected to multiple pools. Northern countries such as Egypt and Morocco are also interconnected with neighbours beyond Africa.

The African Continental Master Plan includes a roadmap towards connecting the five power pools, which will eventually lead to a single market across the continent [153]. The 'integration and implementation' phase is now underway. Africa's demand projections have resulted in the CMP calling for a tripling of generation by 2040 [154], when full continent-wide operation is expected.

B.3.2 South Africa

The country has faced ongoing power problems, including rolling blackouts since 2008, with available generation capacity declining. Eskom, the largest power generator in Africa, dominates the sector and is responsible for generation, transmission, and distribution. A restructuring plan was announced in 2019, but implementation has been

[151] https://ourworldindata.org/grapher/share-of-the-population-with-access-to-electricity

[152] https://www.mmeipa.africa-eu-energy-partnership.org/north-african-power-pool

[153] https://www.nepad.org/continental-master-plan

[154] https://africanclimatewire.org/update/african-continental-power-master-plan-says-africa-must-triple-electricity-by-2040/

slow. Eskom is burdened with around $23.5 billion in debt as of 2023[155], while being owed approximately $4.5 billion in unpaid debts from municipalities.

The National Energy Regulator of South Africa (NERSA) oversees electricity, gas, and petroleum pipelines, and its role is not expected to change following Eskom's restructuring. The restructuring involves splitting Eskom into three independent entities:

- **National Transmission Company (NTCSA):** Manages the transmission network, grid stability, and power transactions on a non-profit basis. NTCSA has started operations and acts as the system operator.
- **NEDCSA:** The distribution arm, expected to begin trading operations by November 2025.
- **Eskom (Holdings) Generation:** Will focus on generation assets.

These entities will operate independently under a new holding company. NERSA has also hinted at the possibility of regional electricity distribution in the future. The energy storage market is highly active, with several large-scale projects in progress, including battery and molten salt thermal projects exceeding 1 GWh[156] in capacity.

These radical changes to the electricity market structure will create new opportunities for FBs, with the future role of NEDCSA being key. The potential for longer-duration time-shifting of power provision using dispatchable FBs is large and could help support the weaker parts of the distribution network, reducing outages.

B.3.3 Nigeria

Nigeria faces significant power issues and relies heavily on portable fossil fuel generators (a mix of diesel and petrol). The Nigerian Energy Regulatory Commission (NERC) has overseen the power sector since 2005. The country's grid operates within the West African Power Pool (WAPP) and is managed by the government-owned Transmission Company of Nigeria (TCN).

The system operator, a semi-autonomous entity under TCN[157], manages grid operations. There are 11 privatised distribution networks (DisCos) handling 11kV and 33kV networks, responsible for metering, billing, and revenue collection, with no standalone suppliers or retailers.

Electricity storage in Nigeria is primarily focused on small-scale solutions, such as 5kWh PV-linked battery systems[158]. Large-scale storage prospects may be limited in the near term due to the country's primary focus on improving its core grid infrastructure.

B.3.4 Kenya

Kenya has a significant share of renewable energy, especially from geothermal and hydro-electric sources[159]. KenGen, which is 70% government-owned, handles only generation.

---

[155] https://www.eskom.co.za/eskom-releases-its-results-for-the-2022-23-financial-year/

[156] https://www.power-technology.com/data-insights/top-five-energy-storage-projects-in-south-africa/?cf-view

[157] https://www.niso.org.ng/Aboutus

[158] https://www.youth-power.net/news/5kwh-battery-storage-for-nigeria/

[159] https://www.iea.org/countries/kenya/electricity

Transmission is managed by the Kenya Electricity Transmission Company (KETRACO), which has a major network expansion planned in its 2023-42 master plan[160].

The Kenya Power & Lighting Company (KPLC) is the sole distribution operator and retailer, with the government holding a 50.1% stake. Rapid rural electrification has brought coverage to much higher levels, potentially reaching close to 100% by 2030. Kenya aims to develop up to 450 MW of energy storage by 2036[161], though there are gaps in the policy framework needed to support this goal.

[160] https://www.trade.gov/country-commercial-guides/kenya-energy-electrical-power-systems

[161] https://bowmanslaw.com/insights/the-role-of-grid-scale-battery-energy-storage-systems-in-helping-kenya-achieve-its-renewable-energy-goals/

Appendix C. Analysis of Data Centre Market Potential by Country

C.1 South Asia

India: has the second-largest data centre capacity in Asia[162] across 245 sites[163], which is expected to reach a total power demand of 1,800 MW by 2026, nearly doubling the current level. This growth is fuelled by a young digitally-savvy population and strong economic growth. Sites are concentrated in Mumbai (50%) and Chennai (18%), with emerging hubs in cities such as Kochi and Jaipur.

C.2 SE Asia

Singapore: previously the leading regional data centre hub, Singapore has faced capacity constraints due to land and energy pressures. After a moratorium (2019-2022), growth has resumed, with 100 data centres now consuming 7% of the nation's electricity, projected to reach 12% by 2030[164].

Malaysia: TNB launched a 'Green Lane Pathway' in 2023 to fast-track data centre developments within 12 months. The country currently hosts 50 sites, with a significant cluster in southern Johor near Singapore.

Others: Thailand currently has 34 sites, mostly in Bangkok, with rapid growth expected. Indonesia hosts 73 data centres, with 16 more planned, driven by investments from major US cloud companies and government projects. However, most sites are still powered by coal, presenting sustainability challenges. Batam Island is a hotspot due to its power availability, having received substantial inward investment due to its status as a Special Economic Zone linked with neighbouring Singapore. Vietnam, a growing tech hub, already has 30 sites with more expected. The Philippines has around 22, mainly in Metro Manila, with capacity projected to reach 300 MW by 2025. While Laos, Cambodia, Myanmar, and Brunei are not major players yet, ASEAN's data centre market is expanding rapidly, presenting significant opportunities for FBs.

C.3 Africa

Africa has nearly 120 data centres across 22 countries, despite being the least developed continent in terms of connectivity. Key hotspots include South Africa (39 centres), Nigeria (14), and Kenya (13), with notable activity in Angola, Ghana, and Morocco[165]. The market is expected to grow rapidly, reaching $3 billion by 2028[166], with top builders such as ADC, Equinix, BCX, and OADC based in either Johannesburg or Lagos.

The Raxio Group, with a presence across several African countries and an HQ in Nairobi, is a leading developer focused on green 'Tier III' data centres[167]. Capacity could hit 1,200 MW by 2030, but challenges remain in energy supply, regulation, and expertise.

---

[162] https://www.business-standard.com/technology/tech-news/india-set-to-cross-1800-mw-in-data-centre-capacity-by-2026-cbre-report-124051501256_1.html

[163] https://www.datacentermap.com/india/

[164] https://www.febis.org/2024/05/24/the-race-to-build-data-centres-in-southeast-asia/

[165] https://www.datacentermap.com/africa/

[166] https://datacentremagazine.com/articles/top-10-data-centre-providers-in-africa

[167] https://www.raxiogroup.com/about-raxio/

Storage-enabled microgrids, especially with FBs, represent an acknowledged opportunity in this sector[168].

[168] https://www.intelligentdatacentres.com/2023/12/11/navigating-africas-data-centre-boom-amidst-grid-challenges-and-environmental-opportunities/

Appendix D. Technical Detail on Sub-components of the FB Stack

D.1 Flow Frames

These define the overall structure and shape of the core stack assembly and play a part in optimising flow performance and, ultimately, battery efficiency. The flow frame holds the electrodes and provides channels for cell electrolyte flow. Using a standard injection moulding process, the frame can be manufactured from common plastics such as polypropylene, HDP or PVDF, typically chosen for the required chemical stability, particularly in aggressive acid or alkali environments. Injection moulding is well understood and has low complexity, and frames can be made in a FB factory, or under contract by established companies.

D.2 Porous separators & ion exchange membranes

The production of porous separators or ion exchange membranes for FBs presents both technical and infrastructural challenges, particularly in developing economies. A suitable polymer base is chemically, thermally, or physically treated to provide the required performance, followed by precision fabrication into films of varying thickness, delivered either in sheets or web.

The choice of separator will consider:

- Chemical and physical stability
- Conductivity of charge carrying ions
- Selectivity (only allow charge carrying ions to cross)
- Ease of handling
- Cost
- Regulations, for example perfluorinated polymers such as Nafion may fall foul of emerging regulation around “forever chemicals.”

Microporous separators tend to be lower cost than ion selective membranes. However, the initial cost needs to be assessed against performance as they are less effective at preventing undesired crossover. Reducing species crossover is more critical for some FB than others. For example, as the VFB has vanadium ion in both the posolyte and negolyte crossover is less of a problem, since rebalancing can be carried out by modifying the oxidation state alone (see Section 4.3.3). However, crossover is the major technical challenge in some aqueous-organic FBs. The zinc/bromine FBs can use a simple microporous separator as the two phases are immiscible, while some FB types do not require a separator at all (soluble lead, zinc/nickel, and copper/lead). The key takeaway is that the choice of membranes is related to the choice of chemistry.

D.3 Electrodes

Each FB stack will have end electrodes that are connected to the external circuitry and a bipolar electrode in each cell, which allows current to be conducted directly between adjacent cells. The choice of materials for the electrodes will depend on:

- Chemical resistance (to both the electrolyte and side reactions such as oxygen evolution)
- Electrical resistance
- Speed of kinetics, i.e., does the electrode need enhanced activity as a catalyst by surface modification?
- Cost
- Mechanical stability
- Ease of manufacture

- Suitability for joining and assembly

The end electrodes are usually housed in a rigid frame with tie bolts used to hold the intermediary electrodes in place against the pressure exerted by the pump to circulate the electrolyte. Some systems, for example, developed by Volterion, use a lower-weight and hence lower-cost construction technique.

The intermediate electrodes are usually based on bipolar electrodes, to reduce materials costs. The electrodes can be made from any conductive materials that are electro-chemically stable in the electrolyte. Carbon based materials are typically used, often composites of graphite and a carbon binder. Some FBs (e.g., the iron hybrid FB developed by ESS) employ titanium electrodes for increased chemical stability.

Some FB designs include flow distribution channels in the electrodes, while other models may use flow distributors as separate components. The electrodes may be extruded, moulded and / or machined, followed by surface treatments to enhance corrosion resistance and conductivity. Ideally, this would be a fully automated process to ensure high and consistent quality. These processes require long production runs to be economical. These requirements necessitate a high degree of industrial capability.

Electrodes should exhibit high electrical conductivity and chemical stability along with a high specific surface area to enhance the battery's performance. In some cases, an electrically conductive carbon felt is sandwiched between the electrode and a separator to increase the surface area at which electron transfer may occur. The production process often involves specialised treatments, such as heat processing or chemical activation, to optimise these properties. These processes require specialised facilities and expertise that are less commonly available in some regions, where local manufacturing tends to focus on simpler components.

Appendix E. Country Manufacturing Analysis

This appendix analyses the broader manufacturing picture in the regions depicted in Section 4.2.1. A more focused analysis of selected countries highlights the typical challenges and advantages these areas face, while also identifying nations with the potential to become early movers in FB production among developing economies.

E.1 Africa

In Africa, development is broadly at an earlier stage than in Asia. This observation applies to the manufacturing sector as much as any other, with the continent only contributing ~1.9% of global manufacturing output[169]. However, with its considerable wealth in minerals and its young and growing population, Africa offers significant potential for industry as it moves up the value chain from resource extraction to more advanced manufacturing.

Several Sub-Saharan countries are explored in this section, but the transition is also occurring in North African nations such as Egypt[170].

E.1.1 South Africa

South Africa has the continent's largest economy and an established manufacturing base. However, the manufacturing sector's share of GDP has fallen significantly to around 12%[171] as the services sector has grown. South Africa is now outside the top 40 largest manufacturers globally[172] but is still a leading player in Africa's industrial transformation.

South Africa has significant industrial activities in the chemical sector, with Africa's largest and most advanced chemical industry[173]spanning around 600 chemicals[174]. Besides chemicals, food and beverages, metals, and automotive are the major industrial subsectors[175].

Notably, South Africa is a top three producer globally of vanadium, as well as chromium, both important as electrolytes, presenting an opportunity for electrolyte manufacture.

E.1.2 Nigeria

Nigeria is Africa's most populous nation and fourth-largest economy. It ranks as the world's 35th largest manufacturer with a 13% of GDP sectoral contribution[171]. The chemicals industry is significant and is primarily driven by Nigeria's status as Africa's largest oil producer (approximately 74 million metric tonnes in 2023).

The country's petrochemical sector leverages these substantial oil and natural gas reserves, and notable products include fertilisers, plastics, and many other petrochemical derivatives. In recent years there has been a push towards more sustainable production

---

[169] https://www.afdb.org/en/the-high-5/industrialize-africa

[170] https://www.unido.org/sites/default/files/files/2020-11/Country_Brief_Egypt.pdf

[171] https://ourworldindata.org/grapher/manufacturing-value-added-to-gdp

[172] https://worldpopulationreview.com/country-rankings/manufacturing-by-country

[173] https://www.maersk.com/insights/sustainability/2024/03/26/africa-chemical-producers

[174] https://www.investsa.gov.za/key-sectors/chemicals/

[175] https://www.adcorpgroup.com/stories/news/the-biggest-industrial-sectors-in-south-africa-and-why-employment-within-these-sectors-keeps-them-going/

methods and the production of basic chemicals for self-sufficiency[176], and the sector continues to grow and evolve under government initiatives on industrial policy and reducing import dependency. However, the industry has been operating well below its design capacity[177].

E.1.3 Kenya

Kenya's manufacturing base is growing, benefiting from a more reliable and better-developed electricity supply than South Africa and Nigeria. Manufacturing represents 8% of Kenya's GDP[171], although this has reduced as a proportion as the broader economy has grown.

The Kenya Association of Manufacturers, focuses on 14 key sectors, including energy, electricals and electronics[178]. KenInvest, the statutory body promoting investment into Kenya, regards renewable energy equipment manufacturing (including energy storage systems) as a key opportunity area[179].

E.1.4 Other African Nations

The other top African economies (as ranked by nominal GDP) are Egypt, Algeria, Ethiopia, Morocco, Angola and Tanzania[180]. Some are significant oil-producing nations and thus possess indigenous process engineering and chemical refining facilities that could drive future potential for manufacturing FB materials.

E.2 South Asia

E.2.1 India

India is a burgeoning manufacturing hub and has been keen to attract industries previously dominated by China. India is already the world's fifth largest manufacturer, with the sector representing 13% of GDP[171].

Manufacturing output in India is projected to grow by 2.94% annually from 2024 to 2029, starting from a value exceeding US$1,500 billion[181].

India's manufacturing sector benefits from a large, semi-skilled labour force, with lower labour costs providing a competitive edge. This advantage is further bolstered by the increasing adoption of Industry 4.0 technologies, such as automation, robotics, and the Internet of Things (IoT), significantly enhancing productivity and operational efficiency across industries. Additionally, there is a growing emphasis on sustainability, with a shift toward environmentally friendly practices and the development of eco-friendly products, aligning India's industrial growth with global sustainability goals.

---

[176] https://blog.matta.trade/industrial-chemicals/

[177] A Review on Utilization of Nigerian Petrochemical Industry. https://iopscience.iop.org/article/10.1088/1757-899X/1107/1/012021/pdf

[178] https://kam.co.ke/sectors/

[179] https://www.investkenya.go.ke/sector/manufacturing/

[180] https://www.statista.com/statistics/1120999/gdp-of-african-countries-by-country/

[181] https://www.statista.com/outlook/io/manufacturing/india

E.2.1.1 Chemical & Pharmaceutical

India is a global leader in pharmaceutical manufacturing, with sophisticated supply chains and advanced process engineering. Technical capabilities in pharmaceuticals can be adapted to other chemical engineering sectors.

The Indian government runs a Production Linked Incentive support scheme for the manufacturing of 'Advanced Chemistry Cell' (ACC) battery storage technologies in the country[182]. The policy includes building up to 50 GWh/annum of domestic battery manufacturing capacity to reduce import dependence. Notably, the ACC programme is technology-neutral and has a strand dedicated to 'niche' technologies, such as emerging FB technologies.

E.2.1.2 Existing FB Manufacturers

FB manufacturing companies are already operating in India.

VFlowTech is a Singapore-based company with a large manufacturing facility in Haryana, outside Delhi.

Delectrik, based in India, targets a range of markets[183], with an early focus on larger MW-scale systems. However, the company sees future market potential in smaller-scale systems, including residential and small commercial sites (such as telecom stations). Discussions with the company confirmed the focus on building a small quantity of larger batteries before scaling towards volume production of their smaller units.

Advanced components, including membranes and bipolar plates, are still being imported from outside India, but Delectrik is already exploring the potential of local manufacturing.

E.3 Southeast Asia

E.3.1 Indonesia

Indonesia has the largest population in ASEAN, with a relatively young profile. Indonesia also represents the largest mining-based economy and has a growing manufacturing sector within this alliance. The country is now the world's ninth largest manufacturer[172], with the sector representing a substantial 19% of GDP[171].

The manufacturing sector is diversified, and the country has not yet established itself as a notable force in any industry (in contrast to Malaysia for example). However, there is a policy drive to promote growth of indigenous manufacturing under 'Making Indonesia 4.0', and chemicals are one of five core sectors included[184], signalling the potential for electrolyte manufacturing.

E.3.2 Malaysia

Malaysia is a much smaller manufacturer, ranking 27th globally, albeit with the sector representing a large proportion of its GDP, at 23%[171]. Electronics, components and automotive are the biggest subsectors, and there is notably a strong cluster of semiconductor manufacturers.

---

[182] https://www.investindia.gov.in/team-india-blogs/inside-indias-production-linked-incentive-schemes-advance-chemistry-cell-acc

[183] https://delectrik.com/products-2/

[184] https://www.indonesia-investments.com/business/business-columns/widodo-launches-roadmap-for-industry-4.0-making-indonesia-4.0/item8711

Other major subsectors include petroleum, chemicals, rubber, and palm oil. The country's resulting process engineering expertise offers a potential pivot into other energy sectors, including FB electrolytes.

E.3.3 Thailand

Thailand is now the world's 20th biggest manufacturer, with manufacturing representing 27% of GDP[171] (almost as high a proportion as China). The major subsectors are food and drink, electronics, chemicals, automotive, and rubber and plastics[185].

Thailand has experience in VFB manufacturing (Squirrel and Cellenium started in the 1980s) and more recently hosted Redflow's Zn-Br FB facility. However, Redflow stopped manufacture in Thailand in mid-2023 as part of a strategy to relocate and expand its production closer to key markets, notably the USA and Australia[186], andis now in administration.

E.3.4 Philippines

The Philippines' 17% of GDP manufacturing share is falling, with electronics being a large subsector[187]. A programme to further develop advanced manufacturing includes a specialist focus on additive manufacturing.

E.3.5 Vietnam

Vietnam is the world's 23rd largest manufacturer, with manufacturing representing 24% of its GDP[171]. Low labour costs have driven rapid manufacturing and foreign investment growth, but much of the industrial base is still low-tech. There has been recent growth in electronics assembly (including smartphones), with other industries still nascent. Vietnam's challenges include its infrastructure, which has struggled to keep up with economic and population growth, and its relatively low-skilled workforce, which is not yet suited to high-tech sectors[188].

E.3.6 Other SE Asian Nations

Economically poorer Asian countries such as Laos, Cambodia, Myanmar, Nepal and PNG are much lower in the manufacturing rankings. The sector is still at an early development stage in these nations compared with those above, so their near-term potential is limited.

Conversely, Singapore is the wealthiest economy within ASEAN and is an established high-tech manufacturing centre. The potential for manufacturing precision products (such as bipolar plates) within the country is thus high, although the local potential for FB has been established as relatively low (it was attributed a score of 11 using the criteria applied for Table 4 , but was not included there as it is not a developing economy).

---

[185] https://research.hktdc.com/en/article/Mzg1NTc4ODc4

[186] https://reneweconomy.com.au/redflow-lands-biggest-project-for-flow-battery-technology-with-stack-of-us-funding/

[187] https://www.statista.com/topics/11457/manufacturing-in-the-philippines/

[188] https://innolab.asia/2024/04/23/vietnams-manufacturing-landscape-unveiling-the-2024-boom/