Enabling Renewable Energy through Lower Cost and Longer Lifetime Battery Storage

Current State and the Future of Redox Flow Batteries for Stationary Energy Storage Applications in Indonesia

IMPRINT

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Executive Summary

Redox Flow Battery (RFB) global deployment history and present barrier

Redox flow battery energy storage systems (RFB-BESS) have been deployed worldwide since their commercialisation in the late 1990s and are expected to continue to grow, particularly in the Asia Pacific Region, where several large-scale renewable energy projects are in the pipeline. While most RFB projects used a 'standard' 4-hour energy to power ratio of BESS(s), there are also emerging projects utilising attractive long-duration capability of RFB, notably for microgrids application. Based on the type of technology, the all-vanadium redox flow battery (VRFB) is the most popular one due to its technical maturity, with an installed power capacity of over 300 MW (around 68% of all RFBs) by 2020, and is predicted to still be the most sought-after with several projects are under construction or recently announced (e.g., VRFB projects in China and South Africa). In 2021, 27 of the 41 RFB manufacturers are producing the VRFB. Meanwhile, alternative RFB technologies, such as zinc-bromine RFB (ZBRFB) and organic RFB (ORFB), have only 3 and 5 manufacturers registered, respectively.

Among all RFB projects, the VRFB plant in Dalian China with 200 MW/800 MWh is the largest project that has the opportunity to showcase RFB-BESS technology. However, although the project announced in 2016 is targeted to start operating in 2020, there is no report confirming the completion of the project. The spike in the price of electrolyte precursors (V_2O_5) around 2019-2020 is most likely the main reason for the delay. Vanadium is a strategic material, native and mined in limited countries (e.g., China, Russia, and South Africa) with a history of price volatility. Therefore, the construction of the VRFB project and electrolyte assembly have high risks of delay in the occurrence of a vanadium supply disruption. On the other hand, other RFB technologies seem to find it difficult to match the performance and maturity level of VRFB, and some of these technology manufacturers also encounter financing problems.

Overview of RFB technology

An RFB consists of three fundamental components, namely electrolytes, electrodes, and membranes, where the type of electrolytes plays an important role in determining the performance of RFB and is commonly used to name the RFB technology instead of the electrodes in typical battery technologies (e.g., Lithium ion batteries (LIB) using LFP or NCM electrodes). In addition, an RFB requires auxiliary components in its architecture, such as tanks and pumps for storing and circulating the electrolytes.

RFB is often solely associated with battery technology that uses vanadium-based electrolyte as the main component, when several other types of flow batteries, in fact, have been developed and also commercialised. This report highlights three promising RFB technologies as an alternative to vanadium-based flow batteries (VRFB), namely Zinc-bromine (ZBRFB), All-iron (All-Fe RFB), and organic (ORFB) flow batteries, and analyses their respective advantages and disadvantages.

RFB pro and cons

RFB technology offers scalability, energy-power decoupling capability, and long-cycle life features as a stationary energy storage. Scalability enables RFB use in various scales that overcome geographic constraints, provide flexibility in the future (e.g., for a system upgrade or other technology integration), and allow initial capital cost reduction.

While scalability is a common advantage of BESS, the "active electrolytes" that can be stored separately from the reactors make RFB an appealing BESS option, as its architecture allows RFB to increase the storage capacity without requiring extra power component cost. In addition, RFB's "active electrolytes" open the possibility of having long cyclability and a higher degree of safety.

Despite the aforementioned advantages, RFB is not yet the first choice for stationary storage applications because there are other technologies that outperform RFB. This report reviews several technical parameters and costs of RFB compared to other BESS technology and PHS as a representative of long-duration and long-term storage technology. Compared to the conventional BESS, the efficiency and energy density of RFB are at least 10% and 90% lower than LIB, respectively. In terms of the technology and manufacturing maturity, RFB also is not yet at the same level as competing ESS technologies (e.g., LIB and PHS). Meanwhile, the high component costs, particularly for electrolytes and membranes of the most advanced RFB, need further reduction to make it an economically competitive storage option.

The present cost of RFB-BESS

The power-energy decoupling capability is one of the charming points of RFB because it avoids the outlay of expensive power components (e.g., RFB membranes) to scale up the energy storage capacity. Although it makes RFB an appropriate BESS option for grid services requiring long-duration storage (>8 hours), RFB is not yet economically competitive for shorter duration applications (such as grid response and peaker in utility-scale systems) due to the relatively higher cost of energy components compared to other storage technologies. Through an application-specific LCOS calculation, IESR estimates suggest that present LCOS of the cheapest RFB (i.e., VRFB) in various applications are still above 20 cents/kWh, 1.3 to 2 times higher than LIB and PHS.

With the increasing demand in the BESS market and declining costs of its components, RFB LCOS(s) indeed could be more competitive in the future, particularly in power reliability applications such as off-grid systems using VRE with long-duration BESS. However, the future RFB LCOS combined with VRE should be able to match the cost of the existing system (i.e., LCOE of the fossil power plant at 8-10 cents/kWh), which requires RFB energy components (including electrolytes) costs <$70/kWh. Given the vanadium precursor alone costs around $160/kWh, the target is unlikely achievable with VRFB. Therefore, there is a need for other RFB technologies using cheaper raw materials to develop and meet the maturity level of VRFB.

Application (scale-duration)	LCOS (USD¢/kWh)				
	VRFB	ZBRFB	LFP-LIB	NCM-LIB	PHS
Secondary response (10 MW-2 hours)	20.1	22.63	14.25	15.87	
Peaker replacement (1 MW-4 hours)	29.49	38.98	21.61	27.12	
Peaker replacement (100 MW-4 hours)	25.58	36.62	18.57	23.38	15.66
Energy trade (1 MW-8 hours)	27.4	39.62	23.25	28.49	
Energy trade (100 MW-10 hours)	23.54	37.55	20.64	25.24	11.6
Power reliability (1 MW-10 hours)	21.12	38.22	18.57	23.53	

LCOS(s) in purple color is the lowest value in respective applications.

RFB deployment potential in Indonesia

The Indonesian government has identified the need for energy storage to enable renewable energy integration but does not yet have detailed regulations and support schemes for BESS adoption. For example, BESS is a key technology required in the ongoing diesel generators conversion program at 200 locations planned to be completed by around 2025. While the type of BESS and converted systems specification will be decided through tender, PLN as the program owner has expressed an interest in RFB-BESS and considered it an economical option.

In the diesel conversion program context, RFB obviously would be a reasonable option among the available BESS technologies due to its long-duration capability. In IESR simulation, however, the LCOE of VRFB-integrated hybrid systems for a hypothetical off-grid site is not cheaper than systems using commercial LIB-BESS, which is consistent with the result of LCOS calculation for power reliability application. Moreover, the durability and performance of RFB-BESS are also not yet proven in Indonesia.

This paper recommends three points to stakeholders in Indonesia before adopting BESS technologies, particularly RFB.

1. To assess the technical aspects of BESS through feasibility studies and several pilot projects.
2. To evaluate the costs of BESS (not limited to the diesel conversion program) using an application-specific LCOS approach.
3. To prepare policy support schemes for BESS(s) deployment (including RFB) and its integration with renewables.

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01. Introduction

Introduction

Countries around the world have collectively agreed to switch from carbon-intensive energy to renewables to curb climate change. Most of these countries have set an ambitious goal of achieving net-zero emissions by 2050. Aligned with this trend, investment in fossil fuel power plants, particularly coal-fired power plants, has been slowing down, while there has been an investment boom in renewables. As a result, renewables' share in the global electricity mix has notably increased from 19.5% in 2010 to 28.6% in 2020, as shown in Figure 1.

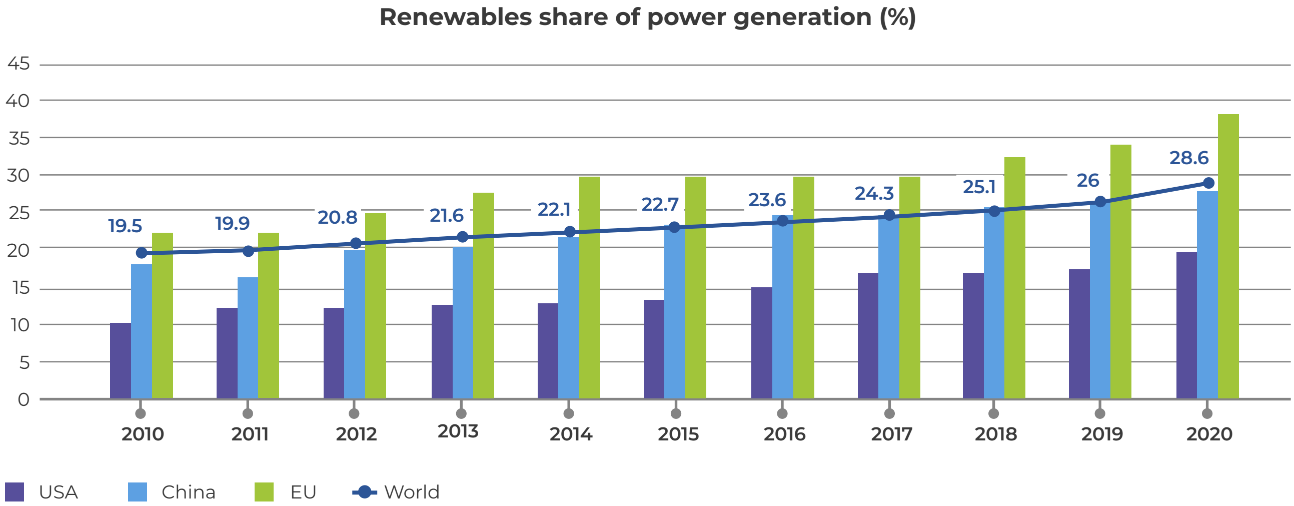


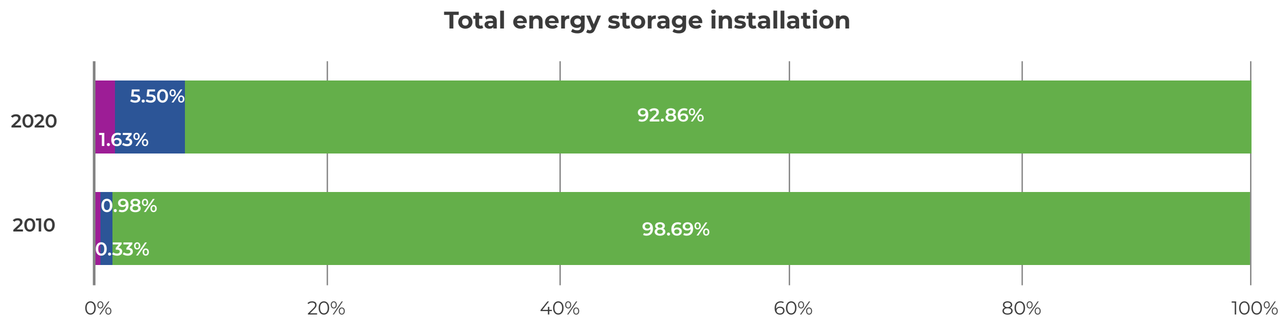
Figure 1. The share of renewable energy electricity generation by selected countries and the world's average from 2010 to 2020 (IEA, 2021a, 2021b).

Among renewable energy sources, wind and solar energy have grown significantly, contributing to around 60% of global renewable capacity addition and accounting for one-third of total renewable capacity by 2020 (IEA, 2021a). Despite the growth, wind and solar energy face intermittency issues that prevent countries from maximising their huge renewable potential.

One solution to overcome intermittency and variability is the use of energy storage systems (ESS). To date, there are at least three different types of energy storage technologies, namely mechanical, thermal, and electrochemical energy storage technologies. Mechanical pumped hydropower storage (PHS) and thermals accounted for over 98% of all ESS capacity installed by 2020. Meanwhile, due to their flexibility compared to thermal and PHS, electrochemical storages[1] such as battery energy storage systems (BESS) are gaining traction, rising from 0.3% in 2010 to 1.6% by 2020.

There was a more than sixfold increase in battery energy storage systems (BESS) power capacity between 2010 and 2020, with a 1.5 GW/5.7 GWh global capacity by 2020 (DOE, 2021). The International Energy Agency (IEA) predicted that wind and solar capacity combined would reach 2,349 GW in 2025 (IEA, 2020b). Assuming that batteries will store as little as 2% of these generations in 2025, roughly 40 GWh of additional BESS energy capacity is needed to balance the VRE generation in the 2025 scenario.

[1] Electrochemical storage system is a device that can store electricity in a chemical form. It includes batteries, fuel cells, supercapacitors, etc.



	2010	2020
Batteries (MW)	243	1,550
Thermal (MW)	723	5,219
PHES (MW)	71,678	88,042

Figure 2. The global energy storage installations for stationary applications in 2010 and 2020 (DOE, 2021).

Among the available BESS technologies, the lithium-ion battery (LIB) currently stands out with its relatively high energy density and low costs due to its long use in electronics and the recent trend of electric vehicles (EV), which has further driven down its manufacturing costs. However, the LIB cyclability is short-lived, and hence it may not be the best choice for long-term stationary storage applications.

A redox flow battery (RFB) came out as an alternative to LIB. RFBs offer a much longer cycle life than LIBs and have the potential to be a cheaper option for long-duration storage applications. The main concern with RFB is that it has not yet reached the same maturity as LIB and its current commercial deployment is still very limited. This report assesses the potential of RFB deployment as a stationary storage in Indonesia and cost estimation of such deployment.

02.
Redox Flow Battery (RFB) Technologies

Redox Flow Battery (RFB) Technologies

While traditional battery technologies such as lead-acid, nickel-cadmium, and nickel-metal hydride have had a relatively small share of deployments to date, RFB is second only to LIB. The numbers displayed in the figure below only comprise operating and battery energy storage systems (BESS) under construction by 2020. The figure does not include several announced BESS projects, such as the California-based 450 MW Crimson and 300 MW Vistra Moss landing LIB-BESS projects and the South African 360 MW BESS network project that likely utilises RFB. In any case, RFB has already taken a large share and is showing a prominent trend in its deployment over the next few years.

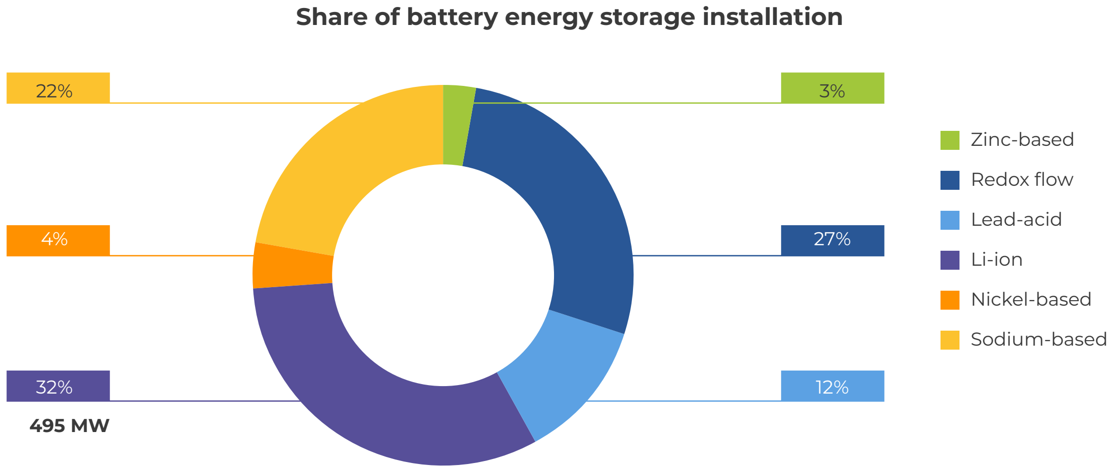


Figure 3. The global share of different battery energy storage (DOE, 2021).

Despite being classified as an electrochemical storage technology, RFB has unique yet advantageous characteristics that cannot be found in other available electrochemical storage technologies. First, the energy and power capacity of RFB can be independent or decoupled from each other, which is similar to pumped hydropower storage in some senses. In RFB and PHS systems, their energy capacity is determined by the size of the reservoirs/tanks, and their power capacity (output rating) depends on the number of turbines/reactors.

Second, instead of using immobilised solid-state energy-storing materials (like solid-state electrodes in LIB), a typical RFB uses porous electrodes. The energy-storing materials, called redox-active species or simply the electrolytes, are pumped from two separate tanks and flow through a reactor in liquid solutions, as shown in Figure 4. By having the energy materials in liquid form (i.e., negative side electrolyte/anolyte and positive side electrolyte/catholyte), rapid degradation due to stress and cracking associated with solid active (electrode) materials can be hindered, thus potentially improving the RFB's cycle lifetime. In addition, typical RFB electrolytes are non-flammable, thereby offering a high degree of safety.

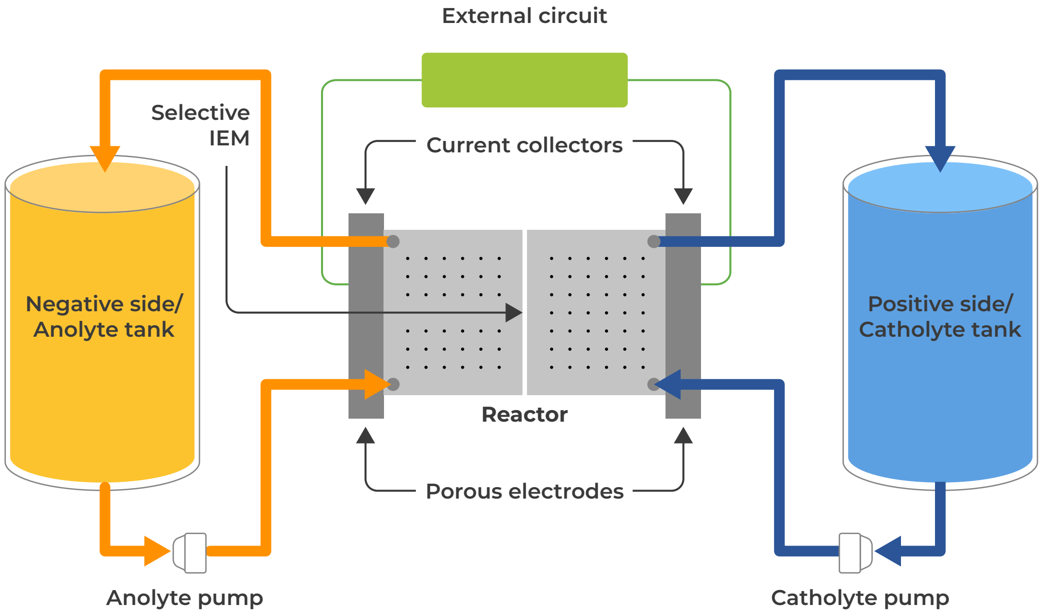


Figure 4. Typical redox flow battery configuration.

On the other hand, present-day RFB technology still possesses several drawbacks. RFB has at least 10% lower round-trip efficiency (RTE) than LIB's RTE and attains only 10% the energy density of its LIB rival (based on VRFB's 73% RTE and 25 Wh/L energy density), making it less attractive as well as a great barrier to widespread commercialisation. RFB needs extra pumps to move the anolyte and catholyte around, which is part of the reason why RFB has a low RTE. Moreover, the trade-off of using liquid active material is that the RFB system's energy density (Wh/kg or Wh/L) will be naturally low, increasing the space requirement.

2.1 RFB components

Identifying the RFB components is essential to understanding and pursuing cost-performance improvement. A unit of an RFB system is composed of these three subsystems:

1. The electrolyte flow and storage components that distinguish RFB from other batteries are electrolyte pipes, pumps, switch valves, valve actuators, and electrolyte tanks.
2. Typical battery systems power electronics, AC/DC rectifiers, electrical circuits, etc. to convert and connect electrical power.
3. Control systems: sensors for flow rates, temperatures, gas release, pH, state of charge (SOC), etc.

Apart from that, RFB's functional components are actually the electrolytes, electrodes, and ion-exchange membranes (IEM). As with other batteries, the RFB incorporates two half-cells[2] linked with a separator (membranes) in between. However, for each RFB half-cell, the negative-side (anolyte) and positive-side (catholyte) electrolytes are stored in two separate tanks. Meanwhile, the electrodes and IEM are located in the reactor where the charge-discharge reactions occur (see Figure 4).

Electrolytes: The physical and chemical properties of the electrolytes affect how well RFB works and how it is built. Ideal electrolytes should have a high concentration of active species, chemical and thermal stability, low viscosity, high ionic conductivity, be safe to use, and be accessible to be monitored (SOC). For RFB with a high energy capacity, it is best to use electrolytes with a lot of active species. Therefore, the use of a solvent, supporting electrolyte, or additive that has high solubility is critical. Also, the viscosity of the electrolytes is an important parameter because it is easier to make RFB that uses less energy when the electrolytes have a low viscosity.

[2] A half-cell is half of an electrolytic or voltaic cell, where either oxidation or reduction occurs. While the half-cell of LIB is one of the two electrodes (anode or cathode), the RFB half-cell is one of the two electrolytes (anolyte or catholyte).

Electrodes: The specific requirements of RFB electrodes are: high electro-active area, low electrical resistivity, chemical stability (in a highly acidic or alkaline environment), ability to operate at high current densities, sufficient mechanical strength, elastic modulus, and durability. In other words, they need to have good kinetics and selectivity towards the reactions of interest while preserving their integrity and stability towards the electrolyte. Each type of RFB can use different electrode materials depending on the targeted performance. Electrodes are generally classified under the following categories: (1) carbon-based or metallic composite, (2) coated or uncoated, (3) structurally 2-D or 3-D, (4) treated or untreated (thermal/chemical process), and (5) flow-by or flow-across mode (Arenas et al., 2017).

Ion Exchange Membranes: An ion exchange membrane (IEM) is a separator that allows ions to transport between the two electrolytes but at the same time blocks the mixing of the electrolytes. Its selection determines the design complexity of the reactor, costs, and lifetime of the RFB system. IEM for RFB must have a high ionic conductivity and enough ion selectivity to keep electrolytes from mixing with each other. IEM parameters like electrolyte uptake and swelling ratio are also important for a long operational life. IEM for cationic or anionic RFBs can be put into five groups: (1) pore-filled, (2) perfluorinated, (3) modified perfluorinated, (4) partially perfluorinated, and (5) non-fluorinated (Arenas et al., 2017). The perfluorinated cation-exchange membrane with the trademark name Nafion® is often used in fuel cells and RFBs, even though it is expensive. It is the most popular IEM today, with its performance being used as the benchmark for alternative IEMs.

2.2 Types of RFB

The RFB concept could be traced back as early as 1949 in a patent by Walther Kangro (Kangro, 1949). Since then, it has been studied and developed using different chemistries in the last few decades. Because vanadium-based flow batteries are so popular, other possible flow battery chemistries are often forgotten. The RFB classification helps to understand the variety of their features better. There are similarities, differences, and interrelationships among different types of RFB. Identifying RFBs forms the basis for their future development. RFBs are generally classified based on their configuration, redox couples[3], and the types of solvents, as shown in Figure 5.

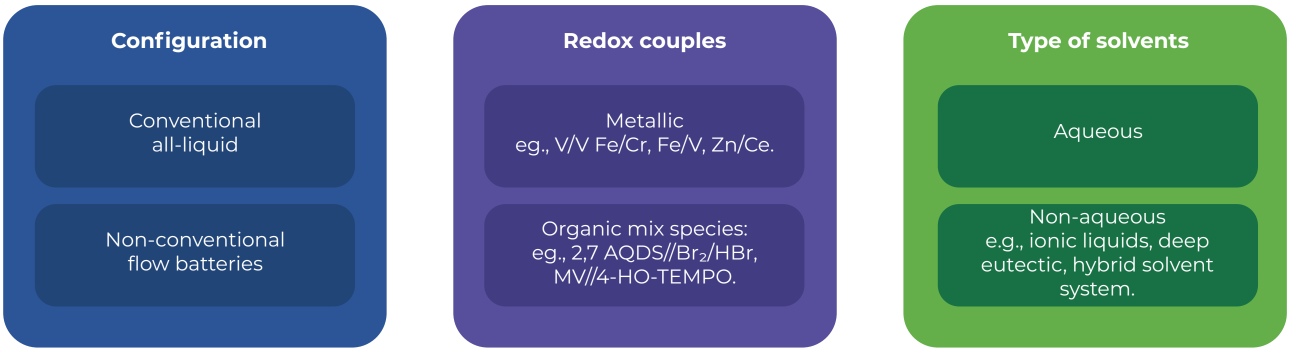


Figure 5. Different classifications of RFBs.

[3] Redox couples of RFB is a pair of compounds or elements that have both oxidised and reduced forms and take part in the oxidation or reduction reaction (during charging and discharging process) of RFB.

The configuration of RFB defines the system architecture and component material choices. The configuration can consist of a single state of electrolytes (i.e., an all-liquid state) at both charge and discharge conditions. This configuration is known as a conventional redox flow battery.

On the other hand, non-conventional configurations are flow batteries with more than one state of reactants (electrolytes before reduction or oxidation reaction) or products (electrolytes after reduction or oxidation reaction). For example, the reactants of zinc-bromine redox flow batteries (ZBRFB) are in the liquid state, but after the charging process, ZBRFB produces solid-state deposits. A zinc-air flow battery is another example. It employs a liquid state electrolyte in one half-cell and gaseous air in the other.

Another way to group RFB technologies, and the most common way, is by their redox couples. This classification was first used to find the best active materials (i.e., redox couples) with high theoretical energy density and operating voltage based on their electrochemistry. RFB can employ all-metallic redox couples such as all-vanadium, all-iron, and iron-vanadium RFBs or comprise organic-based species. Theoretically, there are vast options of redox couples that could be used in RFB. Some of them are shown in Table 1. In practical applications, the chemistries that are relevant to commercialising RFB are limited in many aspects. The following subchapter will describe four types of RFB that have the potential for large-scale commercialisation in more detail.

Table 1. RFB system types, their commonly used solvents, and corresponding properties

RFB system	Redox couples	Typical Solvents	Voltage (V)	Capacity
All-vanadium	V^{2+}/V^{3+} and VO^{2+}/VO_2^+	H_2SO_4	1.2-1.6	20–35 Wh/L
Fe-V	V^{2+}/V^{3+} and Fe^{3+}/Fe^{2+}	H_2SO_4	1.35	15–25 Wh/L
Fe-Cr	Cr^{2+}/Cr^{3+} and Fe^{3+}/Fe^{2+}	HCl	1.2	<25 Wh/L
All-iron	Fe/Fe^{2+} and Fe^{3+}/Fe^{2+}	$FeCl_2$	1.21	76 Wh/L
Zn-Br	Zn/Zn^{2+} and Br_2/Br^-	$ZnBr_2$ in excess of Br_2	1.8	60-85 Wh/kg
Zn-Ce	Zn/Zn^{2+} and Ce^{4+}/Ce^{3+}	Methane sulfonic acid	2.2	-
Polysulfide-Br	S_4^{2-}/S_2^{2-} and Br^-/Br_3-	NaOH	1.54	-
2,7-AQDS//Br_2/HBr,	AQDS/$AQDSH^-$ and Br_2/Br^-	H_2SO_4 and HBr	0.96	25.7 Wh/L

Many organic redox couples have not yet been studied, but most metallic redox couples have been looked at and used in commercial RFBs. However, it is worth noting that the practical performance of the redox couples (i.e., energy densities and voltages) is lower than their (electrochemistry) theory. The main limiting factor is the solvent used to dissolve the redox couples. Each solvent, for instance, aqueous (can be acidic, neutral, or alkaline) or non-aqueous (e.g., ionic liquids and eutectic), has its own properties such as solubility, conductivity, and chemical stability that determine the performance of RFBs. Therefore, it is important to understand the RFB class based on the type of solvents.

2.2.1 Vanadium-based (VRFB)

An all-vanadium redox flow battery (VRFB) is a conventional all-liquid flow battery using metallic redox couples dissolved in an aqueous solvent. In the 1980s, Skyllas-Kazacos and others came up with the idea for this kind of RFB (Skyllas-Kazacos et al., 1986). In VRFB, vanadium exists as a pair of redox couples in four different oxidation states in liquid solutions. The vanadium tetra and pentavalent state redox couple (VO^{2+}/VO_2^{+}) is used on the positive side (catholyte). Meanwhile, the bivalent and trivalent vanadium redox couple (V^{2+}/V^{3+}) is used on the negative side (anolyte), as shown in Figure 6.

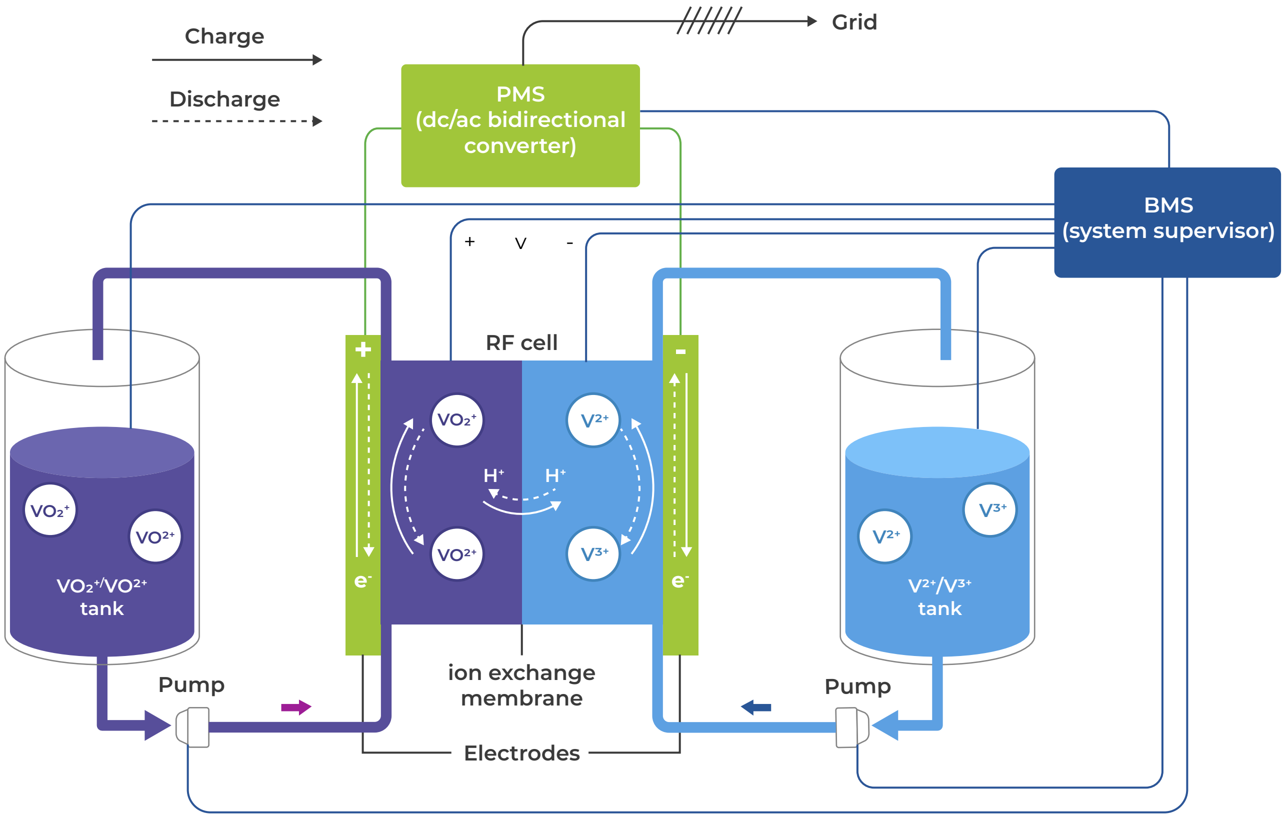


Figure 6. The illustration of all-vanadium redox flow battery system (Sánchez-Díez et al., 2021).

During the charge process, VO^{2+} on the positive side is oxidised to VO_2^{+}, causing protons to pass through the membrane while electrons (*e*-) flow through the external circuit. On the negative side, V^{3+} is reduced to V^{2+}, which is the energy-storing state of VRFB. When the energy needs to be released, the external circuit can be connected to the load, and the chemical reactions in eq. (1-3) take place. All-vanadium redox couples result in a standard output voltage of 1.26 V. But due to side effects[4], the practical voltage is around 1.4 V.

Positive side : $VO_2^{+} + 2H^{+} + e^{-} \rightleftharpoons VO^{2+} + H_2O$ $\quad E_0 = 1.00\ V\ vs.\ SHE$ (1)

Negative side : $V^{2+} \rightleftharpoons V^{3+} + e^{-}$ $\quad E_0 = -0.26\ V\ vs.\ SHE$ (2)

Overall reaction : $VO_2^{+} + V^{2+} + 2H^{+} \rightleftharpoons VO^{2+} + V^{3+} + H_2O$ $\quad E_0 = 1.26\ V\ vs.\ SHE$ (3)

[4] e.g., the Donnan potential at the membrane surface. The Donnan potential appears as a result of Donnan equilibrium, which refers to the distribution of ions between two ionic solutions separated by a semipermeable membrane or boundary (Fievet, 2015).

VRFB is a forgiving system because it uses vanadium-based redox couples in the anolyte and catholyte. When the electrolyte mixing occurs due to a damaged membrane, which is the main issue with RFBs, the VRFB system will not fail from electrolyte cross-contamination because it is possible to rebalance the system through electrolyte conditioning. For the same reason, VRFB could have cyclability over 10,000 cycles, arguably longer than any other RFB technologies.

Using all-vanadium electrolytes can be helpful for VRFB, but it also causes problems that make it hard for VRFB to be widely used. Vanadium is classified as a strategic material whose scarcity or limited supply leads to a high price volatility. The VRFB electrolytes might cost around 48% of the total system cost (Chalamala et al., 2014). Also, a typical VRFB has to use expensive Nafion membranes because the catholyte V^{5+} species are highly corrosive and rapidly oxidise, making it difficult to find membranes to work with (Wang & Fokwa, 2019).

Another issue is that the capacity of VRFB is only around 20–35 Wh/L, which is very low considering that even the traditional lead-acid battery could deliver more than 80 Wh/L of volumetric capacity. A lot of research has been conducted to get a higher VRFB capacity. One example was an attempt to substitute the sulphate solutions used in the Skyllas-Kazacos system with the sulphate−chloride mixed electrolytes, resulting in about a 70% increase in energy capacity (Li et al., 2011). Moreover, numerical modelling was also recently used to design and optimise the VRFB.

2.2.2 Zinc-bromine (ZBRFB)

A Zinc-Bromine redox flow battery is a type of RFB that has a very similar configuration to that of a VRFB (see Figure 7), except for the states of its electrolytes. ZBRFB uses a $Zn//Zn^{2+}$ redox couple in the anolyte and halogen-based $Br^{-}//Br^{2}$ in the catholyte solutions. In ZBRFB, bromine is always in dissolved (liquid) state, whereas the state of zinc is interchangeable between the charge and discharge process. The electrochemical reactions of ZBRFB are described in eq. (4-6).

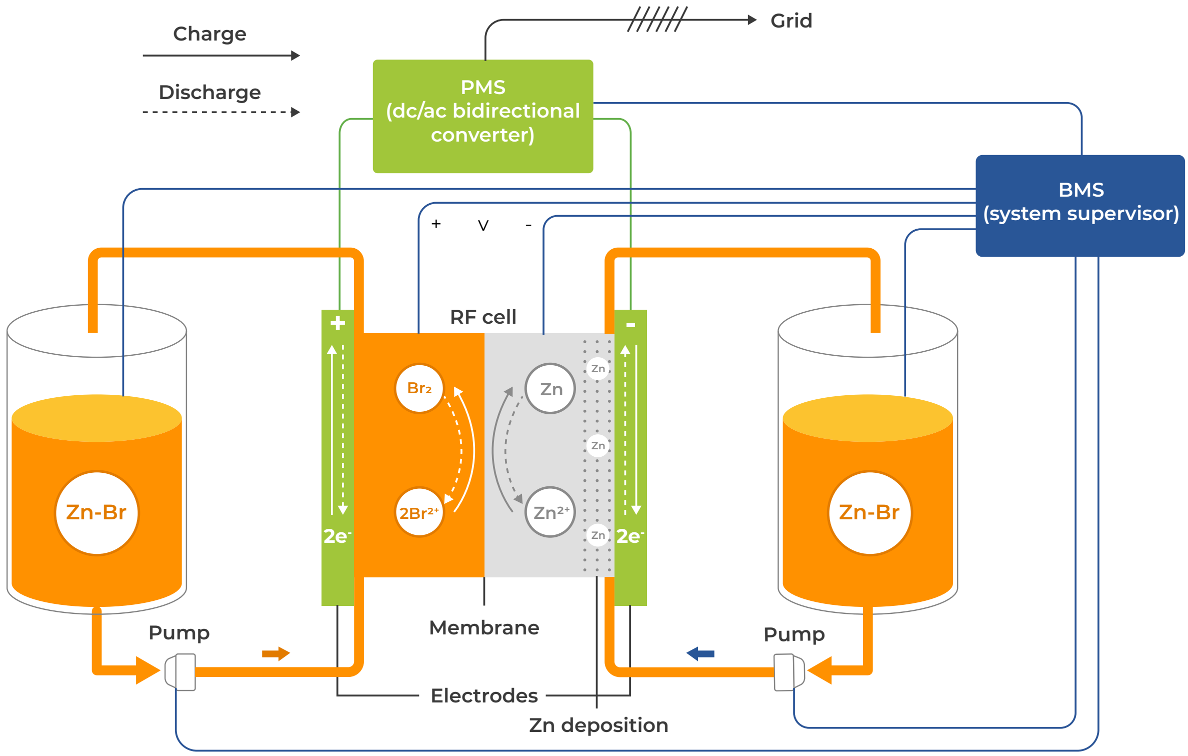


Figure 7. The illustration of zinc-bromine redox flow battery system (Sánchez-Díez et al., 2021).

Positive side	: $Br_2 + 2e^- \rightleftharpoons 2Br^-$	E_0= 1.09 *V vs. SHE*	(4)
Negative side	: $Zn^0 \rightleftharpoons Zn^{2+} + 2e^-$	E_0= -0.76 *V vs. SHE*	(5)
Overall reaction	: $Br_2^+ + Zn^0 \rightleftharpoons 2Br^- + Zn^{2+}$	E_0= 1.85 *V vs. SHE*	(6)

Solid zinc builds up on the surface of the negative electrode of a charged battery. During the discharge process, this zinc breaks down into Zn^{2+} cations through an oxidation reaction. Since more than one phase of reactant/product is involved during the charge and discharge reactions, ZBRFB is usually called a hybrid redox flow battery. ZBRFB has been commercialised since 2000. It has a standard cell voltage of 1.85 V, a specific energy of 60–85 Wh/kg (approximately 15–65 Wh/L), a lifetime of 11–14 years, and discharge durations of up to 10 hours (Sánchez-Dez et al., 2021).

Based on its relatively cheaper redox couples, ZBRFB is one of the feasible alternatives to the VRFB. But bromine on the catholyte side is a problem because it could cause electrolytes to switch places, which can damage the ZBRFB. Bromine is also toxic if inhaled, ingested, or absorbed through the skin. Consequently, an expensive complexing agent called quaternary ammonium bromide compound is needed to solve the catholyte issue, making ZBRFB less affordable than VRFB. A problem also exists on the anolyte side. Since Zn is forming solid deposits, ZBRFB requires a fully discharged process every few days to prevent the growth of Zn dendrites as it may cause ion channel blockage or damage the membrane, inducing battery failure. Researchers are trying to find ways to get around the ZBRFB limitation. For example, they are trying to replace the Br-based catholyte with an iodide halogen analog of the same kind.

2.2.3 All-iron (All-Fe RFB)

An all-iron redox flow battery was developed in 1981 by Hruska and Savinell (Hruska & Savinell, 1981). Iron is an earth-abundant, inexpensive, and non-toxic material. Iron redox couples could exist on both sides of the battery by taking advantage of the three-valence states (Fe^0, Fe^{2+}, and Fe^{3+}) of iron. Using all-iron electrolytes prevents the irreversible loss of the reactant caused by the electrolyte crossover, similar to the all-vanadium counterpart.

The All-Fe RFB has a hybrid configuration. The Fe^0 on the negative side undergoes a plating-stripping mechanism like the zinc ions of ZBRFB (see Figure 8). Meanwhile, the Fe^{2+}/Fe^{3+} redox couple on the positive side is oxidised or reduced in solution during the charge and discharge process. Complete electrochemical reactions are described in eq. (7-9).

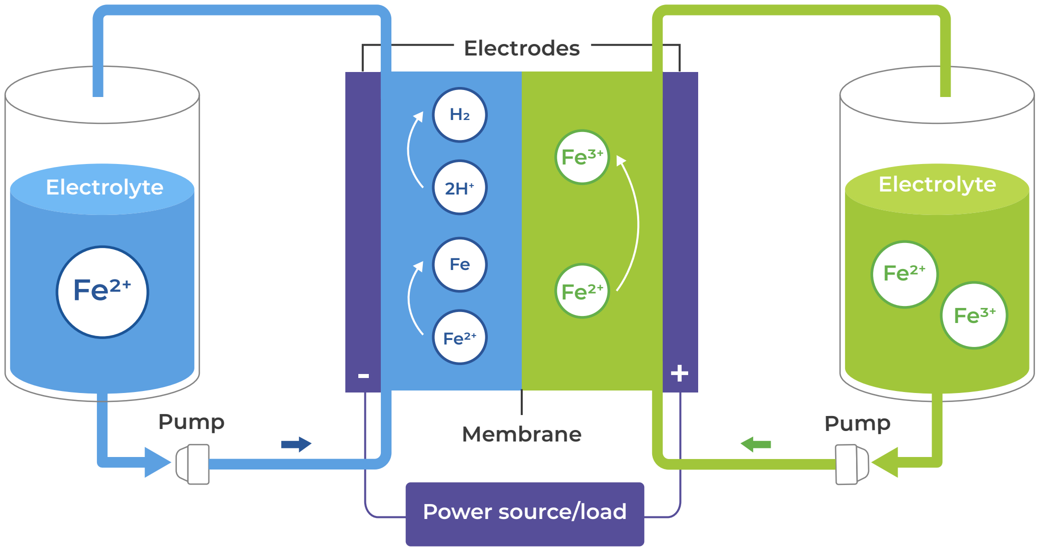


Figure 8. A redox flow battery system made of only iron (Noack et al., 2020).

Positive side $: 2FeCl_3 + 2e^- \rightleftharpoons 2FeCl_2 + 2Cl^-$ $E_0 = 0.79\ V\ vs.\ SHE$ (7)

Negative side $: Fe^0 + 2Cl^- \rightleftharpoons FeCl_2 + 2e^-$ $E_0 = -0.44\ V\ vs.\ SHE$ (8)

Overall reaction $: Fe^0 + 2FeCl_3 \rightleftharpoons 2FeCl_3$ $E_0 = 1.21\ V\ vs.\ SHE$ (9)

The electrolytes of All-Fe RFB are composed of chlorine salt with a high concentration of iron in NH_4Cl. The system has a theoretical energy density of 76 Wh/L and a cell voltage of about 1.2 V. However, the practical energy density of the battery is limited by the significant increase in electrolyte resistivity at high iron concentrations.

All-Fe RFB deployment is not as far along as the other two RFB technologies previously discussed. One of the reasons is that this battery requires daily pH maintenance to keep the acidic environment. Selverston (2017) argued that the kinetics of the electrodes and the hydrogen evolution reaction (HER) are directly affected by the pH of the electrolytes. The HER needs to be suppressed because it promotes the precipitation of the iron solid-precipitates, leading to performance degradation during All-Fe RFB operation.

2.2.4 Organic-based (ORFB)

Metal-free compounds (organics) do not require any redox-active metals, providing a potential low-cost RFB. Organics are a good alternative because they are easy to find in nature (like C, H, O, N, and S), have different structures, can be made more or less soluble, and are good for the environment.

Huskinson et al. (Huskinson et al., 2014) wrote about a popular metal-free flow battery made with 9,10-anthraquinone-2,7-disulphonic acid (AQDS). AQDS showed high solubility of over 1 M (molar) in aqueous (H_2SO_4) solvents as the anolyte. When paired with a bromine catholyte, the AQDS-Br flow battery could deliver a cell voltage of 0.86 V, an energy density of about 25.7 Wh/L, and an efficiency of about 750 cycles (Sánchez-Díez et al., 2021). The battery operates at 40 °C with Nafion 212 present as the proton-exchange membrane. Figure 9 shows how this RFB structure and the AQDS molecules change between the quinone and hydroquinone forms (protons are added or taken away) in a process called redox interconversion.

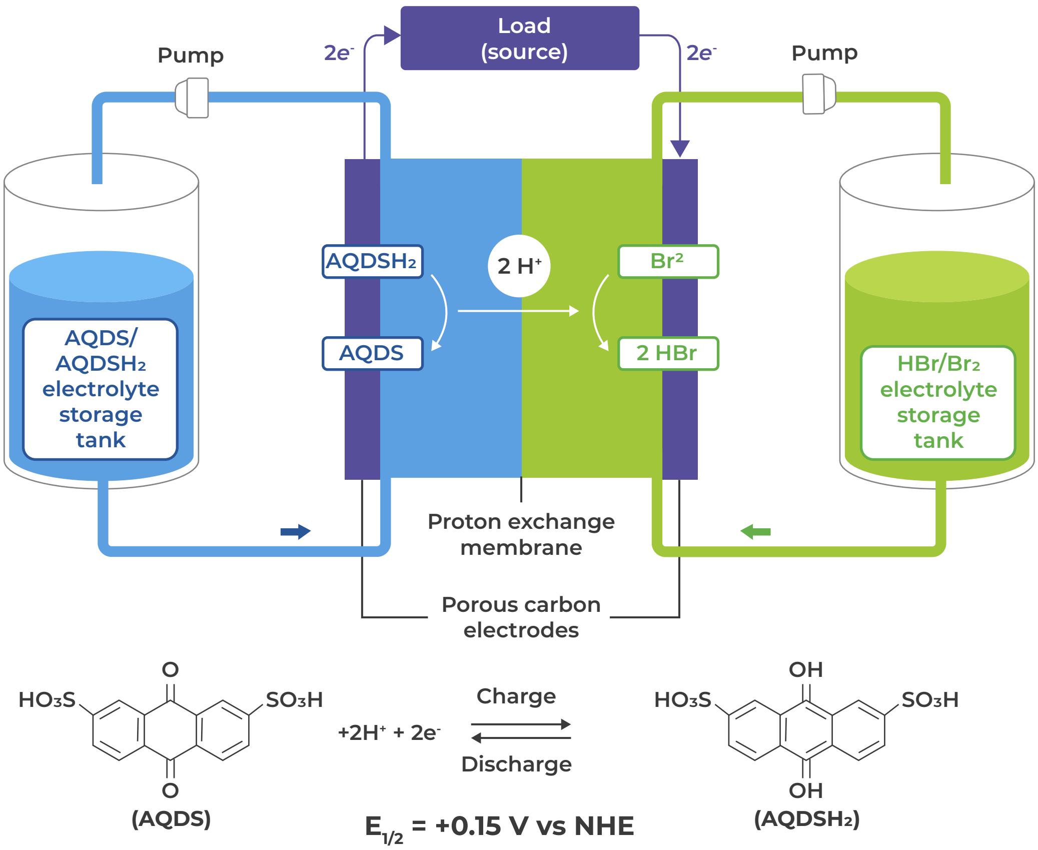


Figure 9. The illustration of the AQDS-Br organic redox flow battery system (Huskinson et al., 2014).

Even though AQDS-Br RFB works very well compared to other ORFBs, it still has a problem with the bromine crossover. An alternative for an inexpenvsive system would be ORFB based on AQDS-$FeSO_4$. However, its operating voltage at 0.62V is much lower than the metallic RFBs (above 1.2 V), leading to high power-related costs.

For ORFBs, using a solvent that does not contain water is a good idea because it could help the battery to work at a wider range of voltages. However, applying quinone-based molecules in non-aqueous systems is hindered by their poor solubility (less than 0.05 M) in most non-aqueous electrolytes. The development of such (low voltage) ORFBs aims for cost-effectiveness in terms of energy costs, particularly because their near-neutral pH allows the replacement of expensive Nafion® membranes (Sánchez-Dez et al., 2021).

For material cost-related reasons, ORFBs are prepared to replace metallic RFBs in the future. Yet, most of the organic materials that have been found so far are fragile and cannot match the long-term cyclability of metal RFBs like VRFB and ZBRFB. As there are thousands of potential organic compounds for ORFB that remain unexplored, computer-aided screening and AI-based self-driving laboratories that are capable of designing, synthesising, and characterising new materials have recently been used to identify the best organic molecules for flow battery applications (Crabtree, 2020).

Among the above-mentioned redox flow technologies, the All-Vanadium redox flow battery (VRFB) and the Zinc-Bromine flow battery (ZBRFB) are the state-of-the-art and the most widely deployed flow battery chemistries today. It should be noted that VRFB has been dominating the patent for RFBs with a share of about 50% in 2018 (IEA, 2020a). The patent number is not necessarily proportional to the current RFB deployment, but it is an early indicator of which technologies could be poised to play ground-breaking roles in the near future.

2.3 Technical parameters and competing technologies

To figure out how well RFBs could work for stationary energy storage, different technical parameters should be looked at and compared to other ESS technologies. Round-trip efficiency (RTE), energy and power density, discharge time, lifetime, response time, and maturity level are some of the technical parameters that are often used for evaluating (Kebede et al., 2022).

The following section will discuss the technical performance of state-of-the-art RFBs (VRFB and ZBRFB) and their competing technologies. LIB is represented by lithium-iron phosphates (LFP) and nickel-cobalt-manganese (NCM) types, while the PHS technology discussed in this paper is based on a scale of 100 MW power rating (large PHS). Their key technical parameters are shown in Table 2 (Mongird et al., 2019,2020; Schmidt et al., 2019).

Round Trip Efficiency (RTE) is the ratio of the net energy that is sent back to the grid (after taking into account the net energy used to charge the battery) to the net energy to charge the battery. The equipment that is needed to run the ESS, such as the power conversion system (PCS) and battery management system (BMS) in the BESS, adds to the auxiliary load. For RFBs, additional auxiliary loads such as electrolyte pumps contribute to a lower RTE of RFBs than LIB-based BESS. The internal resistance during the RFBs charge-discharge process also causes energy losses, and the quantity of losses may vary depending on the chemistry and design. From Table 2, it is clear that RFBs' RTE still needs further improvement to get to LIBs' RTE.

Response time is a measure (typically in seconds or minutes) that a system takes to change its output level from rest to rated power. Typical PHS has a response time of 20 seconds to minutes, but RFB and LIB are technically able to respond to the system in milliseconds when they are charged. However, as a system, they are limited by the standard inverter response time of 1s.

By definition, the E/P ratio is a storage system's energy capacity divided by its power rating. This number is usually given in hours. It describes the duration (hours or minutes) energy storage can work during the half cycle (also called "discharge") and still put out its rated amount of power. Most BESS in use today are made with a standard E/P ratio of 4 hours in mind. Interestingly, the flow battery technologies offer the feasibility of a longer discharge duration battery design due to its decoupled power and energy property explained earlier, which also cuts the system's power component cost.

Cycle life is the merit of RFB from having a liquid state of active materials. In a real application, however, the actual cyclability would be highly dependent on the ESS maintenance. It should be noted that the deviation on RFB cyclability value might be higher than that of more mature technologies because the technology still has less experience in real-life applications both in terms of the number and scale of deployment.

Technology readiness level (TRL) is a measure used for assessing the phase of technology development. It indicates how mature the technology is and scores on a scale of 1 (basic principle observed) to 9 (system used successfully in project operations). Meanwhile, the manufacturing readiness level (MRL) measures how mature the manufacturing of technology is on a scale of 1 (basic manufacturing issues identified) to 10 (high-rate production using efficient production practices demonstrated). According to the literature review and market situations, RFBs still have lower TRL and MRL scores compared to the competing technologies discussed, but they are expected to rise in the next few years.

Table 2. Key technical parameters of RFBs and competing technologies.

<table>
<tr><th>Parameters</th><th>VRFB</th><th>ZBRFB</th><th>LFP</th><th>NMC</th><th>PHS</th></tr>
<tr><td>System round trip efficiency (RTE) (%)</td><td>68-73</td><td><73</td><td colspan="2">86</td><td>78</td></tr>
<tr><td>Response time (seconds; PCS limit)</td><td colspan="4">1</td><td>>10</td></tr>
<tr><td>Typical E/P ratio (hours)</td><td colspan="2">1-10</td><td colspan="2">1-4</td><td>4-16</td></tr>
<tr><td>Calendar life (years)</td><td colspan="2">10-16</td><td colspan="2">10-16</td><td>50</td></tr>
<tr><td>Nameplate cycle life</td><td colspan="2">10,000-14,000</td><td colspan="2">4,000-10,000</td><td>100,000</td></tr>
<tr><td>Construction time (years)</td><td colspan="4">1</td><td>3</td></tr>
<tr><td>Typical energy range</td><td colspan="2">100 kWh to 120 MWh</td><td colspan="2"><200 MWh</td><td>Up to 40 GWh</td></tr>
<tr><td>Typical power range</td><td colspan="2">Several kW – 30 MW</td><td colspan="2">1 kW to 100 MW</td><td>Up to 3,600 MW</td></tr>
<tr><td>TRL</td><td>7</td><td>6 or 7</td><td>8</td><td>7 or 8</td><td>8</td></tr>
<tr><td>MRL</td><td>8</td><td>7 or 8</td><td>9</td><td>9</td><td>9</td></tr>
</table>

Due to their E/P ratio and response time, RFBs could be used to store grid electricity for a long time. This is based on technical parameters. But PHS is usually a better choice in the long-duration storage segment due to its maturity level and length of time. On the other hand, when the discharge time requirement is shorter (1 to 4 hours), the RTE and energy density of LIBs are still better than those of RFBs. To be the first BESS option in this category, RFBs need to improve their performance at least to the LIBs standard.

03.
State of Deployment

State of Deployment

3.1 Demonstration projects and commercialisation of flow batteries

Several RFB storage plants of various sizes and for different purposes (commercial/non-commercial; utility support/microgrids) have been installed worldwide. All-vanadium and zinc-bromine flow batteries, as discussed earlier, are the types of RFB BESS that are the readiest to deploy in real-life applications and the market. The reported capacities by 2020 were 307.56 MW and 144 MW for VRFB and ZBRFB, respectively, which made up 99.2% of the total deployed RFB capacity for BESS (DOE, 2021).

For VRFB, there are at least 27 companies/developers that actively commercialise the technology, some of them take part in projects listed in Table 3. Mitsubishi Chemical was one of the pioneers when they demonstrated a 200 kW/800 kWh VRFB circa 1996 in Japan. Another Japanese manufacturer, Sumitomo Electric, was involved in the construction of the 15 MW/60 MW Minami Hayakita RFB-based storage plant in 2013, which was commissioned in 2015 and designed for renewable capacity firming. There is also an increasing interest in deploying a smaller scale of VRFB (around 2 MW/8 MWh capacity) for microgrids applications, like the one introduced in San Diego California, in 2018. Nevertheless, among all VRFB projects, the Dalian VRB project developed by UniEnergy and Rongke Power is the most anticipated project. Once commissioned, it will become the world's largest VRFB storage plant with 200 MW/ 800 MWh capacity, showcasing buoyant flow battery technologies.

It is worth noting that at the beginning of the RFBs deployment, particularly the VRFB, the system designs used a typical BESS E/P ratio of 4 hours, although longer durations are technically possible. The developers did not explicitly explain the reason. It is assumed that at the initial stage, 4 hours-duration is set as a standard to allow flexibility in grid applications. However, longer-duration VRFB projects are now underway, indicating the technology is progressing.

Table 3. The list of deployed and announced VRFB-based battery energy storage

Project name	Location	Developer	Rated output/ energy capacity	Description
Kashima-Kita	Japan	Mitsubishi Chemicals	200 kW / 800 kWh	Pioneering VRFB deployment in 1996 for Load-leveling purpose.
Minami Hayakita Substation	Hokkaido, Japan	HEPCO and Sumitomo Electric Industry	15 MW / 60 MWh	Commissioned in 2015, and currently operational for renewables capacity firming
RedoxWind	Pfinztal, Germany	Fraunhofer Institute	2 MW / 8 MWh	Constructed in 2016 with 20 MWh capacity at the final stage of development; Operational and integrated wind turbines.
Dalian VFB	Liaoning, China	UniEnergy Technologies and Rongke Power	200 MW / 800 MWh	Under construction since 2016
San Diego microgrid	California, USA	San Diego Gas & Electric (SDG&E) and Sumitomo Electric	2 MW / 8 MWh	Commissioned in 2018, Microgrid operates to power 66 residential and commercial customers

Project name	Location	Developer	Rated output/ energy capacity	Description
ESKOM battery network	South Africa	Consortium include Bushveld Energy and foreign flow battery manufacturers	Part of 360 MW / 1440 MWh	First phase (350 MW) already tendered, and (513 MW) new tenders announced.
Pangea Storage Project	Port Augusta, Australia	Cellcube and Pangea Energy	50 MW / 200 MWh	Letter of Intent signed in 2019
Green Valley Energy Storage Project	California, USA	Concentric Power Inc	16 MW / 128 MWh	Announced by California energy supplier Central Coast Community Energy (CCCE) in 2021 with estimated operational date of 2026
Bodega Energy Storage Project			10 MW / 80 MWh	
Rava Mesa			6 MW / 18 MWh	

a)

b)

Figure 10. a) Rongke power manufacturing facility and b) Electrolyte tanks of VRFB in Fraunhofer Institute.

In the case of other RFB types, ZBRFB was pursued by ZBB Energy, which manufactured a 2 MW/2 MWh system in 2004 and commissioned it in 2007 for PG&E California substation upgrade. Meanwhile, Redflow Ltd. and Primus Power, founded respectively in 2005 and 2009, are producing ZBRFB energy pods. An energy pod is a small-scale battery unit (between 10 kW and 50 kW power output) that has a modular architecture that allows the integration of multiple pods into a single output. So far, their biggest project is a 600 kW system for a California institution that is made up of sixteen 50 kW energy pod modules.

In addition to the two main RFB technologies, the All-Fe RFB type has gotten a lot of attention and is said to be the best alternative to the expensive VRFB. All-Fe RFB has been realised at the commercial level by ESSinc and Electric Fuel®. ESSinc has also produced the scaled-up (in discharge duration time) All-Fe RFB, launching a 50 kW/400 kWh (8-hour duration) prototype (ESS Inc., 2018). On the other hand, Electric Fuel® has demonstration milestones of a 10 kW pilot plant in 2016 and a 100 kW field demonstration in 2017 (Electric Fuel, 2015). The company planned a move to the MW level towards 2020, but there is no update regarding the realisation.

The Network of Flow Battery Research Initiatives (FLORES) found 41 known flow battery manufacturers that were still in business in 2021. Interestingly, as shown in Figure 11, ORFB ranked second in the number of manufacturers, including RFB companies such as Kemiwatt (France), Jena Batteries (Germany), CMBlu

(Germany), and Green Energy Storage (EU). Although these companies barely have any portfolio to date, ORFB developers are expected to be the key players in the future due to the advantage of ORFB's low material outlay.

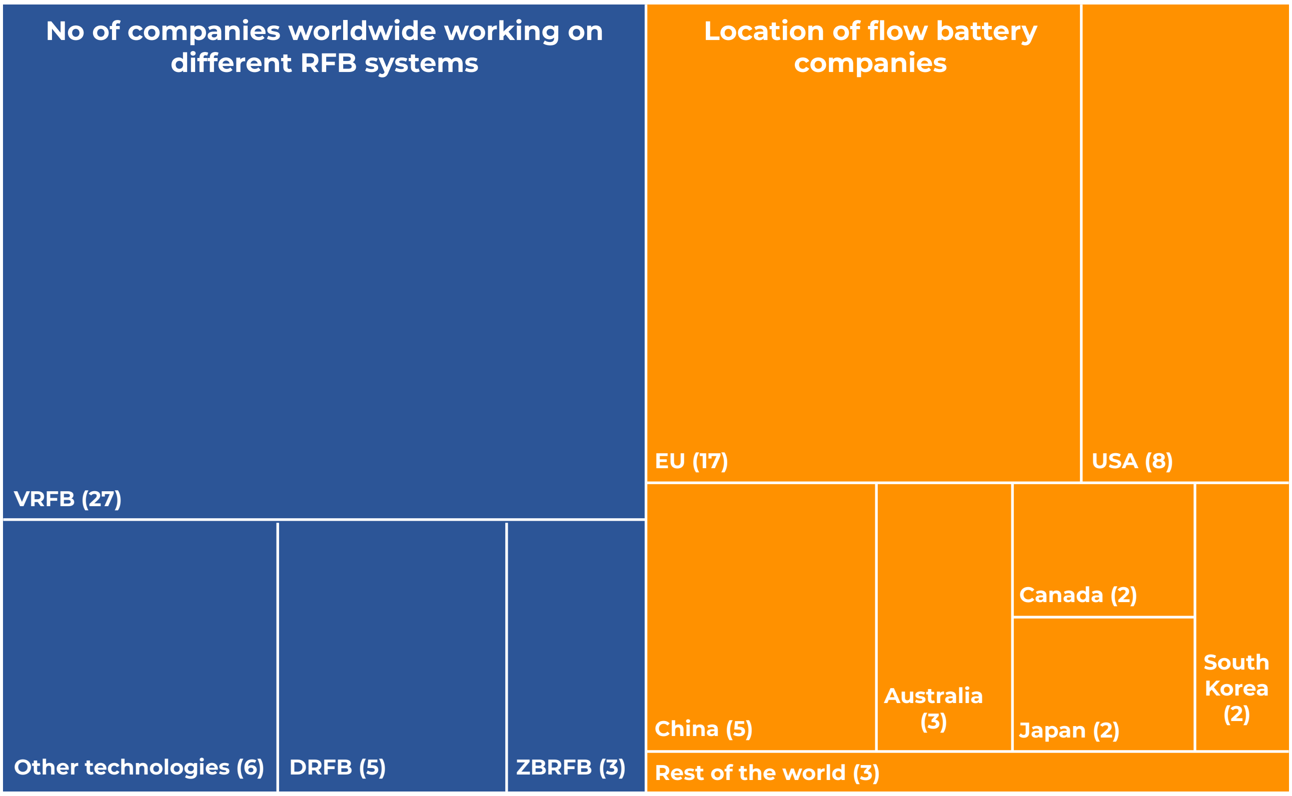


Figure 11. The number of RFB developers and their location (Network of Flow Battery Research Initiatives (FLORES), 2021).

3.2 Deployment challenges

Some successful demonstrations of RFB projects have led to an increasing demand for new RFB-based BESS installations. RFB developers, especially those who make VRFBs, now have to deal with a new problem related to the supply chain. In the meantime, the technology of other flow batteries like ZBRFB, All-Fe RFB, and ORFB has not yet caught up to that of VRFB, which makes people worry about how long they can be used.

Historically speaking, global vanadium demand has been driven by global steel production, with approximately 91% of vanadium production in 2020 consumed by the steel industry (Bushveld Minerals, 2021a). But the widespread use of VRFB would change the demand for vanadium, which is a reflection of the current state of the market for lithium raw materials. Despite being the 20th most abundant element, vanadium resources are native and mined in limited countries, namely China, Russia, and South Africa. A demand shock for VRFB could result in a lag in supply and increases in vanadium prices.

In fact, vanadium pentoxide (V_2O_5) for the VRFB electrolyte precursor has shown price volatility over the past few years, as displayed in Figure 12. The V_2O_5 price was low in 2020 (around $6/lb) due to market inactivity during the COVID-19 pandemic, but has once more seen an increasing price trend since 2021, reaching $12.4/lb by March 2022. The precursor price fluctuation makes a large-scale VRFB plant a high-risk project, as V_2O_5 could contribute to 43% of the total system cost (Viswanathan et al., 2014). The 200 MW/800 MWh Dalian VFB project, announced in 2016, is one example. The first phase of construction

(100MW/400MWh) was expected to be completed in 2020, but there has been no report found to date confirming the realisation. The project developer likely had to stop the electrolyte assembly during the price spikes of V_2O_5 between 2018 and 2019 when it was around $30/lb. The consensus is that a VRFB project is only viable and competitive against its rival (i.e., LIB) when the V_2O_5 price is less than $10/lb (Gillam, 2020).

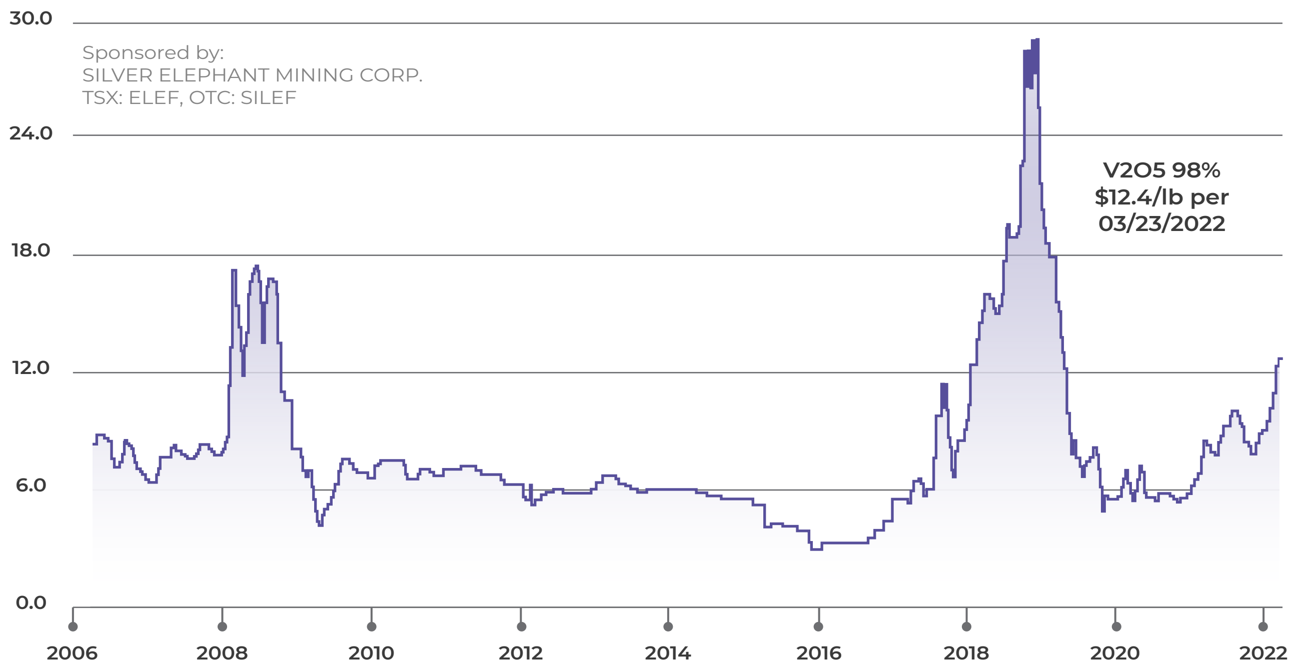


Figure 12. Historical price of vanadium pentoxide from 2006 to 2022 (vanadiumprice.com, 2022).

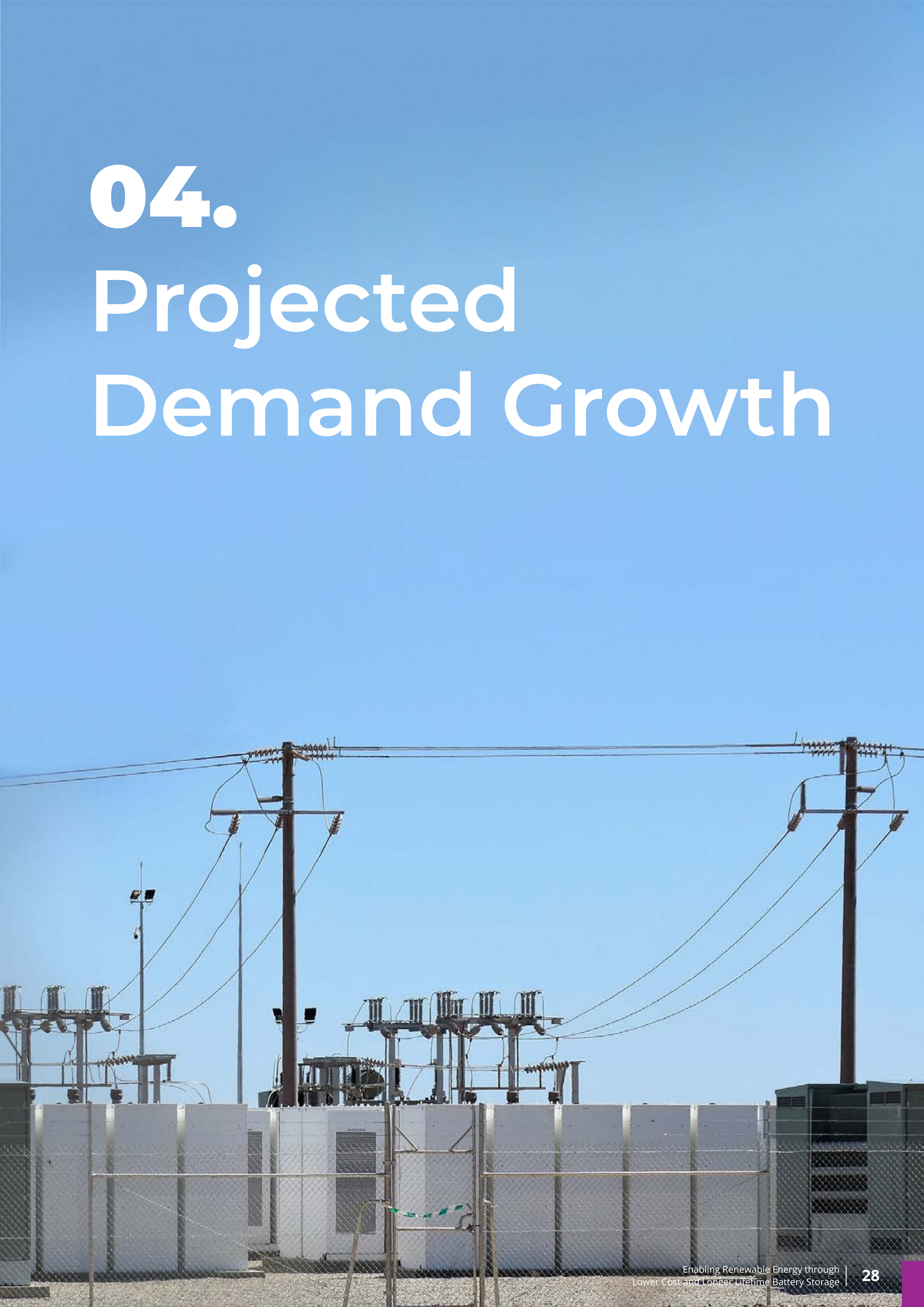
When it comes to other RFB technologies, project funding seems to be the biggest challenge for ZBRFB growth. A ZBRFB company called ViZn Energy (founded in 2009) was struggling to find sources of funding, leading to staff layoffs in 2018 (Deign, 2018). However, with the global REs boom as well as VRFB's material price volatility, the interest in ZBRFB has been rejuvenated. The ZBRFB deployment is now being led by the Australian Redflow company, which reported AU$1.2 million (US$867,000) revenue in six months by December 2021 (Sadauskas, 2022). Founded in 2005, Redflow is doing well because it focuses on the small-scale ZBRFB segments and has enough investors. However, while Redflow is expanding to the US market, there is a question about whether ZBRFB can compete with its LIB rival to become BESS market leader. In Australia itself, BESS new projects are still being dominated by LIB. The steady march of LIB's lower costs, which has been catalysed by the growing EV industry, is one of the factors that could hamper the growth of Redflow.

Similar to ZBRFB, All-Fe RFB deployment also needs a strong capital investment. While expecting revenue in Q1 2022, an iron flow battery market leader called ESSinc (founded in 2011) recently revealed a $477 million net loss in 2021 due to the revaluation of warrant, derivative, and earn-out liabilities, as well as operating losses (Murray, 2022).

ORFB, on the other hand, is a new RFB that currently does not have a portfolio to retrieve funding, which slows down its deployment. ORFB is concerned about the difficulty of matching the performance advancements made by matured RFB technologies (e.g., VRFB). In the industry, the RFB choices would mirror the continued dominance of the first-generation solar PV, where mature technologies are preferred even though the ORFB could be a cheaper option.

In addition to the materials supply chain, the amount of money invested, and specific RFB issues, the level of RFB deployment would depend on whether or not there were domestic regulatory frameworks. Table 3 shows that California has a high level of BESS deployment, which should be affected by the energy storage procurement mandate adopted by the California Public Utilities Commission (CPUC) in 2013 and followed by four assembly bills to streamline the market and speed up storage uptake (The Climate Group, 2017). One of the bills was aimed at resolving interconnection disputes (between public utilities and distributed generations), which is the key (especially for developers) to increasing the BESS value. Generally, there is no special regulation applied to RFB that is distinct from other BESS. The growth of RFB would be much faster if applicable regulation that supports long-duration and colocation BESS was implemented. Unfortunately, many countries, including Indonesia, still do not have clear rules and guidelines for BESS and RFBs.

04.
Projected Demand Growth



Projected Demand Growth

Along with the increasing share of renewable energy, the RFB-BESS capacity has been growing in the last few years. The growth is attributed to the attractive intrinsic features of RFBs, such as power-energy decoupling ability, scalability, a relatively high level of safety, and a long cycle life. According to the US DOE (see Figure 13), the global cumulative power capacity of RFB plants grew from 15.2 MW in 2010 to 427.4 MW in 2020. Meanwhile, their energy capacity increased by about 36 times within ten years (DOE, 2021). Also, BNEF thinks that RFB energy capacity could grow up to 69 GWh, which is 46% of the total 150 GWh of BESS capacity that will be needed in 2030 (Frith, 2020). This means that RFB will be in competition with LIB.

Despite LIB domination in the energy storage market today, RFB technologies have become a popular choice for utility-scale BESS applications because they last a long time and can be discharged for a long time. Technically, RFB is good for long-duration BESS because the power-energy decoupling property makes it possible to increase the energy capacity. Moreover, RFB has shown an increasing cumulative E/P ratio from 2.9-hours in 2010 to 3.8-hours in 2020, in contrast to the E/P ratio trend of its LIB counterpart (from 2.8-hours to 1.75 hours)[5], which indicates the growing demand for RFB in long-duration BESS applications.

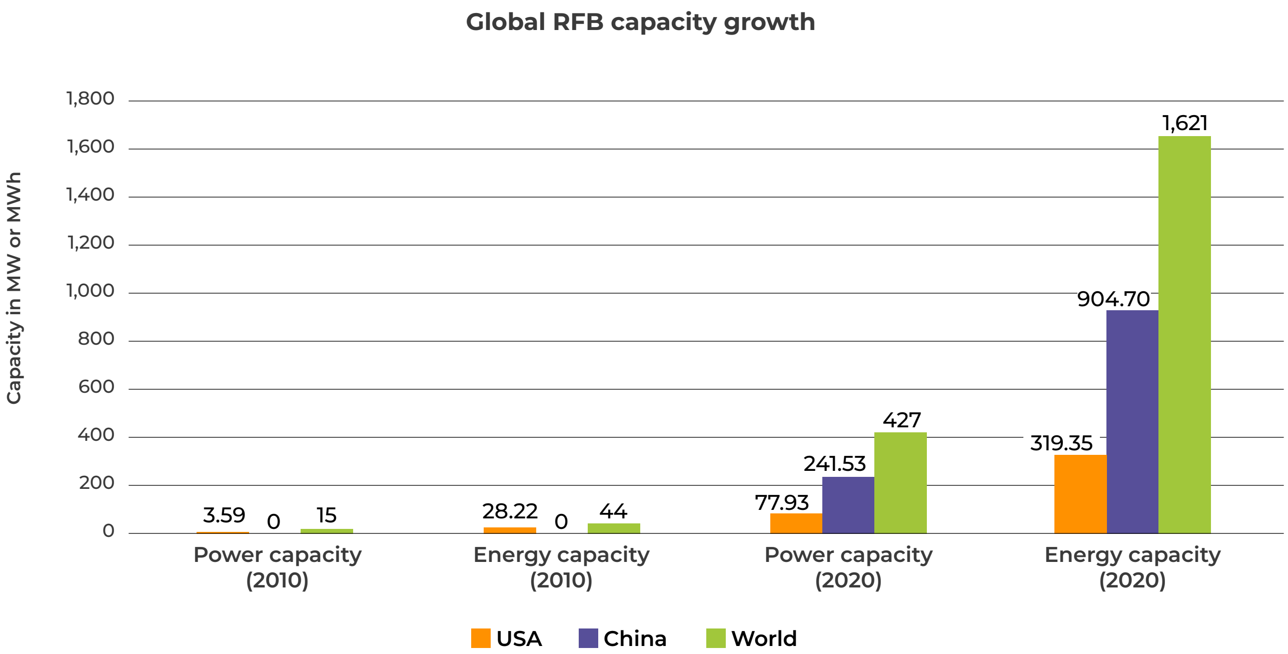


Figure 13. Global cumulative RFB's power and energy capacity growth (DOE, 2021).

Based on the different market forecasts for RFB listed in Table 4, RFB could have a compound annual growth rate (CAGR) of more than 9%, which is a good sign for the RFB market. It is mainly due to the high RFB demands, particularly for utility-scale projects. Corresponding reports also predicted that the Asia-Pacific (APAC) region could have the largest RFB market, which is reasonable considering many governments in this region have declared their ambition to accelerate the use of renewable energy and mandated ESS utilisation, potentially boosting the RFB market. Meanwhile, among various RFB types, VRFB is expected to dominate the RFB market share.

[5] Between 2015 and 2017, DOE recorded global LIBs power capacity addition higher than the energy capacity, which means cumulative E/P ratio <1 hour. The trend was likely driven by the increased demand for LIB for short-duration BESS for electricity grid stability applications (e.g., primary and secondary responses).

In the VRFB supply chain, Chinese vanadium producers are expecting the rise of vanadium pentoxide production to at least 9,100 tonnes V_2O_5 equivalent in 2022 from 3,640 tonnes in 2021 to support new energy storage projects (Argus, 2021). Moreover, one of the world's biggest vanadium producers, South African Bushveld Minerals, has even formed a subsidiary company focusing on VRFB development and anchored the vanadium supply for the battery market (Bushveld Minerals, 2021b).

Table 4. The list of RFB market forecasts.

Forecasted period	CAGR	Largest market	Dominant technology	Major end-user	References
2022-2027	9.6%	Asia Pacific	VRFB	-	Mordor Intelligence
2021–2026	18%	Asia Pacific	Hybrid RFB	Utilities, telcomunication tower	MarketsandMarkets
2021-2026	13%	-	-	-	imarch
2019-2026	13.5%	Asia Pacific	VRFB	Utilities	Research Dive
2019-2026	15.2%	Asia Pacific	VRFB	Utilities	Allied Market Research

05. Application-specific Cost Projections

Application-specific Cost Projections

Energy storage systems (ESS) have been used for a variety of applications and services because they can play different roles in the chain of how electricity is delivered. Each application has different technical needs that will affect how long the ESS will last and how much it will cost. Proper cost estimations of ESS are challenging, mainly because of the diversity of technologies, each with different cost and performance characteristics. The industry's claims on cost estimation often lack transparency in their methodology, while academic studies are usually limited to a specific selection of storage applications. To fill this gap, the cost estimation of RFBs in a few different applications will be discussed in this chapter.

Table 5 describes ESS applications and their technical requirements/parameters that are relevant to RFBs. Identification of parameters is a necessity to ensure the optimal techno-economic and cost-benefit analysis. It should be noted that several ESS applications are excluded from the discussion, considering those applications are served better by other ESS technologies. For instance, RFBs can be used as the electricity grid's primary response due to their fast response time. However, this kind of application requires up to 15,000 annual cycles, so it is suitable for short-duration storage technologies with a much higher cyclability, such as flywheels and supercapacitors (Schmidt et al., 2019). The following section will compare the cost of RFBs with their competing technologies based on the application-specific levelized cost of storage (LCOS).

Table 5. Several relevant applications of RFBs (Schmidt et al., 2019)

Application	Description	System size (MW)	Annual cycle (#cycle/year)	Discharge duration (hours)	Response time (seconds)
Secondary response	Correct anticipated and unexpected imbalances between load and generation	10-2,000	20-10,500	0.25-24	>10^2
Peaker replacement	Ensure availability of sufficient generation capacity during peak demand periods	1-500	5-100	2-6	>10^5
Energy arbitrage	Purchase power in low-price and sell in high-price periods on wholesale or retail market	0.001-2,000	50-400	1-24	>10^5
Power reliability	Cover temporal lack of variable supply and provide power during Blackouts	0.001-10	50-400	2-12	>10^1

5.1 Levelized cost of storage (LCOS)

To decide whether a generation technology has economic feasibility, a levelized cost of energy (LCOE) is generally used to calculate the cost of a cumulative (watt, kilowatt, or megawatt) delivered electricity. In the case of energy storage, the levelized cost of storage (LCOS) is instead used as the indicator. Both values are based on similar factors, such as capital expenditure (CAPEX), operational expenditure (OPEX), and the net annual energy output. Additionally, there is the cost of investment. Instead of the discount rate, a Weighted Average Cost of Capital (WACC) is used in this report to capture the financing cost in the calculation. Most of the time, the WACC is calculated by asking stakeholders about the value of debt, the cost of debt, and the value of equity. It can be calculated by averaging the interest of debt and the expected return of the equity investors proportionately with the shares of debt and equity in the capital.

CAPEX, often described as an investment cost, is a key parameter in calculating the LCOS. There is not a standard way to name things, so investment costs do not always include the same things. In this report, CAPEX includes the costs of energy and power, the balance of system (BOS), system integration, engineering, procurement, and construction (EPC), and project development. While a single variable operational and maintenance (O&M) cost value is applied to each technology, the fixed O&M cost values vary depending on the scale and type of ESS. In particular, RFBs have slightly higher fixed O&M cost assumptions than LIB with equivalent scale due to the limited project experience as well as "growing pains" associated with emerging technology.

Another important parameter to calculate LCOS is the annual net energy output, whose value is derived from ESS technical parameters, such as RTE, Depth of Discharge (DOD), E/P ratio, and number of cycles per year. ESS financial data from the Pacific Northwest National Laboratory (PNNL) reports in 2020 (with producer price index and 2021 US dollars value) is used as the basis of LCOS calculation in this paper, with additional parameters captured from LCOS-related journals. The calculated CAPEX and OPEX values may differ from the actual values due to the rapid changes in the ESS market, but the values presented in this report are still representative of the current market situation.

5.2 LCOS on a case-by-case basis

Before evaluating the application-specific LCOS, the parameter extraction process should take several things into account. For financial parameters, the values should be up-to-date and appropriate for where this LCOS is used. For example, the vanadium material cost that takes a large share in the capital cost is potentially cheaper in countries where the vanadium domestic supply chain does exist (e.g., China and South Africa). Meanwhile, EPC costs could be lower in the area with a high BESS penetration level and project experience. On the other hand, figuring out the technical parameters is easier because everyone agrees on what they are.

Due to the limited project experience and information on the supply chain in Indonesia, the financial parameters (CAPEX and OPEX) values used in this paper are extracted from the global RFB projected cost. The references from which the parameters were obtained are provided in the IESR LCOS calculator tool. The cost of investment is taken into account in all of the calculations in this paper by using 8% of WACC as a fixed parameter. On the other hand, excluding the energy trade cases where 3 cents/kWh charging cost is applied, the electricity/fuel cost to charge the ESS is assumed to be free because the expected energy comes from REs surplus. Furthermore, instead of using the technology's calendar life, a 'corresponding cycle life' is used to depict the real-life ESS lifetime based on specific applications, which is obtained by dividing the respective ESS technology's cycling capability at specific DoD by the annual cycle requirement of a specific application.

Case 1: Secondary response

The characteristic requirements of secondary response ESS are frequent cycles and short discharge duration. Secondary response service does not require a fast-responding ESS, and PHS use is actually possible for this application. However, a typical PHS is built on a large scale to maximise site availability and decrease the EPC-related investment costs. Therefore, it is not suitable for Case 1 shown in Figure 14, where the plant size is limited to a smaller scale of 10 MW/20 MWh.

With a limited ESS size of 10 MW/20 MWh, the E/P ratio of 2 hours is the shortest among cases presented in this study. Moreover, the 1,000 annual cycle assumption was selected and should be an appropriate value for secondary response purposes. For services with frequent cycles, a high DoD parameter is important because it directly affects the amount of ESS electricity output, lowering the LCOS. RFBs benefit from having the capability of high DoD (90%), as it theoretically will not influence their cyclability. On the contrary, their competitors (i.e., LIBs) have to limit their DoD to <80% to optimise their cycling capability.

Case 1:

- 10MW/40 MWh system
- Response time around or <100s
- Interest/WACC rate 8%
- 0 Charging cost (VRE surplus)
- 1,000 cycle/year
- E/P ratio 2h
- DoD: 90% (RFBs) and 80% (LIBs)
- Corresponding cycle life:
  - 8.3 years (RFBs)
  - 6.3 years (LIBs)

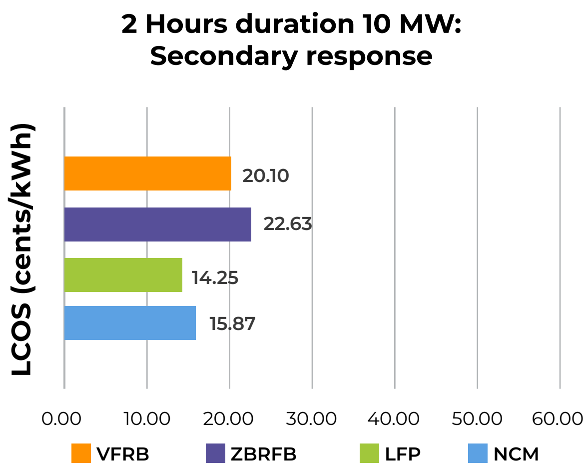


Figure 14. Case 1 LCOS of RFB for secondary response application.

By using the assumptions in Figure 14, for secondary response application, the LFP type LIB apparently has the lowest LCOS with 14.25 cents/kWh, followed by NCM type LIB and VRFB. The critical LCOS driver is their RTE, which is very sensitive in high-frequency ESS applications. RFBs are suffering because of their lower RTE (73% vs. LIBs with 86%).

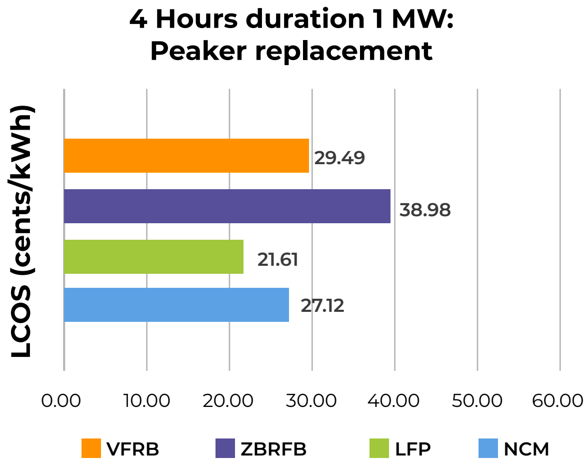
Case 2 and 3: Peaker replacement

The typical annual cycle requirement for ESS as a peaker replacement is less than 100 cycles (Akhil et al., 2013; Schmidt et al., 2019) because peaker power plants in four-season countries (commonly gas turbine facilities) are switched on only during hot summer days to compensate for an escalating load peak over the baseload. However, this study used the 350 annual cycle parameter to simulate a broader utilisation of RFBs as a peaker replacement, particularly to solve the VRE intermittency without relying on the grid's baseload electricity supply. RFB with a low 4-hour E/P ratio is suitable for this application because the daily surplus of VRE electricity is only available for a short time, resulting in limited charging time. RFB systems with this ratio also have the versatility to be deployed for different services as it has been used as a standard and the most commonly used design for RFB deployment (see Table 3).

Two different scales of RFBs, 1 MW/4 MWh in case 2 and 100 MW/400 MWh in case 3, were used to calculate the LCOS for this 4-hour duration application. Scale in case 3 allowed the comparison of RFBs' LCOS with PHS technology. Based on assumptions in Figure 15, the LCOS of VRFB is 29.49 and 25.58 cents/kWh in Case 2 and Case 3. It is common sense that scaling up the RFB system size would drive down project costs. There is around 13% LCOS reduction from scaling up the VRFB plant from 1 MW to a 100 MW rating.

Case 2:

- 1 MW/4 MWh system
- Unspecific response time requirement
- Interest/WACC rate 8%
- 0 Charging cost (VRE surplus)
- 350 cycle/year
- E/P ratio 4h
- DoD: 90% (RFBs) and 80% (LIBs)
- Corresponding cycle life:
  - 16 years (RFBs)
  - 16 years (LIBs)
  - 13 years (NCM)



Case 3:

- 100 MW/400 MWh system
- Unspecific response time requirement
- Interest/WACC rate 8%
- 0 Charging cost (VRE surplus)
- 350 cycle/year
- E/P ratio 4h
- DoD: 90% (RFBs and PHS) and 80% (LIBs)
- Corresponding cycle life:
  - 16 years (RFBs)
  - 16 years (LIBs)
  - 13 years (NCM)
  - 50 years (PHS)

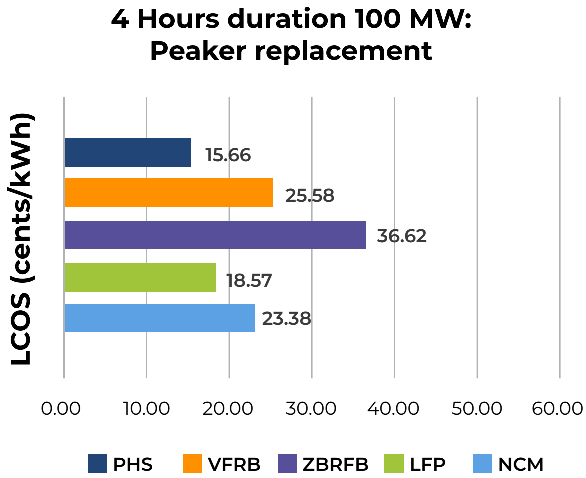


Figure 15. Case 2&3 LCOS of RFB as a peaker replacement.

Compared to its rivals, however, the LCOS value of VRFB is still higher than that of LIB in both cases. Furthermore, in case 3, PHS (100 MW/ 400 MWh) has the lowest at 15.66 cents/kWh. The corresponding cycle life of PHS, which is 2-3 times longer than the batteries, is the main driver of PHS's low LCOS.

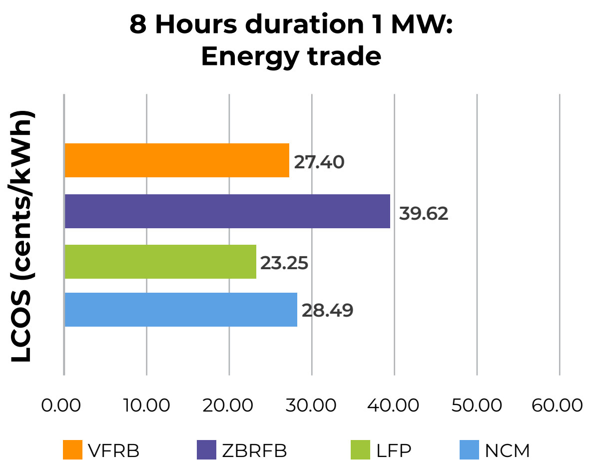
Case 4 and 5: Energy trade

The parameters of energy trade application are identical to those of energy arbitrage described in Table 5. The main characteristics are flexible plant size (1 to 24-hour E/P ratio) and the presence of fuel or charging expenses. However, energy arbitrage has a defined mechanism of purchasing electricity during off-peak periods, storing it in the ESS, and selling it during peak periods when prices are higher. Since this mechanism is not applicable in Indonesia, which has flat electricity tariffs, a stand-alone ESS needs power purchase agreements (PPAs) similar to power generators for the energy trade application. ESS for energy trade also requires interconnection to one or more power generators that supply electricity to the ESS.

In this application, RFB-based ESS should benefit from its long-duration discharge capability (E/P ratio >4 hours). Two cases were used to examine the RFB LCOS for an energy trade application. Figure 16 shows the LCOS of RFBs with 8 and 10 hours of duration. Both cases suggest that VRFB is the best RFB option for this application. VRFB has LCOS of 27.4 and 23.54 cents/kWh in Case 4 and Case 5, respectively. The LCOSs of VRFB are competitive with NCM type LIB in 8-hour and 10-hour durations (case 4 & 5), but not as good as LFP type LIB and PHS. VRFB could only catch up with them when it has cheaper electrolytes and improved efficiency.

Case 4:

- 1 MW/8 MWh system
- Unspecific response time requirement
- Interest/WACC rate 8%
- Charging cost: 3 USDc
- 350 cycle/year
- E/P ratio 8h
- DoD: 90% (RFBs) and 80% (LIBs)
- Corresponding cycle life:
  - 16 years (RFBs)
  - 16 years (LIBs)
  - 13 years (NCM)



Case 5:

- 100 MW/1,000 MWh system
- Unspecific response time requirement
- Interest/WACC rate 8%
- Charging cost: 3 USDc
- 350 cycle/year
- E/P ratio 10h
- DoD: 90% (RFBs and PHS) and 80% (LIBs)
- Corresponding cycle life:
  - 16 years (RFBs)
  - 16 years (LIBs)
  - 13 years (NCM)
  - 50 years (PHS)

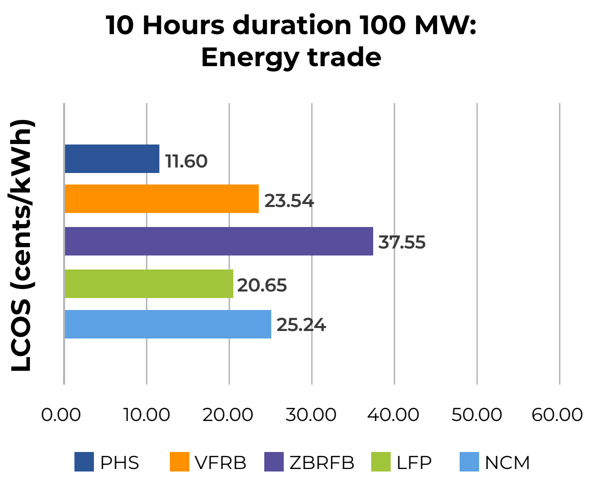


Figure 16. Case 4 & 5 LCOS of RFB for energy trade application.

Case 6: Power Reliability

Around the world, utilities have started to mandate the adoption of ESS to address the needs of the recently evolving electrical power grid (towards renewables). The power reliability described here refers to the role of ESS in mitigating short-duration (<24 hours) outages of the electricity grid. The ESS for this application should be able to fill the electricity demand when the grid runs out of generation. For this reason, RFB could be a suitable option for the purpose of power reliability because it is a fast-shifting source of electricity that can operate for a long enough duration until the primary resource returns.

To simulate the use of RFBs for the microgrid power-reliability application, a 1 MW/10 MWh (10-hour duration) system should be a proper model because it would sufficiently maintain the microgrid supply at night, or when a solar PV, for example, struggles to meet the load demand during a cloudy day. The assumptions for RFBs' LCOS calculation for power reliability applications are shown in Figure 17. The results indicate that VRFB has the lowest LCOS at 21.12 cents/kWh. However, compared to the electricity generation cost of baseload power generators, the VRFB LCOS value is still exceptionally high. A further reduction should target the VRFB LCOS to be less than 20 cents/kWh, which is the LCOE of diesel reciprocating engines (Lazard, 2017). Also, it is worth noting that despite being technically feasible, the real-life deployment of VRFB with a 10-hours duration design is currently rare. From all the aforementioned

Case 6:

- 1 MW / 10 MWh system
- Response time around or <10s
- Interest/WACC rate 8%
- 0 Charging cost (VRE surplus)
- 365 cycle/year
- E/P ratio 10h
- DoD: 90% (RFBs) and 80% (LIBs)
- Corresponding cycle life:
  - 16 years (RFBs)
  - 16 years (LIBs)
  - 13 years (NCM)

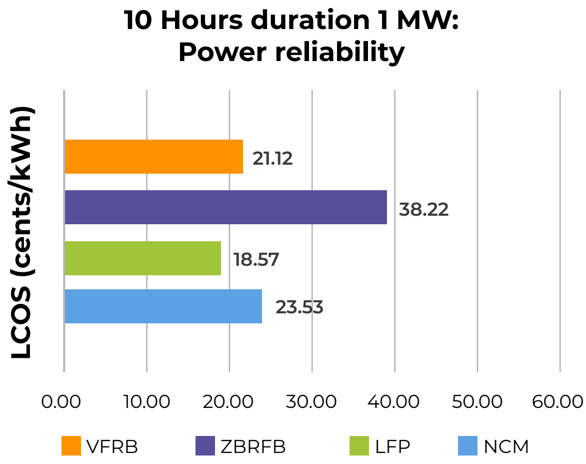


Figure 17. Case 6 LCOS of RFB for Power Reliability Application.

case studies, it appears that VRFB is a more feasible RFB type than ZBRFB. However, compared to other BESS options (LIBs), VRFB employment should only be considered for ESS applications requiring a discharge duration of longer than 8 hours, such as energy trade and power reliability applications. Even though the LCOS of VRFB can be lower than NCM type in 8-hour and 10-hour durations energy trade application (case 4 & 5), LFP type LIB is still a cheaper BESS option. Meanwhile, with LCOS at 21.12 cents/kWh in power reliability applications, the VRFB is still expensive and needs further cost reduction to make it economically viable for VRE support purposes.

06. Potential Deployment in Indonesia

Potential Deployment in Indonesia

6.1 Deployment plan and current status

The Indonesian government, through MoEMR regulation No.16/2020, has identified the need for BESS to support the electricity grid. The BESS integration has also been included in the VRE development strategy of the state utility company (PLN). According to PLN's RUPTL, VRE combined with ESS (hybrid system) is expected to replace conventional baseload power generators in order to achieve the country's 23% renewable energy target by 2025 (PLN, 2021). The latest RUPTL does not specifically mention the preferred BESS technology for the hybrid system, but PLN has expressed an interest in RFB in the media (Bisnis.com, 2022; PLN, 2022), which is the main reason for assessing the RFB potential.

According to the RUPTL, BESS in a hybrid system is required for frequency regulation and firming capacity service purposes. The RFB indeed has the technical capability to meet the requirements of both services. However, it should be noted that the two services have very different characteristics, mainly in terms of duration. Based on LCOS analyses in Chapter 5, VRFB type RFB could be one of the cheapest BESS options for long duration (>8 hours) applications, but it is currently not a relevant option for shorter duration applications.

Moreover, there is limited experience in the technology and previous failures of the deployment of RFBs in Indonesia. The only documented attempt was conducted in 2011 when the Agency for the Assessment and Application of Technology (BPPT) initiated a microgrid demo project called smart micro-grid (SMG) Sumba in the Southwest Sumba Regency. The SMG integrated 500 kWp PV with the 2 x 135 kVA diesel generator and a 400 kW/500 kWh VRFB-based ESS with a configuration displayed in Figure 18. It was inaugurated in 2012 and had been evaluated for two years. From the evaluation, it was found that due to some issues with the VRFB subsystem (damaged components), the SMG could not perform at the optimum level. The evaluation report also suggested that the VRFB could not be utilised appropriately without sufficient electricity generators (to charge the battery) (A. Prastawa et al., 2013; Akhmad et al., 2017).

Furthermore, Prai Witu, a microgrid-powered village in Sumba Regency, has experienced an electricity system collapse due to battery failure (Bloomberg Green, 2022). The failure occurred just months after the battery was commissioned, despite the initial guarantee of ten years of operation. There is no detailed information on the type and specification of the battery. However, the Fluidic Energy battery provider likely used the Zinc-air battery, which is a type of hybrid flow battery. The degradation in this type of battery is often associated with dendritic problems and issues with its alkaline-based electrolyte, which is prone to corrosion and leakage. The latter is possibly the case in Prai Witu. While the dendrite issues can be prevented by regular discharge procedures, controlling the electrolyte could be more difficult. Nevertheless, well-monitoring of the battery performance should help in the early detection of degradation before ultimately damaging the system.

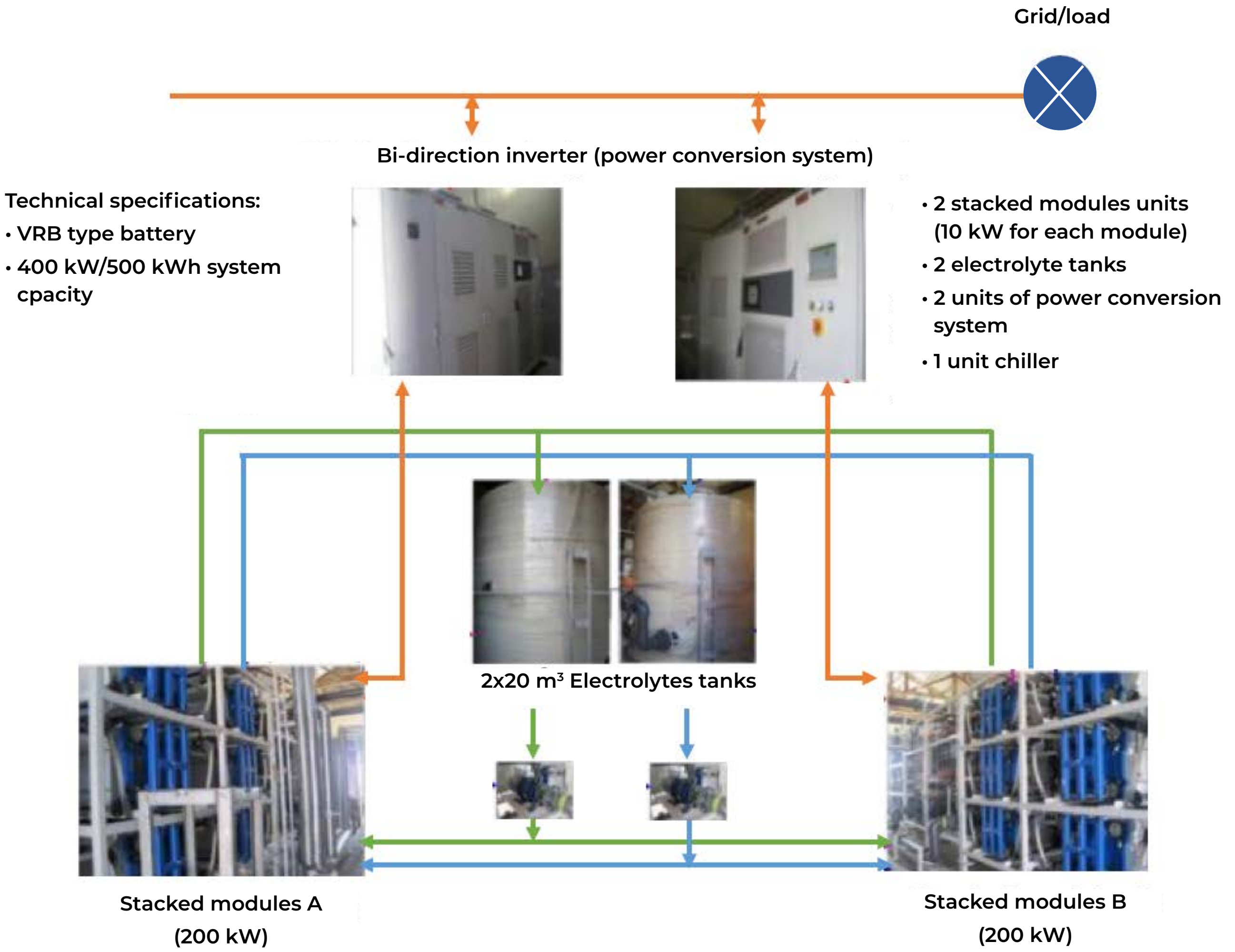


Figure 18. The VRFB-based ESS configuration system in the SMG Sumba demo project is reproduced from (A. Prastawa et al., 2013).

6.2 Opportunities and challenges

In 2019, diesel engine generators contributed to around 4.15% of Indonesia's total electricity production, which was equivalent to the consumption of 2.16 billion litres of oil. To reduce the reliance on oil commodities and accelerate renewable energy utilisation, PLN, through its latest RUPTL, has declared the intention to convert diesel generators to renewables (PLN, 2021). While the diesel generators will be converted as a backup electricity source, the VRE primary sources will be coupled with the BESS to ensure their reliability. In this regard, the number of BESS installations is expected to grow within the next few years.

Currently, there are about 5200 online units of diesel engine generators in 2,130 locations in Indonesia, which translates into the potential of converting roughly 1.2 GW of fossil-fired power plants into clean energy sources. The first phase of the program will target the conversion in 200 locations with a total capacity of around 225 MW. If BESS is included in the converted system design, depending on system and plant site characteristics, there is a need for several BESS deployments on a small to medium scale <10 MW (correspond to the capacity of diesel generators in the conversion program).

Electrochemical batteries are the best candidate for small to medium-scale ESS needed in the diesel generators conversion program because they have the scalability characteristic to meet different system size requirements. Among RFB technologies, the most mature technology that is currently ready to be adopted is the vanadium-based RFB (VRFB), which has had a project cost decline in the last few years. The PNNL studies, for example, indicate the total project cost for 4-hours duration RFB has declined from around $3,430/kW in 2018 to $2404/kW in 2020 (Mongird et al., 2019,2020). However, this change has not really made RFB an appropriate choice for BESS.

The results of the LCOS calculation in Chapter 5 show that in various applications, VRFB, which represents the RFB technologies, still has a relatively high LCOS. As shown in Figure 19, the LCOSs of VRFB in various applications are still higher than 20 cents/kWh. In particular, for power reliability type applications, which is what BESS uses in the diesel conversion program, the present component costs result in a high LCOS value of 21.12 cents/kWh. To be economically viable, the total RFB and VRE electricity must be competitive to electricity from coal plants. In Indonesia's context, the total electricity cost must be less than 8 cents/kWh. Assuming the solar PV costs around 3 cents/kWh, the VRFB storage requires around a 76% cost reduction from the current cost.

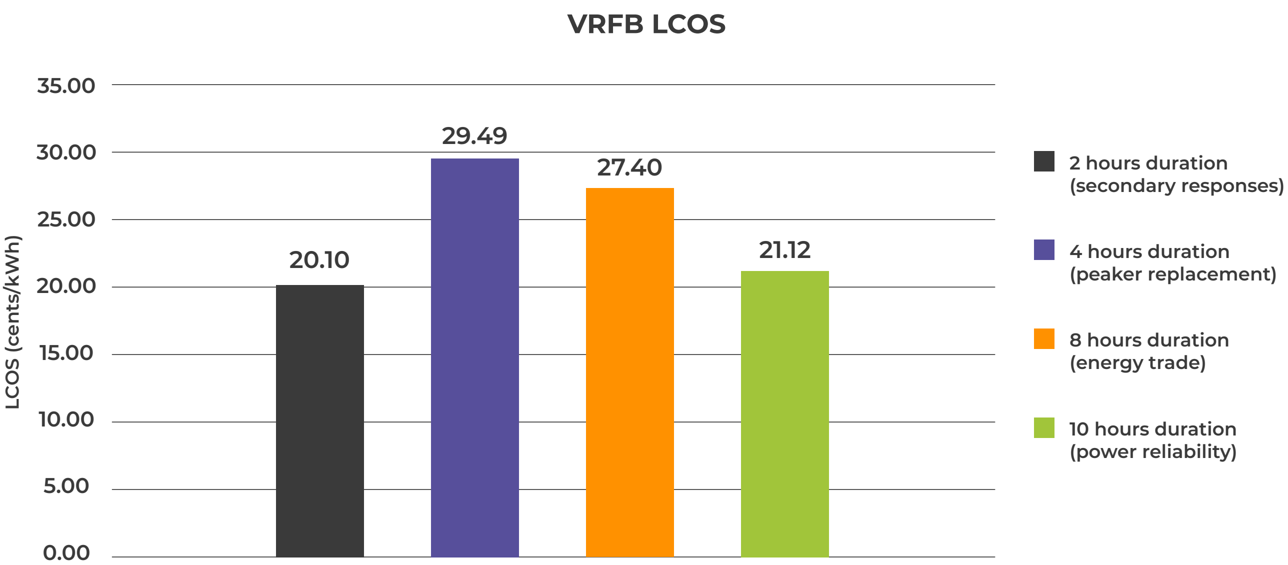


Figure 19. VRFB LCOS in various sizes and applications based on calculation in Chapter 5.

A study on the cost-optimal VRE mix with storage suggests that to provide baseload electricity at 10 cents/kWh, ESS capacity (component) costs must reach approximately $30–70/kWh (Ziegler et al., 2019). However, the amount of vanadium pentoxide (V_2O_5) precursor needed for a kWh VRFB storage capacity is approximately 16 lb, which translates into around $160/kWh (when V_2O_5 price at $10/lb) cost contribution to the total capacity component costs. Therefore, the capacity component cost target of less than $70/kWh seems unlikely to be achieved. Indeed, there are several alternative flow battery technologies for vanadium-based RFB that also have the potential to become cheaper options, as mentioned in Chapter 2. However, the deployment of these technologies also has various challenges, and their maturity has not reached the VRFB level.

Apart from the high cost of components and limited supply chain, the technical aspects of VRFB, such as its efficiency, may require further optimisation. The advantage of VRFB's long life is also not yet proven. The VRFB has unique characteristics, and its system comprises components that are distinct from the renowned batteries (e.g., lead-acid and LIBs). The unfamiliarity may lead to the negligence of control and monitoring duties, potentially shortening the expected lifetime of VRFB. Thus, before adopting the VRFB-type BESS on a large scale, feasibility studies and trials specific to Indonesian conditions (e.g., load profiles, renewables variability, meteorology, etc.) are required to evaluate and gain operational experience. An example of a preliminary feasibility study through simulation is shown in Figure 20.

In adopting ESS technology, consideration should not only be focused on the financial aspects but also on technological maturity. In the context of the PLN's diesel generator conversion program, the reliability of the generator replacement systems based on VRE+BESS (hybrid system) needs to be ensured, especially with the hybrid system planned to be deployed in isolated areas where the inability to meet the demand load (due to ESS issue) has the potential to cause higher losses.

For broader use of flow battery technology in Indonesia, for example, as a prerequisite storage technology for stand-alone PV installations, supporting regulations will likely have to be prepared to allow flow battery technology adoption. The storage (battery) component in stand-alone PV has a 40% local content requirement (LCR) according to MoI regulation No. 4/2017. Meanwhile, neither regulation nor incentive has been specifically applied for the deployment of RFB BESS.

The LCR policy has been dubbed as one of the major hurdles discouraging the development of renewable energy projects in Indonesia, which may relate to RFB deployment. Although it could decrease technology costs in the long term through domestic supply chain establishment, LCR policy is often seen as the cause of increase in project costs, which is a burden to RE developers. Given that the main RFB components (e.g., electrolytes and membranes) supply chain and industry are unavailable, it would be challenging to fulfil the aforementioned LCR policy.

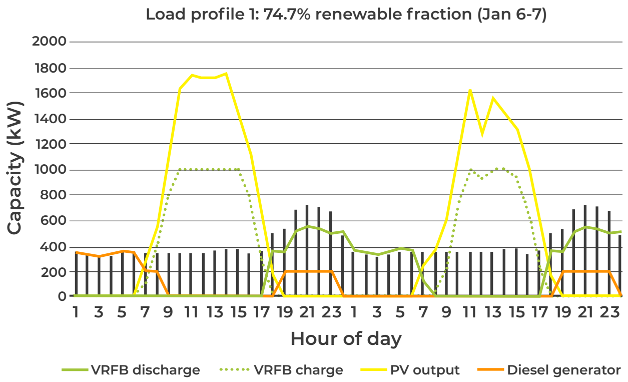
An example of a preliminary (simulation) feasibility study

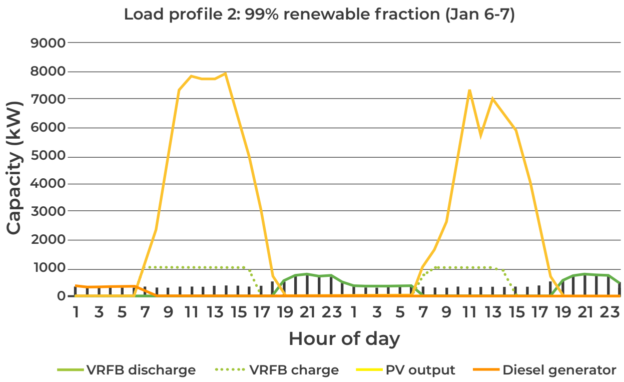
Parameters:

- Discount rate : 8%
- Location : Kupang, Nusa Tenggara Timur
- Project time : 25 years
- Average load : 10,128 kWh/day
- Peak load : 720 kW
- Load factor : 0.59
- Diesel engine CAPEX : $800/kW and $0 in hybrid system
- PV spesification : Generic flat plat; CAPEX: $790/kW; CF:18%; 25 years lifetime
- PCS : Cost $300/kW; 15 years lifetime; 95% efficiency

[Optimized simulation results of VFRB integrated hybrid system microgrid and comparison with LIB]

Diesel engine size (kW)	Diesel price ($/L)	PV size (kW)	Type of BESS (discharge duration)	BESS capacity (kWh)	RE fraction (%)	CO2 emission (kg/year)	LCOE (cents/ kWh)	Notes
800	0.05		REFERENCE NEW DIESEL ENGINE			2,591,676	14.8	
800	1		REFERENCE NEW DIESEL ENGINE			2,591,676	29.6	
800	0.45	2,263	Autosize VRFB (10 hours)	10,000	74.7	698,905	22.9	a,c,e
800	0.45	10,129	Autosize VRFB (10 hours)	10,000	99	25,685	39.2	b,c,e
800	0.45	2,184	Commercial LIB (4.2 hours)	10,080	78	603,173	22.3	a,d,f,g
800	0.45	10,129	Commercial LIB (4.2 hours)	10,080	99.5	14,529	39	b,d,f,g





a. Optimized result of hybrid system with RE fraction >70%
b. Optimized result of hybrid system with RE fraction >99%
c. Storage size is not sufficient to obtain a 100% RE fraction.
d. Storage size is sufficient to obtain a 100% RE fraction with the lowest LCOE at 49.3 cents/kWh.
e. The financial parameters of the 10-hours-duration VRFB in chapter 5 (case 6) are used to calculate the hybrid system's LCOE.
f. HOMER PRO software used for simulation does not provide a 10-hours-duration LIB; the 4-hours-duration LFP financial parameters are used to calculate the hybrid system's LCOE.
g. If available, the CAPEX of a longer duration LIB would be lower than that of 4 hours due to the retraction of the power components cost (/kW) and the decrease of energy components cost (/kWh)

Figure 20. Hypothetical preliminary (simulation) feasibility study of PV+BESS+diesel generator hybrid system in Indonesia.

07.
Conclusion

Conclusion

In general, redox flow battery technologies have several characteristics that are suitable for stationary energy storage, especially their scalability and long cycle life features. Their power-energy decoupling property also enables their superiority in long-duration storage applications. However, their deployment penetration will not be significant without substantial technical improvement and adequate project experience. Also, the cost of RFB components is still relatively high compared to other alternative technologies. On a cost-performance basis, RFB is suitable for BESS applications with a discharge duration longer than 8 hours. Based on our study, large-scale RFB deployments are currently a high-risk investment despite their promising growth projections. It is mainly due to technology maturity and supply chain limitations. Therefore, a cautious feasibility analysis involving site-specific grid conditions should be conducted before making the investment decision.

Key Findings

RFB technologies have met several criteria for stationary storage applications, such as scalability, high cyclability, and fast response time. However, efforts to improve their capacity, efficiency, and cost reduction are still needed.

Compared to LIBs, the RFBs system and design offer the possibility of a longer discharge duration and greater cyclability while sacrificing efficiency and energy density. The latter two are critical RFB technical parameters that are still inferior to the LIBs and need to be improved.

All-vanadium redox and zinc-bromine flow batteries (VRFB and ZBRFB) are the state-of-the-art and the most widely deployed flow battery chemistries today. Meanwhile, all-iron and organic-based RFBs have the potential to replace them due to projected declining material costs.

Based on our LCOS calculations, VRFB could only be a relevant BESS option for applications that require a discharge duration longer than 8 hours, such as small-scale (<100 MW) energy trade and power reliability applications. Meanwhile, there are other storage technologies with a lower LCOS suited better to applications with a duration of less than 8 hours (LIBs) and large-scale applications (PHS).

In Indonesia, experience with RFB projects is very limited, yet the known projects ended up falling short. The application-specific cost calculation results also suggest that RFB BESS technology is still expensive. With the claim that RFB's durability has also not been proven, hasty decision-making to deploy RFB BESS could potentially result in huge financial losses.

Recommendation

1

In-depth pilot projects and feasibility studies are required. Given the fact that BESS technologies are still evolving, selecting a type of BESS technology should be based on more than just price and performance to meet the needs of the application. It is essential to examine the level of maturity and suitability for BESS uses. According to the findings of the IESR, the RFB still needs to be improved from a technical standpoint, and its performance, as well as its long-term viability, has not been tested in Indonesia. In this regard, as a potential adopter, PT PLN, the Ministry of Energy and Mineral Resources (MEMR), and the National Research and Innovation Agency (BRIN) should assess the feasibility of RFB BESS through proof-of-concept pilot projects in several locations in Indonesia. Learning aspects would include but not be limited to the construction process and procurement of RFB components, performance evaluation, as well as maintenance and troubleshooting procedures. A successful demonstration's protocol can be used as a guide for future RFB developers. Indonesia, on the other hand, must seek out other, more mature BESS technologies as a result of the unsatisfactory results.

2

Application specific cost projections. Because each application has its own requirements (i.e., duration, cycle frequency, minimum capacity, etc.), projecting the cost of RFB should always be application-specific. Because battery companies often present only the best possible LCOS value, this exercise is necessary to avoid cost overruns. LCOS is extremely sensitive in the case of BESS because it has parameters such as DoD, cycle count, and charging cost, which vary depending on grid conditions.

3

Preparing policy support schemes for the deployment of storage technologies and integration with renewables. As pilot projects are being implemented, the Ministry of Energy and Mineral Resources (MEMR) can start preparing policies and regulations to support the utilisation of energy storage applications for both utility-scale use and behind the metre applications, as well as integrate them into the long-term electricity plans that fall under the jurisdiction of the Ministry. This policy could attract energy storage technology developers to test their products in Indonesia, including RFBs.

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