NORTH AMERICAN VERTICALLY-INTEGRATED SUPPLY CHAIN AND MANUFACTURING FOR MEDIUM-DURATION VANADIUM REDOX FLOW BATTERIES

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Abstract

The topic of this paper is the strategic value of a North American vertically-integrated supply chain and manufacturing for vanadium redox flow batteries ("VRFB"), particularly with respect to the greatest cost item in their bill of materials, vanadium electrolyte. Vanadium electrolyte typically constitutes 30% to 40% of the cost for VRFB systems, for example $150/kWh of a $500/kWh installed system cost for a 10MW VRFB with 4-hour discharge duration.[1]

With a U.S. national deployment potential of 100+GW of stationary energy storage systems ("ESS") with a 4–12-hour discharge duration for diurnal capacity and energy time shifting,[2] and VRFB as a medium-duration energy storage technology being well-suited technically to provide such "energy shifting," the total available market for VRFB in the U.S. could be as large as $600B including $180B for vanadium electrolyte.[3]

Currently, the supply chain and manufacturing of VRFB relies on material and component sources and production facilities outside of North America, sometimes in "unfriendly" countries. Therefore, there is a pressing need to build up the North America supply chain and manufacturing for VRFB. This is the case for key VRFB components such as vanadium electrolyte, cell stacks, and fit-for-purpose DC power electronics, pumps, tanks, and AC inverters.

In this paper, the focus will be on the supply chain and manufacturing of vanadium electrolyte, with its cost predominating in the VRFB bill of materials. The U.S. Department of Energy ("DOE") has identified the production of vanadium electrolyte as a "critical" manufacturing scale-up challenge under the DOE's "*Energy Storage Grand Challenge Roadmap*."[4]

As a foundation for the discussion of the supply chain and manufacturing of vanadium electrolyte, the paper will first provide a sizing of the ESS market through 2030, globally and in the U.S. Second, the significant need for "energy shifting" by ESS in the U.S. is explored and linked to the product category of medium-duration ESS. Third, the paper will provide a brief overview of VRFB systems and their attributes. Finally, the paper will survey the opportunities for the development of a North American supply chain and manufacturing of vanadium electrolyte, including an overview of the global production of vanadium

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[1] "*2022 Grid Energy Storage Technology Cost and Performance Assessment*," Viswanathan, Mongrid, Franks, Li, Sprenkle, Baxter, Pacific Northwest National Laboratory Technical Report, Publication No. PNNL-33283, August 2022, p. 36; "*2019 Energy Storage Pricing Survey*," Baxter, Sandia National Laboratories Report, SAND2021-0831, January 2021, p. 51.

[2] "*The Four Phases of Storage Deployment: A Framework for the Expanding Role of Storage in the U.S. Power System*," Denholm, Cole, Frazier, Podkaminer, Blair, National Renewable Energy Laboratory, NREL/TP-6A20-77480, January 2021, p. vii.

[3] 100,000,000kW x 12 hours x $500/kWh = $600,000,000,000; 100,000,000kW x 12 hours x $150/kWh = $180,000,000,000.

[4] "*Energy Storage Grand Challenge Roadmap*," U.S. Department of Energy, Research Technology Investment Committee, Energy Storage Subcommittee, DOE/PA-0022, December 2020, p. 39.

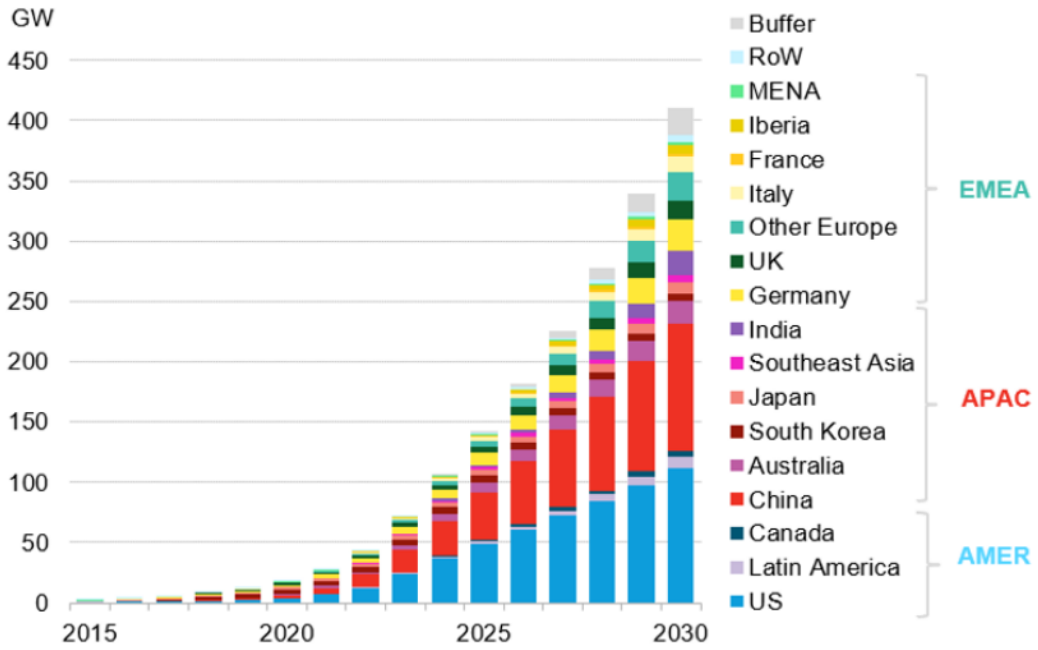
(primary, co-production, and secondary) and a review of current vanadium electrolyte producers in the U.S. The paper will conclude by drawing on the known initiatives of the current producers to quantify the opportunity for vanadium electrolyte production in the U.S, which is a potential 80B liters.

Overview of Stationary Energy Storage Market, Globally and the U.S.

At the end of 2021, 27GW/56GWh of ESS was online globally. An estimated 16GW/35GWh was added to the global ESS online in 2022, with 28GW/69GWh projected to be added in 2023. By 2030, BloombergNEF forecasts that a total of 411GW/1,194 GWh of ESS will be online around the world. In the period 2022-2030, then, the amount of ESS online is expected to increase 15x from a power (MW) perspective.[5]

It is noteworthy the 2022-2030 time period of these forecasts of ESS online globally is the same time period utilized by the DOE in setting its Energy Storage Grand Challenge of a levelized cost of storage ("LCOS") of $0.05/kWh for "long-duration" (10 hours discharge duration and longer) storage. This is a 90% reduction from 2020 baseline costs.[6] The 90% reduction may be somewhat less daunting when viewed from the perspective that online ESS is projected to increase by 1,500% in the same time period.

Segmenting the ESS market by country/region, the two largest markets for ESS will be the U.S. and China. BloombergNEF forecasts that each will have over 100 GW of ESS online by 2030.[7] See **Figure 1**:



Source: BloombergNEF. Note: "MENA" refers to the Middle East and North Africa; "RoW" refers to the rest of the world. "Buffer" represents markets and use cases that BNEF is unable to forecast due to lack of visibility.

Figure 1: BloombergNEF, "*Global cumulative energy storage installations, 2015-2030*"

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[5] "*Global Energy Storage Market to Grow 15-Fold by 2030*," BloombergNEF, Oct. 12, 2022; "*Top 10 Energy Storage Trends in 2023*," BloombergNEF, Jan. 11, 2023.

[6] "*Energy Storage Grand Challenge Roadmap*," U.S. Department of Energy website, Dec. 21, 2020 (accessed Mar. 19, 2023).

[7] "*Global Energy Storage Market to Grow 15-Fold by 2030*," supra.

Focusing on the U.S. market for ESS, in 2022 the U.S. had approximately 5GW/12GWh of ESS capacity. By 2026, that is forecast to grow to 64.6 GW/194 GWh. Throughout that 2022-2026 time period, grid-scale ESS is projected to be 80% of the U.S. market.[8] See **Figure 2**:

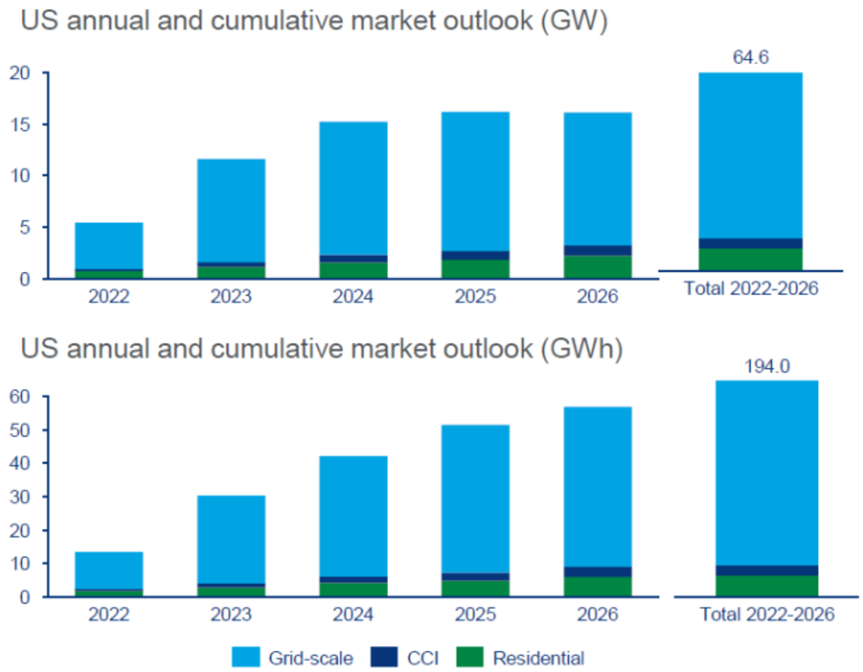

Figure 2: Wood Mackenzie, "US energy storage five-year market outlook"

A critical point for purposes of this paper is that by 2030, more than a majority of the ESS installed in the U.S. – 61% – is expected to provide "energy shifting."[9]

Need for "Energy Shifting" by Medium-Duration ESS in U.S.

The strategic value of a North American supply chain and manufacturing of VRFB, particularly vanadium electrolyte, arises because of the significantly increasing need of the North American electric power industry for ESS capable of reliably and cost-effectively shifting the time between when renewable energy is generated and when it is used. More specifically, when solar generation exceeds demand during the day, and wind generation exceeds demand often at night, ESS are needed to charge with the excess renewable generation, store it, and then discharge during time periods when demand exceeds renewable generation (if any). Those time periods are often 4-12 hours, and so the ESS must be able to discharge continuously for 4-12 hours. This is "energy shifting."

It is useful to situate the need for "energy shifting" by ESS, with other needs for ESS services in the U.S. NREL has described four phases of ESS deployment in the U.S. from 2010 forward:

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[8] "*U.S. energy storage monitor – Q4 2022 Executive Summary*," Wood Mackenzie Power & Renewables, December 2022, p.7.

[9] "*Global Energy Storage Market to Grow 15-Fold by 2030*," supra.

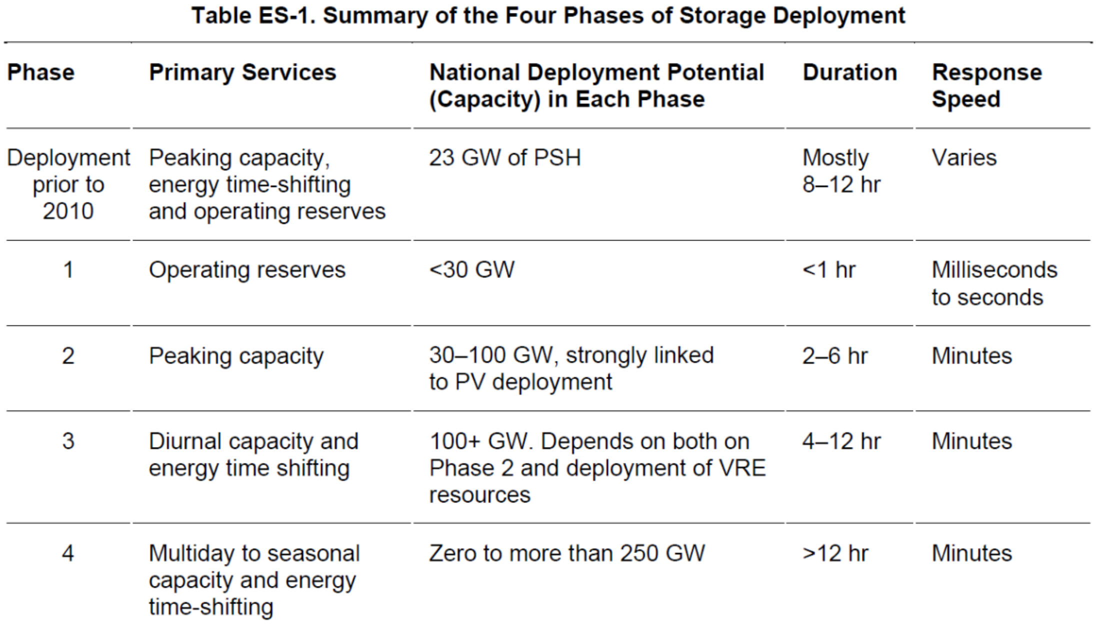

Table ES-1. Summary of the Four Phases of Storage Deployment

Phase	Primary Services	National Deployment Potential (Capacity) in Each Phase	Duration	Response Speed
Deployment prior to 2010	Peaking capacity, energy time-shifting and operating reserves	23 GW of PSH	Mostly 8–12 hr	Varies
1	Operating reserves	<30 GW	<1 hr	Milliseconds to seconds
2	Peaking capacity	30–100 GW, strongly linked to PV deployment	2–6 hr	Minutes
3	Diurnal capacity and energy time shifting	100+ GW. Depends on both on Phase 2 and deployment of VRE resources	4–12 hr	Minutes
4	Multiday to seasonal capacity and energy time-shifting	Zero to more than 250 GW	>12 hr	Minutes

Figure 3: NREL, "*Summary of the Four Phases of Storage Deployment*"

Phase 1 entailed the deployment of ESS with discharge duration <1 hour in the U.S. as "operating reserves", such as in PJM. Phase 2 was the deployment of ESS as "peaking capacity" with a discharge duration of 2-6 hours, such as in CAISO. It appears the U.S. is now in Phase 3, the deployment of ESS as "diurnal capacity and energy time shifting" with a discharge duration of a continuous 4-12 hours, or "energy shifting" for short. As BloombergNEF commented at the end of 2022, "[c]o-located renewables-plus-storage projects, in particular solar-plus-storage, are becoming commonplace globally."[10] There is also early but significant Phase 4 activity using approaches such as hydrogen to supply "multiday to seasonal capacity and energy time-shifting".[11]

As NREL notes, "[t]he four phases, which progress from shorter to longer duration, link the key metric of storage duration to possible future deployment opportunities, considering how the cost and value vary as a function of duration."[12] In this context, "energy shifting" services using ESS with discharge duration of 4-12 hours are increasingly referred to as "medium-duration" in the energy storage industry to help distinguish them from "short-duration" discharge (up to 4 hours) and a "long-duration" discharge (12 hours to 3 days). More recently, the segmentation of ESS technologies into "medium-duration" as well as "short-duration" and "long-duration," has also been utilized by DOE personnel. See **Figure 5**:

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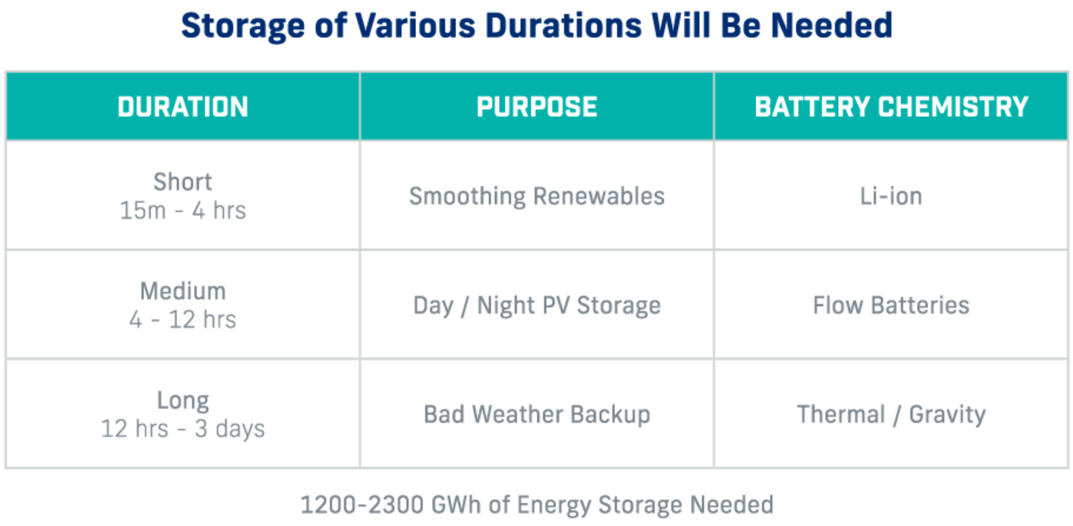
[10] "*Global Energy Storage Market to Grow 15-Fold by 2030*," supra.

[11] NREL explains the time period of 2010 forward was preceded by the period from 1960 to the mid-1990's when pumped storage hydro grew from virtually no installed capacity to ~23GW, and the period from the mid-1990's to 2010 when gas turbine use grew substantially with the advent of cost-effective gas turbines, lower cost natural gas, and the repeal of the 1978 law favoring electric power production from coal. "*The Four Phases of Storage Deployment*," p. 3.

[12] "*The Four Phases of Storage Deployment*," p. vii.



Storage of Various Durations Will Be Needed

DURATION	PURPOSE	BATTERY CHEMISTRY
Short 15m - 4 hrs	Smoothing Renewables	Li-ion
Medium 4 - 12 hrs	Day / Night PV Storage	Flow Batteries
Long 12 hrs - 3 days	Bad Weather Backup	Thermal / Gravity

1200-2300 GWh of Energy Storage Needed

Figure 5: "Grid Decarbonization, Sector Electrification, and Long Duration Energy Storage" [13]

As indicated by the DOE, flow batteries particularly match up to the medium discharge duration "energy shifting." This is part of a broader move within the research community, as highlighted in a recent paper from the University of Nottingham Energy Institute in the UK, recognizing that "[n]o one single set of technologies is suited to deal with this complete range of discharge times."[14]

VRFB Is Well-Suited for Medium-Duration Energy Storage

The following is a representative VRFB module:

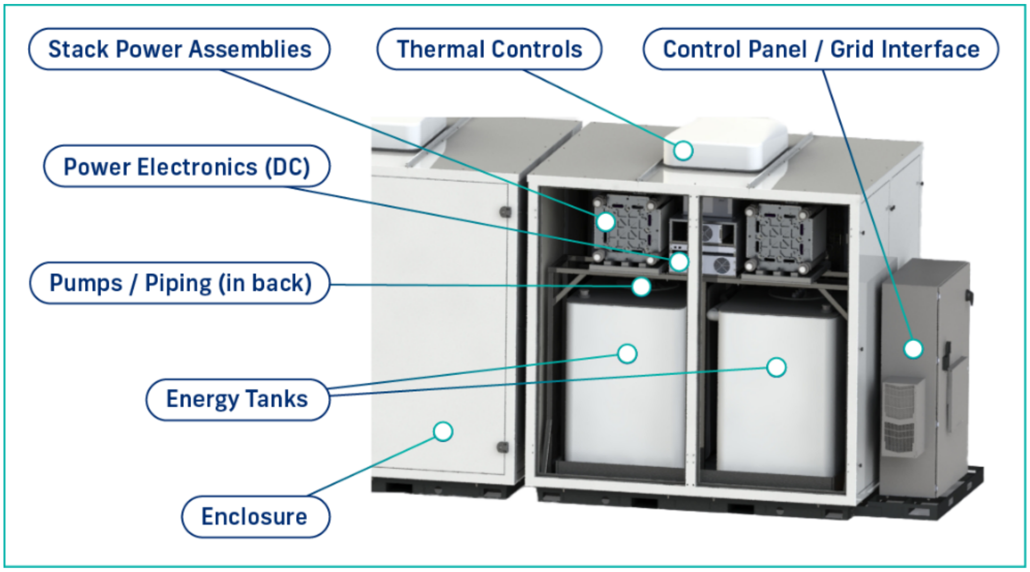


Figure 6: Representative VRFB Module (with control cabinet)

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[13] "Grid Decarbonization, Sector Electrification, and Long Duration Energy Storage," Gyuk, U.S. Department of Energy, Office of Electricity, January 26, 2023, p. 6.

[14] "*Medium Duration Energy Storage – Kingpin of Net Zero Energy*," University of Nottingham Energy Institute, June 8, 2021.

VRFB, a subset of flow batteries, are among the leading candidates to meet the need for medium-duration energy storage due to their characteristics, which include:

- very high cycle life with proper maintenance
- stable energy capacity over the projected service life
- use of non-flammable electrolytes
- ability to service a broad range of discharge durations with a single technology simply by adjusting with the number of stack power assemblies and electrolyte volume
- ability to support both energy functions (e.g., continuous 4-12 hours discharge needed for "energy shifting") and power functions (e.g., voltage and frequency regulation)
- response time of <1 sec with fit-for-purpose DC power electronics and AC inverters

The DOE and the national laboratories with which it works, recognized in the "*2022 Grid Energy Storage Technology Cost and Performance Assessment*" that "VRFB are an attractive technology for a variety of grid-scale applications with a wide range of power and energy needs:"

> "In RFB systems, the power and energy capacity can be varied separately. The power (kW) of the system is determined by the size of the electrodes, number of cells in a stack, and number of stacks in the battery system, whereas the energy storage capacity (kWh) is determined by the concentration and total volume of the electrolyte. Both energy and power can be easily adjusted for storage from a few hours to days, depending on the application. This flexibility makes RFB an attractive technology for a variety of grid-scale applications with a wide range of power and energy needs... The vanadium redox flow battery technology is mature and has been commercially deployed for grid-scale storage."[15]

VRFB are advantaged then in competing to serve as a medium-duration ESS technology meeting the increasing need of the power industry for "energy shifting," driven by the decarbonization of the power grid and the electrification of transportation and other sectors. Further, the intermittency of solar and wind renewable generation necessitates concurrent ESS requirements for "energy shifting" and also reliable and cost-effective power quality management including voltage regulation and frequency support.[16]

Often referred to as stacked services, VRFB are one of the main ESS well-suited to provide both "energy shifting and ancillary power quality services. VRFB's "energy shifting" capability is enabled by their scalability, with their energy subsystems (electrolyte, pumps, tanks) decoupled from the power subsystems (cell stacks, DC power electronics, AC inverters). VRFB's power quality services are enabled by the maturation of the power subsystems, including cells and cell stacks optimized to manage electrolyte flows, voltages, and "shunt currents;"[17] more efficient and less expensive DC power electronics; and AC inverters with more favorable specifications for VRFB including voltage windows.

Multiple promising demonstrations of VRFB have occurred, and there are increasing expectations that VRFB are near their time to take off and gain widespread market adoption.

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[15] "2022 Grid Energy Storage Technology Cost and Performance Assessment," *supra*, p. 35.

[16] "*Program 221: Bulk Energy Storage*," Electric Power Research Institute ("EPRI"); and "*Program 94: Energy Storage & Distributed Generation and Energy Storage*," EPRI; both accessed Mar. 19, 2023.

[17] "*The Mechanism and Modelling of Shunt Current in Vanadium Redox Flow Battery*," Skyllas-Kazacos, McCann, Li, Bao, Tang, ChemicalSelect, July 5, 2016, https://doi.org/10.1002/slct.201600432.

Costs for VRFB Need to Be Improved, Particularly of Vanadium Electrolyte

Though VRFB are well-suited to meet the "medium-duration" ESS market needs, their costs need to be significantly improved. The DOE has identified the range of cost improvements needed for VRFB:

> "In addition to high electrolyte cost attributed to raw materials (i.e., vanadium), other challenges to developing flow batteries are described below.
>
> 1. **Inefficient and expensive manufacturing technologies.** Components such as membranes, bipolar plates, and porous carbon electrodes require specialized properties and are currently expensive to produce. Auxiliary components such as pumps are also expensive to produce.
>
> 2. **Lack of robust, standardized supply chains (limited suppliers) and system integration challenges.** Similar to other battery chemistries, the potential of flow battery systems is limited by non-standardized supply chains, which reduce the interoperability of individual manufacturing innovations that fit within a larger flow cell system. The current most common flow battery chemistry relies on vanadium, a material that is mainly imported. Therefore, supply chain constraints would inhibit market penetration if the demand for this chemistry grows.
>
> 3. **Challenges with manufacturing scale-up.** Flow batteries have not yet achieved manufacturability levels that support deployment sufficient to provide broad economies of scale. Near-term advances for flow systems are focused on achieving comparable technical performance relative to incumbent Li-ion batteries; however, once systems are further developed and commercialized, scaling up manufacturing processes for specialized high-performance components (such as membranes and storage tanks) and materials (such as the active electrolyte) will be extremely critical."[18]

It is beyond the scope of this paper to discuss each of these multiple areas for cost improvements of VRFB. Instead, the remainder of this paper will focus on the "critical" manufacturing scale-up challenge of vanadium electrolyte production.

Vanadium electrolyte typically constitutes 30% to 40% of the bill of materials cost for VRFB systems, for example $150/kWh of a $500/kWh VRFB installed system cost,[19] and so is a key cost reduction target. As previously stated, the total available market in the U.S. for vanadium electrolyte could be as large as $180B. In sum, vanadium electrolyte is particularly valuable, for VRFB as a key component and cost reduction target; for ESS in general because VRFB are well-suited technically to provide the 4-12 hour "energy shifting" increasingly needed to utilize renewable generation reliably and cost-effectively; and for the North American power industry, as we decarbonize the grid and further electrify our infrastructure.

Energy Storage Industry Should Focus on Developing North American Supply Chain and U.S. Manufacturing of Vanadium Electrolyte for VRFB

In light of the above-listed values of vanadium electrolyte, the energy storage industry should focus on developing a North American vertically-integrated supply chain for vanadium electrolyte. In addition, the incentives for manufacturing of clean energy system components in the U.S. under the Inflation Reduction Act of 2022 ("IRA")[20] will further augment the value of vanadium electrolyte produced in the U.S.

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[18] "*Energy Storage Grand Challenge Roadmap*," supra, p. 39.

[19] "*2022 Grid Energy Storage Technology Cost and Performance Assessment*," supra, p. 36; "*2019 Energy Storage Pricing Survey*," supra, p. 51.

[20] See "*New Federal Money for Energy Storage: The Inflation Reduction Act*," Russ Weed, CleanTech Strategies, Dec. 16, 2022, https://www.cesa.org/event/new-federal-money-for-energy-storage-the-inflation-reduction-act/.

In the case of vanadium electrolyte, it is useful to employ the supply chain concepts of "upstream," "midstream," and "downstream." "Upstream" for the electrolyte entails mining of vanadium (whether as co-production from high iron, low vanadium ore smelted to produce vanadium-bearing slag, or primary production from majority vanadium ores), or extraction of vanadium from industrial processes such as steelmaking (secondary production). "Midstream" for vanadium electrolyte refers to the processing of the materials from "upstream," into electrolyte product satisfying the purity, molarity, and other requirements of the "downstream" VFRB manufacturer.

According to one industry source, as of 2021 the breakdown of the "upstream" supply of vanadium (specifically vanadium pentoxide) was 71% from co-production, 17% from primary production, and 12% from secondary production. The available "upstream" breakdown by country, including all three production sources, is 61% China; 17% Russia; 8% South Africa; 5% Brazil; 3% North America. But this breakdown does not include India as an "upstream" source, which the vanadium electrolyte processor US Vanadium disclosed in 2021 is its source for five years of supply of vanadium feed material for its production facility in Hot Springs, AR.[21]

Within the time period ending 2030, it appears the "upstream" co-production or primary production of vanadium in the U.S. is likely to continue to be constrained by availability and regulations on mining. Developments and activities in Canada may open up the possibility of co-production or primary production of vanadium here in North America,[22] but that topic is beyond the scope of this paper. Also beyond the scope of this paper is the further possible "upstream" source of secondary production of vanadium from industrial processes,[23] particularly those located in North America.

The nearer opportunity is the "midstream" manufacturing in the U.S. of vanadium electrolyte, the processing of vanadium pentoxide into electrolyte product. As highlighted above, that electrolyte product typically constitutes 30% to 40% of the bill of materials cost for VRFB systems and could be a $180B market in the US. There are also the significant IRA incentives for U.S. manufacturing of clean energy system components, which includes vanadium electrolyte.[24] In addition, given the volume and weight of electrolyte needed for VRFB to meet the "energy shifting" needs of the U.S. and the cost and transportation emissions consequences if that vanadium electrolyte is manufactured offshore, it would be particularly valuable to have "midstream" vanadium electrolyte production in the U.S.

Current and Potential Vanadium Electrolyte Production in the U.S.

Currently, the U.S. supply chain for vanadium electrolyte is early in its development. There are two U.S. companies known to be producing vanadium electrolyte, Riverside Specialty Chemicals and US Vanadium.

Riverside Specialty Chemicals indicates it has a vanadium electrolyte plant capacity of 20,000 gallons per month at its Delaware production facility, with room to increase that output to meet future demand.[25] Assuming a vanadium electrolyte energy density of 15Wh/liter, Riverside currently has a production capacity of >13MWh of vanadium electrolyte per year.

In conjunction with securing a five-year supply of vanadium for processing into products including ultra high-purity VRFB electrolyte,[23] US Vanadium concurrently acquired in 2021 a materials processing plant

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[21] "*US Vanadium Secures 5-Year Supply Of Vanadium Feed Material For Processing Into High-Purity Vanadium Products And Ultra-High-Purity Vanadium Redox Flow Battery Electrolyte*," US Vanadium website, Sept. 7, 2021 (accessed Mar. 29, 2023).

[22] See, for example, "*Lac Doré Vanadium Project*," VanadiumCorp website (accessed Mar. 19, 2023).

[23] See "*2022 Grid Energy Storage Technology Cost and Performance Assessment*," supra, p. 36.

[24] *IRA, Section 13502, "Advanced Manufacturing Production Credit," subsection (c)(5)(B)(i), "Electrode Active Material."*

[25] Riverside Specialty Chemicals - Vanadium Electrolyte (riverchem.com)

in Hot Springs, AR, for production of vanadium electrolyte.[26] In January 2022, US Vanadium announced it had completed a $2 million expansion of its capacity to produce 4,000,000 liters per year of ultra-high-purity vanadium electrolyte at its Arkansas manufacturing facility.[27] In September 2022, US Vanadium announced it had completed a $5.8 million upgrade of its vanadium processing operations in Hot Springs.[28] Continuing to assume a vanadium electrolyte energy density of 15Wh/liter, 4,000,000 liters of production per year provides approximately 60MWh of vanadium electrolyte per year.[29]

If VRFB hypothetically provided all 100GW of the up to 12-hour discharge duration needed for "energy shifting" in the U.S., and a vanadium electrolyte energy density of 15 Wh/liter continues to be assumed, that would entail a potential of 80B liters of vanadium electrolyte production, or 20,000 times the annual production capacity of the Arkansas electrolyte facility utilized here as a benchmark. Such potential production of 80B liters of vanadium electrolyte, as noted above, could be a $180B market.

Opportunity to Leverage Lead Battery Supply Chain in North America

In response to this need and the production potential, the best practices and even possibly the existing lead battery infrastructure in the U.S. is well-suited to support the anticipated rapid growth of VRFB markets. For instance, both vanadium and lead batteries have sulfuric acid and water as primary components. We estimate close to 300-370 million liters of electrolyte goes into lead batteries in North America every year. This requires a typical plant to receive sulfuric acid in the tanker truck load or even rail car load every day. In contrast, the current vanadium electrolyte small volume practices typically use inefficient supply of raw materials and shipment of finished product in IBC totes. Improved supply chain protocols, combined with the typical savings from economies of scale, are prime examples of how the best practices of the lead battery industry can help drive rapid cost down of the vanadium electrolyte to be more in line with market expectations for ESS systems costs.

The lead battery industry also has extensive vertically-integrated capabilities from engineering to manufacturing to sales and marketing to operations and maintenance services, as well as its robust "circular economy" where 99%[30] of the lead battery materials are recycled. As vanadium electrolyte production levels increase to meet demands, volumes could not only meet, but far exceed levels of the lead battery industry. Thus, vanadium electrolyte suppliers will need to engage in similar practices. A key area of interest is the reclaiming of the vanadium electrolyte at the end of the ESS service lifetime. Over the last several years there have been various models explored, such as a vanadium leasing model that could facilitate this practice and even improve the VRFB ESS cost-effectiveness.[31] In this case, the electrolyte lessor would establish any necessary infrastructure to collect the spent electrolyte from the ESS site and recycle it for use in future deployments.

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[26] *"U.S. Vanadium Acquires Materials Processing Plant in Arkansas as it Continues to Ramp Up Production of 'Made in USA' High-Purity Vanadium Products*," US Vanadium website, Sept. 8. 2021 (accessed on Mar. 19, 2023).

[27] *"U.S. Vanadium Launches North America's Largest Production Facility for 'Made in USA' Ultra-High-Purity Electrolyte for Vanadium Redox Flow Batteries,"* US Vanadium website, Jan. 31, 2022 (accessed on Mar. 19, 2023).

[28] "*U.S. Vanadium's New $5.8 Million Upgrade Improves Vanadium Recovery, Increases Recycling, and Supports Continued Production Rates for Ultra-High-Purity Electrolyte for Vanadium Redox Flow Batteries*," US Vanadium website, Sept. 30, 2022 (accessed on Mar. 19, 2023).

[29] 4,000,000 liters x 15 Watt-hours per liter = 60,000,000 Watt-hours or 60MWh.

[30] "Facts and Figures about Materials, Waste and Recycling; Durable Goods: Product-Specific Data," U.S. Environmental Protection Agency website, Dec. 3, 2002 (accessed Mar. 21, 2023).

[31] Vanadium Electrolyte Rental: A New Option for Storage Projects | Vanadium Price