Vanadium Redox Flow Battery & and Lithium Iron Phosphate Battery Systems for Data Centers

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Executive Summary
This report evaluates the feasibility of deploying a hybrid energy storage system of vanadium redox flow batteries (VRFB) for long duration energy storage (LDES) and lithium iron phosphate (LFP) batteries for short-duration energy storage (SDES) to power a 500 MW hyperscale data center in Phoenix, Arizona with 24/7 carbon-free energy. The system is modeled utilizing a simplified annual generation structure, assuming a 2.8 GW co-located solar site serves as the primary energy source powering the data center and charging the batteries during the day to ensure uninterrupted power through the nights or any cloudy periods.

The proposed hybrid storage system takes advantage of the complementary strengths of each battery technology. LFP batteries provide high-efficiency, short duration storage that is best suited for shorter bursts — effectively covering cloudy day variability and rapid load changes. VRFB systems offer scalable long duration storage (8-16+ hours) with minimal degradation over time, enabling energy shifting across overnight periods and extended low-generation events. The combined VRFB and LFP battery systems help to address the intermittency of solar generation.

Looking at the techno-economic case for each technology, they have a comparable LCOS range of $110-250/MWh depending on duration and utilization. LFP battery systems benefit from higher round trip efficiency (85-90%) and lower upfront costs, making them optimal for frequent cycling. VRFB systems have a lower round trip efficiency (65-75%) but have longer lifespans (20-30+ years) and benefit from longer duration storage applications — improving cost effectiveness over its lifetime. The combination of these two battery technologies results in an effective model that minimizes cost while maintaining reliability.

Still, both technologies face several practical constraints that are worth considering. The assumed 2.8 GW of solar that supplements the data center and charges the battery represents an unrealistic scale needed to compensate for storage losses and capacity factor limitations. A project of this scale would likely incorporate grid interconnection, diversified generation sources, or demand flexibility to reduce land use, interconnection delays, and sheer capital investment. Both battery systems also face site-specific challenges, like thermal degradation for LFP in extreme heat and vanadium supply constraints for VRFB.

Even with these inherent risks and simplified modeling, a combined VRFB and LFP battery system offers the best near term fit to supply 24/7 carbon-free energy to this 500 MW data center. While iron-air battery systems may offer significantly lower cost at long durations of ~100 hours, they are currently at an earlier stage of commercialization (TRL 5-6) and suffer from a lower round trip efficiency of about 50%. These factors make iron-air better suited for multi-day reliability events rather than daily cycling, which VRFB excels at. In the long term, iron-air batteries could become the more viable option once they reach commercial deployment

and can prove higher round trip efficiencies. For now, VRFB remains the best long duration energy storage option, providing consistent and reliable power.

Recommendation: Deploy a hybrid VRFB (16-hour) and LFP (4-hour) battery system paired with utility-scale solar to meet 24/7 CFE data center needs in the near term. Remain flexible to allow for the potential of other long duration energy storage systems like iron-air batteries, as these will likely become more economically and commercially viable in the next decade.

Techno-Economic Analysis

System Configuration and Modeling Assumptions

The proposed system combines vanadium redox flow batteries (VRFB) for long-duration energy storage and lithium-iron phosphate (LFP) batteries for short-duration energy storage, paired with 2.8 GW of solar as supplemental power. This system is designed to support a constant 550 MW data center load, with a power usage effectiveness (PUE) of 1.1. The combined storage system is sized as:

- VRFB: 550 MW → 8,800 MWh (16-hour duration)
- LFP: 660 MW → 2,640 MWh (4-hour duration)

Combining these two storage technologies allows for full coverage of the data center, with LFP batteries addressing rapid load changes and VRFB systems providing overnight/weather reliability. A key modeling assumption with the sizing of the batteries is the use of a solar energy supply, requiring about 2.8 GW of installed capacity. This represents an overbuild of generation to allow for some buffer room when considering capacity factor, weather events, and energy losses. Real-world deployments would likely include grid interconnection and diversified generation to reduce overbuild and system costs. However, this simplified assumption of only utilizing solar allows for a clear representation of storage system performance under a fully decarbonized scenario.

Key Assumptions:

Solar is the only generation source used in this model

The assumption of using a fully powered solar system to supplement the data center and charge the batteries is intentionally simplified in order to determine sizing. By excluding grid interconnection or other generation sources, the model isolates the performance and cost characteristics of the storage system utilizing fully carbon-free energy. This ensures that all reliability requirements are met by the storage system rather than using external sources. While this assumption results in significant solar overbuild, it provides a clear analysis of how combined storage technologies perform when forced to compensate entirely for intermittency.

Fixed storage durations of 16 hours (VRFB) and 4 hours (LFP)

The selected storage durations reflect relatively standard industry configurations and are intended to align with the functional roles of each technology to ensure reliability. A 4-hour duration for LFP is common and widely deployed already, primarily being used for peak shifting and short-duration balancing. The 16-hour VRFB system is meant to cover overnight demand and any extended periods of low solar generation. Typically, optimal durations would be specific to the site conditions, including solar resource variability and load characteristics, but for the simplicity of this model durations were kept fixed.

Blended round trip efficiency of 80%; assuming thermal management losses of ~5% for LFP system

While the system is sized at a total nameplate capacity of 1,210 MW and 11,440 MWh of energy, actual usable energy can be substantially less due to several losses and battery efficiencies. A blended round trip efficiency of 80% is derived from the combination of the two battery systems, with VRFB efficiency at ~75% and LFP efficiency at ~85% (after assuming a 5% reduction due to cooling system). These losses are important to note since they significantly impact system sizing, with this scenario requiring additional solar overbuild to compensate for capacity factor and battery system losses.

No curtailment or transmission constraints

The model assumes that all the generated solar energy can either be consumed by the data center or fully stored and utilized without losses due to curtailment or transmission limitations. This simplifies the analysis by removing the need to model grid congestion, interconnection delays, or operational inefficiencies tied to excess generation. By excluding these constraints, the model likely underestimates energy losses but this allows the analysis to focus on the performance of the combined storage system rather than external limitations.

Cost Structure and Capital Allocation

The capital cost for this project is dominated by the scale of both storage deployment and required solar overbuild, with estimates of:

- VRFB CapEx: $4.8 billion
- LFP CapEx: $881 million
- Solar CapEx: $3 billion

VRFB represents the largest share of total system cost, primarily because of high vanadium electrolyte costs and the large supply needed at this scale. Up to 40% of the VRFB system cost can be consumed by the vanadium electrolyte cost alone, making this a key supply risk worth considering. LFP battery costs are driven by battery cell manufacturing and benefit from significant economies of scale due to widespread commercial deployment. Because of this, LFP systems offer a lower cost per unit of power but ultimately become less cost-effective at longer durations due to the need to scale both power and energy simultaneously. When combining the two systems, total cost is minimized by avoiding any over-reliance on any one technology beyond its optimal operating range.

Levelized Cost of Storage and Duration Dependence

Under the current assumptions, both the VRFB and LFP systems demonstrate similar LCOS ranges with VRFB at around $110-200/MWh and LFP at $115-296/MWh. Looking at LCOS alone depicts that both systems operate at similar costs, however, a key differentiator is duration dependence. LFP systems achieve lower LCOS at short durations due to higher efficiency, lower upfront costs, and high utilization under frequent cycling. As duration increases, LFP costs increase with it since it is built for shorter duration bursts. VRFB systems have a lower efficiency but demonstrate declining marginal cost as storage duration increases, since energy capacity rises by electrolyte volume instead of additional power components. This makes VRFB increasingly cost competitive as it reaches the 16-hour duration — with the combined battery system alleviating higher costs as each technology can help to balance the other.

System Optimization and Tradeoffs

A primary economic challenge of utilizing a solar-only generation profile includes balancing efficiency, duration, and capital cost given the constraints of the system. Two key assumptions drive higher costs leading to overbuild requirements, including solar intermittency and battery efficiency losses. This model is only using solar energy and requires increased generation even with assuming a higher-end 34% capacity factor in Phoenix. Also, the battery system round trip efficiency of about 80% requires further solar oversizing in order to make up for this 20% loss as electricity flows through the system. Still, utilizing the combined battery systems of VRFB and LFP helps to mitigate some of these challenges and reduce costs. LFP minimized losses during frequent cycling and VRFB reduces the need for excessive short-duration storage by providing scalable capacity at long-durations. The total system cost is still relatively high when including solar build out (~$8.7 billion), with land costs and vanadium supply being the primary cost drivers. Ultimately, supplying a 500 MW data center with 24/7 carbon-free energy requires tradeoffs, demonstrating significant upfront capital investments when only utilizing solar as the main generating source of energy.

Comparative Performance Matrix

Physical and Operational Comparison Matrix

Physical & Operational Comparison

	VRFB	LFP	Diesel Backup	
Energy Density	39 m^2/MWh	12 m^2/MWh	Compact, high power density	
C-Rate/Ramp Time	0.0625C, 15 ms from on	0.25C, milliseconds	Fast start, seconds-minutes	➡ *All Dispatchable*
Duration/Discharge Time	Long-duration, 8-16+ hours	Short-duration, 2-4 hours	Continuous, fuel dependent	
Round Trip Efficiency (RTE)	~65-75%	~85-90%	~35-45% (thermal efficiency)	➡ *VRFB limited by RTE*
Technology Readiness Level	7 ⟶ Early commercial	9 ⟶ Fully commercial	9 ⟶ Fully commercial	

Energy Density

For the purpose of this analysis, the focus will primarily be on the storage system and not the solar infrastructure needed to power it. 2.8 GW of solar would be the dominant land user in this scenario, but the focus will be on the battery systems. The VRFB system represents a significant land user with an energy density of around 39 m^2/MWh — assuming the battery containers cannot be stacked. Several configurations demonstrate that the modules can be stacked on top of each other since there is no concern for fires (liquid electrolyte), effectively cutting the energy density in half. The required land needed to support the 550 MW VRFB system would be around ~42 acres. LFP would require much less land at around ~8 acres, given that it is much more energy dense than VRFB. Even though the LFP system is more energy dense than VRFB, the long-duration and scalability components of VRFB help to boost its efficacy.

Ramp Rate, Duration, and Dispatchability

VRFB systems have a ramp rate of 15 milliseconds from on, fast enough to be dispatchable and reliable to power a data center with consistent power. LFP batteries are even faster, meaning they are also reliably dispatchable. The advantage of VRFB systems is that they are capable of sustaining output for up to 16 hours to cover overnight periods and extended low-generation events, critical for maintaining continuous power. Even though the incumbent of diesel is also somewhat dispatchable, it is heavily reliant on fuel which can create higher operational lifetime costs. Both VRFB and LFP are needed to ensure long-term coverage and short-term flexibility.

Round Trip Efficiency and Technology Readiness Level

Round trip efficiency is key in determining the amount of additional generation needed to fully supply power to the data center. With a blended efficiency of 80%, additional solar was worked into the model to compensate for these losses. Since VRFBs have a lower efficiency at around 70%, the more this technology is implemented into the overall system the greater the solar overbuild would need to be. Still, efficiency and duration are directly related as it pertains to evaluating the need for both VRFB and LFP technologies. LFP systems are more efficient at an average of around 90%, but its costs scale linearly with energy capacity, making them less suitable for long-duration applications. VRFB systems provide a more cost-effective solution for extended storage durations because of their scalable energy capacity.

In terms of technology readiness level, VRFB is the only concern as being somewhat in the early commercial stage. There are several global examples of deployed VRFB systems, including a 200 MW plant co-located with 1 GW of solar in Xinjiang, China — proving the technology is scaling with renewable energy. However, this project proposes for a VRFB system nearly 3x as large, an unprecedented scale that will undoubtedly leave the project subject to many risks. LFP and diesel technologies are both fully developed and widely deployed.

Economic Performance

Economic Comparison

	VRFB	LFP	Diesel Backup
CAPEX	$4.8B	$881M	$686M
LCOS/LCOE	$110-200/MWh	$115-296/MWh	$200-400/MWh
Cost Trend, 2030 LCOS	Decreasing, $80-160/MWh	Decreasing, $80-180/MWh	Increasing
Primary Cost Driver	Vanadium electrolyte	Battery cells	Fuel

Diesel fuel costs can drive up LCOE

Economic performance is driven by both upfront capital costs and long-term operational efficiency. LFP systems have lower upfront costs due to mature manufacturing processes and economies of scale, whereas VRFB is still relatively early in the commercialization process which leads to higher upfront costs. VRFB CapEx is heavily driven by vanadium electrolyte, which doesn't have a standardized cost or supply structure and accounts for up to 40% of total system costs. Despite the differences between the two battery technologies, they have relatively similar LCOS ranges, with VRFB at $110-200/MWh and LFP at $115-296/MWh. LFP systems become increasingly expensive as storage duration increases, while VRFB systems benefit from declining marginal cost per additional hour of storage. This means that any one technology would not be optimal from a cost perspective to fully supply energy to the data center, and the hybrid system offers the most cost effective way to deliver carbon-free energy. For diesel as the incumbent, it may appear to be cheaper from an upfront capital investment, but it is highly dependent on fuel costs and likely is much more expensive to operate long-term.

Resource Intensity and Supply Chain Constraints

Several environmental and economic constraints arise from the proposed system, especially at such a large scale. Vanadium is the first constraint, with nearly 90% of production primarily focused in China and Russia. This raises geopolitical risks in obtaining the necessary vanadium electrolyte at fair prices, and demonstrates a primary concern as vanadium can account for 40% of total system costs. Material intensity is also a key constraint as every kWh requires between 3 to 6 kilograms of vanadium. At the current scale, this translates to around 26,000-53,000 metric tons of vanadium needed for the VRFB system — a massive amount that can put a strain on supply. This amount can be up to about 40% of global annual production of vanadium, demonstrating the monumental scale this VRFB system entails and the potential need for phased VRFB deployment.

LFP systems rely heavily on lithium and graphite, with supplies also heavily concentrated in China. However, LFP avoids the use of cobalt and nickel, which reduces both cost volatility and safety risks (fire) compared to other lithium-ion chemistries.

Infrastructure Integration

Grid Interconnection and Transmission Constraints

Phoenix is an area heavily defined by interconnection delays and transmission constraints. Arizona Public Service's (APS) interconnection queue is roughly 78 GW of pending projects, so securing a transmission-level connection could realistically take 5+ years. A project of this size would likely require infrastructure upgrades to avoid worsening transmission congestion. The hybrid VRFB and LFP system would likely help to avoid some of these constraints, as it would enable short-term and long-term load shifting — reducing reliance on constrained transmission during peak periods.

Water Use and Thermal Constraints

Water availability represents a critical constraint on data centers, as they can consume between 200,000 and 5 million gallons of water per day. In Phoenix already, data center cooling accounts for hundreds of millions of gallons annually, with demand expected to increase significantly as new facilities are developed. Water consumption is not typically limited to onsite cooling, as up to 72% of total water footprint occurs indirectly through electricity generation. This reinforces the value of pairing storage with generation that does not require water like solar. Other generation technologies, even carbon-free ones like nuclear, require large amounts of water for cooling. Arizona is currently facing long-term water supply issues driven by Colorado River shortages and groundwater depletion, which is leading to regulatory restrictions on new groundwater development — requiring a 100-year assured water supply for new projects. In some cases, high intensity water users are required to acquire their own water supplies to avoid impacts to existing water users. Given that Arizona is a highly constrained market for water, this is a valid risk for data center development unless air cooling technology becomes more efficient.

Solar Integration

While the focus of this analysis is primarily on the VRFB and LFP hybrid system, it is important to note the impact a solar-only generation has on the overall system. With utilizing only solar, it requires significant overbuild to compensate for intermittency and storage losses. This increases land use and introduces potential transmission and siting challenges. However, solar generation provides an advantage when it comes to reducing indirect water consumption relative to thermal generation. Since solar does not require water for cooling or generation, pairing it with storage technologies minimizes total system water intensity. VRFB and LFP enable solar generation in this model, allowing for 24/7 carbon-free power that is less water intensive than other options like grid integration or nuclear power.

Social License to Operate

What is the technology's reliance on rare materials, including rare earth metals or other scarce materials?

While neither VRFB or LFP strictly rely on many rare earth materials, they both depend on materials with supply chain and scalability concerns. The central input for VRFB is vanadium, which demonstrates a key supply chain constraint as it requires a significant amount of material. The USGS 2023 Minerals Yearbook states that VRFBs require roughly 3-6 kilograms of vanadium per kWh of energy storage and that vanadium accounts for approximately 30-50% of total VRFB battery cost. With an 8,800 MWh VRFB system, this suggests a substantial material requirement, making vanadium availability one of the most important resource constraints in the project.

LFP systems primarily rely on lithium, graphite, iron, phosphate, copper, aluminum, and electrolyte material. These materials are not necessarily rare, but the battery supply chain is concentrated and has a rapidly growing demand. A 2023 IEA reports that lithium demand is expected to grow rapidly with battery deployment and that battery storage and EVs become major drivers of lithium demand by 2030. It also highlights graphite as one of the most concentrated battery supply chains, with over 90% of battery-grade graphite and nearly 95% of projected battery-grade graphite supply growth coming from China. With a growing demand and relatively isolated supply chains, obtaining the necessary materials for a project of this scale may pose risks and potential runaway costs.

Are there geopolitical risks associated with obtaining the raw materials?
The primary geopolitical risks are associated with the majority supply and production of key materials being in China. China's vanadium production in 2023 accounted for nearly 70% of global supply, with very little being produced in the US — only from secondary production like steel manufacturing byproduct. This could create exposure to commodity price volatility, trade restrictions, and geopolitical disruption. The same USGS report notes that cost and raw material availability remain barriers for VRFB market entry, and that manufacturers are exploring electrolyte leasing models to reduce upfront cost and protect customers from vanadium price fluctuations.

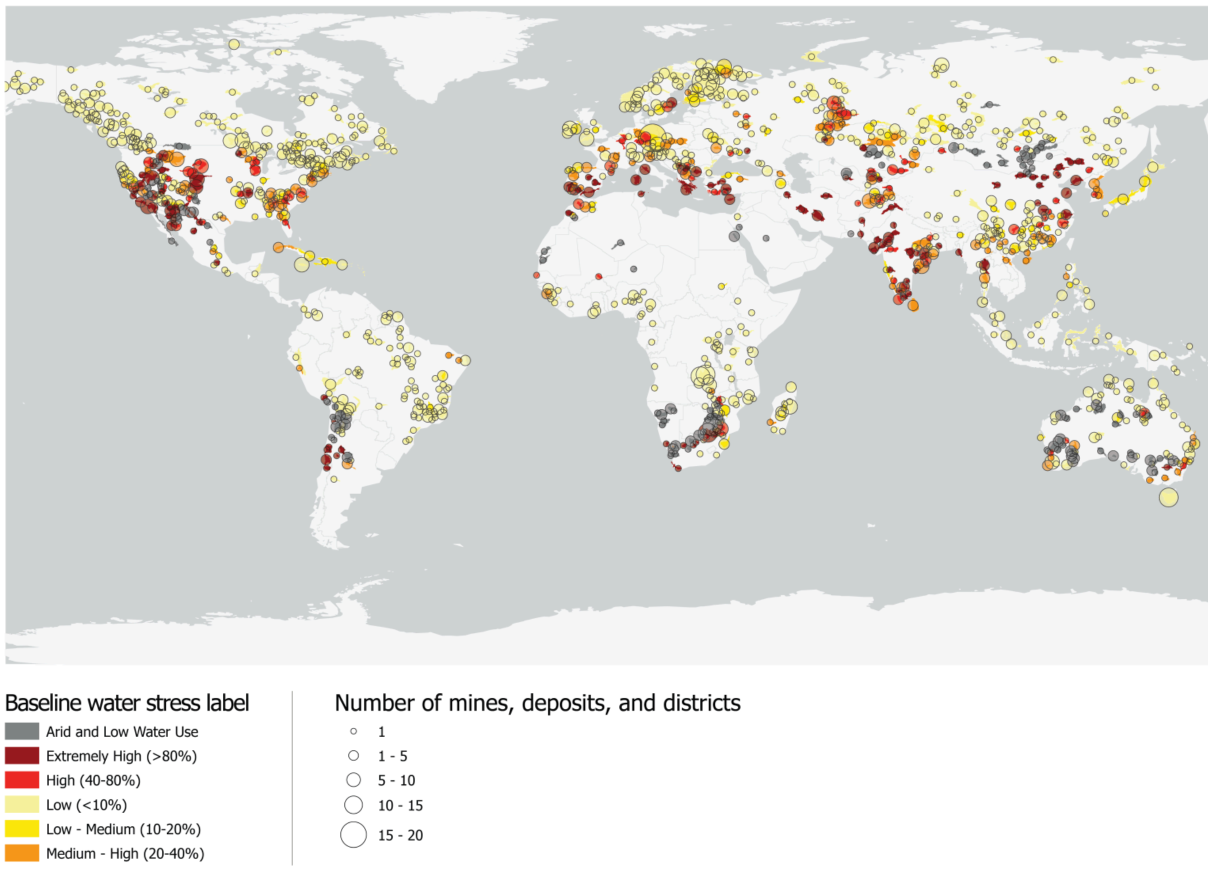
LFP has a slightly different geopolitical risk profile, with the IEA identifying lithium and graphite as among the highest-risk materials for clean energy technologies. The DOE's 2023 Critical Materials Assessment classifies graphite as critical in the short term and lithium as near-critical, based on importance to energy technologies and supply risk.

Section 301 tariffs impose 25% duties on graphite imports, with recent anti-dumping and countervailing duty investigations resulting in additional tariffs of up to 93.5%. Lithium is also subject to tariffs of 25% under the same framework. Considering that around 78% of global graphite production and 65% of lithium production are concentrated in China, these tariffs will undoubtedly put a strain on obtaining the necessary raw materials for the LFP system of this scale.

Are there energy justice concerns with the operation of the technology and/or with the supply chain to obtain the constituent parts and/or with the manufacture of this technology?
The battery system has clear benefits and unresolved risks when looking at it from an energy justice perspective. One clear benefit is the reduced reliance on fossil fuel generation to power the data center, which otherwise would have contributed to local pollution in Phoenix. Still, upstream supply chain impacts remain a concern. Lithium extraction can especially impose energy justice concerns given it is often associated with high water usage rates and negative

impacts to rural or indigenous communities.

16% of critical mineral mines, deposits and districts are located in highly water-stressed areas



Source: USGS and Aqueduct.
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This map demonstrates the relationship between critical mineral mines (largely lithium) and water stress areas. The IEA also notes that many critical mineral refining operations occur in regions with higher-carbon electricity grids, meaning that upstream processing can carry significant environmental burdens even when the final technology supports decarbonization.

VRFB supply chains pose a different environmental justice issue. Since vanadium is often produced as a byproduct of steelmaking or mining, its overall impact highly depends on the production pathway. Steelmaking and mining have differing labor standards and practices globally, and similarly to critical mineral refining, these processes may depend heavily on high carbon electric grids. The best case scenario for this project would be to source vanadium from recycled or secondary production where possible and require environmental/labor standards from the supplier. Still, this may be extremely difficult to enforce given a lack of overall transparency globally.

Would this technology improve or make worse any of the existing key concerns that individuals have with data centers in the US?
Public concern for data centers is still a major issue for this project. Despite the claim of delivering 24/7 carbon-free energy, this project likely requires significant land and water use — both key concerns with many local residents. The VRFB and LFP system could potentially alleviate some of these concerns related to water, as they both use little to no water and give off no noise pollution compared to generators. Land is definitely still a major concern as the VRFB system can consume 50 acres or more for a project of this scale, not to mention the land needed for 2.8 GW of solar.

Evaluate one additional non-energy non-infrastructural consequence of your choice
One additional consequence of the VRFB and LFP storage system is general end-of-life management. With the batteries set to have a lifespan of around 20 years, recyclability and replacement are key issues to consider down the road. VRFB are among the most recyclable battery types, with over 97% of vanadium recovery from the electrolyte at the end of its life due to little to no degradation. LFP batteries also have recycling pathways, but they can be expensive and aren't as cut and dry as VRFB. Both systems should be evaluated early on and have plans for end-of-life to recover as much critical materials as possible.

Risk-Based Failure Analysis

Technical Risks

LFP Thermal Degradation and Performance Loss
LFP batteries are sensitive to high temperatures and can lose up to 40% performance over its lifetime with sustained heat over 100 degrees Fahrenheit, like in Phoenix. The mitigation required for this is active cooling and thermal management, likely liquid cooling as air cooled systems would be inefficient in a hotter climate like Arizona. The liquid cooling would likely use cold plates or channels near battery cells, utilizing a coolant like water-glycol or dielectric fluid. A 5% parasitic load can be assumed for running this cooling system, as well as a range of 5-15% increase to overall system costs.

VRFB Scaling/System Complexity
VRFB systems have unique technical complexity since they rely on large electrolyte tanks, pumps, and flow systems rather than battery cells. At the current scale of the project (8,800 MWh), it would be the largest VRFB system in the world, meaning there is little standardization for deployment and higher risk of failure. The mitigation could be phased deployment and

modular system designs to reduce scaling risk by allowing performance to be validated over time. Using experienced EPC partners can help to improve the overall reliability of VRFB systems as well.

Solar and Storage Sizing Mismatch
Since the system relies heavily on an assumed 2.8 GW of solar generation to supplement the data center and fully charge the batteries, there is inherent technical risk that the suggested sizes may fail to deliver constant power to the data center. Weather variability and forecasting errors could amplify this risk. The mitigation is considerable solar overbuild (already applied) and diversified generation sources, potentially through grid interconnection as a back up. This is likely the **most consequential risk** because an undersized or unbalanced system could fail to deliver constant power to the data center.

Economic Risks
Vanadium Supply and Price Volatility
Because vanadium represents 30-50% of total VRFB system costs, it is highly sensitive to price changes. Global supply is heavily isolated in China and Russia, further elevating this concern. One potential mitigation could be to explore electrolyte leasing models to reduce upfront capital costs and shift the price risk to suppliers. Another option could be to phase VRFB deployment depending on vanadium supply/prices. This risk of vanadium supply uncertainty is the **most likely risk** for driving significant capital expenses, simply because VRFB systems are incredibly reliant on vanadium and the scale of the project requires nearly half of annual global production — mostly from China.

Tariffs and Supply Chain Costs for LFP
LFP batteries are more exposed to US tariffs on lithium and graphite, key materials needed for the system. These tariffs can greatly increase system costs and introduce uncertainty in procurement. A mitigation here could be to source these key materials from non-Chinese suppliers, focusing on domestic sourcing and long-term procurement contracts.

Capital Cost and Overbuild Requirement
Including the solar overbuild into the overall cost estimates puts it at over $8.7 billion. This investment is huge, and requires significant land to develop a project of this size. If capital costs somehow exceed this estimate, the project may become unviable. A realistic mitigation for this risk is to incorporate grid interconnection and optimize storage sizing to reduce total capital investment.

Failure to Meet 24/7 CFE by 2035
If the system fails to meet 24/7 CFE by 2035, some of the most likely causes would be vanadium supply shortfalls, degradation of LFP systems in high-temperatures, insufficient solar generation,

and data center regulatory restrictions related to interconnection or water use. The primary technical concern is LFP degradation and VRFB system complexity, as these two could fail to effectively capture solar energy if these risks are realized. Solar provides the main physical risk to the system, if weather events or lower capacity factors fail to deliver the necessary generation to power the data center. Finally, interconnection delays, water restrictions, and tariffs on key materials all are serious regulatory risks that could easily kill this project.

Recommendation

Deploy a hybrid VRFB (16-hour) and LFP (4-hour) battery system paired with utility-scale solar to meet 24/7 CFE data center needs in the near term. This 2.8 GW solar array will charge the LFP batteries first to cover same-day energy needs like smoothing cloud cover and responding to rapid load swings. The VRFB system will take on excess solar energy, dispatching it through the night and over multi-day cloudy periods when the LFP is exhausted. Remain flexible to allow for the potential of other long duration energy storage systems like iron-air batteries, as these will likely become more economically and commercially viable in the next decade. Explore other clean energy generators outside of solar to lower capital costs and increase reliability of providing consistent power.

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