The Power of Implementing a Vanadium Redox Flow Battery on the UMass Amherst Campus

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1. Executive Summary

In 2020, the Leading by Example (LBE) Council announced that a Carbon Mitigation Task Force would be established for the purpose of achieving net carbon neutrality on the University of Massachusetts, Amherst campus by 2030. To meet this goal, new forms of clean energy generation and storage are expected to be implemented. Our team has focused on vanadium redox flow batteries, or VRFBs, a safer and “greener” alternative to the lithium-ion Borrego battery that currently exists for the university’s energy needs. In this paper we argue that lithium-ion batteries pose safety concerns and profits from socially unjust mining methods. Due to the fundamental differences that flow batteries have, VRFBs offer a solution to energy storage that is much closer aligned with UMass’s goal of minimizing and ultimately, eliminating carbon emissions. Additionally, as this technology is further improved and commercialized, a VRFB can easily be integrated on campus. With a modest allotment of land and reasonable expenses, these batteries can meet the energy requirements of the university while minimizing expenditure and carbon emissions compared to the current technology. VRFBs are uniquely adaptive and can be arranged and expanded as needed, a key consideration due to plans of future campus expansion. All in all, the benefits of VRFBs outweigh those of lithium-ion batteries and we hope to adopt this revolutionary technology to set an environmental standard for the rest of the world.

2. Introduction

The implementation of widespread renewable energy generation is both the opportunity and challenge of our collective lifetimes. One of the biggest hurdles to meet this goal is how to best store the energy generated for use during times of high demand. For UMass to meet their 2030 goal of net-zero carbon emissions, drastic action is required by the carbon mitigation task force. Of the proposals considered, most focus on the implementation of renewable energy on campus in some way. However, without rigorous energy storage infrastructure, the impact of these improvements will be severely dampened.

Currently, UMass uses a lithium-ion battery to store and distribute power to campus and is planning on the construction of another in the near future [1]. However, there are several drawbacks to large-scale lithium-ion batteries, such as their limited capacity, lifespan, and high cost [2, 3]. Furthermore, their construction requires the use of environmentally destructive and inhumane mining practices [4]. Instead, this team proposes the implementation of a vanadium redox flow battery to fulfill the campus’ energy storage and distribution needs in the future.

Unlike solid-state batteries, redox flow batteries store their electrolytes in liquid tanks, allowing them to last longer, be upgraded more easily, and be safer to have on campus [5, 6, 7]. If the university truly intends to not only reach their goal of carbon neutrality by 2030, but to be a leader in sustainability, they must seriously consider energy storage alternatives to lithium-ion.

3. Problem Statement

The UMass campus plans to continue its infrastructure expansion, including new academic, residential, and utility buildings, all of which require energy to function, all while aiming to be carbon neutral by 2030. From 2012-2050, the UMass administration has proposed over 150 new buildings and building additions, almost 7 million square feet in total, all of which will require additional electricity generation by the university [1]. While these two plans may seem contradictory, increasing energy generation and reducing carbon emissions will be possible through the increased reliance on renewable resources and expansion of the Central Heating Plant, both of which will require an expansion of campus energy storage infrastructure.

Currently, 30% of UMass' electricity is purchased from a company that uses fossil fuels to generate power [1]. To reach zero net carbon emissions, UMass will have to make a significant in renewable energy resources, prompting the development of a new storage strategy. By expanding its renewable energy capabilities, UMass will be able to meet the increased demand from additional buildings while simultaneously reducing carbon emissions. However, renewable energy generation is not consistent, and changes according to weather, sunlight exposure, and wind speeds. A clear example of this is the difference in photovoltaic electricity generation during the day and night. Therefore, an increased reliance of renewable energy generation, requires a similarly scaled, similarly sustainable energy storage plan on campus.

Currently, UMass uses a lithium-ion Borrego battery to store and distribute electric power on campus [1]. Unfortunately, there are also several directly associated health and safety issues that are presented with lithium-ion batteries. The primary safety concern with lithium-ion batteries is their potential to combust when punctured. In the past year alone, they have been responsible for several house fires, caused by the extremely flammable electrolytes used for energy storage [5]. Even if large scale lithium-ion batteries don't start a fire, they have been shown to turn a controllable fire into an unmanageable blaze [8]. These safety concerns make the construction of another lithium-ion battery on campus an ill-advised and dangerous proposition for UMass.

Solid-state batteries, most commonly, lithium-ion , (including the one currently used on campus), are prone to degradation over time, making them a bad investment for a campus focused on long-term returns. As lithium-ion batteries undergo multiple charging-discharging cycles, their capacity degrades over time until the battery eventually fails, requiring costly replacement [2, 7]. Batteries which use a different mechanism of electrolyte storage and charging/discharging, such as redox flow batteries provide an alternative energy storage solution which doesn't face these degradation problems.

The materials used in the construction of lithium-ion batteries, specifically in their electrodes, makes them both non-recyclable, and the product of environmentally devastating mining techniques. The use of cobalt comes with a high societal cost, due to inhumane and dangerous mining practices, as well as accompanying environmental destruction. The cobalt used in lithium-ion electrodes is mined in facilities driven by wage-slavery and inhumane working conditions [4]. Furthermore, we have no mechanism of recycling lithium-ion batteries [9]. Further usage of these materials which endanger miners and devastate the environment when there are viable alternatives is completely unconscionable for a university that considers itself a leader in sustainable innovation.

The campus' need for increased energy storage is an inevitable truth. Required to advance our renewable energy generation, lower costs, and support expanding construction, the construction of a new battery at UMass is undeniable. However, the evident problems with large-scale lithium-ion batteries make it a poor solution to this problem. Instead, we suggest the implementation of a vanadium redox flow battery to manage future energy storage at UMass.

4. Solution Technology Explainer

The battery storage team believes vanadium redox flow batteries (VRFBs) are the best way to store energy on our ever-growing campus due to its scalability, energy storage capacity, lifespan, and safety.

UMass currently estimates a need for a 3.5MWh energy storage system over the next ten years [10]. This may seem like a large demand, but commercial grade VRFBs have been shown to have an energy storage capacity of up to 800MWh [11]. This large storage ability is due to its design. The average VRFB is designed to have 2 storage tanks that hold the positive and negative electrolytes and a system of pipes and pumps which enable the electrolyte to flow from the tanks to the battery cells and back. Multiple cells can be stacked and integrated into the battery system. The number of stacks defines the charging and discharging power while the size of the tanks defines the energy storage capacity [12]. So when more stacks are implemented into the system, or if the size of the electrolyte tank is increased, the VRFB can store more energy. The scalability of VRFBs will allow them to meet any increase in energy storage demand across campus over the next 10 years. This scalability is due to the high energy density of the electrolytes used in a VRFB.

VRFBs are so energy-dense due to the use of highly water-soluble electrolytes. Energy density is defined as the ability to store charge per unit volume. A VRFB has a theoretical energy density of 332 Wh L^{-1}, which is substantially higher than other large scale batteries such as lithium-ion, which has a theoretical energy density of 223 Wh L^{-1} [13]. This increased energy density occurs because as a VRFB discharges, reduction occurs at the cathode and oxidation occurs at the anode. Simultaneously, electrons are transferred through an external circuit and proton ions diffuse across the membrane. [13]. Due to the highly water-soluble electrolytes used in VRFBs, more electrons are transferred across the membrane, allowing for a higher energy density. This means a VRFB is a better investment for UMass than a different but comparably sized battery because it can store more energy despite being the same size. The liquid electrolytes also allow the battery to last longer.

The lifespan of most large scale batteries is cut short due to their charge capacity diminishing over time. Charge capacity is a battery's ability to hold a charge for an extended period of time without losing charge. This loss usually occurs due to unwanted chemical reactions within a battery that lead to solid structures, called dendrites, forming within the battery over time, decreasing its ability to store charge [7]. VRFBs do not have this problem because the liquid electrolytes can be completely drained from the tank while the battery structure is emptied out and cleaned, leading to minimal charge capacity reduction during its lifetime [14]. Thus the lifespan of a VRFB would make it a worthwhile investment for the UMass community.

VRFBs are also incredibly safe technology. VRFBs do not suffer from a process called thermal runaway that plagues other types of batteries, like lithium-ion. Thermal runaway is when the battery cell increases in temperature so the lithium melts, which causes the battery to catch on fire and explode [15]. VRFBs do not have this risk due to the liquid electrolytes being easily used as a cooling system in the battery. The electrolyte constantly flows from the storage tank to the cell and back, greatly increasing its heat transfer capacity and increasing safety [16]. Using a VRFB would immediately put the UMass community at a lower risk of an accident that could hurt people due to their inability to have thermal runaway.

In conclusion, the energy storage team is recommending the use of VRFBs on campus due to its scalability, energy storage capacity, lifespan, and safety.

5. Implementation Plan

According to the Leading By Example (LBE) Council, UMass will need an additional 3.5 MWh of energy storage to supplement the current 4MWh Li-ion battery and satisfy the university's growing energy demand [10]. Successful implementation of a VRFB on campus will require a properly sized system with future scalability potential, adequate space for installation, and integration with existing electrical infrastructure. Being able to meet these requirements at an affordable price ensures that a VFRB is a realistic way for UMass to store energy.

A properly sized campus VRFB system will need to have enough tank volume and cell stacks to meet the 3.5MWh requirement. The tank volume will determine the energy storage capacity (MWh), while the number of cell stacks will determine power output (MW). Using the dimensions of a 0.2MW/0.4MWh VRFB currently used in Switzerland [17] as an example, a linear extrapolation results in ~227,500 L of electrolyte being needed to store 3.5MWh of energy. Similar extrapolation yields about 400 cell stacks per MW of discharge power. Due to differences in electrolyte composition and cell stack design, the actual tank volume and number of cell stacks needed will vary depending on the manufacturer [17]. Furthermore, power capacity is independent of energy storage capacity [18]; after UMass installs a VRFB to meet the minimum 3.5MWh requirement, additional cell stacks or tanks can be installed separately to further increase power and storage capacity, respectively. This ensures that UMass will be able to continue scaling up its VRFB to meet demand well into the future.

Housing the VRFB components in containers will provide a variety of battery configuration options, optimizing space and giving the university ample flexibility when choosing an installation site. One example of a containerized battery is an 8MWh VRFB in Washington, made up of 20 containers, each the size of a standard shipping container [19]. Using this example, a 3.5MWh UMass VRFB is estimated to be about 10 standard shipping containers in size, roughly the size of a basketball court. Stacking these containers on top of one another can further reduce the ground area required for a high-capacity VRFB [3]. Part of Lot 12 or unused land near the CHP would be suitable for installation of this size and would place the VRFB near the center of UMass's electrical infrastructure, reducing electrical losses [20]. Given the variety of ways that the containers can be arranged and stacked, the flexibility provided by this modular approach ensures that UMass will be able to fit a VRFB on campus.

Implementing a VRFB on campus will require management systems to control battery operations and a power conditioning system (PCS) to enable integration with existing infrastructure. The management systems monitor each individual container and regulate temperature, power distribution, and data collection through the use of electrical controls and sensors[20]. The PCS controls power flow from campus energy sources to the VRFB and then helps distribute it back out to the microgrid [20]. Having already installed a lithium-ion battery on campus, UMass has similar systems in place to monitor and integrate a battery with the grid [10]. Although a separate PCS and battery management systems will need to be installed alongside the VRFB, the knowledge gained from having implemented these systems at UMass in the past can still be applied, greatly simplifying the monitoring and integration of a VRFB into the UMass microgrid.

Utilizing a containerized VRFB with sufficient electrolyte volume and battery cell stacks will enable UMass to install a 3.5MWh VRFB on campus and integrate it into the university's microgrid. Should UMass's future energy storage demand exceed 3.5MWh, this implementation method will allow for easy scalability by adding additional stacks and tanks.

6. Project Pros/Cons

After a thorough evaluation of UMass Amherst's energy needs, budget considerations, environmental aspirations, and resource acquisition standards, vanadium redox flow batteries (VRFBs) can offer a feasible and unique solution for this campus. As the Leading by Example Council announced, UMass requires a new battery by 2030. To maintain the original focus of utilizing clean technology while also ensuring UMass can technically support this battery, VRFBs are the best solution for long-term use. Although each potential solution, including VRFBs, have pros and cons, vanadium does offer the most advantages for mitigating carbon and storing energy. Specifically, this system will be considered through four main lenses: energy, economics, environment, and social equity.

Working models of a VRFB system only yield an energy density of around 39.9 Wh/L, with a potential for 70% improvement with future research [21]. However, theoretically they can store up to 109 Wh/L more than a lithium-ion battery (LiB) [6]. What greatly distinguishes this battery from others is its scalability, energy capacity, and longevity. The volume of the electrochemical tanks and concentration of electrolytes affect the storage capacity while the number of cell stacks correlates to the amount of power the battery can discharge. Therefore, modifications and expansions are possible even after commissioning the battery [22]. Additionally, these batteries can achieve 100% depth of discharge without impacting its total life cycle, an issue that exists in most large-scale batteries. For comparison, LiBs only have a depth of discharge of 80-95% [3]. The cycle life and discharge rate demonstrate that vanadium trumps its rivals in employing its maximum capacity over a longer period of time.

The cost of storing energy will significantly decrease a VRFB's dependence on a single metal and reduced maintenance costs. The investment bank Lazard modeled the price of VRFBs against LiBs through a Levelized Cost of Energy Storage. Three possible categories that UMass's application of a VRFB would fall into: wholesale, transmission and distribution, and utility-scale [3]. Since UMass could potentially implement multiple categories, the cost would fall within a range inclusive of these functionalities. For the sake of simplicity and comparing prices, we will assume that this battery will only utilize the application of wholesale as it is the most expensive. This approach utilizes a 400 MWh battery for wholesale applications. The prices for lithium-ion and vanadium are \$204-\$298/MWh and \$257-\$390/MWh, respectively. That means that the upper bound price required for lithium-ion would be \$119,200 and \$156,000 for VRFBs. [3]. Two factors should also be noted: Lazard's model has limitations and the price of vanadium is predicted to decrease by 2030 with potential long-term contracts with vanadium suppliers. If more than one complete discharge cycle occurs per day the LCOS would be cut by 50%. Moreover, since the battery is integrated well with a power system, i.e, the Central Heating Plant at UMass, the cost can be lowered further [3]. Another economic advantage is the longevity of flow batteries. The reaction within a VRFBs is between two electrolytes rather than electrolyte and electrode, resulting in no loss in solution's electroactivity when the discharge cycle is repeated [22]. Therefore, once the electrolyte solutions are bought, it does not need to be replaced within the battery lifetime.

Two primary environmental benefits are that VRFBs hold a lowered risk of thermal runaway & require less oil for production, thus significantly reducing carbon emissions from production compared to LiBs. Thermal runaway refers to combustion that can occur from the degradation over several recharge cycles. Furthermore, the environmental polluting potential of vanadium is quite low, especially compared to many other modern-day systems that lack recyclability potential [23]. In brief, metals with high polluting potentials are typically harmful when leaked into water sources or surrounding organisms or ecosystems if not contained properly.

Vanadium's extraction method provides an avenue to improve the social equity of mineral extraction and use due to multiple sources from byproduct mining. However, cobalt, a key metal for producing LiBs, has records of inhumane mining conditions and the use of child labor in these mines that have raised concern [24]. The US and Japan are already extracting the most vanadium from petroleum residue [25]. Despite vanadium being obtained from petroleum, it still offers a more humane source of metal compared to cobalt and lithium mines.

Following such criteria, vanadium is the apparent answer to UMass’s energy storage and can be an appropriate fit for our campus.

7. Conclusion

The battery storage team was motivated by the call to action outlined in the Leading By Example presentation to assist in finding a new energy storage system that would best suit our ever-growing campus while still attending to the carbon mitigation goals.

UMass estimates the need for a 3.5 MWh energy storage system within the next ten years due to the increase in energy demand. The battery storage team chose to pursue understanding the nuances of implementing a vanadium redox flow battery (VRFB) on campus due to redox flow batteries aligning more closely with the carbon mitigation goals compared to the lithium-ion batteries currently used on campus for energy storage. VRFBs are scalable to fit a demand far larger than current estimates (up to 800 MWh), they have a larger storage capacity, longer lifespan, and do not suffer from thermal runaway that can cause safety hazards unlike the lithium-ion batteries currently used on campus.

Given the appeal of VRFBs, plans were derived for how they could be implemented on campus. Despite the large size of a VRFB compared to an average large scale lithium-ion battery, the design structure allows for creative flexibility of implementation so they could take up as little space as possible. It was estimated that a 3.5MWh VRFB would be the size of 10 standard shipping containers or roughly the size of a basketball court. Some suggestions for placement of this battery could be parking lot 12 or unused land near the central heating plant to avoid electrical losses. After the implementation plan was figured out, the team took a step back to contemplate the economic impact of VRFBs on UMass. It was estimated that the required 3.5 MWh VRFB would cost up to approximately $156,000 but the return on investment would still be high due to the long lifespan of the technology. Due to the technology benefits, ease of implementation on campus, and relatively moderate cost, the battery storage team believes that VRFBs are UMass's best solution to its energy storage needs.

UMass Amherst has always lead from the front when it comes to revolutionary ideas; implementing a Vanadium Redox Flow Battery on campus could be another example of the foresight and innovative thinking that our campus brings to the commonwealth in order to ensure a reduction in carbon emissions and meet the carbon net-zero goal by 2030.

8. Appendices

8a. Calculations

Estimated Tank volume for a 3.5MWh UMass VRFB:

(227,500 L) = (26,000 L / 0.4 MWh) * (3.5 MWh)

Estimated # Cell Stacks:

(400 stacks/MW) = (80 stacks / 0.2 MW)

Estimated # containers needed for a 3.5 MWh UMass VRFB:

(~10 Containers) = 9.75 = (20 / 8MWh) * (3.5MWh) + (1 container/electrical controls)

8b. Sources

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