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# VANADIUM REDOX FLOW BATTERIES FOR GREEN ENERGY GRID STORAGE

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***Abstract—*** *Vanadium redox flow batteries have the potential to bridge the gap between periods of heightened green energy production and heightened energy demand, which is one of the biggest obstacles preventing the wider adoption of green energy sources.*

*A flow battery works by pumping a liquid solution of metallic salts through a core, which consists of a membrane separating an anode and a cathode. Reduction and oxidation reactions take place at the electrodes, creating a difference in electrochemical potential between the solutions on either side of the membrane. This process effectively stores energy.*

*Vanadium redox batteries are especially well suited for grid energy storage because of their durability and stability. This is a consequence of both the anolyte and catholyte solutions consisting of different oxidation states of vanadium, which prevents crossover between the species from resulting in irreparable damage. Their long-life cycle and low maintenance costs often makes vanadium redox batteries a financially viable alternative to other battery technologies.*

*UniEnergy Technologies (UET) constructed a vanadium redox battery system in Pullman Washington. The system is relatively small in terms of storage but demonstrated the potential that vanadium redox flow batteries have if scaled for larger grid storage. Researchers and officials involved with the project are optimistic that vanadium redox flow batteries will allow for the wider adoption of renewable energy sources and help to create a more sustainable future.*

*Key Words—Vanadium Redox Flow Battery, Energy Storage, Grid, Green Energy, Sustainability, Evaluation*

## THE NEED FOR GREEN ENERGY STORAGE

In order to promote a sustainable future and avoid the damaging effects of climate change, scientists and engineers have been researching and developing methods to efficiently store the energy produced by renewable energy sources so that they can be more widely adopted as a practical alternative to fossil fuel burning power plants. Among these alternative sources of energy are solar and wind energy. These two forms of energy have increased in popularity over the past few decades, but the intermittent nature of their energy makes them unreliable and poses challenges to grid operators [1]. By developing batteries for grid energy storage, engineers hope they can create a green energy grid that offers grid operators more control over how the energy produced by renewable sources is distributed.

Currently, grid operators have limited control over how the energy from solar and wind sources is distributed to the user. Solar panels tend to produce the most energy around midday when they are exposed to the most direct sunlight [1]. In places like California that have developed a significant amount of solar infrastructure, the solar panels sometimes risk producing more energy than the grid is equipped to handle [1]. To avoid overloading the grid, grid operators often curtail the production of solar energy during its peak period of production [1]. Operators typically curtail the energy output of solar plants by physically disconnecting some solar panels from the grid [1]. As a consequence, significant amounts of the energy produced by solar panels at certain times of day effectively go to waste. Some calculations suggest curtailment rates may at times exceed 30% for certain solar energy plants, meaning that 30% of solar energy produced at peak hours of solar energy production could be going to waste [1].

Large batteries that store the energy produced by the solar panels could prevent that energy from being wasted. The stored energy could be released back to the grid at a later time, creating a more flexible energy grid that can better accommodate the fluctuating levels of output from solar energy sources [1]. Wind energy sources also face the issue of curtailment, often reaching peak energy production during the night when winds are stronger but demand for energy is relatively low [1]. Wind energy could similarly benefit from increased grid energy storage.

Another major shortcoming of solar and wind energy sources is that their energy production is dependent on weather and time conditions outside of human control. A grid that relies entirely on solar energy would provide no power at night if none of the energy produced by the solar panels is stored. In the more distant future, large scale grid energy storage could be a solution to this issue, supplying energy to the grid when solar or wind sources are not producing energy.

A sustainable energy grid must be able to meet the demands of end users, pose little risk to the environment or human health, and be economic viable for energy companies. This paper seeks to demonstrate that vanadium redox flow batteries, a particular type of battery that is well suited for large scale energy storage, can help make energy grids more sustainable in all of these criteria when deployed and utilized appropriately. Vanadium redox flow batteries essentially function by creating a difference in electrochemical potential between two solutions containing different oxidation states of vanadium ions. This paper will begin by describing how a vanadium redox flow battery works and will proceed by evaluating some of the particular benefits of the technology over other types of batteries. This paper will then discuss how the technology should be promoted in the real world to promote sustainability and will describe a real life example of how a vanadium redox flow battery was able to do so in Pullman, Washington. While research is ongoing and some more developments may be needed before they can be more widely adopted, vanadium redox flow batteries are a promising way to create the grid energy storage needed to make renewable energy sources more practical.

## STRUCTURE AND FUNCTION OF VANADIUM REDOX FLOW BATTERY

In order to evaluate the vanadium redox flow battery, it is necessary to have some understanding of how the technology works. This section will seek to explain the electrochemistry behind vanadium redox flow batteries that allows them to effectively store energy produced by solar panels and wind turbines. First, the parts of the vanadium redox flow battery will be identified and then used in context to explain the processes involved with charging and discharging.

### Structure

Vanadium redox flow batteries consists of several parts that operate together to create an effective energy storage device. Two electrolyte solutions are stored in separate storage tanks [2]. One tank is filled with an electrolyte solution containing vanadium II and vanadium III ions, referred to as the anolyte solution [3]. The other storage tank is filled with an electrolyte solution of $VO^{2+}$ and $VO_2^+$ ions, referred to as the catholyte solution [3]. The vanadium atoms in each species of the electrolyte solutions are at different oxidation states, which is how the oxidation reduction reactions that effectively store and release the battery's energy are able to take place [3]. These reactions are described further in the following subsections.

Pumps move the electrolyte solutions from their storage tanks to the central electrochemical cell [2]. A semipermeable membrane splits the cell in half [2]. This membrane prevents crossover between the anolyte and catholyte solutions [2]. Crossover between anolyte and catholyte species can cause corrosive damage and irreversible chemical reactions in certain types of redox flow batteries [3]. This does not occur in vanadium redox flow batteries, and if crossover does occur the proper vanadium species can be regenerated on either side of the cell through electrochemical manipulation, which is one of the particular benefits of vanadium redox flow batteries [3]. Positively charged hydrogen atoms are able to cross the membrane [3]. The flow of protons between the two sides of the cell chamber is necessary to maintain current flow between electrodes [3]. Figure 1, from a paper published in the *Journal of The Electrochemical Society*, shows a visual representation of the structure of a redox flow battery.

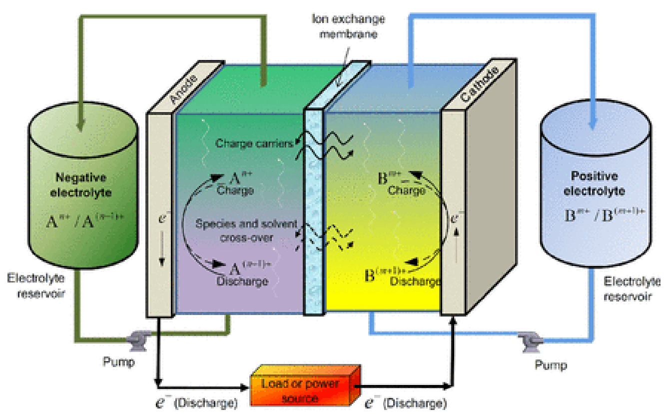


**FIGURE 1 [4]**
**Redox flow battery diagram**

The above figure shows the major components of a generic redox flow battery. The electrolyte solutions are stored in separate tanks and pumped to the electrochemical cell in the center. The ion-selective membrane prevents the electrolyte species from crossing over. Reactions at the porous carbon electrodes create a difference in electrical potential between the electrodes so that they induce a current when connected to a circuit. This current is what sends electricity to the energy grid [4].

There is one electrode on either side of the semi-permeable membrane [2]. The electrodes are where the reduction-oxidation reactions occur. During these reactions, the vanadium ions will either deposit or take an electron from the electrodes [2]. The electrodes will create a current when connected to a circuit as electrons flow, from the electrode where they were deposited toward the opposite electrode where they are taken up by the vanadium ion. This current can be used to send power back to the grid. The electrodes often are made up of porous carbon materials which help to catalyze the redox reactions [4].

### Discharging

When a vanadium redox flow battery is discharging, it is releasing energy that had been stored as electrochemical potential inside the battery. The half reactions below, in figure 2 from a paper in the *Journal of Applied Electrochemistry*, encompass the energy producing and storing reactions that take place inside of a vanadium redox flow battery. The first reaction takes place in the forward direction and the second reaction take place in the reverse direction when the battery is discharging.

$$V^{2+} \leftrightharpoons V^{3+} + e^-, \quad E^0 = -0.26\,\mathrm{V\ vs.\ RHE}$$

$$VO^{2+} + H_2O \leftrightharpoons VO_2{}^+ + 2H^+ + e^-, \quad E^0 = 1.00\,\mathrm{V\ vs.\ RHE}$$

**FIGURE 2 [3]**
**Half reactions of the anolyte and catholyte species**

In one electrolyte solution, the $V^{2+}$ ion is oxidized to $V^{3+}$ and an electron is released to the electrode. The electrode takes on negative charge when it accepts the electron, so it is referred to as the anode. The electrolyte solution containing the $V^{2+}$ and $V^{3+}$ is referred to as the anolyte because it is associated with the anode [2].

On the other side of the cell, $VO_2{}^+$ is reduced to $VO^{2+}$, taking in an electron from the electrode. Since the electrode is losing positive charge, it is called the cathode. Therefore, the solution containing $VO^{2+}$ and $VO_2{}^+$ is called the catholyte.

Discharging is a thermodynamically favorable process, so it will occur spontaneously as long as the electrodes are connected by some circuit. If the electrodes are not connected, no reactions will occur, and the energy can be considered to be stored in the chemical potential of the reactants. The reactants used up in the discharging process are regenerated as products in the charging process.

### Charging

The charging process is also explained by the reactions displayed in figure 2. However, in the case of charging, the first reaction is happening in the reverse direction while the second reaction is happening in the forward reaction.

This means that on the anolyte side of the cell, $V^{3+}$ is reduced to $V^{2+}$ by gaining an electron from the anode. Although the anode is now acting as an electron depositor instead of an electron acceptor, it is still referred to as the anode because such designations are based off of the discharging process. This means the solution with $V^{2+}$ and $V^{3+}$ is always referred to as the anolyte solution. Similarly, the $VO_2{}^+$ and $VO^{2+}$ solution is always designated as the catholyte solution.

On the catholyte side of the cell, $VO^{2+}$ is oxidized to form $VO_2{}^+$ and an electron is released to the cathode. When the reactions occur in this direction, they are thermodynamically unfavorable and need energy input to occur. This energy input can come from any source, including solar and wind energy sources, and it allows for the formation of products at higher chemical potentials. The carbon on the electrodes acts as a catalyst for these reactions, reducing the activation energy so that most of the energy put into the battery is stored in the chemical potential of the products and not lost to overcoming the activation barrier associated with the reactions [4]. The battery can be considered fully charged when almost all of the vanadium in the anolyte exists as $V^{2+}$ and all vanadium in the catholyte exists as $VO_2{}^+$.

Having now established a firm background in the electrochemistry behind vanadium redox flow batteries, the battery can be evaluated against other types of batteries that could be used for grid energy storage.

## EVALUATION OF VANADIUM REDOX FLOW BATTERIES

This section will seek to explain the benefits and shortcomings of using vanadium redox flow batteries over other types of batteries often used for grid energy storage. Our comparisons will focus on the lead acid battery, which is not a redox flow battery, and the iron chromium redox flow battery, which has a design that is similar to vanadium redox flow batteries but with different chemistries. This analysis will be primarily based off of data from research studies about the different types of batteries and will emphasize the factors affecting the sustainability of the vanadium redox flow battery.

### Benefits of Vanadium Redox Flow Batteries Over Lead Acid Batteries

Vanadium redox flow batteries have many benefits over lead acid batteries. One benefit vanadium redox flow batteries have over lead acid batteries is efficiency. Efficiency is defined as the percent of the energy input into the battery which can be converted back to usable electric energy. Vanadium redox flow batteries have an efficiency ranging from 65%-75%, meaning that 65%-75% of the energy stored in the battery is able to be used as power for the grid while the remaining 25%-35% is converted to other forms of energy such as heat. Meanwhile, lead acid batteries only have an efficiency of about 45%, which indicates that about 55% of the energy stored in the battery is rendered unusable by conversion to other forms of energy [5].

Another benefit vanadium redox flow batteries have over lead acid batteries is self-discharge. Self-discharge is a measure of the percent of energy that is dissipated in a battery while not in use. Self-discharge can occur for a number of reasons, but mostly occurs when two or more of the species in a container react, converting the stored potential energy into chemical and heat energy [6]. Vanadium redox flow batteries manage to have a self-discharge of nearly 0%. They are able to accomplish this since the design of the battery keeps the active species in separate containers, which minimizes the ability of the species to chemically react when the battery is not in use. Meanwhile lead acid batteries have a self-discharge of 5%, meaning that, on top of the 55% of energy lost in efficiency, up to another 5% is lost while the battery sits idle [7].

Vanadium redox flow batteries also tend to outperform lead acid batteries in terms of energy density. Energy density is the amount of energy, measured in watt-hours, which is stored in one liter of the solution. Vanadium redox flow batteries have been measured to have an energy density ranging from 15-25 watt-hours per liter, but theoretically could have a value ranging from 30-47 watt-hours per liter. Lead acid batteries, however, have only been measured to have an energy density ranging from 12-18 watt-hours per liter. However, if more developments are made, lead acid batteries could theoretically have an energy density of up to 40 watt-hours per liter [5].

In addition to being more energy dense, vanadium redox flow batteries have a greater depth of discharge than lead acid batteries. The depth of discharge, which is the inverse of the state of charge, is a percent measure of how much charge is able to be discharged in one cycle of the battery [6]. The depth of discharge of a vanadium redox flow battery is around 75%, meaning it can discharge up to 75% of its current energy storage in one cycle. Meanwhile, a lead acid battery only has a depth of discharge ranging from about 25%-30%, meaning it can only discharge that amount of energy in one cycle [5].

One of the most notable benefits of vanadium redox flow batteries over lead acid batteries is that vanadium batteries are able to support many more life cycles, giving them a very long product life span. The number of life cycles it can run through is the measure of how many times the battery can be charged and discharged (one cycle of charge and discharge is equal to one life cycle) before a certain component of the battery decays to the point where it can only store 80% of the energy it could initially [8]. Vanadium redox flow batteries have been determined to produce over 10,000 life cycles, which generally corresponds to lasting between 15-20 years before replacement is needed. Meanwhile, lead acid batteries can only produce about 1500 life cycles and have rarely been seen to last more than 5 years [5].

Furthermore, vanadium redox flow batteries avoid many of the negative environmental consequences associated with lead acid batteries. The use of vanadium in vanadium redox flow batteries is much safer for the environment than other chemicals used in batteries, such as lead and cadmium, as it is significantly less toxic. Conversely, the use of lead in lead acid batteries is significantly more harmful to the environment than vanadium, as it is very toxic. However, the use of vanadium versus lead in the battery is not the only factor which contributes to vanadium redox batteries having a smaller environmental impact than lead acid batteries. The design of vanadium redox flow batteries, when used in stationary applications, produces only 7%-25% of the environmentally harmful emissions (CO2, SO2, CO, CH4, NOx) that lead acid batteries emit [5].

Cost comparisons between the two batteries suggest different results depending on which costs are being considered. When considering the upfront cost of the two types of batteries, the battery that is more expensive can depend on the specifications of the particular model of each battery being compared. What is consistent across models of each battery is that the maintenance costs of vanadium redox flow batteries are significantly less than the maintenance costs of lead acid batteries. The vanadium redox flow batteries have a maintenance cost of about $0.008 per kilowatt-hour, while lead acid batteries have a maintenance cost of about $0.02 per kilowatt-hour [5].

## Shortcomings of Vanadium Redox Flow Batteries When Compared to Lead Acid Batteries

Although vanadium redox batteries are fairly efficient and affordable form of grid energy storage, they do have a few shortcomings. For example, vanadium redox flow batteries are much larger than lead acid batteries. A 40-64V, 14kW vanadium redox flow battery has dimensions of about 0.75 meters long by 1.5 meters wide by 2.0 meters tall for a single cell. Meanwhile, a similar lead acid battery has dimensions of 0.314 meters long by 0.183 meters wide by 0.388 meters tall for a single cell [9][10].

Lead acid batteries also outperform vanadium redox flow batteries in terms of power density. Power density is similar to energy density but instead of measuring the energy (measured in watt-hours) it is the measure of power (measured in watts) per kilogram. Vanadium redox flow batteries have been measured to possess a power density of about 166 watts per kilogram. This is attributed to the limited solubility of the vanadium species, as well as its low specific energy densities. This low power density suggests that vanadium redox flow batteries are not desirable for systems that require high power per unit of volume, such as transportation systems. However, when considering which battery is better suited for grid storage, a low power density is not as critical a factor. For comparison, lead acid batteries typically have a power density of 370 watts per kilogram. This is why lead acid batteries are often used in cars, where it is important to maximize power output and minimize weight. For stationary grid energy storage, lead acid batteries higher power density is not as important [5].

Finally, one of the biggest limitations of the vanadium redox battery compared to lead acid batteries is its relative newness as compared to lead acid batteries. The lead acid battery was created in 1860 by French physicist Gaston Planté, allowing for extensive research throughout its existence. Meanwhile, the first working vanadium redox flow battery was not created until the 1980's, giving researchers significantly less time to optimize the battery and its components [11]. However, this limitation may also be one of the greatest benefits of vanadium redox flow batteries, because there is a lot of room for innovation and improvement.

## Comparison of Vanadium Redox Flow Batteries and Iron-chromium Redox Flow Batteries

The limitation of underdevelopment also attributes to why the vanadium redox flow battery could be used over another type of flow battery, the iron-chromium redox flow battery. As stated above, the difference between vanadium redox flow batteries and lead acid batteries made comparing the prices between the two difficult. However, since the vanadium redox flow battery is so similar to the iron-chromium redox flow battery, comparisons between the two are more straightforward. Evaluation of both concludes that there are two significant differences between each battery.

The first is capital cost, which is the cost that it takes to bring the installation of a battery to operable status. Capital cost is measured in US dollars ($) per kilowatt-hour (kWh). For vanadium redox flow batteries, the capital cost is around $229 per kilowatt-hour, since vanadium is a rarer and therefore more expensive metal. Since iron and chromium are both low cost metals, the capital cost is around $194 per kilowatt-hour [12]. This would suggest that iron-chromium redox flow batteries are less expensive and more desirable than the vanadium redox flow battery.

However, despite lowering upfront costs, the use of iron and chromium in flow batteries creates another set of problems associated with running the battery that can offset initial savings. These problems include imbalanced, prolonged life cycles, significantly faster decay, and self-discharge related to the semi-permeable membrane allowing the iron and chromium species to react while the battery is idle. Each of these problems must be addressed in different ways, such as the addition of catalysts, premixing of iron and chromium salts, or the additional remixing of the electrolytes. All of these add to the iron-chromium battery's maintenance cost and creates a more complex system. The relative simplicity of vanadium redox flow batteries, as compared to the iron-chromium redox flow battery, combined with the potential for development and possibility of lowering the capital cost make the vanadium redox flow battery an overall more promising option for green energy storage [12]. The vanadium redox flow battery has proven itself a viable battery for grid energy storage in real world applications outside of a research setting.

## The Sustainability of the Vanadium Redox Flow Battery

These different aspects are important because they allow for an evaluation of the sustainability of vanadium redox flow batteries. Sustainability can be defined within three branches which are social development, economic development, and environmental protection [13]. Social development, as related to vanadium redox flow batteries, is about maintaining and/or improving public access to power without compromising safety. The high efficiency, low level of self-discharge, and long product life of a vanadium redox flow battery allows it to contribute to a power grid which is better equipped to meet the demands of the public and maintain and improve public access to power. Another branch of sustainability is environmental protection, which is defined as reducing the negative impacts the human species has on the environment [13]. Some aspects that might affect the evaluation of vanadium redox flow batteries as a sustainable device would be size, the chemicals used in the battery, and emissions. Vanadium redox flow batteries can be considered environmentally sustainable because they do not contain toxic chemicals and can help reduce emissions by making green energy sources more viable. One area for environmental sustainability the battery does not fulfill is size, as the vanadium redox flow battery is very large. However, in the context of grid energy storage, size is not the most important factor when considering environmental sustainability. Size is far outweighed by the potential of vanadium redox flow batteries to significantly offset harmful emissions, such as carbon and methane. The last branch of sustainability is economic development, which in context means that the battery must be affordable enough to be economically viable for widespread adoption. As addressed above, the exact cost of vanadium redox flow batteries is unclear, but they appear to be similar in price to lead acid batteries. This combined with the lower maintenance cost and longer lifetime provide evidence that the sustainability of the vanadium redox flow battery is at least the same as, if not more than, the lead acid battery, in regard to economic development [13].

# RESPONSIBLE DEPLOYMENT OF VANADIUM REDOX FLOW BATTERIES

This section will discuss the circumstances in which the deployment of a vanadium redox flow battery can improve the sustainability of an energy grid. The first subsection will describe how the un-strategic deployment of the technology can lead to a net rise in emissions and create a less sustainable energy grid. The second subsection will describe how a strategically deployed vanadium redox flow battery in Pullman, Washington, was able to help create a more sustainable energy grid.

## How Bulk Energy Storage Can Increase an Energy Grid's Emissions

Although vanadium redox flow batteries can help promote a sustainable grid by providing bulk energy storage, it is important that the technology is deployed within the proper context. A paper from the journal *Environmental Science & Technology* demonstrated, through a complex set of models, that implementing bulk grid storage in many places across the US can lead to increased emissions of CO2 and other harmful gasses [14]. The models used to analyze each energy grid took into account several factors, including energy costs throughout the day, the sources of energy each grid relied on, and the spending habits of energy companies [14].

This seemingly counterintuitive finding is largely a consequence of energy companies partaking in the practice of energy arbitrage. Through this practice, energy companies are able to increase profits by taking advantage of the difference in energy prices throughout the day. Energy companies will tend to buy energy at night when the energy is cheaper because the demand is low. Energy companies will then store that energy and release it during the day, when increased demand drives up the price of that energy. Thus, by the process of energy arbitrage, bulk energy storage allows energy companies to increase their profits [15].

While this may make vanadium redox flow batteries and other bulk energy storage an economically sustainable investment for energy companies and grid operators, this can have damaging consequences for the environment. Often times, the energy that grid operators store at night does not come from renewable sources but instead comes from emission releasing sources, like coal of natural gas power plants. When this energy is stored in a battery, some of the energy is lost due to the imperfect efficiency of batteries. This means that introducing a battery to a grid that heavily depends on coal or natural gas results in more emissions being released to the environment to send the same amount of energy to the grid because some of the produced energy is lost in the batteries, requiring more fuels to be burned. This is how the researches behind the paper published in *Environmental Science and Technology* were able to find that grid energy storage can lead to increased carbon emissions when implemented on grids lacking green energy infrastructure. Other factors influenced their analysis, but the practice of energy arbitrage by energy companies best demonstrates how grid energy storage systems, like vanadium redox flow batteries, can be economically viable investments for energy companies but have negative consequences on the environment.

The researches behind the *Environmental Science and Technology* paper note that although bulk energy storage can have environmental consequences, when deployed and utilized responsibly they can have their intended impact of reducing carbon and other gaseous emissions. The following subsection demonstrates how a vanadium redox flow battery was able to provide the grid energy storage needed to promote a more sustainable and efficient energy grid.

## Real World Demonstration of a Vanadium Redox Flow Battery

This potential of the vanadium redox flow battery is already being displayed in Pullman Washington. Pullman is the site of a battery with 4-megawatt-hours of storage capacity that was installed in 2015 [16]. When installed, it was the largest of its kind, bigger than any battery within North America and the European Union [17]. Since, then larger batteries have been put in place at different locations, but its size at the time of implementation was groundbreaking. The battery was not intended to be a pilot of the technology but was instead very much considered to be a grid asset. The battery is mainly used for load shifting, frequency regulation, and voltage regulation. Load shifting is when the consumption of high wattage loads is moved to different times. Frequency regulation is when a power grid operator manipulates the frequency within a system whenever it gets too high or too low. Voltage regulation is when a power grid operator manipulates the voltage within a system whenever it gets too high or too low. The battery also supports the manufacturer Schweitzer Engineering Laboratories, who bought the battery, offering an uninterruptible power supply and black start [16]. Black start is the process of restoring an electric power station or a part of an electric grid to operation without relying on the external electric power transmission network to recover from a total or partial shutdown. During power outages, Schweitzer will use the batteries as a backup electrical source instead of diesel-fired generators. Electricity from the batteries is available almost instantly, while the generators take about 15 minutes to fire up. The batteries could power Schweitzer Engineering Laboratories factories for about three hours [16]. During extremely hot or cold days, when demand for electricity is high, Avista, the energy company in charge of the battery, will also draw on the energy stored in the batteries to level out spikes in demand. According to

David Whitehead, Schweitzer Engineering's vice president of Research and Development, the batteries could store the output of about one wind turbine. At the battery's launch in Pullman, Whitehead said, "That might sound small, but it's an enormous step forward in battery technology: This is large-scale energy storage" [17]. This shows the incredible potential these batteries have. If vanadium redox flow batteries could be further improved, an immense amount of energy could be saved and stored.

In 2017, an even larger battery was put in place in Snohomish County, Washington. With the potential to store 8-megawatt-hours, the new battery shows how further development is allowing us to store more and more energy, hopefully leading to a day when the world will be completely using green energy [18]. When asked about the Pullman battery as it was being activated, Tom Karier, Eastern Washington representative for the Northwest Power and Conservation Council said, "I think it's interesting that these are being built, it's the missing puzzle piece for clean energy resources in the Northwest. With storage, we'll be able to meet the peak electrical requirements, which wind and solar can't do now" [16]. This quote summarizes how the application in Pullman shows the future promise of the technology and the value of storing green energy. Overall, the application in Pullman displays the incredible potential of vanadium redox flow batteries.

## WHY DOES THIS MATTER?

Vanadium redox flow batteries have the potential to provide the grid energy storage necessary for energy grids to further integrate greener sources of energy. Grid energy storage offers flexibility to grid operators, allowing them to store energy that otherwise would have been put to waste through curtailment and distribute it at a later time. The vanadium redox flow battery's design utilizes four different oxidation states of vanadium and two sets of oxidation reduction reactions to buildup electrochemical potential between the two sides of the cell when the battery is being charged. The difference in potential across the battery can then be used to send current across a power grid.

Vanadium redox flow batteries have some particular benefits that make them well suited for grid energy storage. They outperform lead acid batteries in a number of criteria, including efficiency and product life span while also being more environmentally friendly. The simplicity of having all vanadium-based electrolyte lowers the maintenance costs of vanadium redox flow batteries and makes them a more attractive option for grid energy storage than other types of redox flow batteries, like iron chromium batteries. Vanadium redox flow batteries are not the most power dense type of battery, but compactness is not the most critical criteria for grid energy storage. While the battery does have some shortcomings, future research and development has the potential to optimize vanadium redox flow batteries to overcome these shortcomings.

The potential of vanadium redox flow batteries has already been seen in real world implementations of the technology. In Pullman, Washington, the battery acts as a backup generator for Schweitzer Engineering Laboratories in place of diesel generators and also acts as a grid asset, helping to redistribute load on the energy grid. More vanadium redox batteries have been implemented in other places throughout the world and have had similar success in creating a more flexible energy grid better equipped to accommodate green energy sources.

In order for the batteries to have a positive impact on the sustainability of energy grids, it is important that they are paired with significant amounts of green energy infrastructure that does not release emissions. Otherwise, the use of the batteries for energy arbitrage by energy companies can result in a grid that emits more greenhouse gasses. However, when used appropriately, vanadium redox flow batteries can make energy grids more sustainable, meaning that they have a reduced impact on the environment and are profitable for grid operators while still meeting the energy needs of the end user.

While further research and development is ongoing, vanadium redox flow batteries have shown great potential as a fairly efficient and affordable method of grid energy storage. As more units are installed, grids gain more control over how energy is distributed and can avoid having to curtail energy production from solar or wind sources. Maximizing the effective output of renewable sources and having increased control over how that energy is distributed can reduce energy grids' dependence on fossil fuel power plants for regulating power outputs and lead to a net reduction in the production of greenhouse gasses. Ultimately, vanadium redox flow batteries are one piece of the larger challenge of preventing the potentially devastating consequences of climate change.

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