Advantages and Applications of Vanadium Redox Flow Batteries in Sustainable Development

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Abstract: The current field of sustainable development is undergoing unprecedented changes, and the proposal of various renewable energy sources is impacting people's existing environmental protection concepts and ecological thinking. This makes the energy sector a subject of great attention. In the energy field, the battery is of great concern, because the green development of the battery has become an important development goal of future science and technology. This paper discusses the application in vanadium redox flow batteries in sustainability. Results show that the vanadium redox flow batteries have the advantage inn areas mainly include high density and stability, less environmental impact and shorter life span. Vanadium redox flow battery could address three sustainable development goals: solving poverty, being a form of clean energy, involving industrial development, and building a sustainable city. Poverty could be solved by promoting renewable energy development, improving widespread accessity to electricity in rural areas (which need vanadium redox flow batteries), and job creation. The battery can also can increase the usage of clean energy as it is the major component in many kinds of clean energy. It could also used in industrial development with the characteristics of energy conversion efficiency and quick response speed, which are also useful in contributing to the plan for sustainable city in the future.

1 INTRODUCTION

The concept of sustainable development is a significant theory put forward by the United Nations to solve the problem of human development in the future. It covers 19 fields, including tackling poverty, renewable and clean energy, and industrial development. These aspects can promote the coordinated development of ecology and improve energy efficiency, optimising resource allocation and maximising resource upgrade. The world faces a severe energy crisis in the current era, with soaring energy prices and widespread shortages hindering economic development. Storage inadequacies and energy wastage contribute significantly to this crisis. There is a pressing need to advance energy storage technologies to mitigate these challenges (Pathak and Gupta, 2018). The adoption of the Sustainable Development Goals also marks the double cycle and multi-dimensional cross-field cooperation between countries from internal to external, which jointly address the important directions of human development that may challenge the future. Nations have become acutely aware of the irreconcilable contradiction between the availability of resources and the inexhaustible desires of humanity. However, the concept of sustainable development can largely alleviate this contradiction.

Nowadays, in the energy field, many new energy sources are rising, for example, photovoltaic, electric panels, hydrogen energy, and various energy storage methods are also frequently used. Among them, the development of batteries in this process has been large-scale usage and promotion. The batteries are participating not only in areas that could be obvious but also in areas related to sustainable development goals. In this paper, batteries are chosen to be vanadium flow batteries among various batteries such as lithium-ion batteries, lithium iron phosphate batteries, and hydrogen batteries. That is because vanadium flow batteries have prosperous prospects and a high vision in the future in promoting sustainable development. This paper discusses the different functions of vanadium redox flow batteries in reducing poverty, promoting clean energy, and intervening in industry and urban planning. The engagement of batteries in these areas could be analyzed from the perspective of battery energy efficiency and life cycle aspects, which could demonstrate the advantage of vanadium redox flow

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battery use in the practice area. This alignment underscores the multifaceted benefits of addressing global challenges and advancing sustainability objectives (Parasuraman et al., 2013).

2 BACKGROUND OF VANADIUM REDOX FLOW BATTERIES

A flow battery is one in which two liquids are separated by a membrane and circulated to enable ion exchange between them, including iron-chromium flow battery, zinc-bromine flow battery, zinc-air flow battery, and vanadium flow battery. It has characteristics of a long lifetime, recyclable, good reliability and safety, and high efficiency. To be more specific in focusing on vanadium redox flow battery, it is a form of flow battery which presents a promising solution due to their extended lifespan, reliability, and recyclable electrolytes. Currently, most researches aim to enhance its efficiency and reduce costs, positioning them as strong contenders, particularly for large-scale energy storage installations, competing with lithium batteries.

3 CHARACTERISTICS OF VANADIUM REDOX FLOW BATTERY

The first technique of vanadium redox flow battery is it can reduce environmental impact and enhances safety. Using vanadium ions in aqueous solutions minimizes environmental repercussions in production, operation, and disposal, diminishing the ecological footprint. This approach also mitigates safety concerns tied to battery usage. Using non-toxic materials significantly lowers risks to human health and the environment during handling and transportation. The second technique is thermal storage technology, which is the storage of heat for later use. Heat can be stored from hours to months and the storage scale is small to large. For example, heat energy stored in the summer can be used in the winter. The third technique is electrochemical energy storage, which transforms the electric energy into chemical energy for later use. Superconducting magnetic energy storage is an electric energy storage device because of the zero resistance of superconductors, improving the stability of the whole power system. A sodium-sulfur battery is a molten battery that has the characteristic of high energy density.

3.1 Advantages of Vanadium Redox Flow Battery

Vanadium redox flow battery excels in energy storage, offering independent power and energy adjustment for tailored output based on practical needs (Alotto et al., 2014). Its rapid energy release meets high-power demands, enhancing system flexibility and adaptability.

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Table 1: The environmental impact and safeness issue of energies (original)

Technology	W-W h independency	Environmental impact	Safeness issue
Thermal energy storage	Yes	Mild	Mild
Electrochemical energy storage	NO	Low	low
Superconducting magetic energy storage	NO	Low	Low
Sodium sulfur	No	Low	Low

The vanadium redox flow battery excels in rapid charging and extended lifespan. Its swift charging is crucial for applications requiring quick energy influx. The prolonged lifecycle enhances system reliability and cost-effectiveness, reducing the need for frequent replacements and maintenance (Koçak et al., 2020) (Table 2).

Table 2: The response time and lifespan of energies (original)

Technology	Response time	Cycle life $x10^3$
Thermal energy storage	min	10
Superconducting magnetic energy storage	ms	none
Electrochemical energy storage	ms	3
Sodium sulfur	s	6

Vanadium redox flow batteries have the following characteristics:
(1) Power: 0.03-7 MV
(2) Capacity: <10 MVh
(3) Specific energy: 10-30kWh/m^3
(4) Efficiency: 75-85%
(5) Lifetime: 12,000 cycles

3.2 Disadvantages of Vanadium Redox Flow Battery

Despite the advantages of the all-vanadium redox flow battery, certain drawbacks must be acknowledged. Firstly, its relatively low energy density implies limited energy storage within the same volume. For instance, compared to high-energy-density batteries, the vanadium redox flow battery may require a larger physical footprint to achieve equivalent energy storage, presenting a challenge in space-constrained applications.
Secondly, the vanadium redox flow battery's substantial size and complex installation pose challenges. The design, relying on liquid flow, necessitates sizable storage tanks and intricate pipeline systems, complicating the installation process and demanding additional space (Figure 1). This could limit the deployment of vanadium redox flow batteries in urban environments where land and space are at a premium

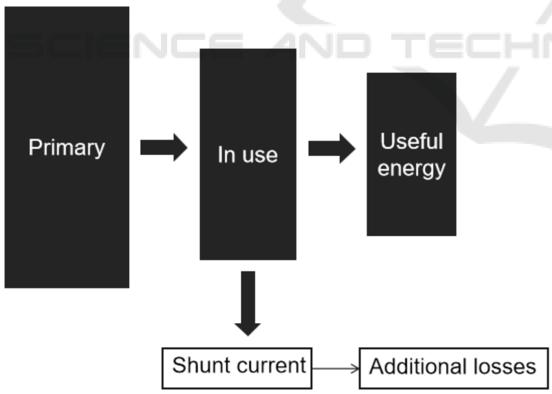

Figure 1: Workflow of the energy application (original)

Thirdly, the energy conversion process of vanadium redox flow battery introduces the efficiency loss of charge, discharge and total energy conversion. While technological advances can mitigate these losses, addressing this issue is critical to prevent system performance degradation, increased operating costs and energy system complexity. In addition, the technical complexity of vanadium redox flow battery exceeds that of conventional batteries, requiring complex control and monitoring systems for proper operation and maintenance (Zhang et al., 2012). This complexity requires greater technical expertise and investment, presenting challenges in building and sustaining systems.

4 APPLICATIONS AND INFLUENCE OF VANADIUM REDOX FLOW BATTERY

4.1 Economic-Society Influence

Vanadium flow batteries can play a significant role in reducing poverty and absolute poverty. Some poor countries and regions need more effective and efficient resource allocation. As a kind of energy storage battery with high efficiency and high energy conversion functions, vanadium flow batteries can better contribute to the power system in poor areas at higher levels. This can be broken down into several aspects, including promoting renewable energy development, improving access to electricity in rural and remote areas, and creating jobs.
Firstly, it could promote renewable energy development: It could provide a stable power supply for residents in rural and remote areas. Energy costs and dependence on fossil fuels can be reduced, providing economical energy solutions for poor areas. As an important part of renewable energy, energy storage flow batteries can help local energy sources to be more diversified, as well as better ecological balance, and make full use of energy efficiency. The local application of renewable energy helps to reduce the use and mining of coal as the main energy source, which can greatly reduce local pollution. The cost of environmental treatment caused by pollution may bring great difficulties to local industrial upgrading and investment promotion, thus further increasing the local poverty rate. When renewable energy comes to the region, there would be more emerging industries in the energy sector, opportunities to help the local economy, and real resources, productivity and productivity would be largely improved. At the same time, a stable supply of electricity from the power system can help increase electricity consumption in poor areas. This means that the electricity demand of the local people can be guaranteed, and the people's livelihood can also provide support for the local people, which is quite useful for consolidating the local energy base and energy development and economic prospects.
Secondly, it can improve access to electricity in rural and remote areas. It could be used as a backup power

supply or tool to adjust the power grid load to improve the stability and reliability of power supply in rural areas. Having a stable power supply in remote areas can help local industries develop. Because industrial development requires a large amount of electricity for a long time, if large-scale industrial development is carried out in the countryside, it can improve the local industrial appreciation, which attracts more investment because there is a better industrial cluster here. This industrial cluster can help create local characteristic industries, stimulating investment and consumption. Therefore, it can help lift local people out of poverty. Many countries, including China, are now integrating rural power grids in this way to boost local industrial efficiency and capacity. Therefore, the scale of rural electricity consumption will gradually develop in the direction of the city. This could slowly integrate the rural power system and integrate the economic development of each rural area into one piece.

Thirdly, in this production of battery, it has job creation. Jobs can be created in the manufacturing and recycling of batteries. An important way to get rid of poverty is to boost the employment of residents. If the employment problem is solved, local consumption and investment will flood. The premise of employment is to allow local people to have more job opportunities, which requires more industries to join the development of rural areas. The packaging and assembly of flow batteries, as well as the manufacturing aspects, can be done locally, which could reduce transportation costs and help local businesses grow. In the process, it can also slowly form a unified large market and encourage competition, learn advanced technology and management experience from other places, and carry out technology integration so that residents can have more jobs and thus have more disposable income to improve the local economy.

4.2 Introducing Clean Energy

The battery can balance the power grid load by storing and releasing energy, promoting utilization of renewable energy and providing technical support for large-scale grid-connected power generation of renewable energy. Vanadium flow batteries reduce greenhouse gas and air pollutant emissions and improve environmental and climate conditions.

Taking the Hongsha Hydropower Station in Hunan as an example (Tang, 2019), it can be known that the purpose of this hydropower station includes:

(1) To accelerate the development and utilization of hydropower resources, vigorously develop rural hydropower, and actively construct new rural hydropower electrification, small hydropower generation ecological protection projects and rural hydropower efficiency expansion and transformation projects.

(2) To optimize the allocation of water resources (Chakraei et al., 2021), improve the structure of water supply sources, and improve the allocation capacity of water resources and the degree of water supply security. Effective use of surface water and groundwater, air cloud water resources and reclaimed water according to local conditions.

(3) To rationally allocate the water resources needs of urbanized areas, major agricultural production areas and key ecological functional, coordinate the allocation of water resources in river basins and regions and comprehensively balance the water resources needs of different regions and industries and the requirements of ecological environmental protection.

(4) To focus on ensuring the safety of water supply for urban and rural residents, major grain-producing areas, energy bases and important cities, and improve the capacity of emergency water supply in response to droughts and emergencies.

This goal is also the goal of most hydropower stations. Combined with vanadium redox flow battery, the goal is easier to achieve, and the main realization process is as follows:

Aiming at the efficiency and energy saving of the first target flow battery, it can greatly help develop and utilize hydropower resources. It can be installed in the power system. To help increase the efficiency of converting water energy to electricity, to increase the power generation rate, which could help industrial production. The flow battery cost is relatively inexpensive, in line with the regional requirements of vigorously developing rural hydropower. The electrification of new rural areas and the expansion of rural hydropower efficiency are very suitable for the flow vanadium battery because the whole sail flow battery can carry much power to undertake many industrial production tasks.

To solve the second goal, improving the deployment capacity of water resources and the degree of water supply security, the long life cycle of the vanadium flow battery could be more stable. It can be recycled, but also through effective maintenance, to ensure it continues working. The water recovery of this vanadium flow battery can also be done.

The application of vanadium flow batteries can also help solve the water resources needs of the third urbanized area and coordinate the allocation of water resources in the basin region, balancing the water resources needs of various industries in various regions, because vanadium flow batteries can be used in various production links. Similarly, much energy will be consumed in water demand scheduling, whether it is a city or a country. At this time, introducing the all-vanadium flow battery clean energy can help ecological reorganization and improve efficiency. The durability of all-vanadium flow batteries is very long, so the flow battery will also play a vital role in long-distance transportation to balance the links between various industries in various regions.

For the fourth goal, the main field of all-vanadium flow batteries is to ensure water supply safety and emergency water supply support capacity. All-vanadium flow batteries can be subject to emergency dispatch and rapid production. Similarly, only one flow battery is required to bear the working power of millions of watts. Therefore, the rapid response of vanadium flow batteries in response to huge floods and various disasters in the field of clean energy applications can also help the ecological environment better recovery.

4.3 Influence in Industry Development and Building a Sustainable City

The broad scope and scalability of industrial applications allow vanadium flow batteries to participate in various assembly steps of industrial production (Kear et al., 2012). In other words, vanadium flow batteries have the characteristics of energy saving, high efficiency and wide application in industry. Productivity in the field of industry emphasizes that efficiency is crucial. Therefore, with vanadium solution by the battery as a part of clean energy, efficiency can also be guaranteed, making the pace of industrial production faster and obtaining higher output—minimum energy consumption. Strengthen the allocation of total factor resources. The future is also promising in the industrial sector. It can ensure a stable energy supply. In the case of peak energy demand or insufficient renewable energy generation, vanadium flow batteries can provide a stable power supply and ensure the continuity of industrial production. Vanadium redox flow battery can Improve production efficiency. The rapid charging and discharging ability of vanadium flow batteries can reduce the uptime of industrial equipment and improve production efficiency. Vanadium redox flow batteries have the characteristics of reducing energy consumption and operating costs: The energy conversion efficiency of vanadium flow batteries can reduce energy waste and loss.

The transformation of results in industry can also empower the construction of sustainable cities. Some of their experiences are shared because an important part of building sustainable cities is building sustainable industries, which is down to specific applications. Every aspect of the city contains the shadow of the application of clean energy. For example, the construction of energy storage systems, energy distribution and allocation systems and better management skills are important parts of the layout for the city's future development. The intervention of sustainable clean energy can help resources not be wasted effective use, and in the future, there can be better results transformation so that people will not be excessive development and waste, and ignore the current energy gap in the future so that the field of energy attention will become relatively small.

Vanadium redox flow battery can be applied in many areas: (1) Energy storage system: provide a stable and reliable energy supply for the city. (2) Smart microgrids: It's a core component of smart microgrids to integrate and optimize distributed energy sources (Jefimowski et al., 2020). (3) Electric vehicle charging facilities: vanadium flow batteries can be used in electric vehicle charging facilities to provide fast charging services. (4) Distributed energy system: vanadium flow batteries can achieve decentralized management and operation of energy. Distributed energy systems can improve the management level so that they are suitable for city construction (Li et al., 2017).

5 CONCLUSION

This paper discusses the application of Vanadium redox flow batteries in sustainability. Advantages mainly include high energy density, long cycle life, safety, durable cost-effective, and unwavering low environmental impact. The typical advantage is high energy efficiency. Take a 35kW vanadium flow battery at 110 L/min flow as an example, the energy efficiency can be maintained at a high level of more than 70%. Another advantage is the long life cycle, which can take up to 30 years. Its disadvantage is that recycling large space due to its size requires a constant flow of fluids to maintain its charge at a high investment. In this paper, the social-economical aspects are taken into consideration.

Vanadium redox flow battery could be applied in three fields. For poverty, it could be achieved by promoting renewable energy development, improving access to electricity in rural and remote areas and job creation. For clean energy, it can promote the utilization of renewable energy and provide technical support for large-scale grid-connected power generation of renewable energy. It can reduce greenhouse gas and air pollutant emissions. For industry, it is a stable energy supply, improving production efficiency and reducing energy consumption and operating costs. Sustainable cities could be achieved by energy storage system, smart microgrids, electric vehicle charging facilities and distributed energy system. These features show that in sustainable development, the vanadium flow battery has its advantages and disadvantages, and the same can be applied in various fields, which paved the way for his prospects.

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