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Procedia CIRP 116 (2023) 648–653

www.elsevier.com/locate/procedia

30th CIRP Life Cycle Engineering Conference.

Life cycle assessment of a vanadium flow battery based on manufacturer data

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Abstract

In the transition towards 100% renewable energy use, the storage of intermittent and fluctuating electrical energy is becoming increasingly relevant. Vanadium flow batteries (VFBs) are safe and reliable options for stationary day storage of energy. VFBs are already operated worldwide under a wide variety of environmental conditions. Thus, the assessment of potential environmental impacts of VFBs by life cycle assessment (LCA) is essential in order to support a sustainable energy system. The presented LCA is based on primary data provided by one of the leading VFB manufacturer companies Enerox GmbH, Austria. This makes it the first published LCA on a VFB completely based on primary data. In addition, in collaboration with Enerox GmbH various scenarios for real-world use cases are considered. This provides new insights, as especially the choice of location for operation as well as the type of renewable energy input to the battery show a significant impact on potential emissions. Consequently, emission reduction potentials as well as recommendations for action considering future use cases for VFBs are derived.

Peer-review under responsibility of the scientific committee of the 30th CIRP Life Cycle Engineering Conference

Keywords: climate change, energy storage, life cycle assessment, vanadium flow battery

1. Introduction

The expansion of renewable energies, i.e. wind and solar power, is in the focus of global politics. Nevertheless, the expansion of intermediate energy storage is just as important for the success of the energy transition. This requires safe and reliable storage technologies to prevent the risk of a blackout. The vanadium flow battery (VFB) is mentioned as a particularly promising storage option in the literature and fulfills all requirements [1]. As a water-based, closed system, it is inherently safe compared to lithium-based battery systems, which pose fire and explosion hazards. Moreover, self-discharge is minimized by design (see section 2), which makes VFB a reliable day and night storage device. For these reasons, VFBs are used worldwide in a wide range of conditions as stationary intermediate storage for fluctuating and intermittent electrical energy. Consequently, emissions from the system manufacturing as well as the provision and storage of energy must be considered in order to assess potential environmental impacts by life cycle assessment (LCA). A recent literature review on different LCAs of VFBs reveals significant differences in VFB design, engineering assumptions and data quality [2]. Thus, the presented LCA of a VFB is based on a fully transparent LCA framework [3] using primary data by a leading VFB manufacturer for the first time in literature. This study aims at the assessment of the optimal use case for VFBs in order to implement emissions reduction potentials in future sustainable energy systems.

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10.1016/j.procir.2023.02.109

2. Vanadium Flow Battery

The VFB is an electrochemical battery storage system that is primarily used as stationary day storage. The electrical energy is converted into chemical energy and consequently temporarily stored in the electrolyte of the battery [4]. The special characteristic of the battery is that the energy conversion unit (electrochemical cell stacks) and the electrolyte tanks are physically separated as illustrated in Figure 1 [5].

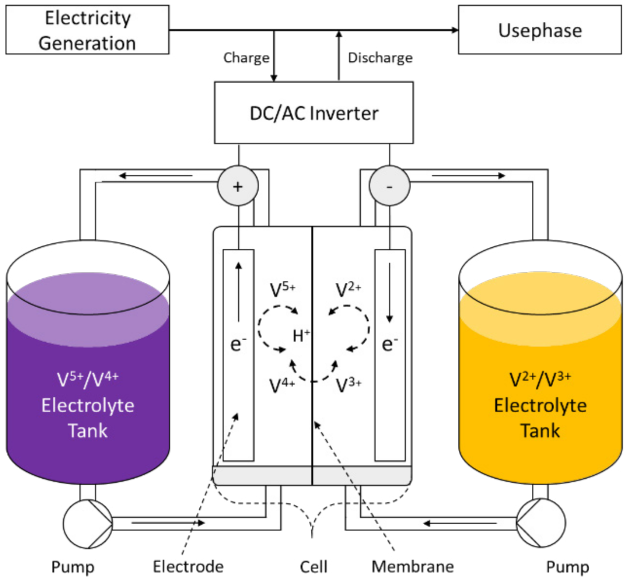

Figure 1: Schematic structure of a vanadium flow battery

Above all, this guarantees a very low self-discharge [6]. The electrolyte consists of sulfuric acid and vanadium pentoxide and a large part of water, which is why the battery cannot burn. Similarly, the special feature of the battery is the independent scaling of power and capacity. More electrolyte is needed to increase capacity, and more cells or stacks are interconnected to increase power. In the stack, electrical energy is converted into chemical energy and vice versa. Accordingly, the electrolyte is pumped from the tanks into the stack when the battery is to store or deliver energy.

3. Goal and Scope

The environmental LCA method framework is based on the international standards ISO 14040/44 [7,8]. The goal of this study is to quantify potential environmental impacts of a VFB in a cradle-to-grave approach considering different operation scenarios. The methodology is based on a recently published LCA on industrial VFB [3]. This model is adapted with manufacturer data for the commercial VFB system CellCube

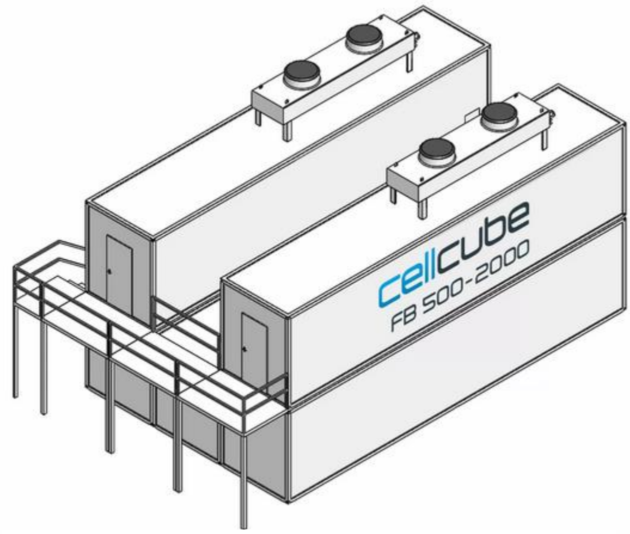

Figure 2: Schematic structure of CellCube FB 500-2000

FB 500-2000 from Enerox GmbH. The battery system is characterized by a net power of 500 kW and a net capacity of 2´000 kWh. This corresponds to an energy-to-power ratio (*E*/*P*) of 4:1 h, which equals discharge duration at full power. The VFB module is shown schematically in Figure 2.

The functional unit (FU) is defined as the storage and provision of the total energy over the entire life cycle of the battery. The total energy is calculated based on the number of cycles as well as the stored energy per cycle.

The considered number of cycles is 20´000 cycles and consequently the total discharged energy is 40 GWh [9,10].

In the study 19 different scenarios are analyzed (Figure 3): 2 different renewable energy inputs (section 6) multiplied by 3 geographic sites (section 7), multiplied by 3 battery operation conditions (section 8). In addition, the special use case of hydropower combined with VFB is analyzed for the location Australia, as such a project is being planned.

The LCI (life cycle inventory) only includes the losses incurred by the VFB in storing and providing the energy to the end user. The provided energy to the consumer is not included. The resulting energy losses are calculated on the basis of the efficiency of the battery.

The geographical system boundaries refer to several variable and fixed parameters. The fixed boundaries are defined by the production of the power units, the energy units and the electrolyte. The locations of the electrolyte are defined by the vanadium mine and the location where the electrolyte is produced. The variable limits refer to the installation sites for the VFBs.

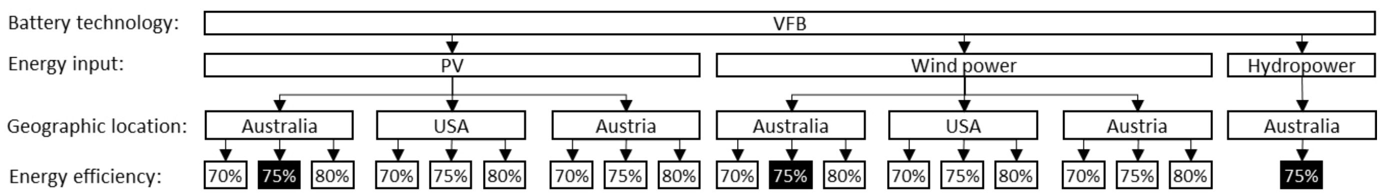

Figure 3: Scheme of the 19 scenarios analyzed; results from the three scenarios highlighted in black are presented in detail in section 9 (Figure 6)

The aim of the study is to identify key contributors of emissions using primary data and real-life applications in order to make recommendations for future action. An important step for this is to investigate assumptions from the literature on key contributors. In the literature [11,12] for example, transportation has a significant share in emissions. Furthermore, the study examines different renewable energy sources, transportation routes, locations, and efficiencies. These assumptions have a significant influence on the emissions and other interacting factors (different amount of electrolyte, solar radiation w/m^2, etc.). Accordingly, a global sensitivity analysis is crucial for this issue and this has been performed for the first time to this extend in the literature for VFBs.

4. Life Cycle Inventory

The life cycle inventory (LCI) is adapted from previous own work [3] and primary data is provided by Enerox GmbH for the model CellCube FB 500-2000. A major difference in respect to our previous LCI is the balancing of the stack, due to a smaller active single cell area considered. The 500 kW nominal power are realized by ~250 stacks installed. Another difference is the containerized design of the CellCube system (five 40′ ISO HC-containers). The mass composition of the stack (Figure 4) is illustrated in relative numbers due to confidentiality. To the same reason, the ion exchange membrane used is not analyzed in detail in the LCA. The stacks, pumps and inverters are replaced once within 20 years (20’000 cycles), whilst the vanadium electrolyte does not need to be replaced [9].

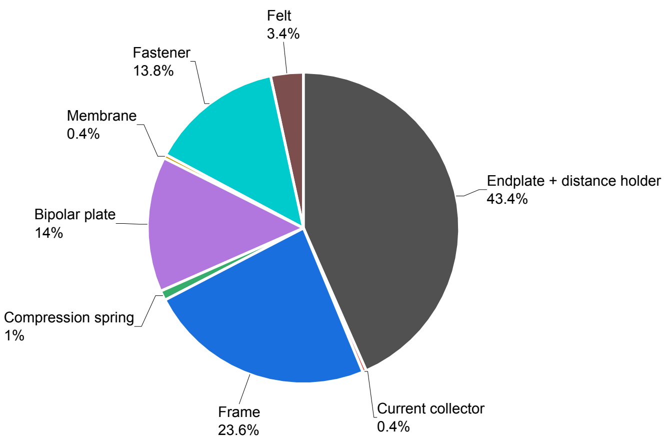

Figure 4: Mass composition of stack components of CellCube FB 500-2000

5. Life Cycle Impact Assessment

The software Umberto LCA+ is used with the database ecoinvent 3.6 (cut-off model) [13]. The life cycle impact assessment (LCIA) method CML-2001 is chosen. The following three impact indicators are considered: global warming potential (GWP), eutrophication potential (EP) and acidification potential (AP).

6. Energy input scenarios

Wind power and photovoltaics (PV) are considered as energy input sources. For the PV systems, a 570 kWp open ground multi silicon system is taken as reference. For the wind turbine, a capacity of 1 to 3 MW onshore plant is considered. Their LCI is adjusted according to the geographic location. Hydropower (run-of-river) is examined for only one special use case in Australia. At that site an innovative combination of the two technologies is projected in order to enhance the efficiency of the pumped storage plant by buffering excess energy in the VFB.

7. Geographic scenarios

An essential aspect is to analyze the emissions of the transport of the individual VFB components, since the transport of the electrolyte is described in the literature [11,12] as being particularly emission-intensive.

The vanadium electrolyte in the present study is produced in a factory close to a port in China. In order to receive a low hazard class for transport, the electrolyte must be produced in a ready-to-use state. On-site production of the electrolyte is not considered.

The power unit is manufactured at Enerox GmbH site in Wiener Neudorf, Austria. The energy unit is assembled near to a port in a neighboring country.

For the balancing of the transports, two actual and one potential locations of VFB operation by Enerox GmbH are defined. The first location is approximately 70 kilometers away from the Enerox GmbH headquarters (Wiener Neudorf) in Lichtenegg, Austria. The second location is Chicago, USA and the third location is Brisbane, Australia. For the calculation of the distances mainly SEAROUTES [14] and in addition Google Maps [15] is used.

8. Battery operation scenarios

Battery operation is influenced by many factors. Therefore, the literature describes different system energy efficiencies for VFBs from 60% up to 90% [16,17]. In the present study common efficiencies of 70%, 75%, and 80% are considered. Changes in efficiencies may depend on obsolete technology, inverter and transformer losses, different operating temperatures, environmental conditions, shunt current, depth of discharge (DOD), load factor, generating power and others [18]. Another significant factor that effect the efficiency is the duty cycle. In the literature [19], changing system efficiencies primarily consider the effects of the provided additional or decreasing amount of energy. However, due to the change in efficiency, the capacity of the battery must also be adjusted accordingly. In case of the VFB, this is in particular the adjustment of the required amount of electrolyte. This again has an impact on the quantity of the potential emission-intensive electrolyte. The transport data are recalculated accordingly in each scenario. The number and size of tanks are assumed to be constant, referring to the maximum electrolyte volume.

9. LCIA results

The absolute results calculated in the 19 scenarios are illustrated in Figure 5. The mean value is shown for different battery operation scenarios.

USA transport emissions are only 3% of GWP. In that case, half of transport emissions are allocated to sea transport (20'000 kilometers) and the other half to truck transport from Baltimore to Chicago (1'100 kilometers). In order to analyze the effects of transport and other individual components of the

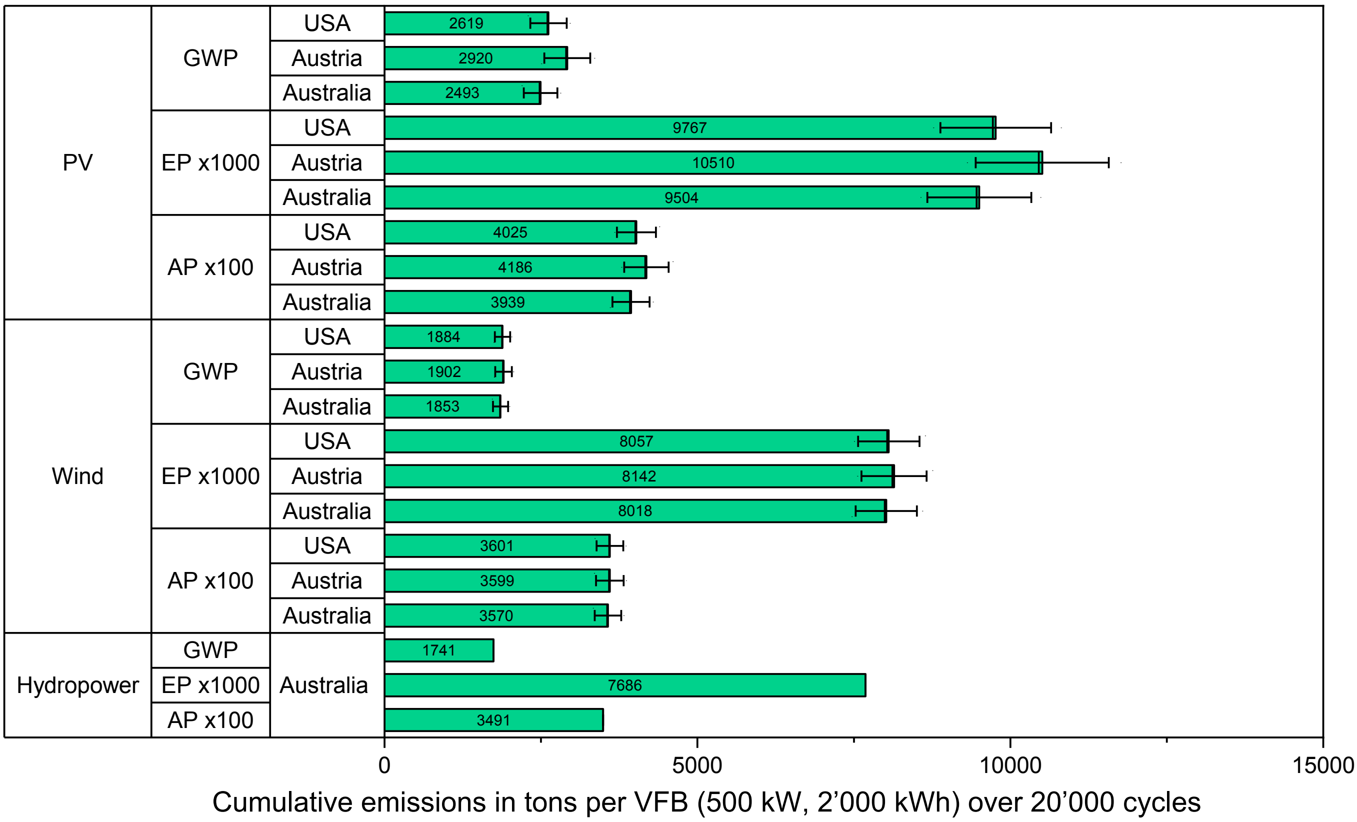

Figure 5: Resulting emissions for a VFB (500 kW, 2'000 kWh) over 20'000 cycles: GWP (global warming potential), EP (eutrophication potential) and AP (acidification potential) for three different installation sites of VFB with photovoltaic (PV), wind power or hydropower as input.

Overall, the best results (0.043 kg CO2 eq (kWh)-1) are obtained in the wind turbines scenario in Australia at 80% battery system efficiency. The calculation for emissions for 1 kWh is calculated by dividing the total emissions over the full life cycle (1´716 t CO_2 eq) by the number of cycles (20´000) and the storage capacity per cycle (2´000 kWh). Whereas, the worst results (0.084 kg CO_2 eq $(kWh)^{-1}$) are calculated in the PV scenario in Austria at 70% battery system efficiency. These findings did not take into account the specific case of hydropower. The use of wind power in Austria results in a reduction of emissions by 35% compared to the PV scenario.
The use of wind power does not lead to significant differences in the results, due to the relatively low emissions from this energy source. In contrast, PV as energy input reveals significantly higher potential emissions for all impact indicators. There is also a large difference between the countries in PV scenarios, since Australia in particular has a significantly higher solar irradiation than Austria. Last but not least, the energy efficiency of the VFB has a significant impact on the results, EP in particular. Considering transport these results refute the statement [11,12] on a particularly emission-intensive transport of the electrolyte. The transport of the electrolyte, which accounts for ~70% of the total system weight (~135 t), does not have a significant impact. Even considering the longest sea route of ~20´000 kilometers from China to the

VFB, a percentage breakdown of GWP results is shown in Figure 6. GWP results are illustrated for a VFB with an efficiency of 75% located in Australia using different renewable energy inputs. The electrolyte clearly dominates the GWP by 57 to 81% in the three scenarios. Additionally, the energy input source for the battery affects the overall balance. The less emission-intensive energy source is hydropower (3.2% of GWP) and the most emission-intensive one is PV (32% of GWP).
In the wind scenario, the generation of energy causes 8.6% of the GWP. The electrolyte dominates the emissions by 77% and the stack causes only 4.6% of GWP. The container is in the same range with 4.2%, whereas the support results in 3.8% of GWP. Support is defined as all components needed for the balance of plant, such as pumps, heat exchangers, but also the various cabling [3]. The inverter accounts for the highest share of emissions in the support segment (1.1% of total GWP). In general, the transport of any VFB components does not show a significant share in GWP (1.6 to 2.2 %). The emissions of the VFB are clearly dominated by the transport of the electrolyte. The emissions from the transport of other components are clearly lower, due to their considerably lower weight.

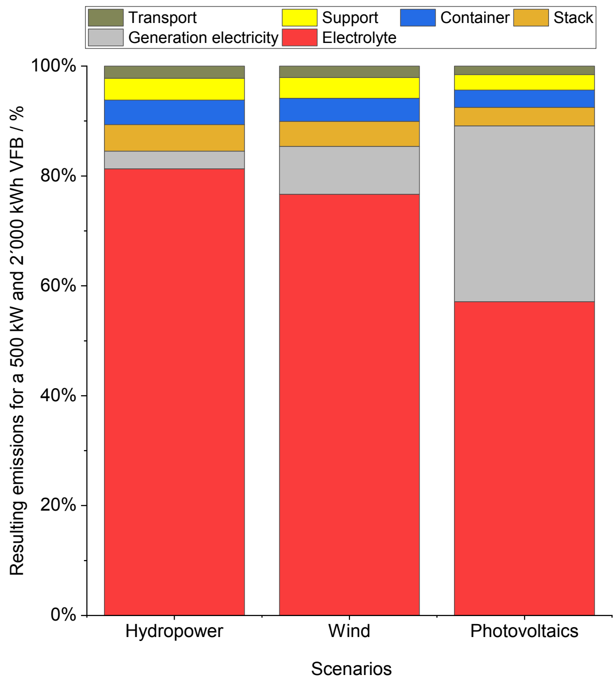

Figure 6: Breakdown of GWP results in percent in three scenarios: VFB (75% energy efficiency) located in Australia fed by hydropower, wind power and photovoltaics.

10. Discussion

The results reveal a significant emission reduction potential in the reuse of the electrolyte, but further studies are needed to precisely quantify this reduction [3]. Furthermore, there are approaches to use less pure vanadium from recycled products. The vanadium can be extracted from steel slag or from fly-ash [20]. Thus, when considering reduced emissions in steel processing, as a coupled process to vanadium production, the vanadium electrolyte may benefit. E.g. the use of hydrogen in steel production is intended to save a large proportion of emissions in the future [21].

The overall data quality of the analysis can be considered as solid and transparent. The stack data are based on primary data from the VFB manufacturer Enerox GmbH, which means that uncertainties are reduced. The specific membrane is not considered in detail, but in previous work no significant impact has been found for the impact indicators considered here [3]. However, further research is needed for the end-of-life of VFB, because at the moment, there are only few VFB systems at the end of life. In the presented conservative approach average recycling rates are assumed for waste materials. Consultations with disposal companies confirmed excellent recycling rates, as some of the stack components are in pure form. Increasing stack lifetime is also to be expected and should be analyzed in future studies.

The statements regarding the high transport emissions could not be compared due to the lack of transparence in the other LCAs [11,12]. One assumption is the use of an airplane as a means of transport in Fernandez-Marchante et al. [11] which would cause a large part of the emissions. This assumption is not applicable to VFBs, since it is forbiddingly expensive and emission intensive.

We deliberately did not compare to similar systems such as lithium-ion batteries because the framework conditions are not given as well as the technologies have different application areas/ charge/discharge cycles.

In addition, the idea of a potential reuse of components is also conceivable. E.g. if the containers do not have to comply with the requirements of the shipping industry a lifetime of 100 years can be assumed under certain conditions [22]. However, it is questionable to what extent this might be realized.

11. Conclusion and outlook

The present LCA study in collaboration with the VFB manufacturer Enerox GmbH provides high quality primary data for the LCI. A set of 19 scenarios combining different renewable energy input sources, geographic locations and battery efficiencies is analyzed. There are significant differences in the analyzed scenarios regarding LCIA results; apart from the fact that the results are always dominated by the vanadium electrolyte in analogy to the mass balance of VFB systems.

VFB fed by PV show significantly higher emissions compared to wind power, independent of the geographic location. Likewise, the choice of location is negligible in terms of a lower transport distance of VFB components with respect to emissions. Transport emissions are again dominated by transport of the electrolyte as the heaviest component. Consequently, local production of battery components has only a minor impact on battery emissions. Likewise, it is important that the battery runs under optimal conditions in order to achieve high efficiency. Consequently, research must continue on stack components to improve the performance of the battery.

Ultimately, a potential reuse via a special treatment of used electrolyte needs to be investigated in order to significantly reduce emissions from VFB. Furthermore, different recycling strategies of system and stack components should be considered in a cradle-to-cradle approach addressing the concept of a circular economy [23].

Acknowledgements

The authors gratefully acknowledge financial support from the German Federal Ministry for Economic Affairs and Climate Action (BMWK) for funding the research project (03ET6156E).

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