WHITEPAPER

ENVIRONMENTAL IMPACT
VRFB vs. LiB

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White Paper

Comparing environmental impacts: vanadium redox flow batteries and lithium-ion batteries

1 The baseline: life cycle assessment of CellCube's FB 500-2000 Rel. 4.0 system

Life Cycle Assessments (LCA) are standardized ISO [1,2] methods **to assess the potential environmental impacts** of goods, products, or services **over their entire lifecycle**. The relevant parameters collected in the assessment are: global warming potential (GWP) in carbon dioxide equivalents (CO_2-eq), human toxicity potential (HTP) in 1,4-dichlorobenzene equivalents (1,4-DB-eq), acidification potential (AP) in sulfur dioxide equivalents (SO_2-eq), abiotic depletion potential (ADP) in antimony equivalents (Sb-eq). Enerox GmbH conducted a life cycle analysis of its newest vanadium redox flow battery (VRFB) product the CellCube FB 500-2000 Rel.4.0 system in order to:

- identify environmental hot spots within the product life cycle
- adress and minimize environmental impacts by promoting other processes and materials
- compare results with other storage technologies
- mitigate measures and impact-orientated interventions

1.1. Integrated data

For the analysis of the environmental impact of the product, the data of all materials, components, and processing steps over their entire life cycle have to be determined and are included in the calculations:

- data on raw material extraction
- transportation
- manufacturing and processing procedures
- energy consumption
- auxiliary and operating materials
- use phase
- disposal paths of the product materials
- waste produced during manufacturing

1.2. Cradle-to-gate and sensitivity analysis

Enerox GmbH chose for its system "CellCube" the cradle-to-gate approach for the impact assessment of the FB 500-2000 Rel.4.0, **including** the extraction of raw materials, manufacturing of the battery, and distribution to the customer. The **energy output** over 20 years was also considered. The sensitivity analysis accounted for the environmental impact of using reused electrolyte.

A good overview of the environmental impact was obtained by carrying out the LCA. However, the next steps are to further mitigate CO_2-eq emissions and rethink product design, processes, materials, and components.

1.3. System and scenarios

- ✓ FB 500-2000 Rel.4.0
- ✓ ISO 14040/14044 standard compliant
- ✓ Cradle-to-gate incl. provision of energy over lifetime
- ✓ 4h system, 1 cycle per day, 20 years lifetime

The production of VRFB components includes raw material extraction, material processing, and product manufacturing. In addition, 10% of the stacks were taken into account for a potential exchange.

2 The results: of the CellCube LCA

2.1. Emissions per MWh

Assuming an energy output of 17 900 MWh over 20 years, environmental impacts per MWh of provided energy are:

- ✓ 32.60 kg CO_2-eq (GWP),
- ✓ 77.30 kg 1,4-DB-eq (HTP),
- ✓ 0.52 kg SO_2-eq (AP)
- ✓ 2.25 g Sb-eq (ADP)

In figure 1, a **specific scenario** was considered: **The CellCube system is installed in Austria, the power units are produced in Austria, the energy units in Slovenia, and the electrolyte is produced in China.**

As can be seen in figure 1, 57% of the GWP is caused by vanadium pentoxide (V_2O_5) production.

The production of the power unit contributes 16% to the overall GWP, the production of the energy unit 11%, and the transport (downstream) in the specific scenario 9%. The remaining percentage is attributed to assembly and infrastructure.

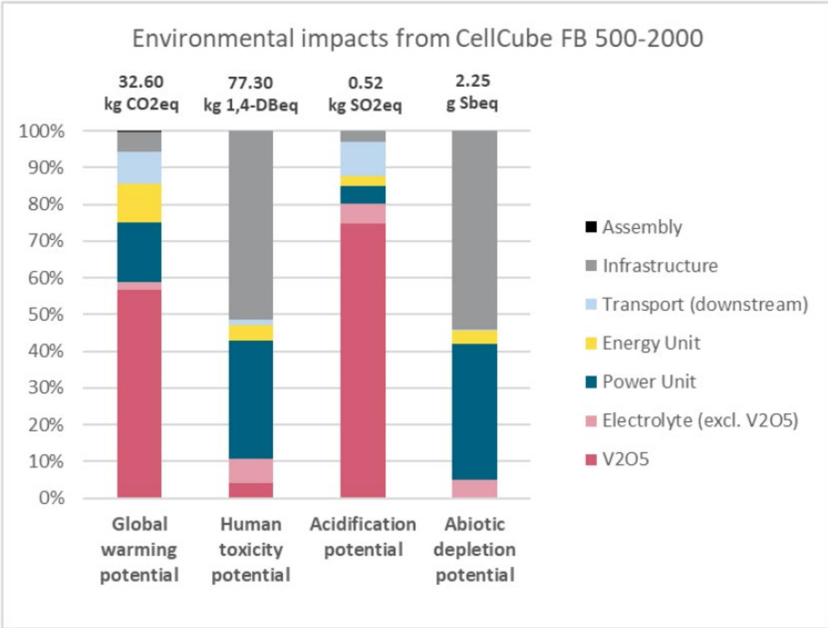
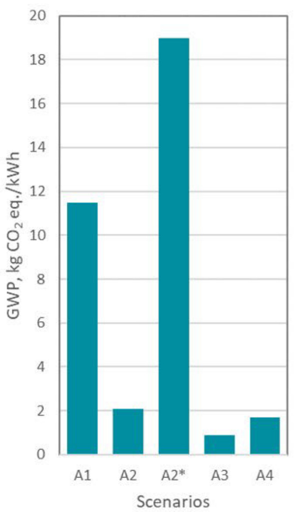


Figure 1: ***Relative contribution to environmental impacts per MWh of provided energy over lifetime (Denkstatt, 2022) [3]***

2.2. Electrolyte source and allocation:

As clearly seen in figure 1, the vanadium electrolyte and the V_2O_5 precursor present a dominant contribution to the LCA of the VRFB. For this reason, it is important to consider different sources of vanadium, as well as its allocation in the analysis.

Figure 2 shows an example from a study by He *et al.* [4] considering different scenarios for V_2O_5 production. Scenario A2* is the one used in the Weber *et al.* [5] study and is also incorporated into our results in figure 1. However, this is the least favorable scenario in terms of GWP as it includes the environmental impact of making steel of which V_2O_5 is a byproduct. Excluding steel production as an independent activity (see scenario A2) produces a much smaller impact.

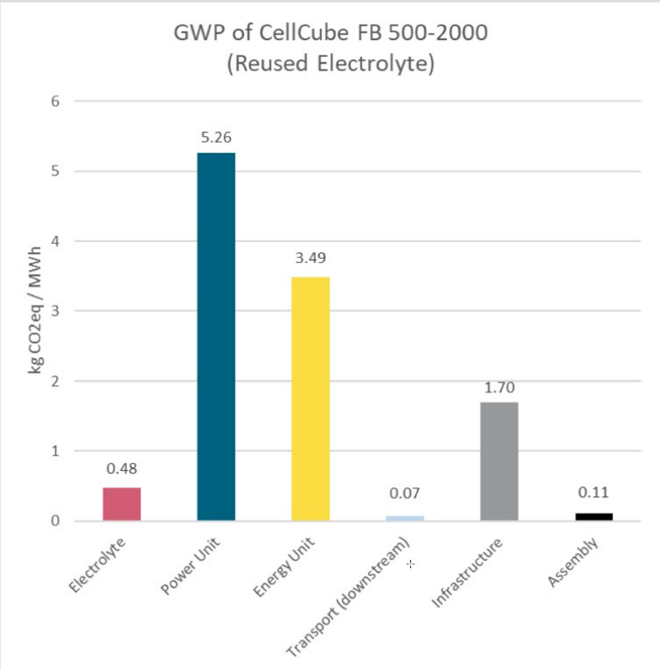


Scenario	Description
A1	The vanadium pentoxide production from blast furnace crude steel making process based on manufacturing data from PAN. Steel, Sichuan, China.
A2	The vanadium pentoxide production from the electric arc furnace steelmaking process based on Weber et al.
A2*	The vanadium pentoxide production plus the allocated impact from the electric arc furnace steelmaking process based on literature data. The steel manufacturing modeling is modified from the Ecoinvent and monetary value is used for allocation.
A3	The vanadium pentoxide production based on manufacturing data from granulate generated in power plant burning crude oil.
A4	The vanadium pentoxide production based on stoichiometric calculation form fly ash generated in power plant burning crude oil.

Figure 2: ***Sensitivity of CO_2 impact to V_2O_5 sourcing and allocation*** (reproduced from He *et al*. 2020 [4]).

A different steel production method (see scenario A1) generates only 60% of the GWP potential of the reference scenario A2*. Meanwhile, sourcing vanadium from the combustion products of power plants (scenarios A3 and A4) produces only a fraction of the impact. These are crucial considerations for interpreting LCA results as well as identifying opportunities for improvement in the environmental profile of the product.

2.3. Sensitivity analysis – REUSED ELECTROLYTE:



- A sensitivity analysis was carried out to represent future scenarios. **For this analysis, 97,5% of reused electrolyte is considered**, i.e. the primary electrolyte amount needed is only 2,5% (5 tons) due to incomplete removal of the electrolyte from an old CellCube system that can be effectively pumped into a new one. 2.5% is a conservative assumption which will amount more likely to 1%.
- **The GWP of 1MWh for the same scenario as described above changes from 32.60 kg CO_2-eq to 11.11 kg CO_2-eq** (figure 3)!

*Figure 3: **Sensitivity analysis for reused electrolyte (Denkstatt, 2022) [3]***

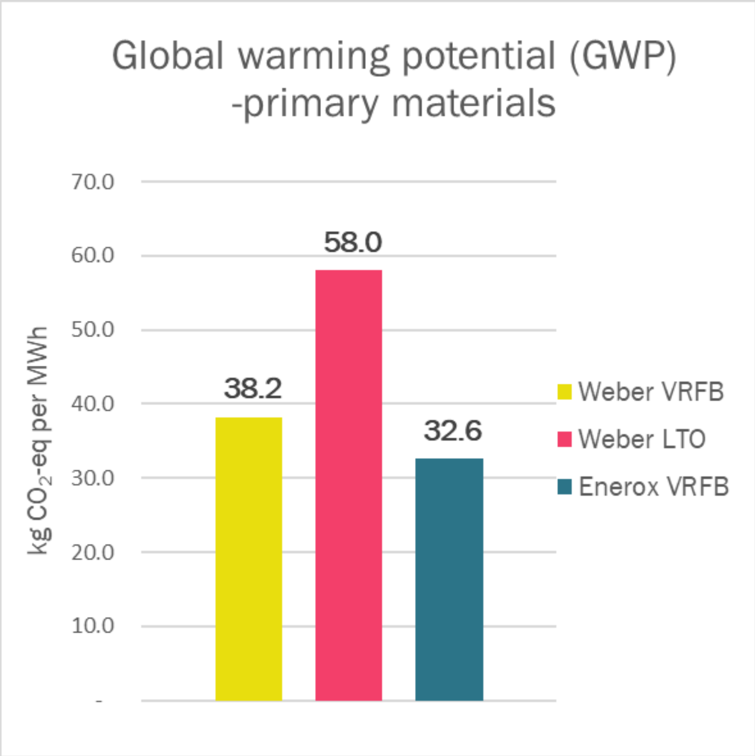
3 The comparison of GWP between VRFB and lithium-ion batteries

One of the most cited studies on LCA was published in 2018 by Weber *et al. [5].* The methodology of CellCube's LCA was also based on this study in order to perform a comparison to lithium batteries (LiB).

The left and middle bars in figures 4 and 5 represent the study from *Weber et al.* [5] for LTOs (*type of lithium-ion battery: lithium-iron-phosphate based cathode with lithium titanate anode)* and *VRFBs.* The right bar in figures 4 and 5 CellCube's VRFB FB 500-2000 Rel.4.0 (Denkstatt, 2022) [3].

The following assumptions were considered in the two scenarios below: powered by renewable energy, over 20 years life cycle, and per MWh (Weber et al., 2018 [5]; Texas A&M University, 2021 [8]; Denkstatt GmbH, 2022 [3]).

3.1. Scenario 1: IMPACT EXCLUDING REUSED MATERIALS for both technologies per MWh:



- **The comparison** (figure 4) **shows the significant difference:**

If reused and recycled material is **not** considered, LTO's generate **25.4 kg CO_2-eq more** than Enerox VRFB for every 1 MWh of capacity.

*Figure 4: **Comparison of LTO and VRFBs excluding reused materials.***

3.2. Scenario 2: IMPACT INCLUDING REUSED MATERIALS for both technologies per MWh:

- In the sensitivity analysis (figure 5), reused materials are considered, especially the electrolyte.
- **The CellCube system lowers its impact by 21.5 kg CO_2-eq per MWh (≙ 66 %).**
- Nevertheless, if reused materials are included in LTOs too, LTOs generate **30.9 kg CO_2-eq more** than Enerox VRBF for every 1 MWh capacity.

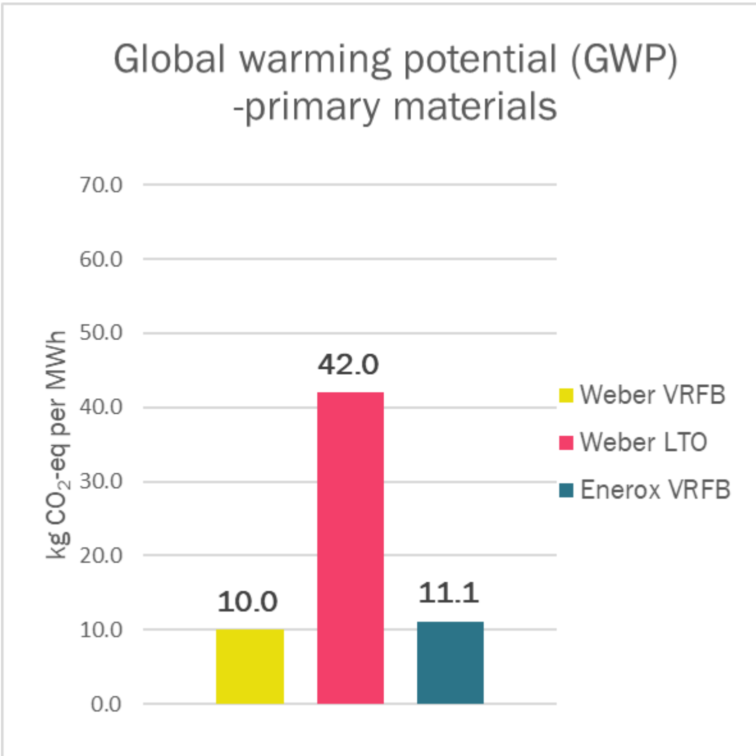


*Figure 5: **Comparison of LTO and VRFBs including reused materials.***

4 Conclusion

LCA studies are a valuable tool for evaluating the environmental impact of products and technologies as well as in identifying improvement opportunities with the highest potential to benefit the planet.

This LCA and the cited studies show that VRFBs offer a highly favorable environmental footprint for large-scale energy storage solutions compared to the more ubiquitous LiB technology. Even with rather conservative estimates on the impact of vanadium production, Enerox VRFB has only 66% of the global warming potential compared to an LTO counterpart.

The sensitivity analysis of these technologies (VRFB and LiB), especially with regard to material sourcing considerations has highlighted a crucial advantage of the VRFB technology: the reusability of the vanadium electrolyte and the ability to utilize waste from other processes for electrolyte production.

Furthermore, by accounting for all components, the LCA showed that 85.5% of the whole Enerox CellCube FB 500-2000 Rel.4.0 battery is directly reusable at the end-of-life (by weight). The remaining materials are mostly recyclable.

This gives the VRFB technology a solid foundation to offer a green solution to the world's energy transition.

References & Imprint

[1] ISO 14040:2021. Environmental management - Life cycle assessment - Principles and framework, Geneva, Switzerland.

[2] ISO 14044:2021. Environmental management - Life cycle assessment - Requirements and guidelines, Geneva, Switzerland.

[3] Dreyer, M., Kral, I., 2022. Life cycle assessment of the vanadium redox flow battery CellCube FB 500-2000. Denkstatt GmbH

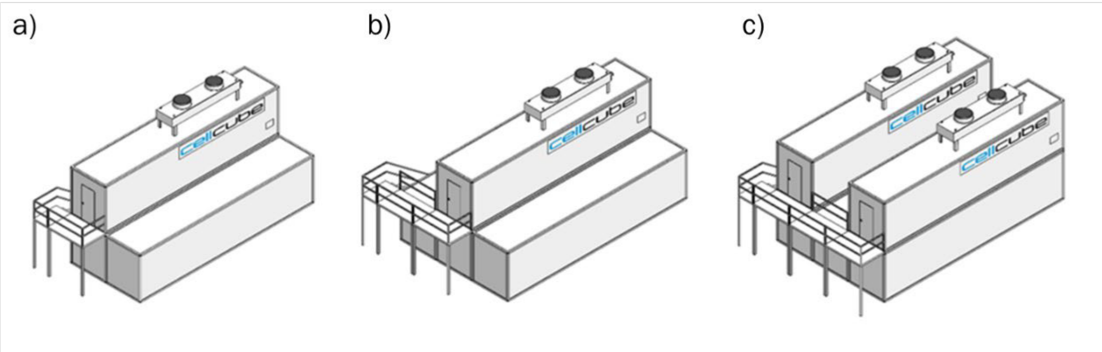
[4] He, H., Tian, S., Tarroja, B., Ogunseitan, O.A., Samuelsen, S., Schoenung, J.M., 2020. Flow battery production: Materials selection and environmental impact. J. Clean. Prod. 269, 121740.

[5] Weber, S., Peters, J.F., Baumann, M., 2018. Weil, M. Life cycle assessment of a vanadium redox flow battery. Environ. Sci. Technol. 52, 10864e10873.

[6] Chen, S., Fu, X., Chu, M., Liu, Z., Tang, J., 2015. Life cycle assessment of the comprehensive utilisation of vanadium titano-magnetite. J. Clean. Prod. 101,122e128.

[7] Jungbluth, N., Eggenberger, S., 2018. Life Cycle Assessment for Vanadium Pentoxide (V2O5) from Secondary Resources. ESU-services Ltd. http://esu-services.ch/data/abstracts-of-lcis/#c154.

[8] Dixit, M., Banerjee, S., Santos, D., Kumar, P.P., 2021. Life Cycle Assessment of Vanadium Products. Texas A&M University.



Enerox VRFB CellCube Releases 4.0: a) FB 250 – 1000, b) FB 250 – 2000, c) FB 500 - 2000

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