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Life cycle assessment of a vanadium flow battery

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Abstract

Battery storage technologies have been showing great potential to address the vulnerability of renewable electricity generation systems. Among the various options, vanadium redox flow batteries are one of the most promising in the energy storage market. In this work, a life cycle assessment of a 5 kW vanadium redox flow battery is performed on a cradle-to-gate approach with focus on the vanadium electrolytes, since they determine the battery's storage capacity and can be readjusted and reused indefinitely. The functional unit is 1 kWh stored by the battery. The initial results show that the environmental hotspots reside mainly in the structural and material components of the battery, evidencing the need for alternative or recycled materials, preferably produced locally. Since the quantity of electrolytes determine the amount of storable electricity, an analysis was conducted on the variation of the impacts with the increase of storage capacity. An alternative scenario with reused electrolytes was also performed. Results show that with the increase of storage capacity, the contribution of the electrolytes to the impacts decrease significantly by stored kWh. In the reused electrolytes scenario, impacts were reduced mainly for the Acidification and Mineral, fossil and renewable resource depletion categories.

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1. Introduction

Presently the increasing energy needs of human societies are mainly met using fossil fuels, which results in significant impacts, not only environmental (e.g. climate change) but also economical and even social (e.g. supply

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Nomenclature

| | |
|--------|--------------------------------------------------------------------------------------|
| AP | Acidification Potential, environmental impact category |
| BOS | Balance of System, composed by cables and monitoring equipment in the battery system |
| CC | Climate Change, environmental impact category |
| FE | Freshwater Eutrophication, environmental impact category |
| IRENA | International Renewable Energy Agency |
| ISO | International Organization for Standardization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LEPABE | Laboratory for Process Engineering, Environment, Biotechnology and Energy |
| MFRRD | Mineral, Fossil & Renewable Resource Depletion, environmental impact category |
| OD | Ozone Depletion, environmental impact category |
| POF | Photochemical Ozone Formation, environmental impact category |
| PVC | Polyvinylchloride |
| VRFB | Vanadium Redox Flow Battery |

security). To minimize those effects there is an ongoing strong investment in renewable energy generation systems [1]. While contributing with lower sustainability impacts to the existing energy supply, they have some limitations, especially the intermittency in the energy availability as climate factors play a role [2]. Energy storage systems (ESS) are key to counter those limitations, as they can store renewable energy produced in excess and supply it when demand is larger than supply, thus reducing the imbalances between supply and demand [3].

IRENA [4] has reported that the total electricity storage capacity could triple in energy terms until 2030, and battery storage capacity could grow more than seventeen times by the same year. Vanadium Redox Flow Batteries (VRFB) are redox flow batteries that use vanadium redox couples in a sulfuric acid solution as electrolytes separated by a proton exchange membrane, being the catholyte and the anolyte stored in separate reservoirs and separated from the power generating cell stacks. VRFB are one of the more suited batteries for stationary usage, as they can be built with a high degree of modularity, have no cross-contamination problems and have an extended system lifetime of up to 20 years. VRFB have a long charge–discharge cycle and are independent of power and energy rating, with low storage losses and high efficiencies of up to 80%. As the electrolytes are stored from the battery stacks, this technology is more flexible when compared with other options as the energy storage capacity can be changed when necessary by adding or removing electrolytes from the system. After use, the vanadium electrolytes that have lost capacity due to air oxidation or ion imbalance can reestablish their capacity by remixing the two half-cell solutions [5], allowing an easy reuse of the electrolyte. Also, depending on the battery design an easy decommissioning for separating different components and materials for recycling can be achieved.

In this work, a cradle-to-gate life cycle assessment (LCA) is conducted to determine the potential life cycle impacts of producing a VRFB prototype developed at LEPABE. A sensitivity analysis was conducted on the variation of total impacts with increasing storage capacity, which leads to higher stored electricity but also to higher amounts of electrolytes and storage tanks. A scenario of incorporating reused electrolytes was also studied to determine the potential reduction in environmental impacts.

2. Methodology

Life Cycle Assessment (LCA) is a systematic and standardized methodology that compiles the energy and material flows that occur during the life cycle of a product or system, to evaluate and analyze its potential environmental effects according to the study's objectives. It consists in four steps: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA) and interpretation [6]. In the first step, the goal and scope of the study is defined. For this, the boundaries of the system in analysis are identified and the functional unit, a “quantified performance of a product system for use as a reference unit” is selected [7,8]. Also, the main goals,

timeframe and technology conditions are defined. The second step, LCI, is the most important and time-consuming step in LCA and consists in the collection of the relevant data from the lifecycle stages that are within the system boundaries, as the reliability and uncertainty of the results depends on them [9]. With the gathered information and using environmental indicators of the effects of each material and energy flow, the potential environmental impacts are quantified [10]. They are interpreted according to the expected outcomes and goals of the study, in order to identify environmental hotspots of to support decision making. For this work, the LCA methodology was applied in a cradle-to-gate approach to the VRFB prototype system (Fig. 1).

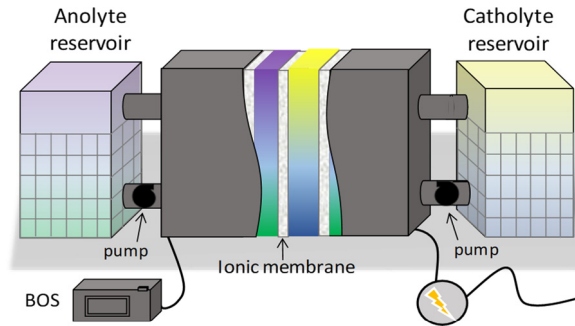


Fig. 1. Vanadium redox flow battery system.

The study is attributional as it analyzes the environmental impacts directly linked with a product. It corresponds to a fully functioning VFRB that included the power generating stacks, electrolyte storage tanks, pumps that ensure the flow of electrolytes between the battery and the storage tanks as well as balance of system (BOS) components: monitoring equipment and cables. The VRFB prototype has 5 kW of power and 18 kWh of capacity that is given by the energy density of 20 Wh per liter of the vanadium electrolytes. The battery and the vanadium electrolytes have life expectancies of 20 and over 100 years, respectively. The Goal of the study is to determine the potential environmental impacts that occur during the production of the battery prototype and analyze possible scenarios that may be feasible solutions to implement and improve the environmental performance of the battery at production level by identifying key eco-design opportunities. The system boundaries are presented in Fig. 2.

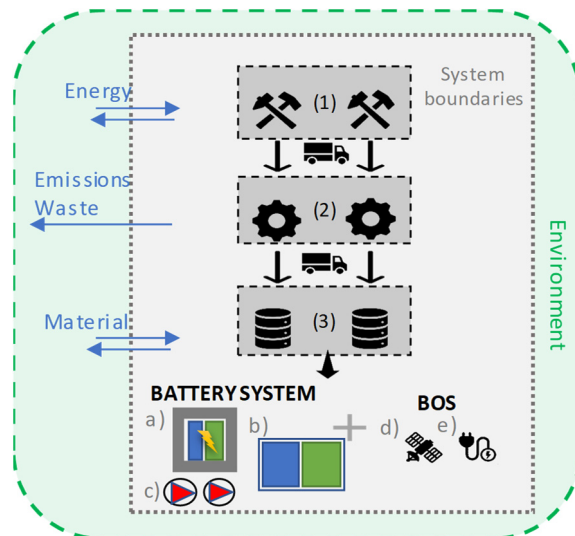


Fig. 2. System boundary of the system's production, including: (1) production, (2) processing and (3) assembly. The battery system components include: (a) vanadium redox flow battery, (b) electrolyte tanks and (c) pumps. The balance of system (BOS) components consists of: (d) monitoring equipment and (e) cables.

The chosen functional unit is 1 kWh stored in the battery, i.e. the results are presented per stored kWh. The system starts with the extraction of raw materials to produce each battery component, structure and the other system components. The raw materials are then transported to the industrial facilities where they are produced. After production of each battery and system component, they are transported to Porto in Portugal via truck or sea ship, where each battery component is assembled into the VRFB prototype and the system is assembled.

Table 1. Main material composition of the vanadium redox flow battery prototype.

| Materials | Weight percentage [%] |
|-------------|-----------------------|
| Electrolyte | 88.31 |
| HDPE | 1.41 |
| Steel | 0.73 |
| Copper | 0.55 |
| PVC | 3.24 |
| Aluminum | 3.77 |
| Rubber | 0.74 |
| Others | 1.25 |
| TOTAL | 100.00 |

Table 1 presents the main material composition of the battery prototype. The main source of data came from the Sunstorage Project [11] battery developers, complemented with information from suppliers and the Ecoinvent database V3.4 whenever necessary for Portuguese and/or European conditions.

3. Results and discussion

The results of the base scenario are presented in percentage in Fig. 3. For the Climate Change category, the transportation of components and the battery structure (which corresponds to the cell stack components) are the main contributors, followed by the vanadium storage tanks.

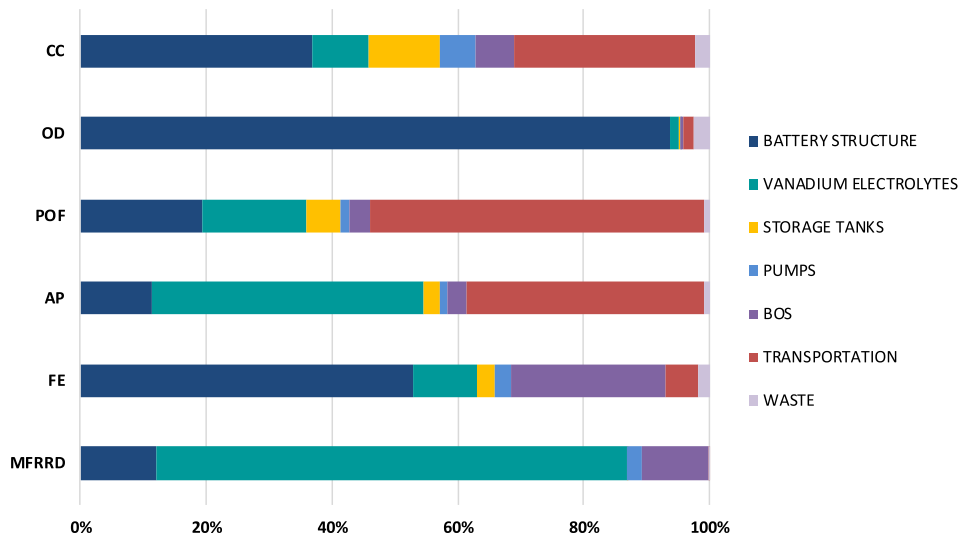


Fig. 3. Total environmental impacts [%] during the production and assembly phase of the battery prototype per unit of kWh stored energy, using ILCD 2011 Midpoint+ V1.10. Impact categories: CC — climate change, OD — ozone depletion, POF — photochemical ozone formation, AP — acidification potential, FE — freshwater eutrophication, MFRRD — mineral, fossil & renewable resource depletion.

Transport has a high contribution, mainly because most components come from outside the country. The electrolyte's raw materials are sent from China, and the electrolyte itself is produced in Germany. Due to their high volume the transportation to Portugal results in a high potential for CC, POF and AP impacts.

The cell stack components that contribute most to the CC category are the polyvinyl chloride (PVC) frames and the Nafion[®] ionic membranes [12]. The membranes contribute more than 90% for the potential impacts in

OD impacts, due to the utilization of the tetrafluoroethylene polymer in its production. Waste generation and transportation have an equally negligible contribution in this category.

For the potential POF impacts transport, battery structure and the vanadium electrolytes contribute respectively with 53%, 19% and 17% for the total impact. From the materials in the battery structure, the PVC frames are the highest contributors. Transport and the vanadium electrolytes generated most of the potential AP impacts of all the analyzed parts with 38 and 43% of total impacts respectively. The potential impacts generated by the electrolytes in this category are mainly due to the sulfuric acid in its composition. Most of the remaining parts do not have a significant contribution in this category, as the third highest contributor is the battery structure with 11%, mostly due to the PVC frames and the copper collectors. The collectors are also responsible for the high contribution of the battery structure in the potential FE impacts with 44 of the total 53% of impacts of the battery structure in this category. In the FE category, the BOS components are more relevant, with 24% of total impacts, mainly due to the electronic equipment for monitoring the system. The electrolytes also contribute to this category with 10% of total impacts. Regarding the potential MFRRD impacts, the vanadium electrolytes has 75% of the total impacts from the system with again the sulfuric acid being the main responsible for the high potential impacts. From the obtained results for the electrolytes, it is clear that there is a need to develop electrolytes with better performance, especially in terms of energy density, which is also supported by the literature [13,14], and preferably with production closer to the assembly location to minimize transportation impacts. In this category, the battery structure and the BOS have also a relevant contribution of 12 and 10%, respectively.

The electrolytes have a significant influence on the environmental performance of the battery on a cradle-to-gate perspective. The vanadium electrolytes contribute significantly to most of the analyzed environmental categories, whether directly with the high potential impacts of the extraction and processing of its raw materials, or indirectly due to their heavy and long transportation from the extraction activities. This also raises other social and economic issues that will be assessed in a future Sustainability evaluation.

3.1. Sensitivity analysis: increasing storage capacity

Since one of the main features of this technology is its modularity, and the power stack is separated from the energy storage in the electrolytes, a sensitivity analysis was conducted to analyze the influence of the quantity of the electrolyte in the system overall environmental impacts. To increase the battery's capacity, it is necessary to increase the electrolytes in storage tanks. For each 1800 L of added electrolyte, two additional tanks and pumps are also added, so that each tank stores 900 L and is able to pump the electrolytes to the cell stack as in the initial scenario, which also increases the storage capacity by 18 kWh. Transport of the added components is also accounted for. The effects in every category varies according to the weight of the contribution from mostly the vanadium electrolytes, transport and storage tanks.

Fig. 4 presents the variation of the overall initial environmental impacts in each category with the increase of the VRFB's system capacity from 18 kWh to 360 kWh, keeping the rest of the system unchanged.

In categories where the vanadium electrolytes have more potential impacts, such as MFRRD and AP, the reduction of impacts is lower, as expected due to the increase of electrolytes with storage capacity. The same happens for the impacts of transportation in AP and POF. Together with the increase of storage tanks and pumps to obtain a storage capacity of 36 kWh, the total impacts reduced per stored kWh are especially relevant in ozone depletion (48%) and freshwater eutrophication (40%), followed by climate change (23%). Both POF and MFRRD categories have their impact reduced by 12%. Upgrading the system to a storage capacity of 180 kWh leads to a reduction of impacts of almost 90% in ozone depletion, followed by FE with 71% and CC with 41%. The variation started to decrease after these values, becoming negligible, showing that an optimal dimensioning for the battery system was reached in terms of environmental performance. The maximum variation between the results for 180 and 360 kWh of storage capacity was 5%, which occurred in the OD category.

3.2. Sensitivity analysis: incorporating reused vanadium electrolytes

The vanadium electrolytes slowly lose capacity over time, which affects the efficiency of the battery system and its storage capacity. Nevertheless, the electrolyte capacity can be recovered by mixing the two half-cell solutions and restoring the capacity balance, allowing it to be reused again [5] and possibly reduce the cradle-to-gate life cycle

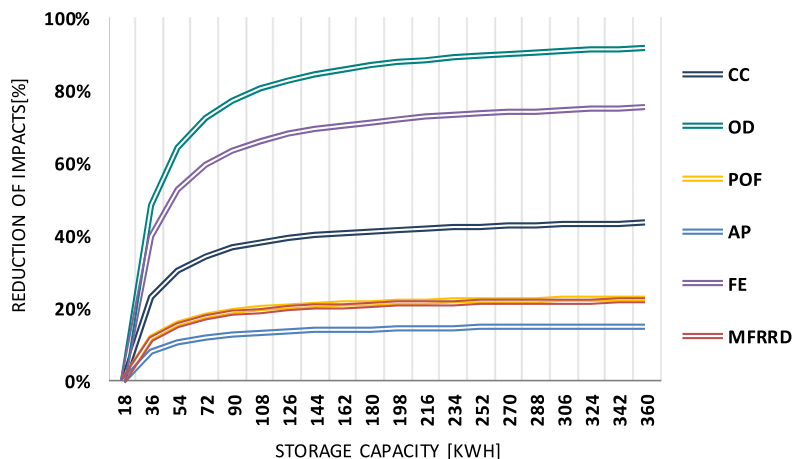


Fig. 4. Impact variation by increasing the storage capacity, i.e. the quantity of electrolytes in storage tanks, up to 360 kWh. Impact categories: CC — climate change, OD — ozone depletion, POF — photochemical ozone formation, AP — acidification potential, FE — freshwater eutrophication, MFRRD — mineral, fossil & renewable resource depletion.

impacts. In order to determine this potential reduction, a scenario analysis was conducted, where the electrolytes are composed of 30, 70% and 100% of reused electrolyte. Data from literature was gathered to consider the energy consumption to mix and rebalance the electrolytes [15]. A transport distance of 30 km to a treatment and recovery facility was also assumed. The reused electrolyte is considered as a waste material free of the production impacts, including only the impacts from transportation to the treatment facility and the energy consumption to mechanically mix and chemically rebalance the electrolyte. There is also avoided primary electrolyte transportation that furthers the reduction of the total impacts. The results are shown in Fig. 5.

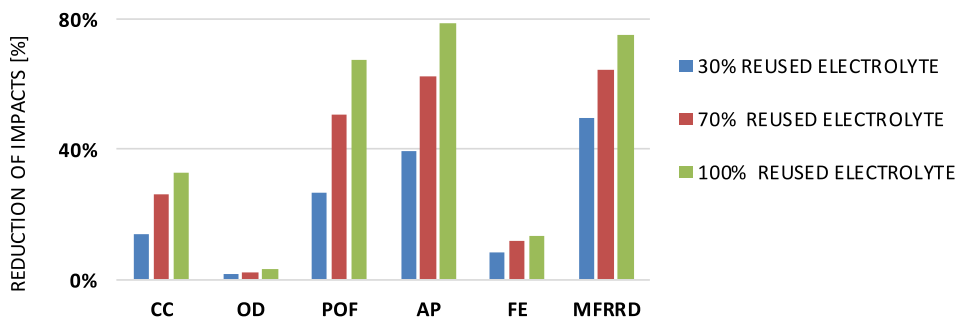


Fig. 5. Reduction of the analyzed environmental impacts by category when incorporating reused vanadium electrolytes in the system. Impact categories: CC — climate change, OD — ozone depletion, POF — photochemical ozone formation, AP — acidification potential, FE — freshwater eutrophication, MFRRD — mineral, fossil & renewable resource depletion.

The obtained results showed clearly that using remixed electrolytes reduces the potential environmental impacts in all the considered categories. This is a relevant result as the V_2O_5 powder is one of the main contributors for the high cost of VRFB [5], so by reusing the vanadium electrolytes it would reduce both the environmental and economic impacts. By incorporating 30% of reused electrolytes, the impacts are reduced by half of the total impacts in the MFRRD category, followed by a reduction of 40% in potential acidification impacts, when compared to the base scenario. With 70% of reused electrolyte, the impacts were further reduced in all categories, especially in the MFRRD and AP categories with 64 and 63% of reduction, respectively. The best-case scenario achieved a reduction of 79% in AP, followed by 75 and 67% reductions of the MFRRD and POF categories, respectively. In the CC and OD categories, no significant reduction was observed, only 4 and 1% in climate change and ozone depletion respectively, which was expected since the vanadium electrolytes do not contribute significantly to these categories, reduced the impacts.

4. Conclusions

This article conducted a cradle-to-gate attributional LCA on a VFRB prototype and analyzed the potential environmental impacts of producing the battery system. The initial results showed that the battery's cell stack and the vanadium electrolytes are the main contributors to the environmental impacts from the production stage. The quantified impacts can be reduced by using recycled or local materials and components. Considering that the battery is easily scalable to address larger consumers, a second scenario was considered to quantify the variation of the environmental impacts when increasing the system's capacity up to 360 kWh. The results showed that, although the quantity of electrolytes and tanks were increased to reach a higher storage capacity, the environmental impacts per stored kWh were gradually reduced and reached an optimal system dimensioning after 180 kWh of storage capacity in terms of environmental performance. An analysis was also conducted on the vanadium electrolytes to quantify the potential reduction in each category by using already existing vanadium electrolytes that were transported and remixed to regain their original capacity. The results showed that for some categories the impacts were significantly reduced, especially in the AP and MFRRD categories, most likely due to the avoided raw materials extraction and consumption. Future work will involve a cradle-to-grave LCA of the VRFB prototype as well as an Economic and Social-LCA for a full Sustainability evaluation.

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References

- [1] Caetano NS, Mata TM, Martins AA, Felgueiras MC. New trends in energy production and utilization. *Energy Procedia* 2017;107:7–14. <http://dx.doi.org/10.1016/j.egypro.2016.12.122>.
- [2] Mata TM, Sousa IRBG, Caetano NS. Transgenic corn oil for biodiesel production via enzymatic catalysis with ethanol. *Chem Eng Trans* 2012a;27:19–24. <http://dx.doi.org/10.3303/CET1227004>.
- [3] Martins AA, Simaria M, Barbosa J, Barbosa R, Silva DT, Rocha CS, Mata TM, Caetano NS. Life cycle assessment tool of electricity generation in Portugal. *Enviro Dev Sustain* 2018;20:129–43. <http://dx.doi.org/10.1007/s10668-018-0179-y>.
- [4] IRENA, 2017. Electricity storage and renewables: Costs and markets to 2030, International Renewable energy Agency, October, ISBN 978-92-9260-038-9.
- [5] Tomazic G, Skyllas-Kazacos M. Redox flow batteries. In: *Electrochemical energy storage for renewable sources and grid balancing*. Elsevier B.V.; 2015, p. 309–36. <http://dx.doi.org/10.1016/B978-0-444-62616-5.00017-6>.
- [6] Mata TM, Smith RL, Young DM, Costa CAV. Life cycle assessment of gasoline blending options. *Environ Sci Technol* 2003;37(16):3724–32.
- [7] ISO 14040, 2006. Environmental management - Life Cycle Assessment - Principles and Framework. International organization for standardization.
- [8] ISO 14044, 2006. Environmental management - Life Cycle Assessment - Requirements and Guidelines. International organization for standardization.
- [9] Mata TM, Martins AA, Neto B, Martins ML, Salcedo RLR, Costa CAV. LCA tool for sustainability evaluations in the pharmaceutical industry. *Chem Eng Trans* 2012b;26:261–6. <http://dx.doi.org/10.3303/CET1226044>.
- [10] Smith RL, Mata TM, Young DM, Cabezas H, Costa CAV. Designing environmentally friendly chemical processes with fugitive and open emissions. *J Cleaner Prod* 2004;12(2):125–9.
- [11] Sunstorage Project, 2019. Harvesting and storage of solar energy. Faculty of Engineering, University of Porto, Portugal <www.sunstorage.pt> (accessed on 05/07/2019).
- [12] Notter DA, Kouravelou K, Karachalios T, Daletou MK, Haberland NT. Life cycle assessment of PEM FC applications: electric mobility and μ -CHP. *Energy Environ Sci* 2015;8:1969–85. <http://dx.doi.org/10.1039/C5EE01082A>.
- [13] Dassisti M, Mastroilli P, Rizzuti A, Abbate PL, Cozzolino G, Chimienti M. LCA of in-house produced small-sized Vanadium Redox-Flow Battery. In: Olabi AG, Alaswad A, editors. *State of the art on energy developments, proceedings of the 8th international conference on SEEP - part 1*. Paisley: University of the West of Scotland; 2015, p. 232–7.
- [14] Dassisti M, Mastroilli P, Rizzuti A, Cozzolino G, Chimienti M, Olabi AG, Matera F, Carbone A. Vanadium: A transition metal for sustainable energy storing in redox flow batteries. In: *Reference module in materials science and materials engineering*. Elsevier; 2016. <http://dx.doi.org/10.1016/B978-0-12-803581-8.04007-8>.
- [15] Weber JF, Baumann M, Weil M. Life cycle assessment of a vanadium redox flow battery. *Environ Sci Technol* 2018;52(18):10864–73.