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Life cycle assessment of a renewable energy generation system with a vanadium redox flow battery in a NZEB household

J.R. Gouveia[a], E. Silva[a,b], T.M. Mata[a], A. Mendes[a], N.S. Caetano[a,b], A.A. Martins[a,*]

[a] *LEPABE, Faculty of Engineering University of Porto, R. Dr. Roberto Frias, 4200-465 Porto, Portugal*

[b] *CIETI/ISEP (School of Engineering), Polytechnic of Porto, R. Dr. António Bernardino de Almeida 431, 4249-015 Porto, Portugal*

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Abstract

Buildings are responsible for a significant part of the global energy consumption. Besides the need to improve their energy efficiency, new buildings also need to generate their own energy, preferably from renewable sources, to become more sustainable. As renewable energy generation is strongly dependent on the climatic conditions, energy storage must be considered when designing such a system. In this study, a cradle-to-grave life cycle assessment (LCA) study of a renewable energy generation system with a prototype Vanadium flow battery integrated in a Near Zero Energy Building (NZEB) is performed. A combined grid-connected PV and a solar thermal system generates the energy, and it was dimensioned to supply the annual energy needs of a household in Porto, Portugal considering the local climatic conditions. As an end of life scenario, it is assumed that the battery is dismantled and most of the materials are recycled. A functional unit of 1 kWh of supplied energy to the system was considered, and study results show that environmental impacts are reduced when the energy is produced onsite and the battery components are recycled or reused. A sensitivity analysis was conducted changing the household's geographic location.

Keywords: Energy storage systems; Life cycle assessment; Near zero energy buildings — NZEB; Vanadium redox flow battery

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[*] Corresponding author.
E-mail address: amartins@fe.up.pt (A.A. Martins).

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Nomenclature

AP	Acidification Potential, environmental impact category in mol c H^+ eq
BIPV	Building Integrated Photovoltaic Technologies
BOS	Balance of System, composed by cables and monitoring equipment in the battery system
CC	Climate Change, environmental impact category in kg CO_2 eq
EU	European Union
EPBD	Energy Performance of Buildings Directive
FE	Freshwater Eutrophication, environmental impact category in kg P eq
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LEPABE	Laboratory for Process Engineering, Environment, Biotechnology and Energy
MFRRD	Mineral, Fossil & Renewable Resource Depletion, environmental impact category in kg Sb eq
NZEB	Near Zero Energy Building
OD	Ozone Depletion, environmental impact category in kg CFC^{-11} eq
POF	Photochemical Ozone Formation, environmental impact category in kg NMVOC eq
PV	Photovoltaic/Photovoltaic panels
REGS	Renewable Energy Generation Systems
VRFB	Vanadium Redox Flow Battery

1. Introduction

Buildings, either residential or corporate (office or industry), are responsible for a significant part of primary energy consumption at a global scale, especially in more developed economies [1]. In the European Union (EU) they are responsible for approximately 40% of the energy consumption and 36% of CO_2 emissions [2]. Energy is consumed not only to power all electrical appliances used to perform common domestic activities but also for air conditioning purposes. Thus, to reduce the environmental impacts of energy usage in buildings various policies and strategies are being developed and adopted at the international, national and regional levels, with a focus in the reduction of the carbon emissions [3].

The EU's Energy Performance of Buildings Directive - EPBD [2] outlines the European strategy in this area. Besides setting the goals for energy efficiency and onsite renewable energy generation, it also defines construction requirements and a building certification scheme to classify their performance in terms of energy efficiency and serve as a communication tool. The implementation varies in the various EU members; as dominant climatic conditions vary within the EU [4].

One of the key aspects of the EBPD is the increasingly demanding requirements for energy efficiency while maintaining the thermal comfort and living conditions. In particular, the EPBD requires all new buildings to be Near Zero Energy Buildings, NZEB, by the end of 2020. According to the EPBD, a NZEB corresponds to a building with a very high-energy performance. To achieve this goal, the energy requirements should be fulfilled using renewable energy produced on-site or in the building vicinity. Moreover, the construction techniques should support as much as possible a high efficiency of energy utilization, especially to ensure the conditions for thermal comfort with the minimal energy consumption possible. Although specific time goals are defined in the EPBD, no specific details are given in the directive concerning the definition of a NZEB. Thus, no harmonized definition exists within the EU. The member states are responsible for the definition of what constitutes a NZEB in their national implementation plans, taking into account the specifics national or regional contexts, as for example dominant construction techniques and climate conditions.

The generation of onsite renewable energy in a NZEB also poses some challenges. For a normal residential or commercial building two forms of energy are needed: thermal energy, mostly to heat water, and electricity to provide lighting and run all the electrical appliances used in daily activities. To supply this energy, various renewable energy generation systems (REGS) may be used, currently a combination of a flat plate collector for water heating and a photovoltaic (PV) system for electricity generation. While the considered systems are the ones commonly used in the market, other types of buildings components exist to fulfil those goals, such as hybrid solar/thermal solar panels or other Building Integrated Photovoltaic technologies (BIPV), as for examples roof tiles [5]. Other REGS, such as wind or superficial geothermal, are much less used, as their environmental impacts are larger (e.g. noise in wind systems) or may require larger investments and/or maintenance costs (e.g. superficial geothermal).

Regardless of the REGS implemented, the variability of the climatic conditions and the natural cycles, as for example day and night, will lead to changes in the quantity of renewable energy that can be generated at a given moment. To ensure the readiness of onsite generated renewable energy irrespective of its availability or not, and to increase the system resilience, there is a need for energy storage systems. For electricity, various types of batteries can be used, all with their advantages and disadvantages.

Vanadium Redox Flow Batteries (VRFB) are one of the most promising technologies in stationary storage systems due to their long charge/discharge cycles, high efficiencies and avoided cross-contamination, and to being particularly suitable to systems where a regular supply of energy is required. Although they have lower energy densities when compared with lithium batteries, they are cheaper, the energy storage capacity does not change noticeably with utilization, and the component's materials and electrolyte can be easily recycled and reused. The selection of the most adequate option depends in many factors. Besides the technical (for example, the consumption profile) and economic aspects, presently the minimization of the environmental impacts is increasingly seen as an important factor when selecting the most appropriate technology [6].

2. Methodology

Among the various methodologies available to assess the environmental impacts of a product or process, Life Cycle Assessment (LCA) is currently seen as the most adequate and accepted. In this work, an attributional LCA study is performed on a prototype VFRB, developed by LEPABE in the context of the Sunstorage project [7], (Fig. 1), integrated in a grid-connected photovoltaic (PV) system. The REGS was dimensioned to supply the full-electric energy requirements of a typical NZEB (Near Zero Energy Building) household for the local average climatic conditions in Porto, Portugal.

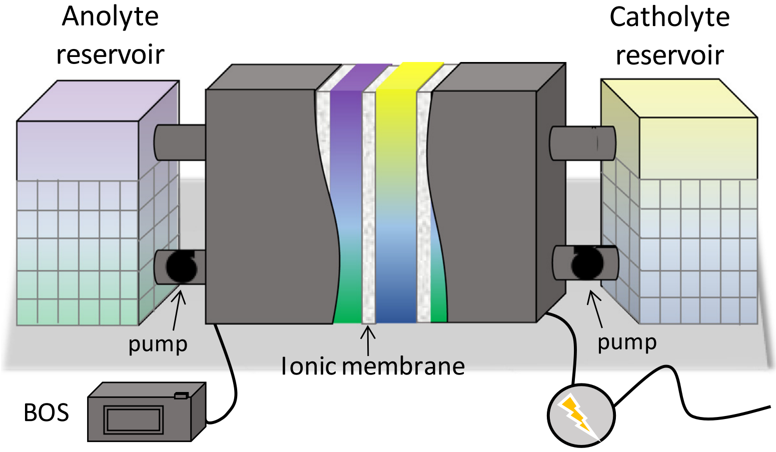

Fig. 1. Schematic of the VRFB system composed by the battery, electrolytes and storage tanks, pumps and balance of system components (BOS) composed by cables and monitoring equipment.

Among the various methodologies available to assess the environmental impacts of a product or process, Life Cycle Assessment (LCA) is one of the most accepted and used [8,9]. The methodology defined in the [10] and [11] standards was used to do the present LCA study. A cradle-to-grave study was conducted, including the materials extraction, components production, assembly, usage and final disposal/recycling of components and materials, as shown in Fig. 2.

The study followed an attributional approach. Concerning the final life cycle phase, the current dominant forms of waste disposal or recycling were considered for each material: recycling and/or reutilization for the metals (copper, steel and aluminium), incineration with energy recovery for plastic materials. The VRFB has 5 kW power and

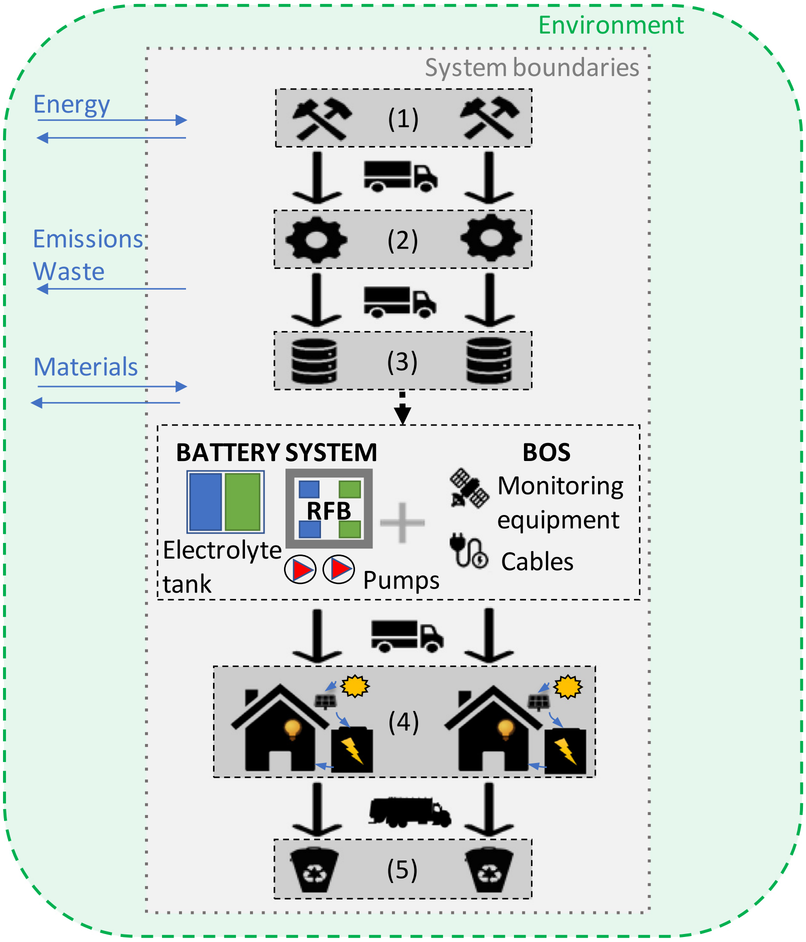

Fig. 2. System boundaries of the present study. (1) production, (2) processing, (3) assembly and (4) use. Battery system components: cell stack, tanks, pumps, monitoring system and cables. Photovoltaic (PV) and balance of system components (BOS): PV panels, an inverter and cables.

18 kWh of energy storage capacity, a system voltage of 48 V and an inverter of 2.5 kW. A functional unit of 1 kWh supplied to the household is defined, as it is the main measure of the system performance. The system has an expected operational life of 20 years, and during its use, the Nafion® membranes are replaced after 10 years, and the pumps are replaced at the 15-year mark. As there are wide variations in the size and other building characteristics, in this study a base case study was assumed of a household with 3 occupants and an area of 100 m^2 in Porto, Portugal. The household dimensions and occupants were defined based on information concerning the average family in Portugal [12,13].

The characteristics of the REGS are determined by imposing that the household is a NZEB. This requires a working definition of a NZEB, as well as the main elements of the REGS, and the expected energy needs for the household. Based on the latter, the main characteristics of the REGS can be determined.

As no practical and consensual definition exists concerning what is a NZEB, and the EPBD [2] is flexible in this question, for this work it is assumed that the NZEB is a building in which the energy imported (national energy mix) from the outside of the system boundary equals the energy exported to the exterior. In the real context, this definition imposes that the net energy balance is zero, and ensures that even when the battery is fully discharged the household has access to the energy it needs.

The REGS dimensioning was done using a MS Excel™ tool developed by Silva [12], that estimates the energy requirements using existing regulations for building energy certification and using freely available information for the solar insolation [14]. As a NZEB should have a high-energy efficiency, its energy requirements should be at least those defined in the existing regulations [15]. Moreover, the tool includes a small database of commercially available and widely used PV modules and solar heaters, warranting that the calculated values are based on existing equipment. The tool was used before performing the Life Cycle Inventory (LCI), in order to be able to properly account for the total quantity of materials and other inputs needed to build the RGS. The LCI was built using primarily the data gathered from the prototype developers, complemented with data from the Ecoinvent V3.4 life cycle inventory database [16], information gathered from the suppliers and Silva [12].

No allocation procedures were necessary. For the Life Cycle Impact Assessment, the chosen quantification method was the International Reference Life Cycle Data System (ILCD) 2011 Midpoint+ V1.10 [17] and the calculations were performed using the Simapro V8.5.2.0 LCA software. The following environmental impact categories were quantified per supplied kWh and scaled for results analysis: climate change - CC [kg CO_2 eq], ozone depletion – OD [kg CFC-11 eq], photochemical ozone formation - POF [kg NMVOC eq], acidification potential - AP [mol c H^+ eq], freshwater eutrophication - FE [kg P eq], and mineral, fossil & renewable resource depletion - MFRRD [kg Sb eq].

3. Results and discussion

The application of the tool resulted in a REGS with a total of 15 PV panels with 250 W of power each, assuming 14% of energy loss in conversions. The annual electricity supplied to the NZEB includes 21% of energy provided from the grid, to account for those periods when the dimensioned PV system cannot produce enough for the demand, mainly due the climatic conditions. Yet, in some periods, there is an excess of energy produced by the PV panels that cannot be stored in the flow battery. That surplus energy is injected in the electric grid, thus ensuring that the household net energy requirements are zero, in agreement with the definition of NZEB considered in this work. Fig. 3 presents the values of the environmental impacts per kWh of supplied energy for the NZEB system.

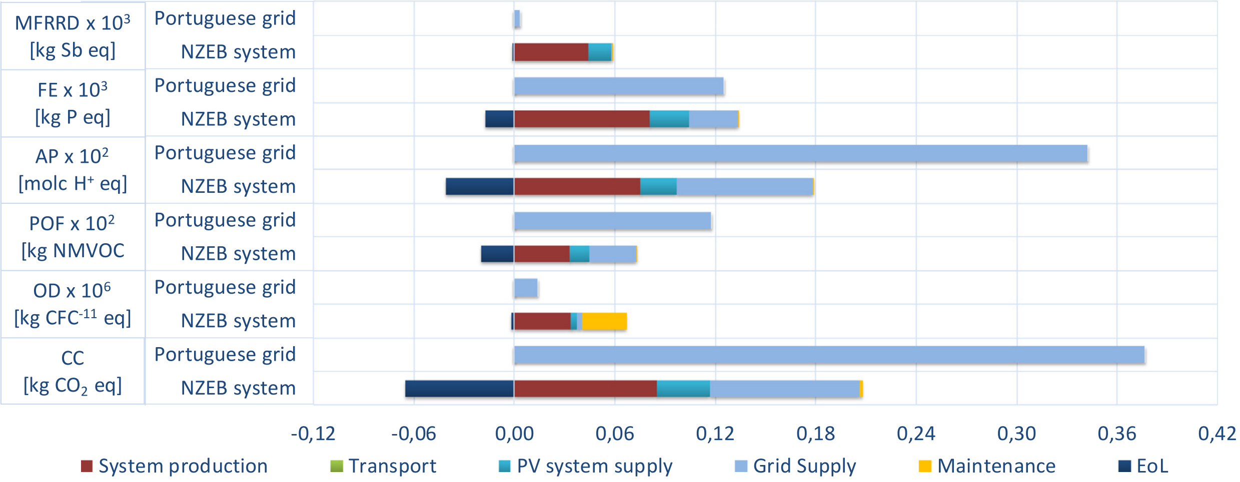

Fig. 3. Environmental impacts per kWh of supplied electricity. Some categories were scaled to fit the graphic.

The values are presented divided by life cycle stage and include the impact of the electricity supplied by the Portuguese grid, due to the need to use exterior electricity to fulfil the household needs. The figure shows that, with the exception of the mineral, fossil & renewable resource depletion (MFRRD) and ozone depletion (OD) categories, the impacts related to the utilization of electricity from the electrical grid are significantly higher than the potential impacts from the NZEB system. The grid impacts also have an important contribution to the overall impacts of the NZEB system in most categories. In order to reduce the use of energy from the Portuguese grid an alternative would be to maximize the onsite or local renewable energy generation to reduce the environmental impact, but it would lead to larger environmental impacts, as more PV modules panels and electricity storage capacity would be necessary.

The system production aggregates the life cycle stages of producing the battery, PV and water heating systems. Concerning the OD category, the maintenance/substitution of the membranes and pumps have a large contribution of almost 40%, mostly due to the production of the Nafion ionic membrane which uses tetrafluoroethylene in its production. In this category, the production stage contributes significantly to the total impacts due to the battery production, which is the second highest contributor with 35% of the total life cycle impacts, also due to the membrane. With the exception of the OD and acidification potential (AP) categories, the PV system production is the largest contributor of the environmental impacts from the production stage.

The flow of material and energy necessary to produce the PV system influences mostly the MFRRD category with 55% of total impacts and the FE category with 43% of total impacts. Energy losses during the life cycle stage of utilization of the system have their highest contribution in the MFRRD category with 24% of impacts. An increase in the efficiency of the PV modules or the utilization of lower environmental impact materials in their construction are potential solutions. The battery production is responsible for 16% of the total impact in this category, which is related to the production of the vanadium electrolytes. Forms of reducing these potential impacts in MFRRD are to locally produce the electrolyte, recycle/reused it after reconditioning and adjustment of the electrolyte characteristics, or development of new electrolytes with larger energy densities; though for the last option the environmental impacts may increase instead of reducing.

In Fig. 3 the impacts of the recycling/reusing are also presented, corresponding to the negative valued bars (positive impacts). It can be seen that only for the FE, AP, photochemical ozone formation (POF) and climate change (CC) are the impacts of recycling/reusing noteworthy. However, the impact reduction/avoidance is always lower than 35%, being the largest for the Climate Change category with 32%. Therefore, there is a need to use more recyclable materials, in particular in the PV system and non-metallic elements, plastics and others, that are used in the battery.

As one of the main goals of having NZEBs is the reduction of the environmental impacts due to the energy consumption in buildings, Fig. 3 also includes a comparison between the NZEB system and an equivalent household in which 100% of the electricity is supplied by the Portuguese electricity grid. The results show that in most categories the environmental impacts of energy supplied in the NZEB is lower. The exceptions are of the MFRDD and OD categories, where quite large differences where observed, causing an increase of the potential impacts of over 1800 and 380%, respectively. This is mainly due to the photovoltaic panels, ionic membrane and the vanadium electrolytes production. For the remaining categories the NZEB has lower environmental impacts. While for the Freshwater Eutrophication category the difference is very small (not to forget the negative impact of the end-of-life must be summed to the other impacts), for the remaining considered categories the difference is substantial, larger than 50%. In particular, for the Climate Change category a reduction of more 62% is observed, showing that NZEB households can contribute significantly the carbon emissions under the current Portuguese conditions, thus justifying the current strategy and goal of all new buildings to be NZEB by the end of 2020.

A sensitivity analysis of the geographic location of the NZEB household was conducted to understand the influence of the local climatic conditions and the transportation of the VRFB system in the overall environmental impacts. The location selected was Portimão, in southern Portugal. This location has higher sun exposure and is around 550 km from the battery production site. The PV system and solar panels were dimensioned considering the climate conditions from Portimão and using the same methodology explained above, being the remaining characteristics the same, particularly the number of occupants, type of PV panels, solar heater and battery storage capacity.

Fig. 4 shows the reduction of the values of the environmental impacts when changing the location from Porto to Portimão. The figure shows that the increase of solar exposure combined with the reduction of energetic needs reduces the values of almost all the impact categories, except for the MFRRD category, which had a low increase of 8% of total impacts. The biggest reduction of impacts was in the CC category, followed by AP and POF, mainly due to the reduction of the energy necessary from the Portuguese grid during its utilization to fulfil the NZEB energy needs.

4. Conclusions

In this work a cradle-to-grave life cycle study of a renewable energy system with a Vanadium redox flow battery in NZEB household NZEB was done. A specific definition of a NZEB based on the net electricity input and output from/to the exterior electricity supply network was considered. The energy needs were calculated using a computational tool that considers the existing constructions regulations for thermal comfort and energy efficiency. The results show that the NZEB has lower environmental impacts when compared to a complete electricity supply from the electric grid in most categories. Moreover, recycling and/or reusing system components, particularly from

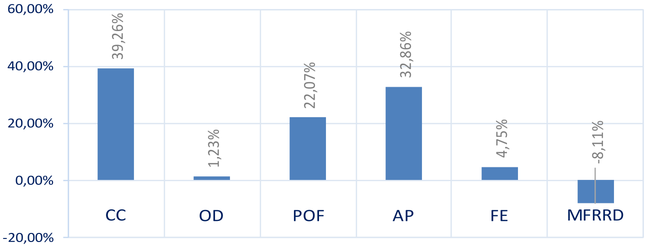

Fig. 4. Variation between the initial NZEB system scenario in Porto, north of Portugal, and the alternative scenario in Portimão.

the battery, and improving the efficiency of the PV system to depend less on the grid supply can also contribute to reduce the system's overall environmental impact. The sensitivity analysis shows that the geographic factor can have a significant impact on the total life cycle impacts, especially in the utilization phase due to different climatic conditions. The results from this work will be used as a baseline for an Economic and Social-LCA for a full cradle-to-grave Sustainability Assessment, and the influence of considering other NZEB definitions will also be considered.

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