

Article

Environmental Assessment of Electrochemical Energy Storage Device Manufacturing to Identify Drivers for Attaining Goals of Sustainable Materials 4.0

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Abstract: Electricity from the combination of photovoltaic panels and wind turbines exhibits potential benefits towards the sustainable cities transition. Nevertheless, the highly fluctuating and intermittent character limits an extended applicability in the energy market. Particularly, batteries represent a challenging approach to overcome the existing constraints and to achieve sustainable urban energy development. On the basis of the market roll-out and level of technological maturity, five commercially available battery technologies are assessed in this work, namely, lead–acid, lithium manganese oxide, nickel–cadmium, nickel–metal hydride, and vanadium redox flow. When considering sustainable development, environmental assessments provide valuable information. In this vein, an environmental analysis of the technologies is conducted using a life cycle assessment methodology from a cradle-to-gate perspective. A comparison of the environmental burden of battery components identified vanadium redox flow battery as the lowest environmental damage battery. In terms of components, electrodes; the electrolyte; and the set of pumps, motors, racks, and bolts exhibited the greatest environmental impact related to manufacturing. In terms of materials, copper, steel, sulphuric acid, and vanadium were identified as the main contributors to the midpoint impact categories. The results have highlighted that challenging materials 4.0 are still needed in battery manufacturing to provide sustainable technology designs required to the future urban planning based on circular economy demands.

Keywords: energy storage systems; batteries; life cycle assessment; circular economy strategies; chemical energy storage; material 4.0; sustainable technology

1. Introduction

The use of renewable energy sources is foreseen as a route that contributes significantly towards reducing carbon emission levels in European Union (EU) countries [1]. Among the large number of renewable energy technologies, photovoltaic panels combined with wind turbines have been reported as technologies that can be used to promote circular urban metabolism [2]. However, there are still some challenges that hinder their extensive application. In particular, the successful deployment of these types of technologies is limited because of fluctuations of both solar radiation and wind velocity, leading to unavoidable oscillations in electricity production. In contrast, one important advantage of these technologies is that they also allow electricity production in areas where off-grid systems are needed [2]. In this vein, Bhandari et al. [3] proposed using hydro, wind, and solar photovoltaic

energy to develop off-grid hybrid systems based on different energy sources. Naqvi et al. [4] also reported about the benefits of renewable off-grid systems based on biomass. Therefore, a renewable energy system comprising different technologies can be implemented not only to mitigate the effects of intermittent wind and sunlight, but also to supply energy to remote areas.

Renewable energy systems require the selection and design of suitable energy storage systems (ESSs) that can be combined with wind and solar renewable energy sources in order to guarantee their sustainable deployment [5]. Among the existing ESSs, batteries have attracted considerable attention because they can be considered one of the most suitable approaches to store energy, considering that they involve different technologies and applications with geographical independence. Technically, there are some positive reports concerning the application of batteries to renewable energy systems. Zhang et al. [6] analysed the use of battery storage and hydrogen storage both connected to a photovoltaic system, whereas Li et al. [7] studied combined systems of batteries, wind energy, and heat pumps for a building's energy needs. Moreover, the integration of renewable energy to batteries is favourable from an economics point of view. Studies performed by Gioutsos et al. [8] and Ding et al. [9] reveal that battery storage costs will decrease, while their renewable energy capacities will increase in the coming years; the predicted potential decrease in costs may reach up to approximately \$400/kWh in 2025 [9].

According to the battery characteristics, it is expected that new designs and production could bring substantial benefits towards the sustainable cities transition in Europe [10]. In general, the application of batteries is mostly foreseen to enhance renewable energy opportunities in micro-generation systems, allowing them to supply and distribute steady electrical power [11,12]. Power provided by the current battery approaches can only meet energy demand at a lower scale, suitable only for local use or in micro-grids owing to low energy density (low storage capacity) [13].

State-of-the-art of batteries involve broad and various specifications classified by their chemistry into four main types: lead-, lithium-, and nickel-based systems and redox flow [13–15]. Concerning the above selected battery types, lead–acid (PbA) is the oldest and most used rechargeable battery; accordingly, they are mature technologies at a commercial stage [13,14]. Li-ion battery type is the most prominent with a 55% market share [13]. The lithium family is broadly differentiated in terms of metal chemistries. Compared with other traditional cathode materials, such as lithium cobalt oxide, lithium manganese is low cost, pollution-free, safe, and has good rate performance. Among the different lithium–metal chemistries batteries, lithium manganese oxide (LiMn_2O_4) is one of the most common consumer-grade lithium batteries. Besides manganese–oxide components being earth-abundant, inexpensive, and non-toxic, LiMn_2O_4 represents average values for the lithium family owing to its moderate specific power, moderate specific energy, and moderate level of safety when compared with the other types of lithium-ion batteries [13–15]. Regarding technologies that use nickel–electrode, five technologies were identified. Among them, nickel–cadmium (NiCd) and nickel–metal hydride (NiMH) are more popular than the others, but NiCd is the most utilized nickel–electrode technology in modern utility industries [15]. Finally, the most studied and currently most mature and promising redox flow technology is vanadium redox flow batteries (VRFB) [14].

Taken into consideration the most common and established battery technologies in the current market, five batteries have been selected to perform the comparative analysis presented in this work based on their technological maturity, market roll-out level, and related costs.

These batteries are as follows:

1. Lead–acid (PbA) battery;
2. Lithium manganese oxide (LiMn_2O_4);
3. Nickel–cadmium (NiCd);
4. Nickel–metal hydride (NiMH);
5. Vanadium redox flow battery (VRFB).

One of the keys to advancing their energy storage performance lies in minimising manufacturing impact by both finding novel materials and reducing resource consumption by fostering circular economy strategies. The manufacturing processes of these batteries entail the consumption of some problematic materials, not only in terms of their impacts on human health and the environment, but also in terms of their scarcity and costs, which are important limitations to the sustainable battery deployment in the market.

On the one hand, some battery components such as electrodes and electrolytes are made of hazardous materials that are mainly responsible for the environmental burden attributed to batteries. Examples of such hazardous materials are lead and sulfuric acid used in lead–acid batteries [16] and cadmium used in nickel–cadmium batteries [17]. Lithium is not a health hazard material by itself; however, Li-ion batteries include hazardous materials in the form of minor components such as copper, which is responsible for the ecotoxicity potential of such batteries [18]. Flow batteries are also considered environmentally benign; however, their vanadium system includes highly acidic solutions (electrolytes) that pose an extremely corrosive hazard to the environment [15,19].

On the other hand, in terms of absolute quantities of materials needed for manufacturing batteries, certain materials are supply risks based on their scarcity on Earth. This is a major concern in today's battery manufacturing industry. Cobalt, natural graphite, rare earth elements, silicon (metal), and vanadium have been recently listed as critical raw materials (CRMs) by the European Commission [20]. Although currently not a CRMs, lithium's increasing importance in the market owing to its role in the Li-ion battery industry [21–23] may eventually require constraints in its consumption to ensure that it does not become a supply risk.

The abovementioned material concerns constitute a challenge for energy storage in the near future of sustainable materials 4.0. To overcome this challenge in a sustainable manner, further developments should focus on reducing the environmental impact of the key materials used during battery manufacturing. The life cycle assessment (LCA) methodology is a widely used procedure for measuring sustainability [24] in different sectors and equipment, such as industrial furnaces [25], processing technologies in the agri-food sector [26], or materials for vehicles in the transport sector [27,28]. However, there is a lack of knowledge in the battery field, particularly in the quantification of environmental burdens associated with the battery manufacturing stage.

On the basis of a detailed review of the literature in the battery field, environmental assessment of the five selected battery technologies has generally adopted a “cradle-to-grave” type of LCA [29,30], although Weber et al. [31] have also considered a “cradle-to-cradle” perspective. These types of LCA approaches assign a high degree of uncertainty to the life cycle inventory (LCI) of the manufacturing stage of the system's full lifecycle [32]. Furthermore, a comparative report involving all of the five selected battery technologies was not found. Although other technologies have been addressed [33–35], the results from the existing reports are difficult to compare under similar reference scenarios. Other studies that have involved almost all the selected technologies have focused on energy analysis [36]. Consequently, there is a need to conduct an exhaustive evaluation of the environmental burden associated with the manufacturing stage of ESSs.

Therefore, this work was aimed to execute a comprehensive environmental analysis of the manufacturing stage of the five selected battery technologies. Firstly, the five battery technologies were assessed to identify the best technology in terms of environmental impacts by applying the LCA methodology. This comparative study used a cradle-to-gate perspective aiming to obtain consistent LCI based on more reliable data. For this purpose, an updated database of scientific and specialised literature was generated and systematically assessed to confirm the quality of the data. The technology with the least negative cradle-to-gate environmental impact was defined as the benchmark system. Secondly, a deeper environmental analysis of the benchmark system was developed to determine which materials constitute a challenge owing to their inherent environmental hazard or scarcity as a path towards attaining the goals of sustainable materials 4.0. Special attention was given to battery components, particularly the materials, which pose as an important environmental burden. Thus,

apart from assessing the specific life cycle impacts related to each battery technology, special attention was paid to identify the critical components based on material consumption and availability during the manufacturing process by applying the key midpoint impact categories when analysing the existing technologies.

As a summary, the main aims of this study were as follows:

- To identify the benchmark battery technology based on environmental performances during the manufacturing stage of selected systems by applying a consistent and updated LCI.
- To determine the key manufacturing components and materials of the benchmark battery technology that causes the more significant environmental impact.
- To identify new avenues of research in materials 4.0 that give importance to both environmental impacts and material availability, which are key issues for promoting the sustainable commercialisation and fair access of products while preserving the sources of raw materials for batteries within the EU.

2. Materials and Methods

An LCA was performed to quantify the environmental impacts of the five selected battery technologies. As a general framework, LCA attempts to translate the emissions, resource extraction, and processes associated with manufacturing (i.e., inputs and outputs along the value chain) into potential environmental impacts. This methodology involves four interrelated phases, as described in ISO 14040:2006 [37] and ISO 14044:2006 [38], namely, goal and scope definition (1), inventory analysis (2), impact evaluation (3), and interpretation (4).

2.1. Goal and Scope

The main objective of this analysis was to assess the environmental performance associated with the particular ESSs using a cradle-to-gate perspective. This approach aims to identify key aspects related to a certain production phase [34,36]. This methodology was selected to provide a high degree of precision to the analysis of the manufacturing stage, which is the first stage that must be evaluated in an emergent technology based on the environmental LCA point of view. Within this approach, a detailed analysis of the critical components in terms of materials consumption and availability was included. This study does not include any spills or breakages in the batteries before the lifespan considered. Nevertheless, in the case that these types of failures would happen, additional emissions could be considered as direct emissions into the analysis (in the case of spills) or as additional components/batteries manufacturing and end of life treatment in the case of components. Both issues will increase the environmental impacts associated with the affected indicators, not only, for example, the ones associated to the acidity of the electrolyte. Therefore, although safety is a technical indicator and, therefore, it is not included into the environmental indicators studied by ReCiPe method, it would be possible to note that low levels of safety provoking spills or breakages will increase environmental impacts mostly associated to emissions flows and end of life stages involved for manufacturing of components/batteries.

2.1.1. System Description and Boundaries

As shown in Figure 1, the analysis was from the cradle-to-gate and the system boundaries were limited to the battery manufacturing stage. Among the battery components assessed, the comparative analysis considered electrodes, electrolytes, separator, and case (or cell container), except for the VRFB, whose components were analysed in terms of three subsystems: power (i.e., electrodes, ionic membranes, flow frames, and bipolar plates); energy (i.e., electrolyte and electrolyte container); and peripherals (i.e., pumps, motors, racks, and bolts). In other words, the system boundaries were defined to include raw material mining and conditioning, component production, and assembly of each battery technology.

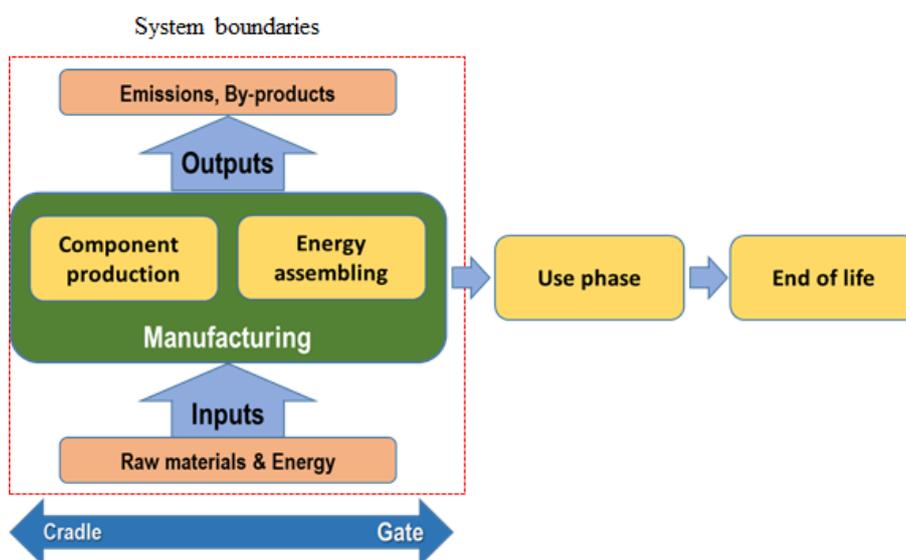


Figure 1. System boundaries defined for the life cycle assessment (LCA) of the selected batteries.

To guarantee that all relevant environmental impacts were represented in the study, the analysis used the following cut-off criteria regarding the material and energy flows [39]:

- **Materials:** flows of less than 1% of the cumulative mass were excluded because their environmental relevance is not a concern. However, it was ensured that the sum of the ignored material flows did not exceed 5% of the mass or environmental relevance.
- **Energy:** flows of less than 1% of the cumulative energy were excluded from this analysis. However, it was ensured that the sum of the ignored energy flows did not exceed 5% of the energy or environmental relevance.

2.1.2. Functional Unit

The functional unit was defined to provide a reference to which the process inputs and outputs were correlated. As this study aims to compare several energy storage systems, the functional unit was defined as 1 kWh of storage energy. The lifetime of the battery technologies was standardised to 20 years to compare all the batteries on the same time scale.

2.2. Life Cycle Inventory

One of the more important stages of the LCA methodology is making the LCI, as the collected data must be reliable to obtain consistent life cycles studies. However, the collection of information related to the inputs and outputs, in terms of material and energy, of chemical battery systems was difficult. This is because of the limited availability of data and the high variability of the data associated with different battery types reported in the literature. Therefore, the raw data (e.g., databases and journals) were critically assessed from a comprehensive selection of the literature to perform a consistent LCI. This selection consisted of reports and papers that provided the availability of data to support a complete LCI of the five battery technology manufacturing stages.

This assessment was complemented with the use of Ecoinvent 3.4 (Ecoinvent. Ecoinvent 3.4 database: Zurich, Switzerland). Based on this extensive revision of available scientific data, an updated database of scientific and specialised literature was generated for performing life cycle studies.

Recycled materials and end-of-life impacts were not included in cradle-to-gate analyses, which means the analysis performed in this work is based on considering the total amount of resources as virgin materials. In addition, energy consumption for assembly was assumed to be an average European electricity mix in order to establish a common energy source for the manufacturing stage of all five battery technologies.

To normalise the data, all inputs and outputs (energy and materials) related to the battery manufacturing stage were managed consistent with the functional unit (1 kWh of storage energy) and reference lifetime (20 years) according to the cradle-to-gate approach.

In order to confirm that the data conformed to the quality requirements, the normalised data were modelled by SimaPro software version Analyst 8.5.0.0 (PRé Consultants. SimaPro 8 LCA software. The Netherlands 2010) and the results were compared to existing LCA published data. Only when the level of consistency and reproducibility of results had been validated, did we consider the LCI of each battery type (raw data from previously published works) as definitive.

In summary, the following methodology was carried out:

1. The cradle-to-gate LCI raw data per kilogram of battery material for all batteries was gathered. Particularly for VRFB, LCI raw data were obtained as kilogram of battery material per MWh of energy storage in 20 years.
2. Raw data were referenced to the functional unit, 1 kWh of electricity storage. With the objective to normalise the raw data, information concerning specifications of the selected batteries were collected in all cases. It comprised average specific energy, cycles/all lifespan, and lifetime. These battery specifications were used to normalize average values of gathered data in terms of kilogram of battery to the functional unit (1 kWh of storage capacity, considering 20 years of working time).
3. Eventual material replacement was also considered according to the reference lifetime of each battery technology. Because it was dependant on the lifetime of batteries, the number of batteries required for a service life of 20 years was calculated. In this sense, the LCA of batteries was done based on the normalised LCI of the manufacturing stage scaled with respect to the replacement of consumed materials needed to attain the reference service life.
4. The cradle-to-gate impacts of the five battery technologies resulting from the modelled systems in SimaPro software were compared with LCA results published in previous works in order to validate the LCI level of consistency and reproducibility.
5. The LCI raw data leading to the more accurate results were selected as the ones to be included in this work.

The main LCI results used for the characterisation of selected batteries are presented in Section 3.1.

2.3. Life Cycle Impact Evaluation

In this study, the environmental analysis was implemented with SimaPro software version Analyst 8.5.0.0 using the ReCiPe 2016 v1.1 midpoint evaluation method, which calculates 18 midpoint impact categories. These indicators are global warming potential (GWP), stratospheric ozone depletion (ODP), Ionising radiation (IRP), ozone formation human health (HOFP), ozone formation terrestrial ecosystems (EOFP), particulate matter formation (PMFP), terrestrial acidification (TAP), freshwater eutrophication (FEP), marine eutrophication (MEP), Terrestrial ecotoxicity (TETP), freshwater ecotoxicity (FETP), marine ecotoxicity (METP), human carcinogenic toxicity (HTPc), human non-carcinogenic toxicity (HTPnc), Land use (LOP), mineral resource scarcity (SOP), fossil resource scarcity (FFP) and water consumption (WCP).

On the basis of all these categories, the ReCiPe midpoint approach covers all possible environmental interventions, which defines the environmental mechanism throughout the quantification of the impacts at intermittent stages of the cause–effect chain [40]. Additionally, the ReCiPe midpoint method is the one of the most recent and comprehensive methods currently available in life cycle impact assessment [41] and expresses the relative severity on an environmental impact category [42]. A detailed description of the 18 indicators [43,44] is shown in Table 1.

Table 1. Environmental midpoint impact categories studied.

Impact Category	Acronym	Unit	Description [43,44]
Global warming	GWP	kg CO ₂ eq	Based on climate change, which causes a number of environmental mechanisms that affect both the endpoint human health and ecosystem health.
Stratospheric ozone depletion	ODP	kg CFC-11 eq	Destruction of the stratospheric ozone layer by anthropogenic emissions of ozone-depleting substances.
Ionising radiation	IRP	kBq Co-60 eq	The routine releases of radioactive material to the environment affect the human health.
Ozone formation, human health	HOFP	kg NO _x eq	Ozone is not directly emitted into the atmosphere, but it is formed as a result of photochemical reactions of NO _x and non-methane volatile organic compounds (NMVOCs). Ozone concentrations lead to respiratory distress.
Ozone formation, terrestrial ecosystems	EOFP	kg NO _x eq	
Fine particulate matter formation	PMFP	kg PM _{2.5} eq	It represents a complex mixture of organic and inorganic substances coming from both anthropogenic and natural sources. Particles with a diameter of 2.5 may have more visible impacts on respiratory morbidity.
Terrestrial acidification	TAP	kg SO ₂ eq	Measurement of emissions that cause acidifying effects to the environment.
Freshwater eutrophication	FEP	kg P eq	Over-enrichment of watercourses with ammonia, nitrates, nitrogen oxides, and phosphorous. Its occurrence can lead to damage of ecosystems, increased mortality of aquatic fauna and flora, and loss of species dependent on low-nutrient environments.
Marine eutrophication	MEP	kg N eq	It refers to the runoff and leach of plant nutrients (phosphorus and nitrogen) from soil and discharge into riverine or marine systems. This may lead to hypoxic waters and, if in excess, to anoxia and “dead zones”, which cause marine ecosystems disturbance.
Terrestrial ecotoxicity	TETP	kg 1,4-DCB	Assessment of toxicity based on maximum tolerable concentrations in freshwater and marine aquatic ecosystems and terrestrial ecosystems.
Freshwater ecotoxicity	FETP	kg 1,4-DCB	
Marine ecotoxicity	METP	kg 1,4-DCB	
Human carcinogenic toxicity	HTPc	kg 1,4-DCB	Effect of a chemical on the function of environmental persistence (fate), its accumulation in the human food chain (exposure), and the toxicity (effect) of the chemical.
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DCB	
Land use	LOP	m ² a crop eq	The land use impact category reflects the damage to ecosystems because of the effects of occupation and transformation of land
Mineral resource scarcity	SOP	kg Cu eq	Represent the amount mineral resources consumed, both directly and indirectly
Fossil resource scarcity	FFP	kg oil eq	Represent the amount fossil resources consumed, both directly and indirectly
Water consumption	WCP	m ³	Represent the amount of water consumed, both directly and indirectly

2.4. Interpretation

All previous steps in the LCA methodology culminate into this step, because all data and results require interpretation. In this work, special interest was paid to interpreting results in terms of identifying environmental impacts of components of the five existing battery technologies. The direct relationship between LCI-normalised data and LCA results was assessed in detail to determine the more critical battery components and materials, based on a detailed comparison of environmental impacts. Particular attention was given to elucidating impacts related to raw material consumption and the availability of resources, which are the key drivers for promoting the sustainable development of chemical storage devices.

3. Results and Discussions

3.1. General Characteristics of Batteries and LCI

The main characteristics of the selected batteries were collected from the literature review and presented as average values in Table 2.

Additional information concerning the LCI of batteries, including items used for manufacturing components and energy used for assembly, is shown in Tables 3–7. Specific information about the original raw data (as reported in the literature) and normalised data (as calculated in this study based on the functional unit and reference lifetime) is also presented.

Table 2. Specifications of the selected batteries.

Battery Type	Average Specific Energy Wh kg ⁻¹ Cycle ⁻¹	Cycles/All Lifespan	Lifetime	Data Reference
Lead–Acid (PbA)	38.8	750	10	[14]
Lithium Manganese Oxide (LiMn ₂ O ₄)	148.8	5500	12.5	[14]
Nickel–Cadmium (NiCd)	62.5	2250	14.7	[14]
Nickel–Metal Hydride (NiMH)	76.3	1633	9.0	[45–47]
Vanadium Redox Flow Battery (VRFB)	19.9	12.068	12.4	[14,31,34,47–49]

Table 3. Life cycle inventory (LCI) results for lead–acid (PbA) battery.

Pb–Acid Battery Manufacturing			Raw Data [50]		Normalised Data	
			Value	Unit	Value	Unit
Assembly	Energy consumption	Electricity	10.71	MJ/(kg battery)	0.74	MJ/(kWh storage)
Component production	Electrodes	Antimony (Sb)	0.71	g/100 g battery	0.49	g/(kWh storage)
		Arsenic (As)	0.03	g/100 g battery	0.02	g/(kWh storage)
		Copper (Cu)	0.01	g/100 g battery	0.01	g/(kWh storage)
		Lead (Pb)	60.97	g/100 g battery	41.96	g/(kWh storage)
		Oxygen (O ₂)	2.26	g/100 g battery	1.56	g/(kWh storage)
Electrolyte	Sulfuric Acid (H ₂ SO ₄)	Water (H ₂ O)	10.33	g/100 g battery	7.11	g/(kWh storage)
			16.93	g/100 g battery	11.65	g/(kWh storage)
Separator	Glass		0.20	g/100 g battery	0.14	g/(kWh storage)
		Polyethylene (PE)	1.83	g/100 g battery	1.26	g/(kWh storage)
Case	Polypropylene (PP)		6.73	g/100 g battery	4.63	g/(kWh storage)

Table 4. LCI results for LiMn₂O₄ battery.

LiMn ₂ O ₄ Battery Manufacturing			Raw Data [50]		Normalised Data		
			Value	Unit	Value	Unit	
Assembly	Energy consumption	Electricity	42.75	MJ/(kg battery)	0.08	MJ/(kWh storage)	
Component production	Electrodes	Carbon (C)	14.96	g/100 g battery	0.29	g/(kWh storage)	
		Lithium manganese (LiMn ₂ O ₄) oxide	23.63	g/100 g battery	0.46	g/(kWh storage)	
		Polyvinylidene fluoride	1.19	g/100 g battery	0.02	g/(kWh storage)	
		Styrene butadiene rubber	1.19	g/100 g battery	0.02	g/(kWh storage)	
		Aluminium (Al)	20.73	g/100 g battery	0.41	g/(kWh storage)	
	Electrolyte	Copper (Cu)		15.55	g/100 g battery	0.30	g/(kWh storage)
			Propylene carbonate	3.15	g/100 g battery	0.06	g/(kWh storage)
			Ethylene carbonate	6.3	g/100 g battery	0.12	g/(kWh storage)
			Dimethyl carbonate	3.15	g/100 g battery	0.06	g/(kWh storage)
	Separator	Lithium hexafluorophosphate (LiPF ₆)		3.15	g/100 g battery	0.06	g/(kWh storage)
Polypropylene			5	g/100 g battery	0.10	g/(kWh storage)	
Case		Steel	2	g/100 g battery	0.04	g/(kWh storage)	

Table 5. LCI results for Ni–Cd battery.

Ni–Cd Battery Manufacturing			Raw Data [50]		Normalised Data		
			Value	Unit	Value	Unit	
Assembly	Energy consumption	Electricity	19.6	MJ/(kg battery)	0.19	MJ/(kWh storage)	
Component production	Electrodes	Nickel (Ni)	28.67	g/100 g battery	2.78	g/(kWh storage)	
		Cadmium hydroxide (Cd(OH) ₂)	20.73	g/100 g battery	2.01	g/(kWh storage)	
		Cobalt hydroxide (Co(OH) ₂)	1.43	g/100 g battery	0.14	g/(kWh storage)	
	Electrolyte	Potassium hydroxide (KOH)		4.89	g/100 g battery	0.47	g/(kWh storage)
			Sodium hydroxide (NaOH)	0.35	g/100 g battery	0.03	g/(kWh storage)
			Lithium hydroxide (LiOH)	0.63	g/100 g battery	0.06	g/(kWh storage)
			Water (H ₂ O)	16.47	g/100 g battery	1.60	g/(kWh storage)
	Separator		Polypropylene	4.47	g/100 g battery	0.43	g/(kWh storage)
	Case	Steel		14.78	g/100 g battery	1.43	g/(kWh storage)
			Polyethylene	4.47	g/100 g battery	0.43	g/(kWh storage)
Polypropylene (PP)			3.11	g/100 g battery	0.30	g/(kWh storage)	

Raw data for VRFB were processed assuming material and energy requirements for 20 years and delivering 1095 MWh. The discharge efficiency and depth of discharge specifications were also calculated to properly normalise the data. On the basis of literature values, average discharge efficiency is 79% [14] and depth of discharge is assumed to be 100% [45].

Table 6. LCI results for Ni–MH battery.

Ni–MH Battery Manufacturing			Raw Data [50]		Normalised Data	
			Value	Unit	Value	Unit
Assembly	Energy consumption	Electricity	9.79	MJ/(kg battery)	0.17	MJ/(kWh storage)
Component production	Electrodes	Nickel (Ni)	42.07	g/100 g battery	7.51	g/(kWh storage)
		Lanthanum (La)	10.07	g/100 g battery	1.80	g/(kWh storage)
		Cobalt	4.85	g/100 g battery	0.87	g/(kWh storage)
		Copper (Cu)	1.2	g/100 g battery	0.21	g/(kWh storage)
	Electrolyte	Potassium hydroxide (KOH)	3.35	g/100 g battery	0.60	g/(kWh storage)
		Sodium hydroxide (NaOH)	0.88	g/100 g battery	0.16	g/(kWh storage)
		Water (H ₂ O)	11.67	g/100 g battery	2.08	g/(kWh storage)
	Separator	Polypropylene	2.57	g/100 g battery	0.46	g/(kWh storage)
		Nylon	3	g/100 g battery	0.54	g/(kWh storage)
		Stainless steel	11.28	g/100 g battery	2.01	g/(kWh storage)
Case	Polypropylene	4.53	g/100 g battery	0.81	g/(kWh storage)	
	Polyethylene	4.53	g/100 g battery	0.81	g/(kWh storage)	

Table 7. LCI results for vanadium redox flow battery (VRFB).

Battery Manufacturing			Raw Data [49]		Normalised Data	
			Value	Unit	Value	Unit
Assembly	Energy consumption	Electricity	4.90	MJ/(kg battery)	0.08	MJ/(kWh storage)
Components of Power Subsystem	Electrodes	Copper (Cu)	0.78	g/100g battery	0.13	g/(kWh storage)
		Carbon felt, graphite	0.26	g/100g battery	0.04	g/(kWh storage)
	Ionic membranes	Polysulphone and (polystyrene manufacturing assumed)	0.44	g/100g battery	0.07	g/(kWh storage)
		Flow frames, bipolar plates	Polypropylene, rubber, carbon black	1.39	g/100g battery	0.23
Components of Energy Subsystem	Electrolyte	Water (H ₂ O)	47.85	g/100g battery	7.71	g/(kWh storage)
		Sulfuric acid (pure)	25.95	g/100g battery	4.18	g/(kWh storage)
		Vanadium pentoxide	10.07	g/100g battery	1.62	g/(kWh storage)
	Electrolyte container	Polypropylene (PP)	2.55	g/100g battery	0.41	g/(kWh storage)
Components of Periphery	Pumps, motors, racks, and bolts	Stainless steel	10.70	g/100g battery	1.72	g/(kWh storage)

3.2. Comparative LCA of the Selected Batteries

Under the cradle-to-gate perspective, Figure 2 shows the environmental impact distribution in terms of percentage for each battery. As expected, the component production stage had a greater environmental impact compared with the assembly stage in most impact categories, as also found in previous studies of batteries [45].



Figure 2. Relative environmental impact distribution for the batteries study cases. Yellow bars: component production. Blue bars: Assembly stage. Abbreviations were defined in Table 1. VRFB, vanadium redox flow battery.

In this work, generally, the component production stage show impacts over 50% in more than 88% of the 18 impact categories. In particular, the impacts of SOP and FFP were 100%. In this vein, it should be required that decision-makers develop strategies focused on minimising the environmental impact of the battery technology component production, for instance, by researching new materials.

Although the assembly stage can also be an area of concern for developing effective actions to reduce the environmental impact of batteries, based on the LCA results, it was excluded from the batteries’ comparison. Under this perspective, the comparison of the 18 impact categories by excluding the assembly stage is shown in Figure 3.

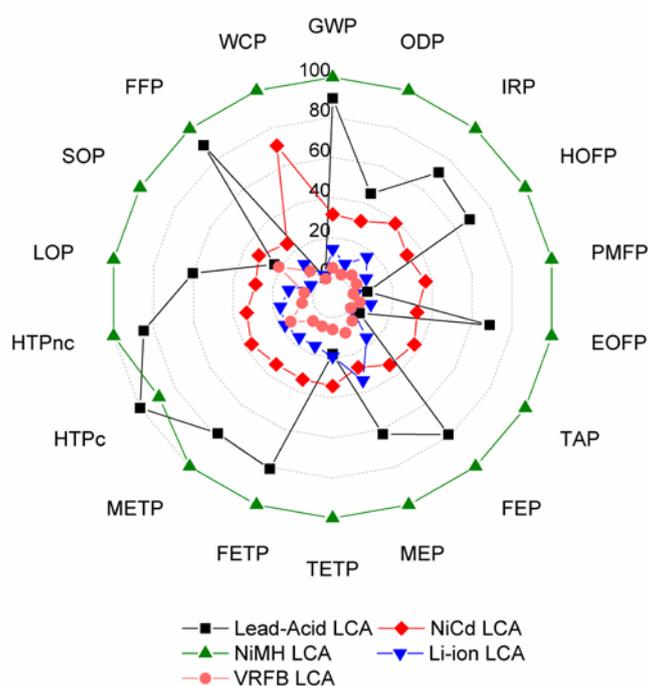


Figure 3. Environmental LCA comparison for the midpoint environmental categories. Data correspond to the normalised percentage results for the manufacturing stage of the technologies.

Data indicate that the battery with the highest environmental burden in almost all impact categories is the NiMH battery. On the basis of the NiMH battery network analysis of all impact categories with a node cut-off of 1%, the environmental impacts are generally attributed to the use of materials needed for electrode production, particularly nickel mine operations. The batteries with the next highest environmental impacts were lead–acid and Ni–Cd. Differences found between the two nickel–electrode batteries agree well with other studies performed to compare environmental impact of the two technologies. Ni–Cd appeared to have a lower potential impact on resource Ni–MH battery based on the ReCiPe indicators [51], mostly because of the differences in nickel consumption. Van den Bossche et al. [45] also determined a better environmental performance for the production stage of the Ni–Cd battery compared with lead–acid and Ni–MH given in eco-indicator points.

On the contrary, Li-ion battery and the VRFB were the two batteries with the lowest environmental impacts. The better environmental performance of these two battery technologies compared with the others agrees well with previous works [14,31,34,46]. Particularly, Weber et al. [31] compared the total impacts of battery manufacturing (including upstream processes, without using recycled material) following the CML method, considering the following impact categories: global warming potential (GWP); human toxicity potential (HTP); acidification potential (AP); and depletion of abiotic resources, reserve base (ADP). In comparison with the lithium-ion battery, the VRFB showed lower environmental impacts in three of the four assessed categories [31]. Although this is a similar trend to the one elucidated in this work, it is important to highlight that the Li-ion type was different.

In this research, the technology with the least negative cradle-to-gate environmental impact was defined as the benchmark system to be deeper assessed in terms of materials used during the component production process and environmental burden related to each impact category. Such a focus will provide key knowledge regarding the materials that may constitute a challenge owing to their inherent environmental hazard or scarcity as a path towards attaining the goals of sustainable materials 4.0.

On the basis of the comparison of the environmental burden of battery manufacturing, the vanadium redox flow battery is identified as the lowest environmental damage battery among all selected battery types. In general terms, 94% of the 18 impact categories showed an environmental

impact below 15% in the VRFB case. Thus, VRFB can be considered as the benchmark technology, and thus it is environmentally assessed in more detail with respect to battery component and materials (see Section 3.3).

3.3. LCA of VRFB

VRFB, which has been defined as the benchmark battery technology, is further analysed in this section, with the aim of finding the components and materials responsible for the greatest environmental burden in each impact category, based on the LCA with a cradle-to-gate approach.

3.3.1. LCA Results Based on Battery Component Comparison

The environmental impact distribution related to the manufacturing of each VRFB component is shown in Figure 4. Again, the impact of each component depends on the category analysed. For instance, the electrodes are responsible of an environmental burden between 50% and 88% in nine impact categories. The electrolyte, however, mainly affects two impact categories (i.e., SOP and WCP), being responsible for 95% and 60% of the environmental impact, respectively.

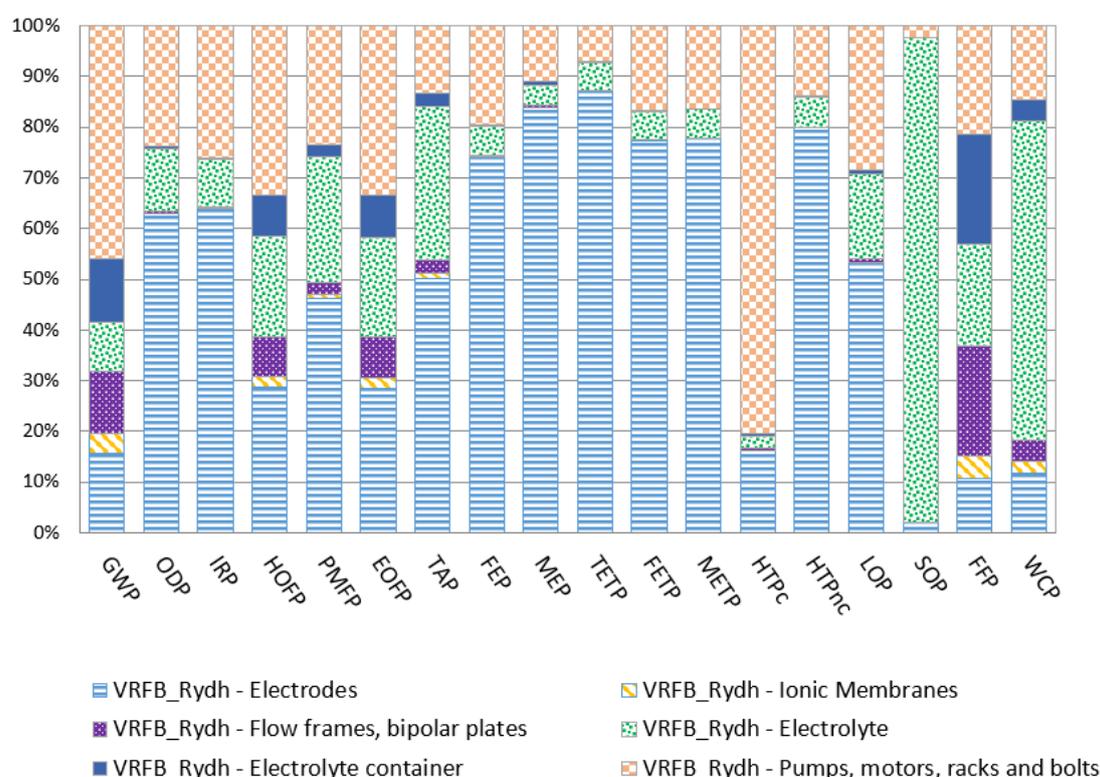


Figure 4. Environmental impacts associated to the VRFB components in terms of normalised percentage distribution.

Pumps, motors, racks, and bolts, collectively, cause an impact of 80% in the HTPc category, but only 46% in the GWP category; and finally, the impacts of the rest of the VRFB components range between 2% and 22%, depending on the category analysed. In conclusion, the VRFB components producing the most effects in the impact categories mentioned above are the electrodes; the electrolyte; and the set of pumps, motors, racks, and bolts, in that order.

These results indicate that manufacturing improvements on the aforementioned components might result into better environmental performance in the VRFB. For instance, by improving the components when they are being designed, specifically, for emerging battery technologies comparable to the VRFB.

3.3.2. LCA Results Based on Battery Material Comparison

As mentioned in Section 3.2, the component production stage is mainly responsible for the environmental impact of batteries. In the case of the VRFB, the electrodes; the electrolyte; and the set of pumps, motors, racks, and bolts, in that order, were identified as the key components mentioned owing to their environmental impacts (Section 3.3.1).

In this section, each impact category is analysed separately in order to provide more insight into the key materials that contribute most to the environmental burden. It was done through a network analysis using a node cut-off criterion of 1% for each impact category explored. In addition, the key materials were selected using a cut-off criterion of over 20% for an environmental burden in each impact category individually assessed.

As an example, the GWP category network is presented in Figure 5 for the VRFB components. In this case, a cut-off criterion of 14% was selected for improving visualizations because similar results are obtained for a cut-off criterion of 1%. It clearly shows that low-alloyed steel is responsible for 46% of the environmental burden and, therefore, it is identified as a key material. This agrees with the significance assigned to the set of component pumps, motors, racks, and bolts discussed in the previous section, because low-alloyed steel plays an important role in these components. Further network analysis revealed that the environmental burden associated with this type of steel is mainly the result of the production of pig iron, which is used to produce alloyed steel. According to the database developed in this study (Ecoinvent 3.4.), the coke required for pig iron production is the initial contributor in the GWP category.

It is known that the conventional route for iron- and steel-making uses massive amounts of coke as a carbon source, which is responsible for most of the CO₂ emissions of the steel industry. Therefore, actions taken to reduce these emissions will minimise related impacts. One action proposed by Fick et al. [52] uses biomass as a renewable carbon resource. They suggest that biomass is a good substitute for fossil coal and even partial substitution could lead to a significant reduction in CO₂ emissions. Their results showed that, for a 20% substitution of total coke by biomass resources, around 300 kg of CO₂-eq per ton of pig iron produced could be saved, which represents a reduction of 15% in the total greenhouse gas emissions.

Thus, Table 8 is generated following a similar network analysis for other impact categories. As mentioned previously, key materials with an environmental impact of more than 20% associated to the VRFB battery components are the ones gathered in this table. Particularly, copper used in the electrode component had an important environmental burden (between 28% and 84%) in 13 impact categories. In general terms and depending of the impact category analysed, it is mainly caused by the copper source, that is, primary production or treatment of secondary copper.

Other material is that discussed previously in the GWP category (low-alloyed steel), the results of which are shown in Table 3, and range from 22% up to 46% in nine impact categories. The reason for those contributions comes from the steel material production stage, as already explained above. Finally, sulphuric acid and vanadium are materials with considerable impacts, which belong to the electrolyte component. The first one exhibits an environmental impact from 25% to 63%, being the highest value of this range in the category WCP, which is attributed mainly to the production of this acid. The second one is vanadium, showing the highest environmental burden in a unique category, as it is the SOP accounting for 95% of the impact, which refers to damage to resource availability. This result addresses a very important issue related to the material availability because the chemistry of VRFB is based on vanadium, which is considered a critical raw material [20]. The SOP category as well as the rest of the midpoint categories consider the environmental burden attributed to the production processes and the amount of raw material consumed. For specific materials such as vanadium, the environmental implications include the issue of material availability, which is particularly relevant for this material because it was included in the 2017 list of CRMs. This list includes 27 raw materials that are now considered critical by the European Commission [20].

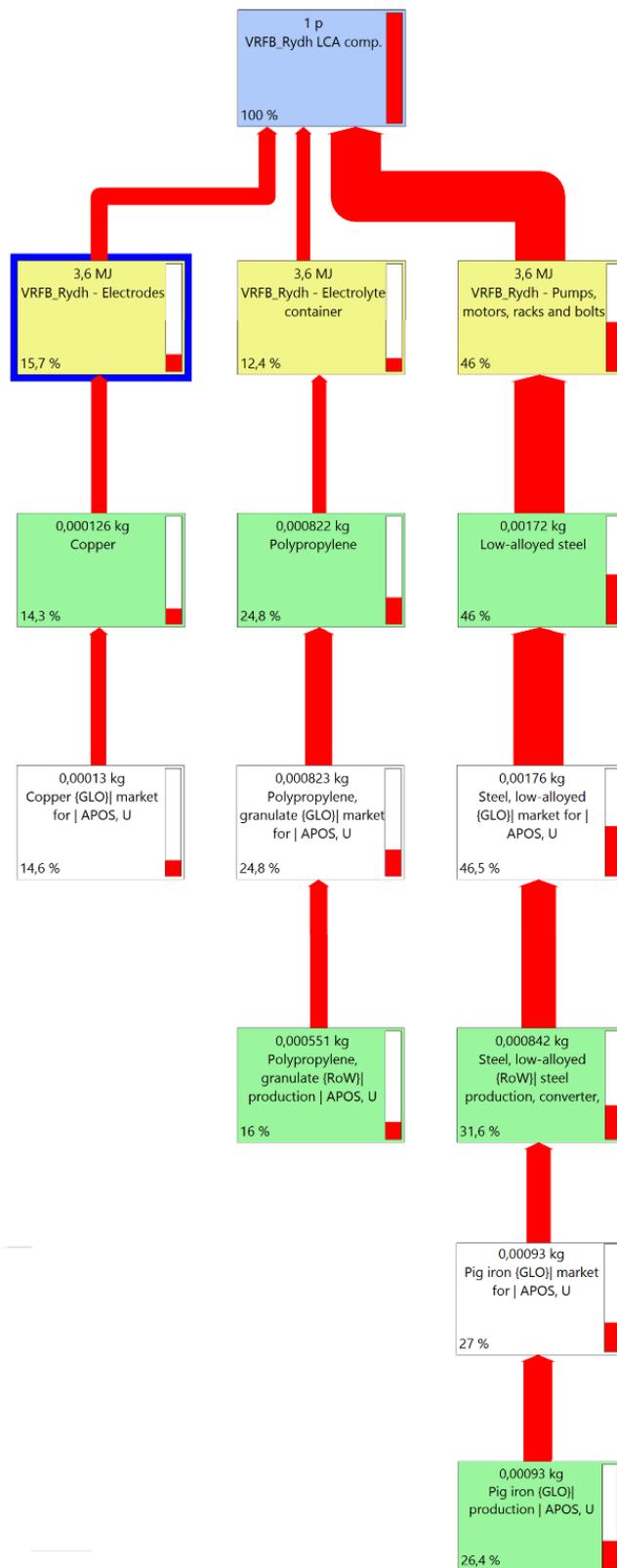


Figure 5. Global warming (kg CO₂ eq) network with a node cut-off of 14%. Notice that low-alloyed steel is the main contributor of the CO₂ emissions.

The impact attributed to the consumption of a critical raw material such as vanadium for the VRFB constitutes a key driver for promoting the substitution of critical materials by other strategies to develop

a more sustainable chemical storage device manufacturing process. Therefore, the use of vanadium should be considered as a challenging issue for research in materials 4.0; such research may lead to the development of new pathways for materials' syntheses. This is a key issue that developers involved in emerging technologies need to consider. Thus, the findings in this work constitute a preliminary step to identify innovative benefits of novel technologies under development. In addition, the results provide more insight into components that may require more intense engineering or pre-design efforts. On the basis of the large amount of existing knowledge on materials, prototyping, testing, validation, and life cycle assessment of the key components, significant knowledge on reducing environmental impacts, from conceptualisation to sustainable manufacturing, can be achieved.

Table 8. Environmental impact of VRFB key materials per battery component in terms of normalised percentage contribution to each impact category.

Impact Category	VRFB—Electrodes (%)	VRFB—Electrolyte (%)	VRFB—Pumps, Motors, Racks, and Bolts (%)
GWP			Steel (46)
ODP	Copper (63)		Steel (24)
IRP	Copper (64)		Steel (26)
HOFP	Cooper (29)		Steel (34)
PMFP	Copper (46)	Sulfuric acid (25)	Steel (23)
EOFP	Cooper (28)		Steel (34)
TAP	Copper (50)	Sulfuric acid (30)	
FEP	Copper (74)		
MEP	Copper (84)		
TETP	Copper (87)		
FETP	Copper (77)		
METP	Copper (77)		
HTPc			Steel (80)
HTPnc	Copper (80)		
LOP	Cooper (53)		Steel (28)
SOP		Vanadium (95)	
FFP			Steel (22)
WCP		Sulfuric acid (63)	

4. Conclusions

A detailed LCA of the environmental impacts of five types of battery technologies was conducted. On the basis of a comprehensive literature search and in-house databases, a complete characterisation of PbA, LiMn₂O₄, NiCd, NiMH, and VRF batteries was performed, focusing on the manufacturing stage. We performed a complete LCI of the battery components and the energy consumption for the assembly stage.

The LCA shows that Ni–MH batteries produce the most significant environmental impact, while the VRFB produced the smallest environmental impact. Therefore, VRFB was considered the benchmark battery technology.

A deeper analysis of the VRFB was performed by comparing the environmental burden of each battery component and impact category. The electrodes; the electrolyte; and the set of pumps, motors, racks, and bolts were identified as the components with the highest environmental impacts. Exploring each impact category separately, key materials were elucidated by their significant contribution to the attained environmental burden. The results revealed that steel, copper, sulphuric acid, and vanadium were the materials that contributed the most to the environmental impact. Particularly, vanadium impacts were not only related to effects on the environment, but also were associated with availability or supply risk issues, because it is currently classified as a critical raw material based on its scarcity on Earth. This is a relevant aspect to consider for further innovative developments.

This research has generated knowledge concerning the environmental impacts of battery components and materials, which is required for further development of new storage technologies as well as for addressing the challenging manufacturing goals of materials 4.0 based on circular economy strategies.

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Abbreviations

CRMs	Critical raw materials
EOFP	Ozone formation terrestrial ecosystems
ESSs	Suitable energy storage systems
FEP	Freshwater eutrophication
FETP	Freshwater ecotoxicity
FFP	Fossil resource scarcity (FFP)
GWP	Global warming potential
HOFP	Ozone formation human health
HTPc	Human carcinogenic toxicity
HTPnc	Human non-carcinogenic toxicity
IRP	Ionising radiation
LCA	Life cycle assessment
LCI	Life cycle inventory
LiMn ₂ O ₄	Lithium manganese oxide
LOP	Land use
MEP	Marine eutrophication
METP	Marine ecotoxicity
NiCd	Nickel–cadmium
NiMH	Nickel–metal hydride
ODP	Stratospheric ozone depletion
PbA	Lead–acid
PMFP	Particulate matter formation
SOP	Mineral resource scarcity
TAP	Terrestrial acidification
TETP	Terrestrial ecotoxicity
VRFB	Vanadium redox flow battery
WCP	Water consumption (WCP)

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