

Environmental assessment of vanadium redox and lead-acid batteries for stationary energy storage

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Abstract

The environmental impact of both the vanadium redox battery (vanadium battery) and the lead-acid battery for use in stationary applications has been evaluated using a life cycle assessment approach. In this study, the calculated environmental impact was lower for the vanadium battery than for the lead-acid one. The net energy storage efficiency of the vanadium battery was greater due to lower primary energy needs during the life cycle. Favourable characteristics such as long cycle-life, good availability of resources and recycling ability justify the development and commercialisation of the vanadium battery. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Life cycle assessment; Lead-acid secondary batteries; Vanadium redox batteries; Applications/stationary energy storage

1. Introduction

To overcome daily and seasonal varieties in the supply of, e.g., photovoltaic cells and wind energy, these technologies have to be combined with energy storage systems which improve their usefulness as electric power sources. In remote places, an autonomous electrical system may be less expensive, have greater efficiency and less impact on the environment than if the load has to be connected to a high capacity grid [1].

Secondary batteries used as storage systems provide several favourable characteristics in energy distribution [2,3]. Their fast response time makes them suitable for dynamic system operations. Batteries connected to the electricity grid can improve power quality and reliability. Lower environmental impact may also be achieved by load levelling and peak load reduction. Thus, it is possible to achieve a high utilisation rate for generating facilities which have high production efficiency.

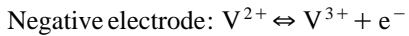
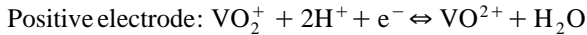
To assess the environmental characteristics of energy storage in batteries, the efficiency and the environmental impact during the life cycle of the battery has to be considered. Several authors [4–6] have made life cycle assessments of lead-acid batteries as well as other batteries to be used in electric vehicles. The energy and environmental impacts of lead-acid batteries have also been studied [7].

To increase the share of renewable energy, energy storage systems need to be inexpensive and large. Classical secondary batteries suffer from limited system life and high cost. Systems with a combination of water electrolysis, hydrogen storage and fuel cells have low overall energy efficiency. One interesting battery under development is the vanadium redox flow battery (vanadium battery). It offers high overall efficiency and the cost for additional storage capacity is limited to the active materials and storage tanks. In this paper, the environmental impacts of both the vanadium battery and the lead-acid battery have been compared for use in a back-up power system.

2. Vanadium and lead-acid batteries

Demonstration units of the vanadium battery have been built in Japan and Thailand [8] where the system has been tested for load levelling and as back-up power in photovoltaic plants. The battery consists of two electrolyte containers with the electrolytes of V^{2+}/V^{3+} and V^{4+}/V^{5+} in sulphuric acid solution, two electric pumps and a battery stack. The electrolytes are pumped into the stack where they are separated by an ionic membrane. The electron exchange takes place at carbon felt electrodes in the

aqueous phase according to the following reaction [9] (discharge in the right direction):



One advantage over other redox flow batteries (e.g., the $\text{Fe}^{2+/3+}$ – $\text{Cr}^{2+/3+}$ system) is that cross contamination of the electrolytes does not damage the system since the metal ions are of the same element. Electrolyte service life is thus indefinite. At the current stage of development, the stack membranes must be replaced approximately every 5 years, but cycle-life for the whole system is expected to be rather high. Favourable features are that the capacity can be increased by enlarging the size of the storage tanks and the power output can be raised by increasing the flow rate or enlarging the stack assembly. The battery can be recharged electrically, or by exchanging the electrolytes by charged ones.

The lead-acid battery is the most commonly used battery in terms of kW h. It is well established since it is less expensive than other batteries, has high peak-power and is recyclable. In stand-by power applications, service life can be more than 10 years and batteries built for cycling can have a cycle-life of 1500–2000 cycles. Deep discharges as well as over-charging shorten cycle-life and the battery requires maintenance by water refilling due to gas evolution [10].

3. Methodology

In this paper, a life cycle assessment (LCA) approach was used to compare the batteries. LCA is a technique for

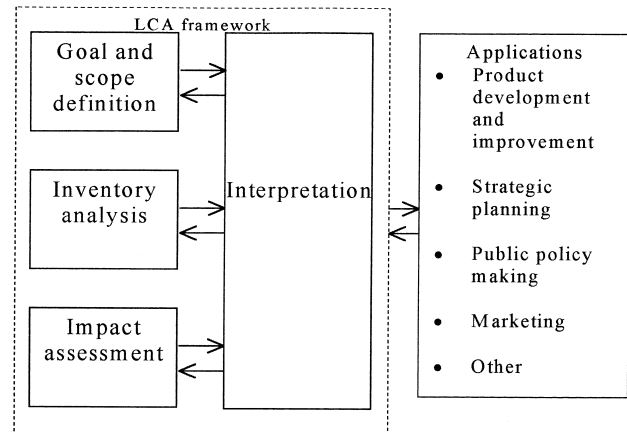


Fig. 1. Phases of a life cycle assessment [11].

assessing the environmental aspects and potential impacts associated with the life cycle of a product [11]. The phases within this work compile an inventory of relevant inputs and outputs of a product system (Fig. 1). The environmental impacts associated with the inputs and outputs are evaluated and interpreted to the objectives of the study.

The inventory of emissions and energy was assisted by the software LCA inventory tool [12]. The impact assessment was made by classifying and characterising the inventory results with regard to global warming potential, photo-oxidant formation, acidification, eutrophication and resources. The weighting (aggregation of all the inventory results to a single impact value) was made by means of the quantitative methods of Environmental Theme (ET) and Environmental Priority Strategies (EPS) in product design [13]. In the ET method, the different impacts are weighted against political emission goals for various impact cate-

Table 1
Specifications of the model systems for storage of electrical energy

	Lead-acid battery	Vanadium battery
References	[15,16]	[17,18]
Design and assembly	Traction battery with tubular plates, 4–9 wt.% Sb, $C_5 = 1125 \text{ Ah cell}^{-1}$ 2 (parallel) \times 100 cells (serial)	4 stacks \times 80 cells (serial)
Positive electrode	$\text{PbO}_2(\text{s})/\text{PbSO}_4(\text{s})$	$\text{VO}_2^+(\text{aq})/\text{VO}^{2+}(\text{aq})$
Negative electrode	$\text{Pb}(\text{s})/\text{PbSO}_4(\text{s})$	$\text{V}^{2+}(\text{aq})/\text{V}^{3+}(\text{aq})$
Electrolyte	1.295 kg dm^{-3} , 5 M H_2SO_4	1.8 M V in 4.2 M H_2SO_4
Ion membrane	Polyethylene separator	Selemon membrane
Discharge voltage 5–90% SOC (V)	180–207	310–500
Operating temperature ($^\circ\text{C}$)	–10 to 40	10 to 45
Energy efficiency (%)	70–80	72–88 ^b
Specific energy at 20 $^\circ\text{C}$ (W h kg^{-1})	37	(28) ^a 20
Energy density at 20 $^\circ\text{C}$ (W h dm^{-3})	105	(47) ^a 30
Cycle-life (cycles)	1800 ^c	$\gg 2000^d$
Total system volume (dm^3)	4300	(9600) ^a 15 000
Mass of one system (kg)	12 100	(16 100) ^a 22 200

Nominal power 50 kW and energy storage capacity 450 kW h.

^aPossible to have 3 M vanadium in 5 M H_2SO_4 ; related improvements are shown in brackets.

^bIncluding 3% energy loss to pumps.

^cAt 35% depth of discharge (1200–1500 cycles at 70–80% DOD).

^dNot determined. Shelf life is very high but at current state of development, maintenance includes replacement of membranes approximately every 5 years.

Table 2
Material requirements^a for the operation of lead-acid batteries on daily cycling for 20 years (7300 cycles) delivering 150 kW h day⁻¹

Material	Component	Mass (kg)	Wt.%
Lead	Active material, grids and poles	29400	61.2
Water	Electrolyte (dilution to 1.295 s.g.)	6400	13.3
Sulphuric acid (pure)	Electrolyte	4600	9.6
Polypropylene	Cases and covers	3888	8.2
Sb, Sn, As	Grid alloys	1012	2.1
Polyethylene	Separators	960	2.0
Polyester	Tubular mats	144	0.3
Copper	Connectors	130	0.3
Others	Expander and oxygen in PbO ₂	1440	3.0
Total		47974	100.0

^a4 × 200 cells. Recycled materials not taken into account.

gories (e.g., acidification, greenhouse effect). The EPS method, on the other hand, is based on the willingness to pay to restore five safeguarded objects (e.g., human health, natural resources etc.) to their normal status.

4. Goal definition and scoping

The scope of this paper is to assess and compare the environmental impacts of the vanadium and lead-acid batteries. The net energy storage capacity and the availability of vanadium and lead resources are compared.

For the lead-acid battery, the influence of 50 and 99% secondary lead-acid use and different maximum cycle-life is assessed. The functional unit (FU) is defined as *an electricity storage system with a power rating of 50 kW, a storage capacity of 450 kW h and an average delivery of 150 kW h electrical energy per day for 20 years*. These specifications exemplify the electricity requirements for several remote houses for 10–70 persons [2] and provide an autonomous system for 3 days. The analysis is restricted to the energy storage systems and space require-

ments, losses in converters, control units etc. are assumed to be equal. The environmental impact of electricity production to charge the batteries is not included since equal energy efficiencies is assumed. The energy storage system is furthermore assumed to be assembled and used in the Gothenburg region, Sweden. The vanadium battery is not yet in full-scale production, but is assumed to be assembled in Sweden and materials are manufactured by domestic suppliers, whenever possible. Important construction materials are analysed, by collecting available data, from the extraction of resources to the final deposit. Materials which are recycled and re-used in other products are allocated with the 50/50 method [14]. Post operation, the system is disassembled and the materials re-used or deposited.

The specifications of the systems studied are shown in Table 1. The lead-acid battery is of traction design with antimony grid-alloys for long cycle-life.

5. Results

5.1. Inventory

The energy and material requirements for the vanadium battery were based on a hypothetical manufacturing scenario and these data may differ for a future production. The vanadium electrolyte is assumed to have very long life and its only treatment is filtering before re-use. Vanadium can be extracted in different ways, e.g., by mining or recovery from petroleum residues. Due to the lack of data, a scenario for the vanadium recovery from boiler soot needed to be estimated. This resource was assumed to be a secondary material since it would otherwise have been deposited.

Data for the manufacturing of lead-acid batteries were collected from factories supplying Swedish battery manufacturers. The batteries were recycled at Boliden Bergsöe in Landskrona, Sweden, where lead and alloying metals are recovered. Less than 50% secondary lead is used in

Table 3
Material requirements^a for the operation of the vanadium battery for 20 years

Material	Component	Mass (kg)	Wt.%
Water	Electrolytes (1.8 M V, 4.2 M H ₂ SO ₄)	11 251 ^b	47.7
Sulphuric acid (pure)	Electrolytes	6103 ^b	25.9
Vanadium pentoxide	Electrolytes	2369 ^b	10.0
Steel	Pumps, motors, racks, bolts	2516	10.6
Polypropylene	Electrolyte containers	600	2.5
Polypropylene, rubber, carbon black	Flow frames, bipolar plates	328	1.4
Copper	Connectors, end electrodes	184	0.8
Polysulphone and fluoride ^c	Ionic membranes	104	0.4
Carbon felt, graphite	Electrodes	60	0.3
Others		86	0.4
Total		23 601	100.0

^aRecycled materials are not taken into account.

^bIncludes 1–2% addition due to losses during use.

^cPolystyrene manufacturing assumed.

Table 4

Energy requirements of the battery life cycles and to cover losses during use of the lead-acid and vanadium battery systems (20 years and delivering 1095 MW h)

	Lead-acid				Vanadium	
	50% secondary Pb		99% secondary Pb		99% secondary V ^a	
	Electricity (MW h)	Other primary energy (MW h)	Electricity (MW h)	Other primary energy (MW h)	Electricity (MW h)	Other primary energy (MW h)
(1) Material	49	118	21	108	7	30
(2) Transport	0	18	0	15	0	3
(3) Battery production	64	25	96	25	29	10
(4) Recycling	6	14	6	14	3	–4
(5) The sum of (1) to (4)	120	175	92	162	39	39
(6) Primary energy (5) × 0.4 ^b	70		65		16	
(7) Electricity losses during use ^c	365		365		365	
(8) The sum of electricity (5) + (6) + (7)	555		522		420	
(9) Net electricity delivered from the battery during 20 years	1095		1095		1095	
(10) Gross energy requirement (8) + (9)	1650		1617		1515	
(11) System efficiency (9)/(10)	0.66		0.68		0.72	

^a99% secondary vanadium assumed to make the systems comparable.

^b $\eta = 0.4$ Efficiency in the conversion of primary energy to electricity.

^cAt 75% total efficiency (losses in batteries and converter) and 1095 MW h.

new batteries since the lead oxide production requires high purity.

The material requirements for the lead-acid battery are shown in Table 2. Over 20 years, 200 cells will be replaced four times and approximately 25 000 l of water will be added intermittently. The data for the vanadium battery (Table 3) include electrolyte adjustment, pump maintenance and replacement of ionic membranes every 5 years.

5.2. Impact assessment

Table 4 shows that the energy used for transportation is considerably greater for the lead-acid than for the vana-

dium battery since it uses more and heavier materials. For both batteries, heat is recovered from the recycling process when polypropylene containers are incinerated, which gives an energy gain for the vanadium battery. For the lead-acid battery, an increase in the use of secondary lead from 50–99%, the electricity and primary energy needed in the material production decrease by 43% and 8%, respectively.

To compare the overall energy requirements, primary energy (specific heat value) was recalculated as electrical energy. The energy efficiencies of the batteries were assumed to be equal since it varies with the rate of discharge and no definite values were found for the chosen systems. The net system efficiency values in this study vary with the chosen allocation method. The lead-acid battery re-

Table 5

Emissions of selected substances and contributions from the different processes during the life cycle of the lead-acid and vanadium batteries

Emitted substances and contributing processes	Lead-acid 50% secondary lead	Lead-acid 99% secondary lead	Vanadium 99% secondary V ^a
CO ₂ (ton FU ⁻¹)	29.3	25.4	8.5
Mtrl/Trp/Prod/Recyc (%)	43/18/19/20	36/19/22/23	67/11/16/6
SO ₂ (kg FU ⁻¹)	215	147	28
Mtrl/Trp/Prod/Recyc (%)	38/7/8/48	11/7/11/70	61/23/20/–4
CO (kg FU ⁻¹)	57	42	5.2
Mtrl/Trp/Prod/Recyc (%)	35/38/34/–7	21/42/46/–9	41/87/7/–35
CH ₄ (kg FU ⁻¹)	33	32	8
Mtrl/Trp/Prod/Recyc (%)	16/6/20/57	14/5/21/60	102/6/1/–8
NO _x (kg FU ⁻¹)	242	172	45
Mtrl/Trp/Prod/Recyc (%)	48/39/6/6	38/45/9/9	47/45/6/2
N ₂ O (kg FU ⁻¹)	0.72	0.52	0.15
Mtrl/Trp/Prod/Recyc (%)	34/47/16/3	17/57/22/4	19/49/29/2

Emissions from electricity production to charge the batteries are not included.

^a99% secondary vanadium assumed to make the systems comparable.

FU = 150 kW h day⁻¹ for 20 years, E_{\max} 450 kW h.

Mtrl = materials, Trp = transport, Prod = battery production, Recyc = recycling.

Table 6

Results of the characterisation of five impact categories for lead-acid and vanadium batteries (electricity production to charge the batteries is not included)

Impact categories	Lead-acid 50% secondary Pb	Lead-acid 99% secondary Pb	Vanadium 99% secondary V ^a	Ratio Pb _{50%} /V	Ratio Pb _{99%} /V
Global warming potential ^b	21 617	17 366	8929	2.4	1.9
Photo-oxidant formation ^c	116	96	29	4.0	3.3
Eutrophication ^d	32	23	6	5.3	3.8
Acidification ^e	229	180	59	3.9	3.1
Resources ^f	648	258	70	9.3	3.7

^a99% secondary vanadium assumed to make the systems comparable.^bCarbon dioxide equivalents (CO₂, CO, N₂, CH₄).^cEthene equivalents (C₂H₄, CO, CH₄, hydrocarbons).^dChemical oxygen demand equivalents (BOD, COD, NH₃, NO_x, N_{tot}, P_{tot}).^eSulphur dioxide equivalents (SO_x, NO_x, NH₃, HCl, H₂S).^fUse to reserve ratio.

quires 2.9–3.5 times more energy than the vanadium battery in the production and recycling phase. The energy losses of the batteries make up 22–24% of the total energy requirements during the life-cycle. For the vanadium battery, the net system efficiency can be increased to 0.89 if the whole energy storage capacity (450 kW h) is utilised daily. A higher utilisation of the potential capacity is not possible for the lead-acid battery, since deep discharges shorten its cycle-life.

Table 5 shows that the carbon dioxide emissions for the lead-acid battery were mainly due to the production of materials (43 and 36%), where lead mining and polypropylene production were the largest contributors. Also for the vanadium battery, the production of materials (67%) was the largest emission of carbon dioxide, mainly from steel production.

In the recycling processes, polypropylene is incinerated and the energy is used for district heating, which is assessed as a decrease in emissions of SO₂, CO and CH₄. For the lead-acid battery, the smelting process used to produce secondary lead needs considerable amounts of primary energy, which also cause large SO₂ emissions.

The emission values are multiplied with characterisation indices [14] to get a value of the impact on a certain category. The results show that the vanadium battery has a lower impact (1.9–9.3) compared to the lead-acid battery (Table 6). For the lead-acid battery, the use of resources shows the greatest difference between 50% and 99% sec-

ondary lead use (60%). For the other impact categories, a doubling of the secondary lead use decreases the environmental impact by 17–28%.

Weighting showed that the vanadium battery had a lower environmental impact value than the lead-acid battery (Table 7), mainly due to less use of oil resources and lower carbon dioxide emissions. The largest environmental impact for the vanadium battery originated from the production of polypropylene tanks and flow frames as well as steel stacks. For the lead-acid battery, lead mining and refining contributed most to the impact, followed by polypropylene production.

In contrast to ET and other weighting methods, the EPS method evaluates the outtake of primary resources. The degradation of metals resources is included in the second row in Table 7. The resource weighting is based on the geochemical occurrence in the Earth's crust which gives scarce metals a high index (240 ELU kg⁻¹ for Pb and 28.3 ELU kg⁻¹ for V, respectively). Therefore, the extensive use of lead is the dominant contributor to the environmental impact value of the lead-acid battery. The use of secondary material decreases the environmental impact for the product examined since the burden is shared with (allocated to) the products which used the material first. The ratios between the batteries range from 2.9 to 682. When 100% primary vanadium is considered, the EPS resource ratios are 3.7 and 85 (99% and 50% secondary Pb).

Table 7

Total environmental impact of lead-acid and vanadium batteries after weighting with the Environmental Priority Strategies (EPS) in product design and the Environmental Theme (ET long-term goals) method

	Lead-acid 50% secondary Pb	Lead-acid 99% secondary Pb	Vanadium 99% secondary V ^a	Ratio Pb _{50%} /V	Ratio Pb _{99%} /V
EPS excluding resource weighting (ELU)	10 259	7068	2117	4.8	3.3
EPS including resource weighting (ELU)	1.8 × 10 ⁶	78 084	2639	682	30
ET long-term goals	3.3 × 10 ⁶	2.7 × 10 ⁶	9.4 × 10 ⁵	3.5	2.9

^a99% secondary vanadium assumed to make the systems comparable.

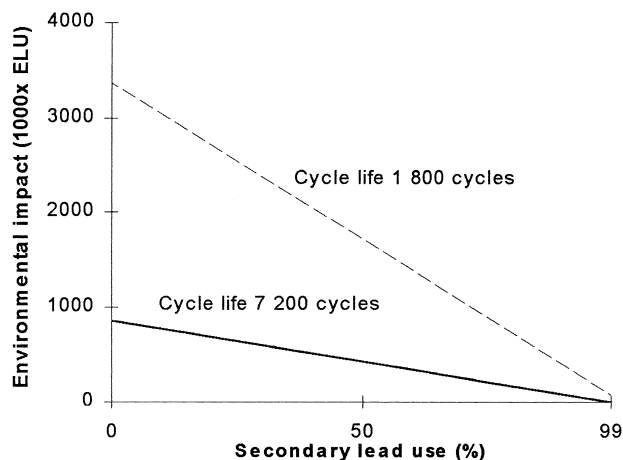


Fig. 2. Environmental impact during the life cycle of the lead-acid battery assuming different operational cycle-lives at 30% DOD and secondary lead use (weighted with the EPS method including resource out-take).

Fig. 2 shows how the environmental impact of the lead-acid battery, weighted with the EPS method, depends on cycle-life and use of secondary lead. The impact can be decreased by 94% if the rate of secondary lead use increased from 50 to 99%, at a cycle-life of 1800 cycles.

5.3. Use and resources of vanadium and lead

The capacity-determining elements in the batteries studied are the active materials vanadium and lead. Table 8 shows the theoretical energy storage capacity calculated by assuming that all reserves were used to build batteries with the system specifications and thereafter kept in functional batteries. This storage capacity is greater for the vanadium battery if the known vanadium reserves were used.

Vanadium has a wide industrial usage, e.g., in metallurgy, electronics and dyeing. Vanadium gives additional strength and resilience to alloyed steel and its use in metallurgical applications accounts for 97% of the total use in the USA [19]. The availability of vanadium and the economics of its production are intimately connected with the particular co-product involved. About 60% of the world's supply of vanadium originates from vanadiferous

magnetite deposits from which vanadium is extracted as a by-product of iron.

Vanadium is a trace metal in petroleum products and a major anthropogenic source of vanadium is the combustion of fossil fuels. Reserves in oil sands worldwide are estimated to supply vanadium for an exceedingly long time into the future. Vanadium recovery plants, e.g., in Japan (Kashima-Kita) and Germany (Gfe), have been constructed to treat fly ash from boiler plants fired by the Venezuelan crude oil (Orimulsion). Orimulsion has an average vanadium content of 310 ppm and its increasing use and recovery may contribute to an annual production of 4200 tons of vanadium by the year 2000 [20].

More than 70% of lead production in the western world is used in batteries and the remaining 30% in chemicals, extrusions and alloys. Stationary batteries account for 15%, whereas 75% is used for starting, lighting and ignition (SLI) batteries in cars and the rest (10%) in traction batteries [21]. About 55% of the refined lead production of the western world (total 5000 ktons in 1997) consisted of secondary lead. When secondary lead is used in batteries, impurities can promote self-discharge and accelerate water losses due to electrochemical dissociation. For low-maintenance, high-quality batteries (e.g., submarine and stand-by power), a maximum of 20 to 60% secondary lead is used to fulfil the lead specifications. However, traction batteries which are regularly discharged and daily overcharged can be built with up to 100% secondary lead without affecting quality [22].

6. Discussion

The lead-acid battery is well-established and the inventory data were taken from real production which makes the results reliable. The vanadium battery is still under development and no large scale production data are available. There are considerable uncertainties about manufacturing and maintenance, and unidentified impacts can be expected. To obtain more reliable data on the vanadium battery, the development and possible future commercial introduction of this battery must be followed. The manu-

Table 8
Annual production rates and reserves of lead and vanadium [23]

	Primary production worldwide 1997 (ktons pure element year ⁻¹)	Reserve ^a (ktons)	Static reserve life ^b (years)	Material requirement ^c (kg pure element kW ⁻¹ h ⁻¹)	Theoretical energy storage capacity ^d (TW h)
Lead	2900	68 000	24	16	4.2
Vanadium (mining)	35	10 000	286	3	3.3
Vanadium (recovery)	3.4 ^e	6000	1974	3	2.0

Vanadium can be either mined or recovered from petroleum residues and spent catalysts [23].

^a Identified resources mined economically at prevailing prices.

^b Number of years the reserve will last at present mining rate.

^c kg material kW⁻¹ h⁻¹ installed capacity of the studied system.

^d Reserve divided by material requirement.

^e Partly secondary vanadium from spent catalysts.

facturing and recycling of lead-acid batteries in Sweden as well as electricity production are considered to have low emissions compared to other production sites in the world. Thus, the environmental impact of the lead-acid battery has to be classified as a low impact scenario in comparison to a lead-acid battery life cycle in another country.

Depending on the type of electricity production (e.g., coal fired boiler or hydropower) to charge the batteries, the environmental impact to cover energy losses over a battery life cycle is often higher than the energy used in the manufacturing of a battery. If the production of electricity for charging the battery causes high emissions, the development of a more efficient battery requiring greater energy in the production phase could prove worthwhile.

The vanadium battery had a higher net energy storage capacity than the lead-acid battery. The difference would increase more if the greater specified energy efficiency of the vanadium battery had been considered and if the whole potential capacity would have been fully utilised.

The results of the impact assessment indicate that the vanadium battery provides energy storage with lower environmental impact than the lead-acid battery. System improvements with regard to the environmental impact of the lead-acid battery would be most effective with greater use of secondary lead and improved battery life. This may be achieved by the development of less expensive secondary lead refining techniques and by new lead specifications [24]. The cycle-life may be improved by optimised lead alloys and charging regimes as well as by introducing mechanical pressure on the electrodes.

In a stationary application, the weight of the battery system is of limited importance. However, process and transport emissions are almost proportional to weight and environmental benefits are achieved by reducing the material requirements and transportation needs. The mass of the vanadium battery system is mainly made up by water (48 wt.%). This water can be distilled and added to a concentrated electrolyte at the site of use. The development of electrolyte with higher concentration can reduce the volume of the storage tanks and the space requirements for the installation.

For both batteries, the use of fossil fuels and release of carbon dioxide, mainly in the processes of metal extraction and plastic production, have a significant impact.

Improvements should be directed towards sustainable processes if the batteries are to be competitive in the long run. This implies material substitution to the least harmful alternative and higher efficiency in material and energy utilisation. Measures should also be taken to sustain or improve long-term productivity and biodiversity [25].

The toxic properties of lead have been known for thousands of years and this has led to strict environmental regulations. Mayer and Wilson [26] have reviewed the exposure ways and health effects of lead, concluding that lead-in-blood levels have decreased during recent decades, at least in the more industrialised countries. In contrast to

lead, vanadium is considered to be essential for a number of organisms. The toxicity of vanadium compounds decreases with both decreasing oxidation state and solubility [27]. The toxic effects have been reported to be acute, never chronic.

Extraction of resources from the lithosphere increases the risk of future contamination. The EPS weighting method tries to include this impact by evaluating the outtake of resources. As indicator of global sustainability, the ratio between anthropogenic extraction from the lithosphere (i.e., mining, fossil fuels) and natural flows (i.e., weathering and volcanic processes) gives an index of the human impact on bio-geochemical cycles. If this ratio exceeds one, anthropogenic extraction can have a major influence on the natural flows and quantities in the ecosystem. The ratios were calculated to be 12 and 0.32 for lead and vanadium, respectively [28]. Materials accumulated in the technosphere tend to leak to the ecosphere and these values suggest that we can expect increasing background lead concentrations in the future.

The batteries studied consist of relatively pure active materials which makes these batteries more suitable for recycling than many others. The recycling rate of used SLI batteries in many European countries is 80–95% [29] and even higher for industrial batteries. Metals can be locked up by their use in batteries, keeping them concentrated in the technosphere and thus preventing them from being dispersed in uncontrolled flows (Hoover technology) [30]. However, this requires high recycling rates, low process losses and high levels of re-use. The technological opportunities to achieve a closed technospheric flow of lead were investigated by Karlsson [31]. He concluded that, with very high recovery of lead-acid batteries in Sweden, the lead losses to the environment from production and recycling processes were very small compared to natural lead flows and historical lead losses during industrialisation.

Provided that no other means for SLI batteries than lead-acid becomes commercially available, the increase in cars worldwide will compete with stationary batteries for lead reserves. However, by utilising a dual battery system in cars, the use of lead can be reduced substantially [32]. Lead in other products will probably decrease in accordance with political policy. The Swedish Parliament has adopted government bill 1990/91:90 [33] with the aim of phasing out the use of lead in the long run, mainly through voluntary measures.

A large-scale introduction of vanadium batteries would increase the demand for vanadium and its mining. Vanadium recovery from boiler soot has great potential and is growing in importance due to stricter environmental legislation. This treatment gives better resource utilisation and may substitute the need for vanadium (and e.g., nickel) mining and reduce the need for landfill areas and the risks of contamination. On the other hand, the combustion of oil does release, for example, huge amounts of carbon dioxide

and some of its environmental impact could be allocated to products using vanadium, in order to indicate that the resource is not free of pollution.

The result of this environmental assessment provides no definite answers since it changes with the analysed system. New processes developments and environmental findings can change the evaluation of certain emissions and materials. The LCA methodology can, however, be used to find processes where significant improvements can be made, as well as new questions generated. In this study, the vanadium battery was found to make less environmental impact and have higher energy efficiency than the lead-acid battery. Favourable characteristics such as long cycle-life, good availability of resources, and recycling ability justify the development and commercialisation of the vanadium battery.

7. Conclusions

In this study, the calculated environmental impact was lower for the vanadium battery than for the lead-acid one. The net energy storage efficiency of the vanadium battery was greater due to lower energy losses during the life cycle. Favourable characteristics such as long cycle-life, good availability of resources and recycling ability justify the development and commercialisation of the vanadium battery.

The energy requirements (recalculated as electricity) for the production and recycling phase were 2.9–3.5 times greater for the lead-acid battery than for the vanadium battery. The resulting net energy efficiency was 0.68 for the lead-acid and 0.72 for the vanadium battery.

With the EPS weighting method, the greatest environmental impact of the vanadium battery originated from the production of polypropylene and constructional steel. For the lead-acid battery, lead extraction contributed most to the environmental impact, followed by polypropylene production.

The recovery factor of lead-acid batteries and the rate of re-use of secondary lead in new batteries is of major importance for the environmental impact. To avoid accumulation of lead in the ecosphere and material constraints, secondary smelters should focus on producing primary-grade metal. Battery manufacturers should also endeavour to develop new lead alloy specifications and batteries of improved design with operational procedures for long battery life.

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