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ENVIRONMENTAL CONSEQUENCES OF THE USE OF BATTERIES IN SUSTAINABLE SYSTEMS : BATTERY PRODUCTION.

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ABSTRACT

Adoption of small scale micro-generation is sometimes coupled with the use of batteries in order to overcome daily varieties in the supply and demand of energy. For example, photovoltaic cells and small wind turbines can be coupled with energy storage systems such as batteries. Used effectively, battery storage can increase the versatility of a micro-generation system by satisfying the highly variable electrical load of an individual dwelling, therefore changing usage patterns on the national grid (Jenkins et al 2008). In addition, a significant shift towards electric or hybrid cars would also increase the number of batteries required. However, batteries can be inefficient and comprise of materials that have high environmental and energy impacts. In addition, some materials, such as lithium, are scarce natural resources. As a result, the overall impact of increasing our reliance on such “sustainable” systems may in fact have an additional detrimental impact.

This paper outlines previous work in this area, and reviews the data available about battery production and use in terms of their life cycle environmental and energy impacts. Problems associated with resource availability are also highlighted. The impact of the production of batteries is examined and presented in order that future studies may be able to include the impact of batteries more easily within any system.

INTRODUCTION

Increasing environmental awareness, national and international targets associated with climate change and renewable energy, and the desire to reduce our reliance on fossil fuels is beginning to result in a change in the way in which we produce, use, and store energy. Adoption of renewable energy production, and small scale micro-generation is sometimes, but not always, coupled with the use of batteries. These help to overcome daily varieties in the supply and demand of energy. For example, photovoltaic cells and small wind turbines can be coupled with energy storage systems such as batteries. Used effectively, battery storage can increase the versatility of a micro-generation system by satisfying the highly variable electrical load of an individual dwelling, therefore changing usage patterns on the national grid (Jenkins et al, 2008).

In addition, a significant shift towards electric or hybrid cars could also increase the number of batteries required. There are many drivers for electric and hybrid vehicles, for example more stringent controls on emissions in some areas in Europe have resulted in interest in so called zero emission (at the tail pipe) vehicles. This interest can be coupled with incentives such as in London where hybrid cars are exempt from the congestion charge. However, batteries can be inefficient and comprise of materials that have high environmental and energy impacts. In addition, some materials, such as lithium, are scarce natural resources. Some materials and metals are also considered to be harmful when sent to landfill. As a result, the overall impact of increasing our reliance on such “sustainable” systems may in fact have an additional detrimental impact.

Life Cycle Assessment (LCA) is an environmental management tool that determines the environmental impacts of a product or system over its entire life; from production, through use and to disposal. It can determine impact against a wide range of environmental issues, including quantifying the global warming gases produced, the embodied energy, and the depletion of raw materials as a result of the product or system under analysis.

The use of LCA can therefore help to quantify the environmental impact over the production, use and disposal of batteries. This paper outlines previous work in this area, and reviews the data available about battery production and use in terms of their life cycle environmental and energy impacts. Problems associated with resource availability are also highlighted. Streamlined life cycle assessment is undertaken on the types of batteries used within and alongside micro-generators and hybrid vehicles. Areas where potential improvements can be made are highlighted, as are areas where resource problems may increase if more batteries are required in future.

LCA METHODOLOGY

Whilst a full life cycle assessment of the use of the batteries in either a vehicle or a renewable energy system is not undertaken within this study, the same methodology is adopted, albeit in a truncated form.

The commonly accepted methodology for LCA was produced by the Society of Environmental Toxicology and Chemistry (SETAC) in the 1990's. This method has been adapted into an ISO series for LCA (ISO 14040 & 14044)

There are four main steps (shown in Figure 1): Goal definition is the stage in which the scope of the project is outlined. Here the study boundaries are established and the environmental issues that will be considered are identified. The inventory stage is where the bulk of the data collection is performed. This can be done via literature searches, practical data gathering or, most commonly, a combination of the two. Impact assessment is where the actual effects on the chosen environmental issues are assessed. This stage is further subdivided into three elements: classification, characterisation and valuation. The first two of these are fairly well established, although there is still ongoing research. However, the valuation stage is fairly subjective and still arouses debate in the literature.

Classification is where the data in the inventory is assigned to the environmental impact categories. In each class there will be several different emission types, all of which will have differing effects in terms of the impact category in question. A characterisation step is therefore undertaken to enable these emissions to be directly compared and added together. The characterisation stage yields a list of environmental impact categories to which a single number can be allocated. These impact categories are very difficult to compare directly and so the valuation stage is employed so that their relative contributions can be weighted. This is subjective and difficult to undertake and many studies omit this stage from their assessment. Instead they employ normalisation as an intermediate step. Improvement assessment is the final phase of an LCA in which areas for potential improvement are identified and implemented.

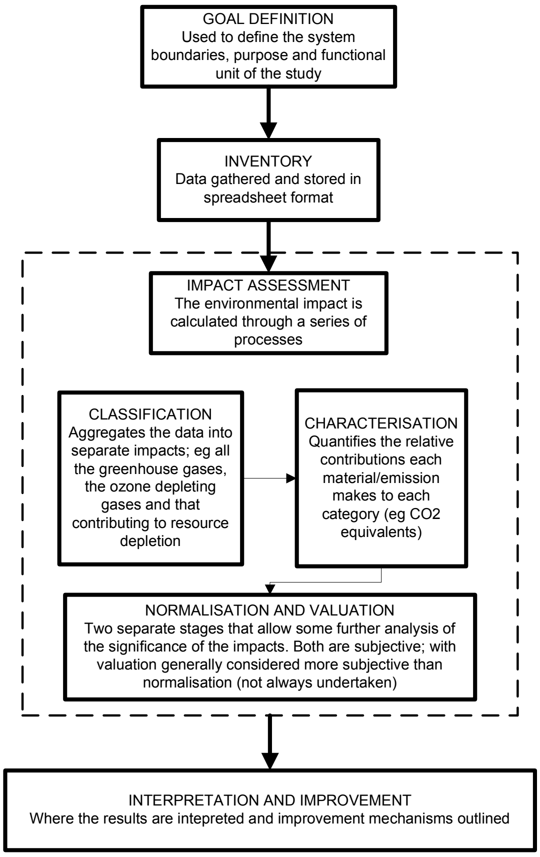

Figure 1. Stages contained within an LCA

Many people employ the use of LCA software in order to help process inventory data. Software also often includes some life cycle inventory databases. In this study SimaPro software was used, and numerous databases were employed. EcoInvent is the primary database used, but where data were not available from this, other sources were obtained. There are also a number of commercially available impact assessment tools. These employ databases, such as the IPCC data for greenhouse gases, in order to undertake the classification, characterisation, normalisation and valuation stages. For this study the Recipe method was adopted. This enables the user to study the data at both the mid point and the end point. That is; the more traditional characterised data (in terms of CO2eq), and also to establish what effect this may have on climate change in terms of lives/land/ecosystems lost. In this paper the mid point data is shown; this is because the calculations made in order to determine the potential impact of any of these emissions to a given environmental problem, such as climate change or ecosystem damage are more uncertain than those made to determine raw materials and emissions. In addition, by presenting the data in the mid point format the data is more easily transferable to future research studies.

BATTERY TYPES AND PRODUCTION

There are numerous different types of batteries; including lead-acid, nickel cadmium, lithium-ion, sodium sulphur, nickel-metal hydride, sodium-nickel chloride, redox flow batteries, and zinc-air. These vary in efficiency, energy storage capacity, the number of charging/discharging cycles they can perform, and cost. Sodium Sulphur (Na-S) are suited to high power applications with daily charge-discharge cycles (Nourai, 2002) (such as renewable energy systems and vehicles). These batteries are sealed, have a rapid response system, last approximately fifteen years; but they are comparatively expensive (Toledo et al, 2010). Lithium ion (Li-ion), nickel cadmium (NiCd) are ideal for small size applications, but are expensive for multi MW load leveling applications where several hours of discharge time is needed. Lead acid batteries are widely available, but can differ widely in design (Rantik, 1999). Their performance at low temperature and their cycle life is below average (Denholm & Kulcinski, 2003), but can still offer storage solutions in some cases.

Many papers and research documents outline the embodied energy and efficiencies of various battery types (eg Samaras & Meisterling (2008), Rydh & Sanden (2005a&b), Doughty et al (2010) Nourai (2002) Toledo et al (2010) & Rydh (2001)). Some have also considered greenhouse gases (Denholm & Kulcincski (2004), Zackrisson et al, (2010) and wider environmental impacts (Ranktik (1998)). In terms of life cycle impacts, within these papers numerous boundaries and data inputs selections have been made.

	Lead Acid Battery*	Nickel Cadmium*	Nickel Metal Hydride*	Lithium Ion (with NMP as solvent)[2]	Lithium Ion (with water as solvent)[2]	Sodium Sulphur[3]
Antinomy (Sb)[e]	0.71					
Arsenic[e]	0.03					
Copper	0.01	2.05		4.76	4.77	
Glass	0.02					
Lead	60.7					
Oxygen	2.26		4.31			
Polyethylene	1.83			0.93 (3.48)	0.93	
Polypropylene	6.72	3.1	5	1.45	1.45	
Sulphuric acid	10.3					
Water (unsalted)	16.9	11.48	6			
Cadmium		24.6				
Cobalt		1.4				
lithium hydroxide		0.7				
Nickel		20.2 (31.2)	24			
Nickel hydroxide[d]		17.4				
Potassium hydroxide		5.22	3			
Steel (low alloy)		11.7	43.5			
Steel (unalloyed)		2.05				
Other inorganic substances[e]		0.1				
Aluminium			0.37	2.68	2.7	
Chromium			2.14			
Titanium			0.79			
Vanadium			7.11			
Zirconium			2.5			
Hydrogen			0.27			
Leveling agents[e]			1			
LiFePO4				43.6	43.7	
Carbon Black				2.79	3.3	
PVDF[a]				*5.06*		
Styrene arcylate latex[b]					*3.63*	
Ethylene glycol dimethyl ester				16.24	16.27	
Lithium Salt (lithium chloride)				2.89	2.9	
Transistor				1.03	1.04	
resistor				1.03	1.04	
graphite				17.47	17.51	
Styrene butadiene latex[c]					*0.62*	
Sulphur						12
Sodium						8
Ceramics						20
Tetrafluroethylene				(2.55)		
PMMA					(1.82)	
Polystyrene					(1.82)	
ABS					(0.6)	
Steel						60

*Percentage components based on Rantik, 1999.

[2] Percentage components based on Zackrisson et al., 2010

[3] Percentage componets based on Gaines and Singh, 1995

[a] No data for this material was found, so as in Zaxkrisson et al a split between tetrafluroethylene and polyethylene was modelled

[b] No data for this material was found, so as in Zackrisson et al the data was split between PMMA and polystyrene

[c] No data for this material was found, so as in Zackrisson et al the data was assumed to be similar to ABS

[d] No data for this material was found, and so the amount of Nickel contained within it was calculated based on the molecular weights.

[e] No data for these materials were available and so have not been modelled in the system

Table 1. %Material Composition of the Batteries

For this reason it is difficult to draw conclusions based on the wide variety of studies undertaken. Nevertheless, it is notable that few previous studies have examined or tried to quantify the raw material and mineral depletion or use associated with the production of batteries. Those that do, focus mostly on their use as part of a full life cycle (eg their use within electric vehicles (Rantik, 1998) or PV (Rydh, 2005)).

This paper builds on these research studies by providing an information base relating to the production of six batteries. However it does not produce a full life cycle study for any of these, instead a cradle to gate study is presented rather than a full life cycle assessment. By doing this, data regarding the battery production can be taken and used in various future full life cycle assessments. This will enable this data to be used more flexibly for future studies.

The data were collected from previously published material and gathered into a spreadsheet. Data associated with the impact of the production of the materials was taken, where possible, from the EcoInvent database. Where no data were available from this, data were obtained from the Idemat database, or estimated using chemical substitutions and estimations.

BATTERY DISPOSAL

The Waste Batteries and Accumulators Regulations came into force in May 2009. These regulations form part of the producer responsibility suite of regulations and requires battery producers (under these regulations any one who places batteries, or products containing portable batteries, into the UK market is classified as a battery producer) to take responsibility for their waste. Producers who place more than 1 tonne of portable batteries onto the UK market each year have to pay for the collection, treatment, recycling and disposal of waste batteries, in proportion to their market share. Similarly to the packaging directives, they can do this by joining a compliance scheme which will arrange for the collection, treatment and recycling of waste batteries for them. The compliance scheme will also register producers with the appropriate environment agency. Producers who place less than 1 tonne of portable batteries onto the UK market each year will not have to pay for the collection and treatment of waste portable batteries but they will still have to register themselves with their local environment agency.

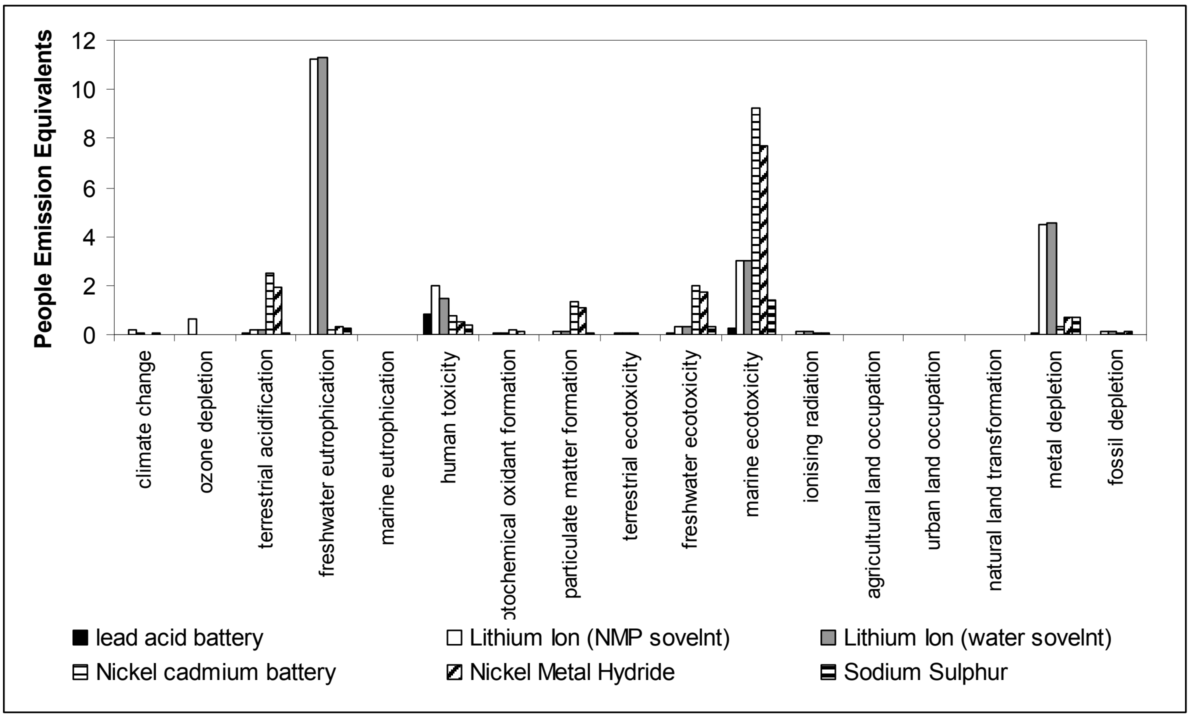

Figure 2 Normalised data for battery production (to produce 100kg)

As a result of this legislation, it is anticipated that more batteries will be recycled in future. This should mean that more of the materials are recycled, resulting in a reduced impact on raw material depletion. For the current study a mix of recycled and virgin materials have been modelled; this is based on the current norms for the materials modelled. Where materials are not commonly recycled they have been modelled as virgin materials, but where they are, for example, aluminium, a percentage of recycled materials has been included.

RESULTS AND DISCUSSION

Data for the material composition of the batteries is shown in Table 1. This has been compiled from a variety of published sources. Data for the production of antinomy and arsenic could not be obtained, and so were omitted for the production of the lead acid battery. Further research is required to ensure the accurate modelling of these materials. Data for the material composition of the Sodium Suphur battery was difficult to obtain, and so data from a rather old reference has been used. Ideally further information about the production and composition of these types of batteries should be found to ensure an accurate comparison.

Figure 2 shows the normalised data for the production of the differing batteries per weight basis. This has been modeled using the Recipe midpoint impact assessment methodology. The major impacts are towards freshwater eutrophication (an over nutrification of inland waterways) from the two lithium ion batteries and marine ecotoxicity from the nickel metal hydride and nickel cadmium battery. The lithium batteries also have the largest impact on metal depletion.The primary material responsible for this is the lithium iron phosphate ($LiFePO_4$), but there is also some impact on metal resource depletion from the use of the electronic component, the transistor. Data for the production of the transistor was taken from the EcoInvent database. It is based on a review of the production process of many transistors used in the EU and represents an average of these. The primary impact associated with the lithium iron phosphate is associated with the production of the ferrite, not the lithium. The lithium iron phosphate also has the most significant impact towards the freshwater eutrophication. This is due to the use of the phosphates. Tabular data for the climate change, metal and fossil fuel depletion impacts are also shown in Table 2.

	Climate Change (kg CO2 eq)	Metal depletion (kg Fe eq)	Fossil fuel depletion (kg oil eq)
Lead Acid	0.048	0.020	0.018
Lithium Ion (NMP Solvent)	0.066	0.027	0.026
Lithium Ion (Water Solvent)	0.173	0.278	0.022
Nickel Cadmium	0.271	0.435	0.034
Nickel Metal Hydride	0.096	0.067	0.030
Sodium Sulphur	0.151	0.105	0.046

Table 2. Characterised data per kg of battery production

However, the comparison of the impact of the production of these batteries by weight is not strictly fair; as some perform better per weight than others. The energy density, or specific energy of the batteries differ significantly. Even within types of batteries there is a range in performance. This is shown in Table 3.

Battery Type	Energy Density (MJ/Kg)	Kg /MJ
Lead Acid	0.13 – 0.18	5.56 – 7.69
Lithium Ion	0.46 - 0.72	1.39 – 2.17
Nickel Cadmium	0.14 – 0.22	4.55 – 7.14
Nickel Metal Hydride	0.27 – 0.34	2.94 – 3.7
Sodium Sulphur	(approx) 0.72	(approx) 1.39

Table 3. Energy Densities of the Batteries

Therefore, in order to understand the true relative impacts of the production of the batteries they must also be examined on an energy basis (Table 4). This shows that there is a wide variation in data – examining the most significant categories (based on both the normalised and the characterised data) the

Impact category	Unit	Lead Acid	Lithium Ion	Nickel Cadmium	Nickel Metal Hydride	Sodium Suphur
climate change	kg CO2 eq	4.8 - 6.6	17.3 - 27.1	9.6 - 15.1	15.6 - 19.7	1.62
ozone depletion	kg CFC-11 eq	(2.24 - 3.35)E-07	(3.34 - 5.23)E-04	(7.64-12)E-07	(5.44 - 6.85)E-07	1.26E-07
terrestrial acidification	kg SO2 eq	0.088 - 0.121	0.09 - 0.14	4.3 - 6.76	2.17 - 2.73	0.018
freshwater eutrophication	kg P eq	0.00016 - 0.00023	0.02 - 0.03	0.0012 - 0.0018	0.0012 - 0.0015	0.00049
marine eutrophication	kg N eq	0.003 - 0.004	0.003 - 0.004	0.004 - 0.006	0.002 - 0.003	0.00063
human toxicity	kg 1,4-DB eq	5.45 - 7.55	3.2 - 5.01	3.97 - 6.24	1.66 - 2.09	0.61
photochemical oxidant formation	kg NMVOC	0.028 - 0.039	0.033 - 0.052	0.376 - 0.591	0.195 - 0.245	0.0071
particulate matter formation	kg PM10 eq	0.022 - 0.031	0.028 - 0.044	0.875 - 1.374	0.446 - 0.562	0.0083
terrestrial ecotoxicity	kg 1,4-DB eq	0.0005 - 0.0006	0.0012 - 0.0019	0.0017 - 0.0027	0.0009 - 0.0011	0.00022
freshwater ecotoxicity	kg 1,4-DB eq	0.022 - 0.03	0.029 - 0.045	0.605 - 0.950	0.336 - 0.424	0.029
marine ecotoxicity	kg 1,4-DB eq	0.023 - 0.032	0.064 - 0.1	0.64 - 1.01	0.343 - 0.432	0.030
ionising radiation	kg U235 eq	1.1 - 1.5	2.65 - 4.14	3.39 - 5.33	2.32 - 2.92	0.29
agricultural land occupation	m2a	0.123 - 0.17	0.149 - 0.233	0.21 - 0.323	0.13 - 0.16	0.040
urban land occupation	m2a	0.083 - 0.115	0.217 - 0.339	0.288 - 0.453	0.167 - 0.21	0.049
natural land transformation	m2	0.0011 - 0.0015	0.0021 - 0.0033	0.0019 - 0.0029	0.0013 - 0.0016	0.00033
water depletion	m3	0.07 - 0.097	0.123 - 0.193	0.247 - 0.388	0.138 - 0.174	0.022
metal depletion	kg Fe eq	1.983 - 2.746	27.791 - 43.499	6.654 - 10.456	9.267 - 11.669	4.47
fossil depletion	kg oil eq	1.845 - 2.555	2.16 - 3.38	2.959 - 4.645	4.699 - 5.917	0.53

Table 4. Characterised Data for battery production on an energy density basis

details of the total CO$_{2e}$ and the metal depletion are shown in Figures 3 and 4.

For both the metal depletion and the greenhouse gas emissions, the lithium ion batteries perform worst out of the alternatives considered on a per kg and on an energy density basis. The sodium sulphur and the lead acid batteries are the best performers – although especially for the sodium sulphur battery it is possible that a full range/compliment of the material composition was not available for analysis.

Again, this does not necessarily tell the full story, as differing battery types have differing life spans and are able to charge and discharge differing number of times, and estimates of these can vary significantly. For example, the number of cycles a nickel cadmium battery can undertake is estimated at 500 – 1000, a nickel metal hydride 300 – 800 cycles, and lithium based between 100 and 600 cycles (Rydh& Svard, 2003).

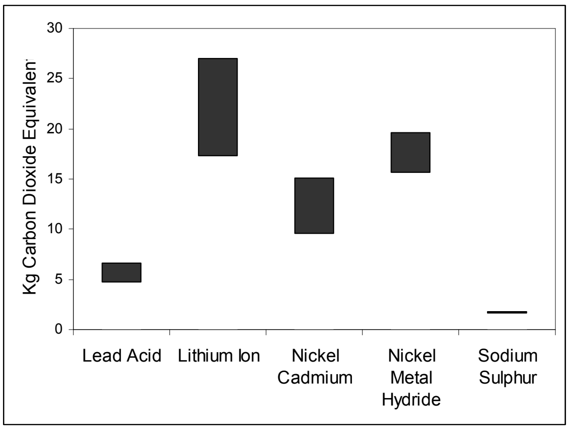

Figure 3. Characterised Data for CO_{2e} produced based on an equal energy densitiy basis

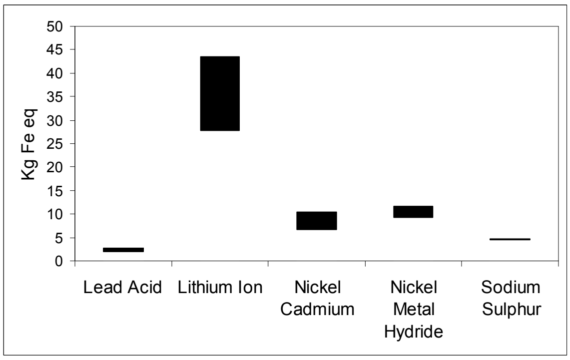

Figure 4. Characterised Data for Fe eq produced based on an equal energy densitiy basis

RESOURCE DEPLETION

The use of lithium and cadmium are perhaps the most significant in terms of metal resource depletion. This is due to their high lithospheric extraction indicator (LEI), which is the ratio of anthropogenic to natural metal flows, and the significance related to global metal mining (Rydh, 2003). Increased reliance on virgin materials for battery production using these materials may result in higher prices and resource depletion. Increased recycling and material extraction from batteries should reduce this, and the introduction of the EU battery directive should mean an improvement in this area. Currently, mostly virgin materials are used in battery production, and any metals/materials extracted from battery recyling are used in other industries. This does still have the impact of reducing the need for virgin metals, but increased use of recycled materials within the batteries is required.

CONCLUDING REMARKS

This paper presents data about the environmental impacts of the production of a number of different battery types. The use of these batteries is predicted to increase as a result of small scale renewable energy generation, and the use of the electric vehicle. The data is presented on a per kg production basis, and on an energy density basis. However, there are many other aspects that are considered when selecting a battery; many of which will effect the overall life cycle impact of the battery. These include issues such as the number of cycles a battery can undertake, performance in different temperatures and the requirement to discharge quickly. Therefore differing batteries will be selected for different purposes.

The aim of this paper is to provide a database of the materials required to produce these batteries, together with the associated environmental impact. In this way the data can be taken and used in future life cycle assessments of the differing technologies. This therefore provides the basis for future research.

The data used in the study are the best that were available to the author. However, there are believed to be limitations to some of the data, in particular to that relating to the sodium sulphur battery. Future work should be undertaken to improve this dataset. Detailed information about specific manufacturing processes was also not available and so the calculated environmental impacts are based on material composition and general processing data only. Again, further work is required in order to refine this.

On both a per kg and an energy density basis, the lithium ion batteries have the largest contribution towards metal depletion. However, the nickel based batteries contribute more towards issues such as marine pollution. Selection of batteries for different applications will depend on the specifications; but consideration ought to be made to the environmental impact. This paper brings together a number of data regarding the production of different batteries, but further work is required in this area in order to update data, especially for the sodium sulphur battery.

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