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Environmental Consequences of the Use of Batteries in Low Carbon Systems: the Impact of 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 variability 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. When used effectively with renewable energy production, batteries can increase the versatility of an energy system by providing energy storage that enables the systems to satisfy the highly variable electrical load of an individual dwelling, therefore changing usage patterns on the national grid. 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 or “low carbon”systems may in fact have an additional detrimental impact.

This paper reviews the currently available data and calculated and highlights the impact of the production of several types of battery in terms of energy, raw materials and greenhouse gases. 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. It is shown that lithium based batteries have the most significant impact in many environmental areas in terms of production. As the use phases of batteries are extremely variable within different situations this has not been included here, instead providing comperhensive data for the production stage.

Key Words: Battery, low carbon technology, resources

1. 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 variability 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. As a result, energy storage is more important now than it has ever been as we move from a fossil fuel society to one that is driven by a more intermittent renewable energy supply. We will increasingly rely on energy storage as part of our future low carbon lifestyles. In particular, the battery is the key defining component for the future if renewable sources at the community level are to proliferate. 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 [1].

The UK government is currently actively promoting low carbon technology through carbon reduction targets [2], promotion of low carbon transport [3] and, for example, subsidies to purchase electric vehicles [4], and the production of electricity through the feed in tariff [5]. In addition to the use of batteries with low carbon electricity production systems, a significant shift towards electric or hybrid cars could also increase the number of batteries required and produced. 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.

As a result, vehicle manufacturers are building increasing numbers of hybrid and electric vehicles. For example Toyota are heavily marketing their hybrid vehicle, the Prius; in its first ten years over two million were sold [6]. As a result of incresing demand major global battery manufacturer claimed that it would double production in 2011 from 2010 [7]. Additionally, batteries are increasingly required in developing countries which are adopting small scale off grid renewable technologies with battery storage in order to have 24 hour electricity availability. In developed countries policy incentives such as the feed in tariffs and planning policies to promote on site energy production are all increasing small scale renewable use. All of these low carbon technologies can require battery storage.

However, batteries can have varying efficiencies and comprise materials that have high environmental impacts. There are also a number of different type of batteries, many of which are suitable for use, but with differing environmental impacts. It is therefore essential that we understand the impact of their production, use and disposal so that we do not create unintended negative environmental consequences, and so that we can understand and quantify the full impact of the selection of differing types of battery. For example, some materials contained within some batteries, such as lithium, have been cited as scarce natural resources and could be limiting features on future battery production [8]. Indeed, it has been estimated that if developing countries used metals at the same rate as developed countries the amount of metals required could be up to nine times as much as we currently globally use [9]. Until recently the resource availability of only a few metals, for example copper, lead, zinc and iron, had been estimated [9]. However, with the increasing reliance on batteries for hybrid and electric vehicles the use and production of lithium has also been questioned [8], and questions of “peak lithium” have been raised (eg [10]). More widely, the availability of some of the metals required for energy production technologies has been examined, but this is currently limited [11].

As a result of the impact of producing of batteries, the overall impact of increasing our reliance on such “sustainable” systems may in fact have an additional detrimental impact, and thus this impact must be determined. 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. This paper focuses on the materials required and production of the batteries, not their use or disposal.

2. LCA Methodology

Whilst a full life cycle assessment of the use of 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. Within this paper the use and disposal impact is not measured. Therefore the paper does not present an LCA, but uses the same methodological approach for the production of batteries. In this manner it presents results in a format that will enable future researchers to use the data for their own particular use patterns, be they for renewable energy systems, hybrid or electric vehicles or alternative uses.

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 [12] & 14044 [13]).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 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, and is not recommended under the ISO standards. It is important to note that the LCA impact assessment is not geographically specific, and that any impacts ought to be considered as potential, not actual, impacts.

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 can be very difficult to compare directly and so the valuation stage is often employed so that their relative contributions can be weighted. This is subjective and many studies omit this stage from their assessment (as per the ISO guidance). 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.

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, primarily EcoInvent. 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 Recipe [14] and cumulative energy demand methods were adopted.

Recipe was developed in the mid 1990s by RIVM, CML , PRé Consultants, Radboud Universiteit Nijmegen and CE Delft [14]. Cumulative Energy Demand (CED) calculates the total energy taken to produce a product or process over its life time, including all processing, material extraction and transportation. Exactly the same system boundaries are used in the study for data analysed with Recipe and CED. Recipe enables the user to study the data at both the mid-point and the end-point.Mid-point is the more traditional characterised data and is shown in units such as CO_{2eq}. End-point data aims to establish what impact this might have on the environment, ecology or human health, for example and end-point indicator for CO_{2eq} would try to show what effect the product or process 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.

3. 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 [15] (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 [16]. 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 [17]. Their performance at low temperature and their cycle life is below average [18], 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 14, 15,19, 20, 21, 22, 23]. Some have also considered greenhouse gases [17, 24] and wider environmental impacts [16]. In terms of life cycle impacts, within these papers numerous boundaries and data inputs selections have been made.

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 [16] or PV [19, 20]).

This paper builds on these research studies by providing an information base relating to the production of six battery types. 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, including future life cycle assessments.

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.

4. Battery Disposal

Several hundred thousand tonnes of batteries are disposed of annually within the European Union. In order to deal with this waste the EU Battery Directive was recently introduced [25]. 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.

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, based on the global average of recycled aluminium [26].

5. 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, despite a thorough literature search. This is perhaps because these batteries are less comonly produced and used than the alternatives, and as a result, data from a rather old reference [27] has been used. Ideally further information about the production and composition of these types of batteries should be generated to ensure an accurate comparison. If these batteries are to be used in future further research into this is recommended.

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 lithium batteries 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. This result doesn't indicate that ferrite stocks are running out; the results compare demand with available stocks, and the ease with which the ferrite can be extracted. Ferrite is one of the most abundently mined and processed metal globally [9]. As a result our demand is such that we are now having to extract ferrite from lower and lower grade ores, which has higher environmental and economic consequences. Manganese is also used in the production process of the ferrite: this is again well used and a relatively abundant mineral within the earths crust. It has been noted, that as a mineral that is in high demand, little information about its global availability and cost (both financially and environmentally) has been collated [9]

There are three main types of lithium deposits; brines, sedimentary, and pegmatites (igneous). Much of the global lithium is supplied through the brine deposits as it is close to the surface. The largest mines are in South America, China and Tibet. It had been predicted that half the world's total reserves of lithium might be mined out by 2050 [8]. However, recent review of all lithium availability suggested that the global reserves are approximately 39Mt, but expected demand will not exceed 20Mt by 2100 [28].   Therefore, whilst continued use of lithium needs to be monitored and it is proposed that there is not an immediate shortage. Never the less, mining of lithium can cause significant human health and social impacts. The largest global reserve of lithium is in a scenic area of Bolivia and the Bolivian government is keen to ensure that any extraction will have minimum environmental impact [29]. The lithium based batteries also show an impact on human toxicity. This is partially due to the lithium mining process, but is also due to the use of copper and the impacts associated with copper minining. Tabular data for the climate change, metal and fossil fuel depletion and cumulative energy demand are also shown in Table 2.

Table 2 shows that the most energy intensive batteries in terms of their production is the lithium ion and the nickel metal hydride. The batteries with the lowest cumulative energy demand are the lead acid and sodium sulphur batteries. This pattern is repeated in the other catergories, with the highest embodied CO_2 and metal and fossil fuel depeltion resulting from the production of the lithium and nickel based batteries. 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 during their life cycle. 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. In addition, some batteries will have a far longer life span than others, with the ability to undergo more change/discharge cycles.

Therefore, in order to understand the true relative impacts of the production of the batteries they must also be examined on an energy basis, and are therefore shown here on a per MJ capacity basis (Table 4).

Examination of some of the key issues in greater detail shows the range of impacts for greenhouse gases (CO_{2eq}), fossil fuel depletion and cumulative energy demand (Figures 3 – 5). 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 per energy capacity 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/complement of the material composition was not available for analysis, and therefore these results have high uncertainty. The cumulative energy demand shows a differing pattern, with the sodium sulphur again performing best, but with the two nickel based batteries having the largest energy impact.

Again, differing battery types have differing life spans and are able to charge and discharge a differing number of times, and estimates of these can vary significantly. Therefore, life cycle impacts will vary significantly according to these. 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 [30]. New technologies should improve battery performance, and the use of, for example, nano materials and technogies in energy storage systems may show benefit in the future [31].

6. Resource Depletion

In terms of absolute resource depletion the use of lithium and cadmium are perhaps the most significant. 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 [30]. Never the less, it is estimated that there is enough lithium to meet demand for this centuary. However, there are environmental impacts associated with the mining of these materials.

Unlike the other often discussed finite resource, fossil fuels, it is possible to recycle and reclaim metals, and this should be encouraged. 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.

7. Concluding remarks

Batteries are essential to our renewable energy and low cabon future. Therefore understanding their impact is key. 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 capacity basis. The results show that for the materials required in battery production the lithium ion batteries have the most significant contribution to greenhouse gases and metal depletion, but the nickel metal hydride batteries have a more significant cumulative energy demand. 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, and consideration of the full life cycle impacts for any particular application is therefore important.

Whilst many materials used to produce batteries are finite resources it is unlikely minerals such as lithium will run out in the near future due to our use of batteries. However, the impact of mining is still high, and so increased recycling and material recovery must be adopted.

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. If batteries are to become a significant energy storage mechanism for either low carbon energy production or electric vehicles their impact cannot be overlooked.

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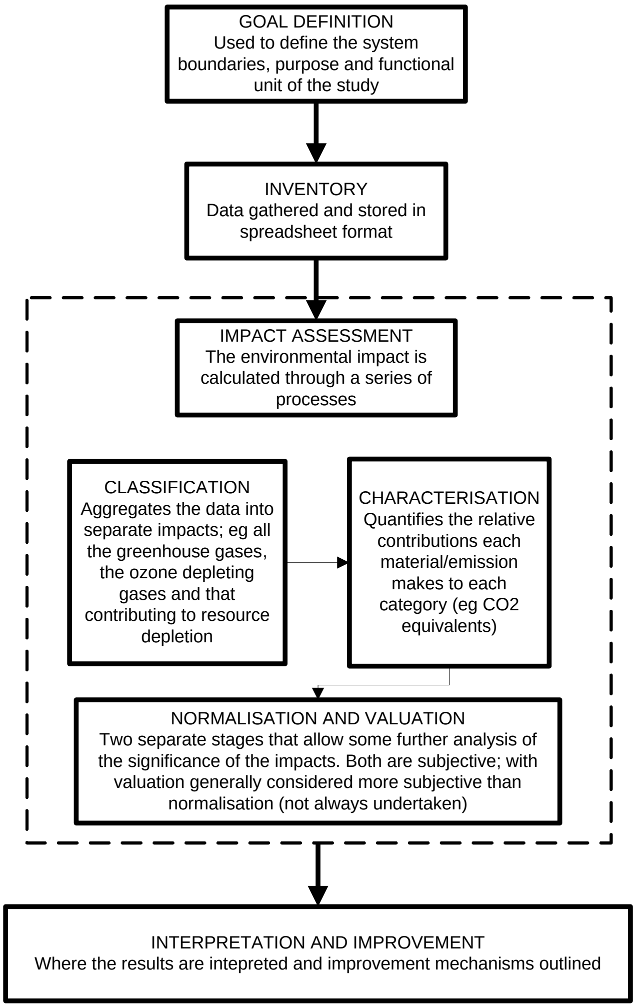

Figure 1: Stages contained within an LCA

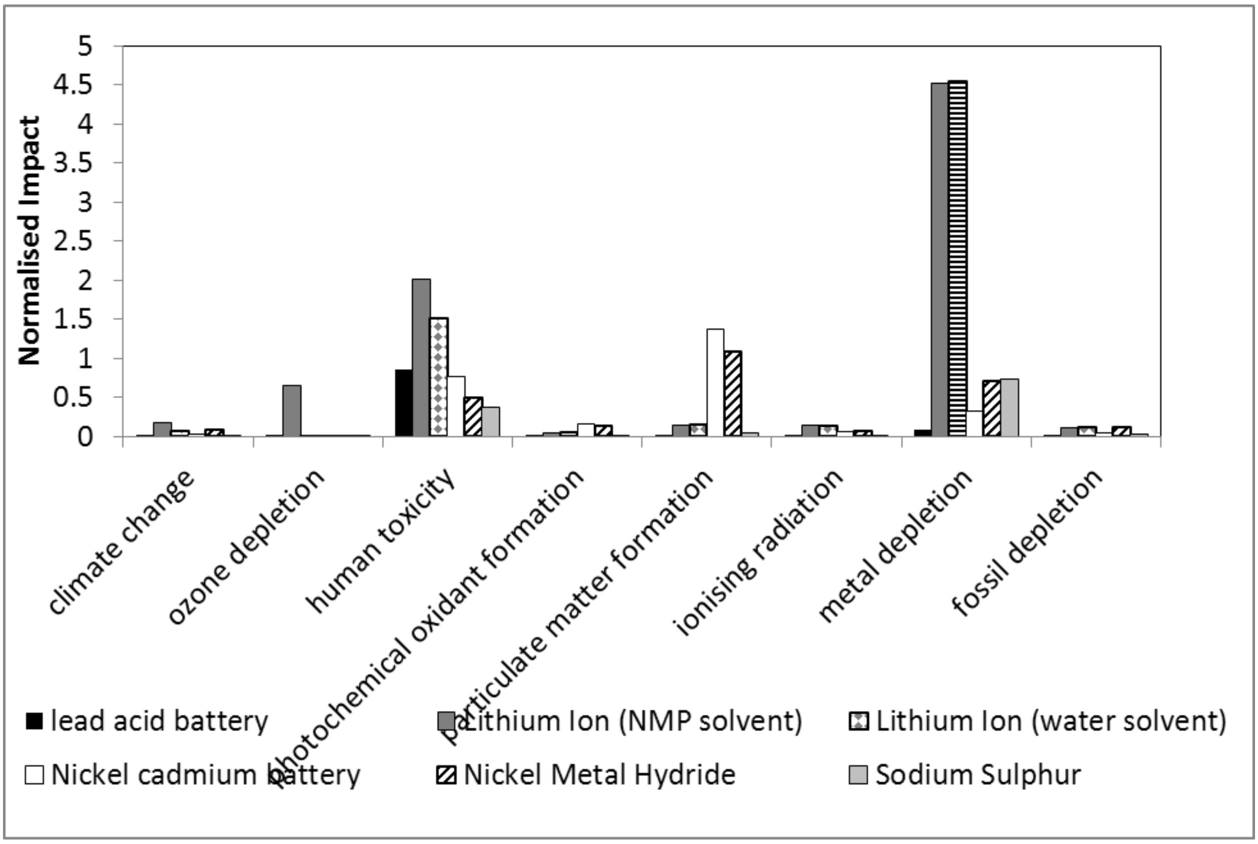

Figure 2: Normalised data for battery production (to produce 100kg)

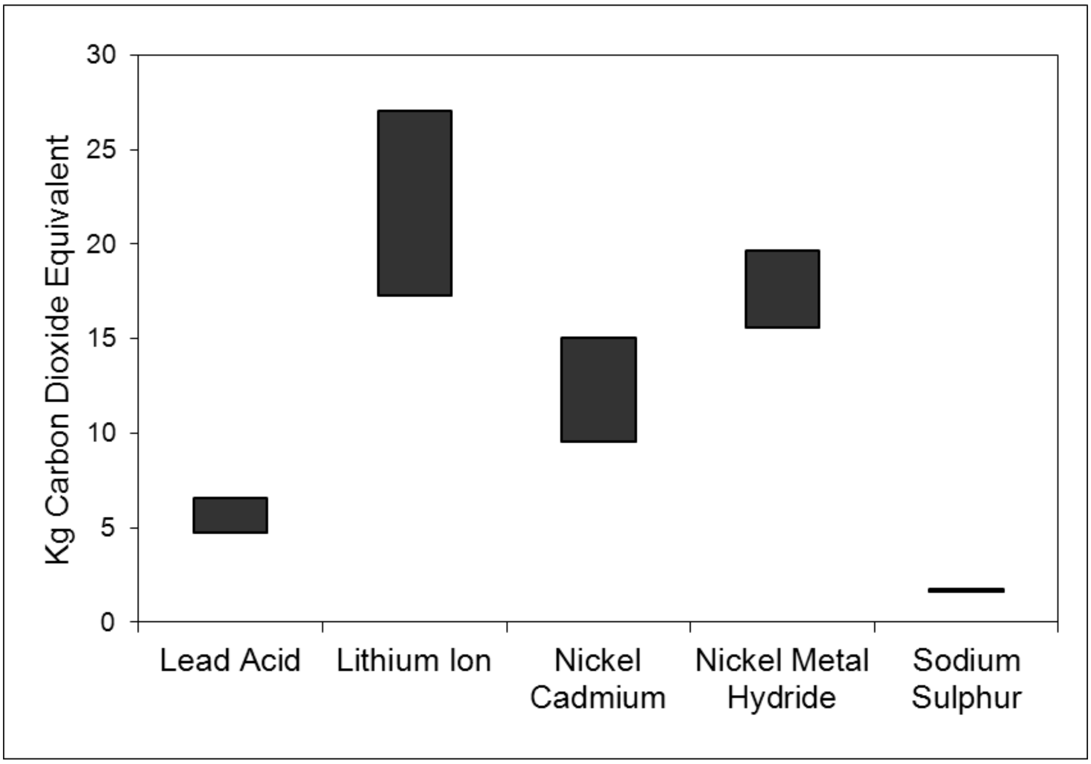

Figure 3: CO_{2eq} per MJ capacity

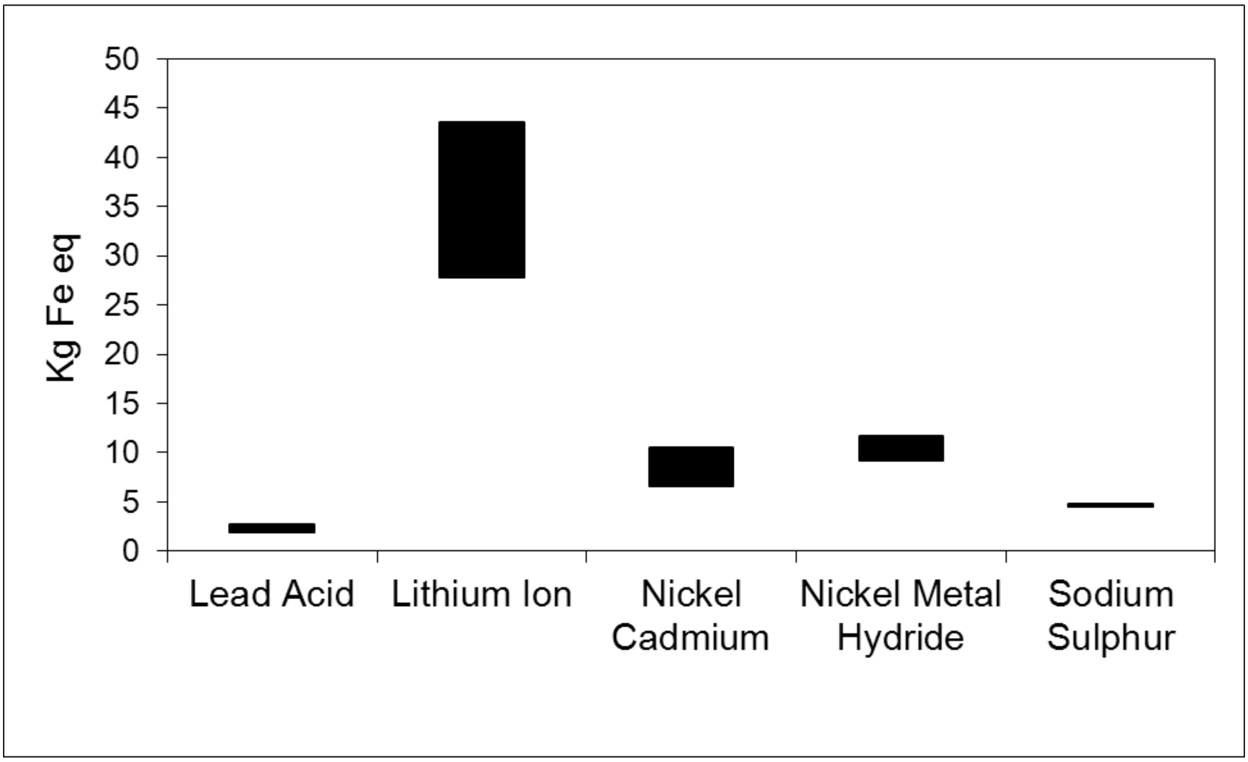

Figure 4: Fe_{eq} per MJ capacity

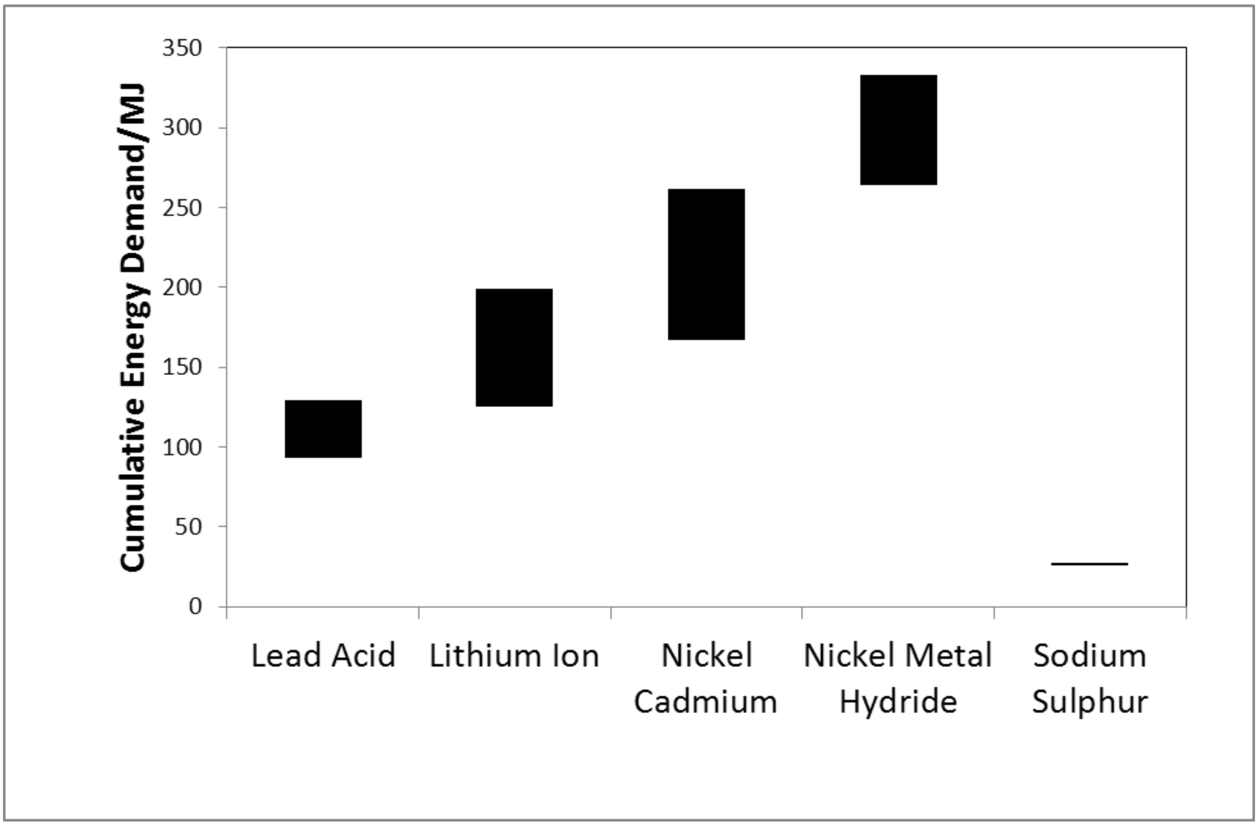

Figure 5: Cumulative energy demand per MJ capacity

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