Comparing Life Cycle Assessment of Li-ion batteries and fuel cells in chargers for small electronic applications

HENRIK LARSSON

Department of Environmental System Analysis
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2011
Report No. 2011:21
ISSN No. 1404:8167

REPORT NO. 2011:21
ISSN NO. 1404:8167

Comparing Life Cycle Assessment of Li-ion batteries and fuel cells in chargers for small electronic applications

A comparison of the environmental impact of portable cell phone chargers

HENRIK LARSSON

SUPERVISOR
Maguns Karlström, Vätgas Sverige

EXAMINER
Bengt Steen

Department of Environmental System Analysis
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011

Comparing Life Cycle Assessment of Li-ion batteries and fuel cells in chargers for small electronic applications
A comparison of the environmental impact of portable cell phone chargers
HENRIK LARSSON

Technical report no 2011:21
ISSN No. 1404:8167
Department of Environmental System Analysis
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone + 46 (0)31-772 1000

Chalmers Reproservice
Göteborg, Sweden 2011

Abstract

This work aims to compare the environmental impact of two different cell phone chargers. The chargers are for portable use. The first one, which is on the market, is powered by two lithium AA batteries. The second charger, a prototype, receives energy from a hydrogen-powered fuel cell. Three different means of supplying the fuel cell with hydrogen are examined: sodium borohydrate and two different aluminum alloys. All three of these compounds react with water to produce hydrogen and oxygen, the former used in the fuel cell and the latter being absorbed by the waste product.

To determine the environmental impact of the various products a comparing life cycle assessment, LCA, is made. A life cycle assessment is a way to analyze the environmental impact of a product or process, ideally from cradle (extraction of materials, etc.) to grave (recycling, landfill, incineration). Since this is a comparing LCA it focuses on the things that differ between the various products, and excludes plastic casing on the charger etc. that both chargers have in common. Two different methods of LCA are used to see whether the results are influenced by the method used. The methods are CML 2001 and EPS 2000.

CML 2001 focuses on the potential damage materials and processes can have on the environment. According to this method the fuel-cell charger is beneficial to the battery powered charger if used more than three times, which is likely with a product like this. The materials of the fuel cell have a high impact on the environment, but are needed only in small quantities. Emissions from the lithium production are the primary cause of environmental impact from the battery-powered charger. This would be lower if the lithium was recycled, but presently the used batteries are incinerated so the metal is wasted.

EPS 2000 takes into consideration how future generations are affected by a process or product, weighting depletion of resources significantly higher than in CML 2001. According to the EPS 2000 method the charger needs to be used approximately 580 times before being the preferred option. This use is not likely as one would have to use it for 4.5 years if charging a cell phone every three days Since platinum, gold and indium have a large impact due to their rarity the fuel-cell charger (including gold and platinum) with aluminum alloys (containing indium) are the worst option. Sodium borohydrate as a fuel is better than lithium batteries (due to depletion of lithium), but as platinum and gold are so much rarer the fuel cell has a high starting cost.

The conclusions from this study are two; recycling significantly affects the environmental impact, and various LCA-methods have different results due to different ways of weighting the impact categories.

Sammanfattning

Syftet med det här arbetet är att jämföra den miljömässiga påverkan av två olika mobiltelefonladdare. Laddarna är mobila och den ena, som finns på marknaden, drivs av två litium AA-batterier. Den andra laddaren, en prototyp, får energi från en vätgasdriven bränslecell. Tre olika metoder att förse bränslecellen med vätgas undersöks: natriumborhydrid som reagerar med vatten samt två olika aluminiumlegeringar som även de reagerar med vatten för att spjälka vattnet till vätgas och syre.

För att utröna miljöpåverkan från de olika produkterna har en jämförande livscykelanalys utförts. En livscykelanalys undersöker miljöpåverkan en produkt har, gärna från vaggan (utvinning av material mm) till graven (återvinning, deponering, förbränning). Eftersom detta är en jämförande LCA koncentreras den till det som skiljer de olika produkterna åt, och exkluderar exempelvis plasthölje på laddare mm som bägge laddare har gemensamt. För att se huruvida resultatet påverkas av vilken metod av LCA som används så används två olika metoder, CML 2001 och EPS 2000.

CML 2001 koncentreras på potentiell skada material och processer kan ha på miljön. Enligt denna metod blir den bränslecellsdrivna laddaren fördelaktig om man använder den mer än tre gånger, vilket är troligt om man köper en sådan här produkt. Materialen i bränslecellen har hög miljöpåverkan, men behövs endast i små mängder. Utsläppen vid litiumproduktionen är det som främst gör att den batteridrivna laddaren påverkar miljön. Påverkan skulle minska om litiumet återanvändes, men i nuläget går batterierna till förbränning så metallen går till spillo.

EPS 2000 fokuserar på hur framtida generationer påverkas av processen, vilket gör att uttömmande av resurser bedöms betydligt högre än i CML 2001. Enligt EPS-metoden behöver man använda laddaren 580 gånger innan det är miljömässigt fördelaktigt med den bränslecellsdrivna versionen. En så hög användning är inte sannolikt, då man skulle behöva använda den i 4,5 år förutsatt att man laddar sin mobil var tredje dag. Eftersom platina, guld och indium påverkar miljön mycket pga. dess sällsynthet blir den bränslecellsdrivna laddaren (som innehåller guld och platina) med aluminiumlegeringarna (som innehåller indium) det sämsta alternativet. Natriumborhydrid som bränsle är bättre än litiumbatterierna (pga. resursförbrukningen av litium), men eftersom platina och guld är så mycket sällsyntare har bränslecellen en hög startkostnad.

Slutsatserna man kan dra från studien är två; återvinning påverkar miljöpåverkan i hög grad, samt olika metoder har olika resultat.

Acknowledgements

This report constitutes my final thesis at the department of Environmental System Analysis at Chalmers University of Technology. The report was performed on behalf of a company in the fuel cell industry.

I would like to thank my supervisor Magnus Karlström and my examiner Bengt Steen at Environmental System Analysis at Chalmers University of Technology for their helpful attitude, extraordinary patience and constructive criticism during the project. Without you this would not have been possible. I would also like to thank my family for their continuous support during my studies. Without your determined contribution this project would not have been finished.

Henrik Larsson
Stockholm December 2011

Contents

1 Introduction

This chapter introduces the background of the study, as well as the purpose of it. It also includes the directives and delimitations.

1.1 Background

The fuel cell was invented 1838, but has lately become a product under rapid development. It uses hydrogen and oxygen (normally taken from air) to produce electricity. It is publicly marketed as a green technology since the emissions are clean, consisting only of water (and sometimes carbon dioxide depending on fuel). However, the production of the fuel is of considerable importance, as it uses hydrogen or hydrogen rich compounds which are either not naturally occurring or originates from fossil fuels.

The current application of fuel cells are wide, from powering vehicles and submarines to providing electricity in space and being included in power solutions for buildings. Several companies are currently trying to introduce the fuel cell to the portable electronics market. It can either replace or compliment the batteries used by cell phones, computers etc., or provide the electricity to charge an internal battery. When introducing a new product on the market today, the environmental impact is of a not negligible importance to the customer. This is especially true of products with new technology that is marketed as “green”.

As a tool to examine environmental impacts, life cycle assessment (LCA) has become increasingly common. It can follow a product from cradle to grave, thereby including raw material acquisition, production, use and finally waste disposal. It is ideal to identify problem areas and thereby help producers allocating money for environmental improvement to the most effective use. It can also compare different products or technologies against each other on an environmental viewpoint by weighting the impact categories against each other, thereby getting a total impact for the product.

The LCA methodology is standardized by the International Organization for Standardization (ISO), but there are several different methods to choose from inside the methodology when conducting a LCA. The different ways of conducting LCAs is often mentioned as a negative side of LCA, since it is possible to choose a characterization and weighting method that makes the product seem either favorable or unfavorable depending on the purpose of the study.

1.2 Purpose

The purpose of this study is to compare the environmental impacts of a fuel cell powered cell phone charger to a lithium battery powered one. It includes three different options of energy carriers for the fuel cell. The goal is to be able to pinpoint possible problem areas with the fuel cell technology for portable electronics, and to compare it to an existing, working technology represented by the battery powered charger.

1.3 Directives and delimitation

The methodology used to fulfill the purpose of the study is a LCA based on data previously recorded in earlier LCA projects. Data for materials used in the manufacturing of products included in the study has been gathered from LCA databases, and includes transportation, energy consumption, emissions to air and water and raw material depletion. It does not include the losses during assembly/production of the energy carriers or chargers, except when so stated. Elements of the products have in some cases been excluded, as both chargers contain them and they therefore make no difference to the comparison.

2 Product description

2.1 Energizer Energi To Go® INSTANT CELL PHONE CHARGER

Energizers Instant cell phone charger is powered by two AA-type batteries (Figure 2.1). According to Energizer (1), it should be powered by Energizer Lithium batteries for best performance. During measuring two of these lithium batteries, Energizer L91 (2), have been used. They are among the most powerful AA-battery available today.

The charger consists of a cord, outer cast of plastic, steel as conductor and electronics inside.

Figure 2.1 The Energizer Energi To Go® INSTANT CELL PHONE CHARGER.

2.2 Fuel cell powered Cell Phone Charger (prototype)

The Cell Phone Charger is a fuel cell powered charger under development. Products of similar design already exist on the market, even though the energy carrier might be different on those. The charger is powered by PEFC fuel cells, which uses hydrogen and oxygen as fuel.

A fuel cell is an electrochemical reactor, with hydrogen added on one side and oxygen on the other. The fuel cell uses a proton conducting electrolyte, as shown in Figure 2.2 (16). This means water is produced on the right side, which must be drained or vaporized to keep it from stopping the flow of oxygen.

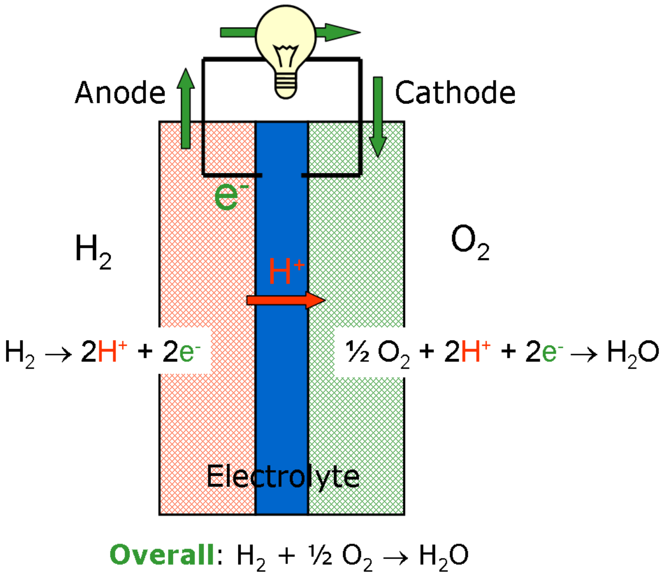


Figure 2.2 Fuel cell

The oxygen is taken from air, and the hydrogen is either stored in a tank or produced on demand. In this LCA the hydrogen is produced on demand, see chapter 2.3.2 and 2.3.3.

The fuel cell powered Cell Phone Charger consist of a plastic cast, containing a tank for hydrogen and the fuel cells. Although the prototype uses hydrogen stored in a tank as fuel, the LCA is done with hydrogen produced on demand according wishes from the developer, a European company.

2.3 Energy carriers

2.3.1 Lithium batteries

Lithium primary batteries work by the chemical formula $Li+FeS_2=>LiS_2+Fe$ (2) (3). When this process takes place electrons move from the anode, made of lithium or lithium compounds, through en extern circuit (which powers an appliance) and back to the porous carbon material, serving as cathode current collector. The electrons then proceed into the cathode, where it connects itself to a charged ion or molecule. The total potential of the battery depends on the amount of lithium and iron disulfide present.

2.3.2 Sodium borohydride

Sodium borohydride, $NaBH_4$, can, in presence of water, produce hydrogen for a fuel cell. The process, $NaBH_4+2H_2O=>4H_2+NaBO_2$ (4), works like all spontaneous chemical reactions because the binding energy in sodium borohydride and water is higher than that of the final products, hydrogen and sodium metaborate (borax). The problem with this reaction is that it cannot be stopped with the exception of removing one of the compounds. This means losses in use are hard to avoid, since it will be hard to apply the exact right amount of sodium borohydride to avoid excess hydrogen after providing a full charge.

2.3.3 Aluminum alloy

The aluminum alloy contains aluminum, gallium, indium and tin (5). There are two different compositions of the alloy, of which the first with 50% aluminum is already developed, and the other with 95% aluminum currently in development (6). The reaction producing hydrogen takes place in presence of water, the formula is: $2Al+3H_20=>Al_2O3+3H_2$. The other metals in the alloy work only as catalysts, by hindering the aluminum oxide to form a protective layer which would stop further reactions. Therefore these materials can be directly recycled. Just as with sodium borohydride, losses during use are hard to avoid, since exact determination of the electricity need often is hard to determine.

3 Theoretical Framework

The need to compare different products and services in an objective manner has led to standardization of methods to measure and present environmental properties. The LCA, Life Cycle Assessment, is one such method and will here be described.

3.1 Life Cycle Assessment in general

3.1.1 Life cycle assessment

A LCA considers the entire life cycle for a product or service, including acquiring raw materials, production/refining of energy and materials, manufacturing, usage and finally end of life treatment and diposal (7)(Figure 3.1).

Through this systematic approach it is possible to compare different products or services against each other, as well as identifying and separating major and minor environmental impacts and therefore help allocate funds and efforts of reducing these effects in the most efficient way.

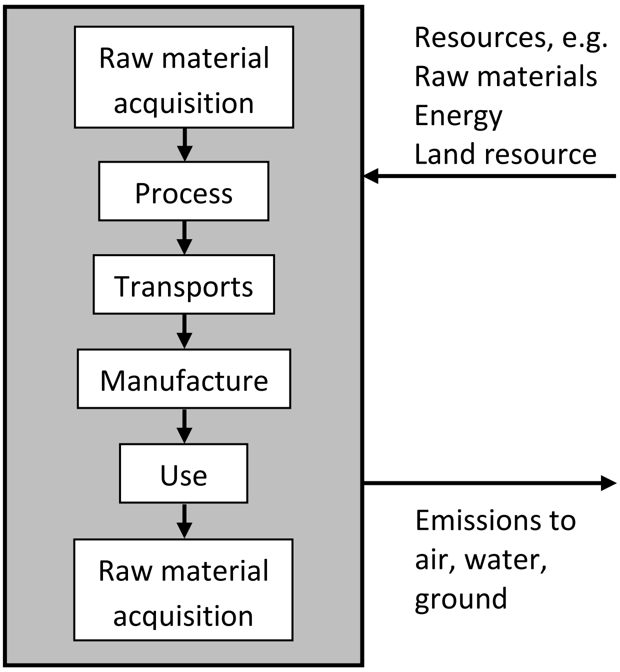


Figure 3.1 Life cycle model. Arrows represent flows of energy and matter, boxes indicate physical processes.

The four stages in a LCA-study (8) are:

1. The goal and scope definition (3.2)
2. The inventory analysis phase (3.3)
3. The impact assessment phase (3.4)
4. The interpretation phase

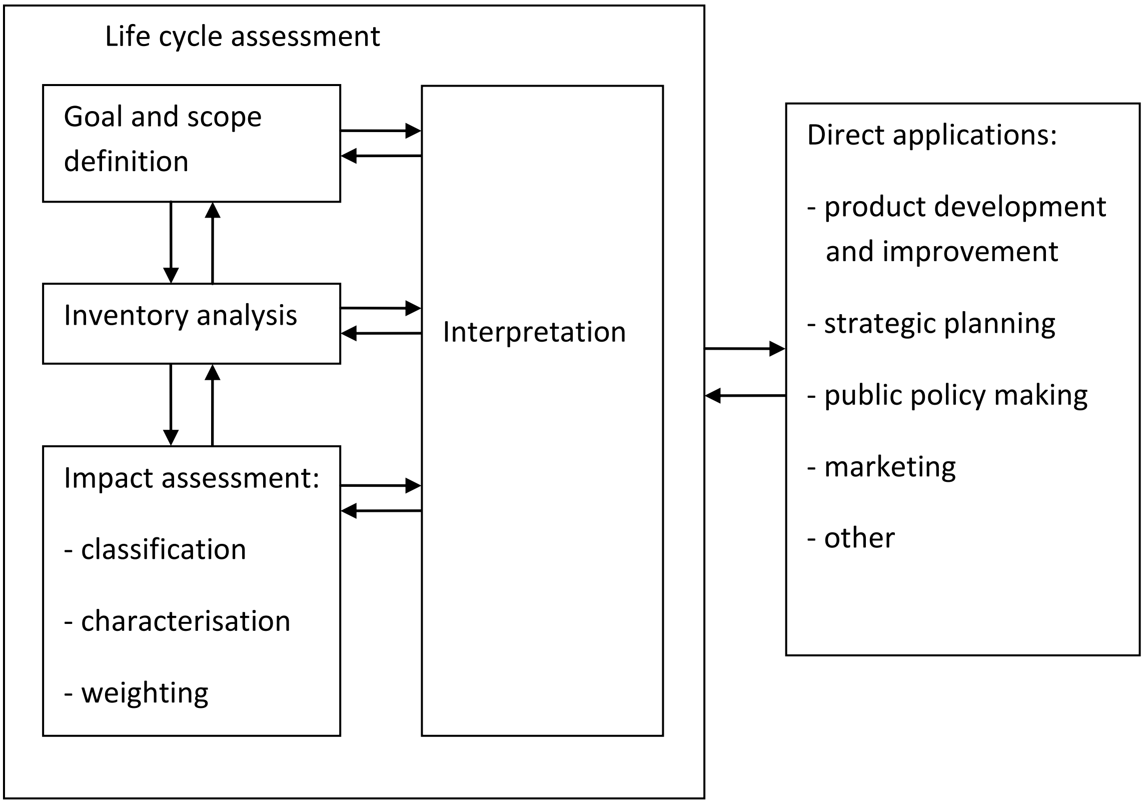


Figure 3.2. ***LCA standard***

3.1.2 Standardization

Since there are several possible ways of performing an LCA, the International Organization for Standardization (ISO) has implemented a voluntary international standard of LCAs, the ISO 14040-series (7).

The ISO-standards in use presently are:

- **ISO 14040:2006** Environmental management – Life cycle assessment – Principles and framework
- **ISO 14044:2006** Environmental management – Life cycle assessment – Requirements and guidelines
- **ISO/TR 14047:2003** Environmental management -- Life cycle impact assessment -- Examples of application of ISO 14042
- **ISO/TS 14048:2002** Environmental management -- Life cycle assessment -- Data documentation format
- **ISO/TR 14049:2000** Environmental management -- Life cycle assessment -- Examples of application of ISO 14041 to goal and scope definition and inventory analysis

The ISO 14040:2006 replaced the previous ISO 14040, ISO 14041, ISO 14042 and ISO 14043, which is why the references in ISO 14047 and ISO 14049 refer to these documents.

3.2 Goal and scope definition

The goal of an LCA states the intended application, the reasons for carrying out the study, the intended target audience and whether the results are supposed to be made public (8).

The scope should be sufficiently well defined to satisfy the goals, and includes (8):

- functional unit, which is the reference unit which all data can be referred to
- system boundaries in relation to time horizon, geographical boundaries, division into foreground and background systems
- choice of impact categories and method of impact assessment
- level of detail in the study, and through this the data requirements
- whether or not a critical review is to be performed

3.2.1 Functional unit

The functional unit defines the performance characteristics of the chosen product. The purpose of the functional unit is to provide a reference, against which the inputs and outputs can be related. This is necessary to be able to compare the results from the LCA against other LCAs, and in this case to be able to compare the different products against each other (8).

Example: If the function we study is growing corn, both irrigation and fertilization are factors. The functional unit here could be *kg corn produced per area*, and how the factors affect the environment and size of the crop can be studied.

3.2.2 System boundaries

The results of an LCA depend very much on where you put the boundaries for the study, i.e. what is to be included in the resource flow and what is to be excluded. Therefore these need to be clearly stated.

3.2.2.1 Boundaries in relation to natural systems

When defining boundaries against natural systems one has to define how far the material and energy flows needs to be examined. Since a constant exchange of matter and energy is taking place between biosphere, technosphere and lithosphere, the time perspective is a very important factor both regarding the cradle and the grave for a material. It can be very hard to determine where the border between nature and the technosphere, especially considering the grave.

3.2.2.2 Geographical boundaries

The geographical location can affect the life cycle depending on the technical level of the region and the environmental preconditions. Some areas are very sensitive to certain emissions, and different energy production can have a large effect on energy intensive production like metal or pulp production. Infrastructure, transportation and waste management might also be important.

3.2.2.3 Time boundaries

If a study is limited to a short time perspective, there is a risk that long term environmental effects are not included. The environmental effects of different emissions and resource depletion vary greatly. Gases affecting the greenhouse effect or the ozone layer can have environmental repercussions for time interval’s from less than a year up to several centuries. Exotoxic substances can have acute effect for days or weeks but chronic effects for decenniums.

3.2.2.4 Boundaries within the technical system

To be able to compare different processes and products there are usually some parameters that needs to be specified, to make the comparison fair. It may be i.e. to keep the output at a certain level, or to make sure the environment is similar during both experiments.

3.2.2.4.1 Cut-off criteria

To reduce the complexity of a study it is usually limited to the parts judged to be relevant to the studies intended application. In most models experience has shown that a few parameters explain most of the variations in the results. According to the “Pareta principle” 20% of the parameters explain 80 % of the variations (approximated value). Therefore cut-off criteria’s are chosen, to reduce the number of parameters to examine. A cut-off criteria could be i.e. material weight >5%. In that case, all materials of less than 5% of the products total weight are discarded.

3.2.2.4.2 Allocation

The flow of materials and products are a complex network, with subsystems and primary systems. In many cases processes produce several different products, and waste treatment has several different inputs. Allocating raw materials, energy demands, emissions etc. to them can be a very tedious task. Another problem with allocation is recycling, and whether emissions and resource depletion produced from refining the raw materials and producing the previous product should be included or not. (8)

3.2.2.5 Boundaries for comparing life cycle assessments

When comparing two different systems it is imperative that the same functional unit is used. Differences between the systems should be identified and reported.

Problems can also occur if, for example, one of the products is recycled and the other incinerated in the end of the life cycle. These problems can be solved in two ways, by expanding the system or by allocation.

3.3 Inventory analysis (LCI)

The LCI requires a model of the flow through the technical system, including an incomplete mass and energy balance. Only the relevant flows are to be included in this, as environmentally indifferent flows, like diffuse heat and emissions of water vapor from combustion, don’t have noticeable effect. The LCI includes (8):

- Construction of a flow chart, according to the system boundaries.
- Data collection and documentation of said data, for all the activities of the defined system. This includes raw material demands, produced products and emissions to and from the system during the entire period the LCA is evaluating (normally cradle to grave of a product).
- Calculating the environmental loads, in relation to the functional unit, of the system. This may include allocation, as many processes turn out more than one product.

3.4 Impact assessment (LCIA)

The aim of LCIA is to describe (if possible) or indicate the impacts of the environmental loads calculated during the LCI. One of the purposes is to describe how the system impacts the environment rather than just informing of the quantities of the emissions and resource use.

The other purpose is to reduce the number of parameters, to simplify comparison.

There are three steps in the LCIA; classification, characterization and weighting (7). The first two of these are compulsory, while the last is optional.

3.4.1 Classification

In this step, the inventory data is sorted and assigned to various impact categories. Different impact categories can be chosen depending on goal of the study and LCA methodology, common ones are global warming, resource depletion, acidification and eutrophication.

3.4.2 Characterization

In the second step of the LCIA the relative contributions of emissions and material usage to each environmental impact category are calculated. This is done using equivalency factors defined, from modeling cause-effect chains, in the LCA methodology. An example is that all acidifying emissions (SO_2, NO_X etc) from the LCI are multiplied with their respective equivalency factor, and then summed up to indicate the extent of the impact of acidification (9).

3.4.3 Weighting

In the weighting step, the results gathered from the characterization are interpreted (8). This can be done in different ways, either by using established weighting procedure (of which there are many different), or by using expert panels. Since there are many different ways to do this, it is the most controversial part of the LCA. Weighting means assigning importance to the impact categories, and then summing them up to a single number.

As different methods emphasize different, the results can be very different depending on methodology chosen. For example, one can put great emphasis on resource depletion and the other on acidification, as one might be important to humanity in years to come and the other might harm health or nature presently.

4 Methods

4.1 Methods during data collection

4.1.1 Interviews

Some data have not been published, and therefore contact with people involved in different projects and companies have been necessary. This has been done both by phone and email, and the information obtained has been deemed accurate.

4.1.2 SimaPro 7

SimaPro is software developed for life cycle assessments. The databases in SimaPro are extensive, and have been used to a high degree in this study. Because of the quantity of data, care has to be applied to what data is used since the production and locality is different between different cases.

4.1.3 Literature studies

Books have been used mainly to explain the different processes and methods.

As it is very time efficient to find information on the internet, and this method have been used extensively. However, one has to bear in mind that a critical view has to be taken upon facts stated in various outlets, since many are subject to changes and publications without experts having confirmed the data to be correct. Therefore one needs to evaluate the information, and in some cases confirm them by multiple, independent sources.

During the collection, governmental institutes have generally been considered trustworthy. Books available via libraries web sites, has equally been deemed reliable, whereas reports and papers from other sources has been confirmed whenever possible.

The internet has been the primary source of specific data when this was not available in SimaPro 7.

4.1.4 Tests

Tests have been conducted during the thesis. This was done to measure the products fuel consumption, under a constant voltage and effect. The tests were conducted by Anders Lundblad at KTH Stockholm, with the same equipment for both chargers.

5 Goal and Scope Definition

The goal and scope of the LCA are defined, including system boundaries. Methods for aggregation and evaluation of the inventory results are presented and explained.

5.1 Goal of the study

This study is made to compare two different technologies which can be used to power small electronic products. The products compared in this study are two portable cell phone chargers, one created by a European company developing fuel cells for small applications and therefore powered by a hydrogen fuel cell. The other product is produced by Energizer and powered by two AA lithium batteries.

The study is done from cradle to use, and the purpose is to identify the major causes of environmental impact. The study is not done cradle to grave since no waste products are hazardous to the environment, however some recycling has been included. The products will be compared as far as possible, though exceptions might be made because of lack of data. Different sources for hydrogen will be investigated. Production of the fuel cell charger will not be included since the product is not yet in production, the material is however included.

The study's application is to help the fuel cell developer to identify where the environmental impact should be reduced, if at all, and in what kind of use it may be superior to the battery powered charger from Energizer.

The LCA is critically reviewed by examiner Bengt Steen and supervisor Magnus Karlström at Environmental System Analysis at Chalmers.

5.2 Scope of the study

5.2.1 Product systems

Since this is a comparing LCA all parts of the systems studied will not be included. Many parts in the cell phone chargers are similar or identical, and have low potential for environmental impact. Therefore the entire Energizer charger and everything but the gold, platinum and copper in the fuel cells of the fuel cell powered charger have been excluded from the study. The excluded parts include cords, plastics and electronic components, with a total weight of approx. 30 grams.

For the study transportation of batteries and hydrogen carriers have also been excluded, simulating a comparable distribution system.

5.2.2 Energizer® Energy To Go® Instant Cell Phone Charger

The product datasheet specifies that Energizer Lithium batteries should be used, which is also the case (2). The efficiency of the charger is approx. 67%.

5.2.3 Energizer L91 AA battery

The Energizer L91 battery is a Li-FeS_2 battery where lithium and iron disulfide reacts, forming iron and lithium disulfide. The battery contains 0,98 grams of lithium and has a capacity of approximately 4Wh/battery in room temperature. Since numbers on the composition have been unobtainable, a similar battery with the same amount lithium has been used for the study (1) (3).

5.2.4 Fuel cell powered cell phone charger

The charger is currently under development, and the present composition has been evaluated. The efficiency of the charger is approx. 48%, including electronic losses, leakage and heat losses in the fuel cell.

5.2.5 NaBH4, sodium borohydride

Sodium borohydride is one of the energy carriers examined in the study. When reacting with water, it oxidizes to $NaBO_2$ (Borax) and hydrogen (4), which is used in the fuel cell.

5.2.6 AlGaInSn

Prof. Jerry Woodall et al. at Perdue University has developed an alloy of aluminum, gallium, indium and tin that, when in contact with water, oxidizes the aluminum to aluminum oxide, which produces hydrogen (6). This is then used in the fuel cell.

5.2.7 Functional unit

The functional unit of the study is *Wh of electricity emitted from the charger*, as this production is the purpose of the products.

5.2.8 System boundaries

The LCA-data originates from the projects BUWAL250, ETH-ESU 1996, IDEMAT 2001 (all three in SimaPro) and ”Life cycle analysis of fuel, 1996” by Magnus Blinge et al. (CPM database). Therefore, the boundaries in these systems are used in addition to the ones stated below.

5.2.8.1 Boundaries in relation to natural systems

In most cases material has been regarded as produced from virgin material, but platinum and aluminum has been including average recycled material. In some cases recycling has later been simulated by reducing the emissions and raw material demands. The chemical processes of producing sodium borohydride have been considered closed, which means inputs to one part of the process can be filled with outputs, or waste, from other parts of the process.

The study includes emissions to air, soil and water, as well as resource depletion and effects to the biosphere. Waste treatment has been considered, but since no hazardous materials are included it has not been incorporated, with the exception of recycling.

5.2.8.2 Geographical boundaries

Since raw materials are to a very large degree exported throughout the world, average world production data has been used. The same perspective has been used for environmental impact. However, electricity and heat production has been based on European average data.

5.2.8.3 Time boundaries

The goal has been to use LCA-data previously entered in SimaPro and CPM, since the project is limited and it is not possible to conduct the necessary LCAs during its course. Prizes and similar information has been based on numbers from 2008, but most information is from 1996, 2001 and 2003. In all cases, data as recent as possible has been used when deemed reliable.

5.2.8.4 Boundaries within the technical system

Tools, machinery and other real capital have not been included except in the study, with the exception of them being included in some LCAs used. Allocation methods are similarly as described for the LCA-projects described under 3.2.2. In the cases allocation has been needed to be made outside of this, it has been based on weight and value of the product.

Packaging has not been included in the study.

5.2.9 Choice of environmental parameters

The environmental parameters are slightly different depending on method chosen (see 5.2.5), but contain the use of resources, energy consumption and emissions to air, soil and water.

5.2.10 Choice of methods for aggregation and evaluation

There are several different weighting methods to choose from when a LCA is to be performed. Two has been chosen, differentiating from each other both in time and thinking.

5.2.10.1 CML 2001, version 2.04, World 1990

CML 2001 is a LCA methodology developed by the Center of Environmental Science of Leiden University (10). In the method it is possible to see all impact categories from Ecoinvent 2.0[1], altogether 50 categories. Of these, eight has been chosen;

- Abiotic/resource depletion
- Acidification
- Eutrophication
- Global warming 100a
- Human toxicity 100a
- Freshwater aquatic toxicity 100a
- Marine aquatic ecotoxicity 100a
- Photochemical oxidation

These have been chosen to get a spread of environmental impacts, and the time frame has been chosen to be 100 years as many emissions effect the environment for substantially more than 20 years. The benefits of including long term effects have been estimated to outweigh the uncertainties that grow larger the longer time frame used, e.g. what the environment will look like by then.

This methodology considers the potential damage emissions could have according to their properties, e.g. toxic potential to humans, and thereby getting the characterization factor used to show their contribution to the impact categories. One of the basic problems, still limiting the success of CML Methodology is practical applicability. The CML method does not offer an unambiguous solution to the problem of final valuation (11). The impact categories have therefore been valuated as of equal importance in this report for the purpose to produces a final “score” that is comparable between different processes and products.

5.2.10.2 EPS 2000, version 2.03

The EPS system is mainly aimed to be a tool for a company's internal product development process, and has been evolved with the usefulness as highest priority.

It assigns emissions and resources to impact categories when actual effects are likely to occur in the environment, based on likely exposure (12). Therefore potentially toxic

---

[1] Ecoinvent 2.0 is a database for science-based, industrial, international life cycle assessments, supplying transparent life cycle inventory (LCI) data of known quality (18).

emissions can be assigned low values because of the low probability that emissions of dangerous levels will be emitted. Empirical, equivalency and mechanistic models are used to calculate default characterization factors, used to calculate the environmental impact of emissions and raw material depletion in the impact category.

The impact categories are divided amongst five safe guard subjects;

- Human health proliferate
    - Life expectancy, expressed in Years of life lost (person year)
    - Severe morbidity and suffering, in person year, including starvation
    - Morbidity, in person year, like cold or flue
    - Severe nuisance, in person year, which would normally cause a reaction to avoid the nuisance
    - Nuisance, in person year, irritating, but not causing any direct action
- Ecosystem production capacity
    - Crop production capacity, in kg weight at harvest
    - Wood production capacity, in kg dry weight
    - Fish and meat production capacity, in kg full weight of animals
    - Soil acidification, or base cat-ion capacity, in H+ mole equivalents (used only when models including the other indicators are not available)
    - Production capacity of (irrigation) water, in kg which is acceptable for irrigation, with respect to persistent toxic substances
    - Production capacity of (drinking) water, in kg of water fulfilling WHO criteria on drinking water
- Abiotic stock resource
    - Depletion of elemental or mineral reserves and depletion of fossil reserves
- Biodiversity
    - Extinction of species, expressed in Normalized Extinction of species (NEX)
- Cultural and recreational values
    - Changes in cultural and recreational values are difficult to describe by general indicators as they are highly specific and qualitative in nature.

Because of low importance and difficulty of defining factors, production capacity of irrigation and drinking water, as well as cultural and recreational values, has not been included in the study.

In the EPS default method, weighting is made through valuation. Weighting factors represent the willingness to pay to avoid changes. The environmental reference is the present state of the environment. The indicator unit is ELU (Environmental Load Unit).

5.2.11 Strategy for gathering data

Data has primarily been gathered from SimaPro, a LCA software including a number of databases. A cut-off criteria has been used, eliminating all parameters that affect the characterization less than 5% according both methods chosen. It has been documented in MS Excel.

Some information has been obtained through published reports, books and by asking persons involved in the products by email or telephone.

6 Inventory Analysis

The inventory analysis includes data collection and calculations to quantify relevant in- and outputs of the system. It also includes creating flowcharts of the systems in question. The inventory results are shown in appendix 1.

6.1 Flowcharts

The first step of the inventory analysis is to examine what materials and activities that are included in the system investigated. With this knowledge a flowchart of the system can be constructed, to more clearly describe what is included in the LCA. The waste treatment is included in the flowcharts to give a better perception of the system, but is not included in the LCA.

6.1.1 Energizer® L91 battery

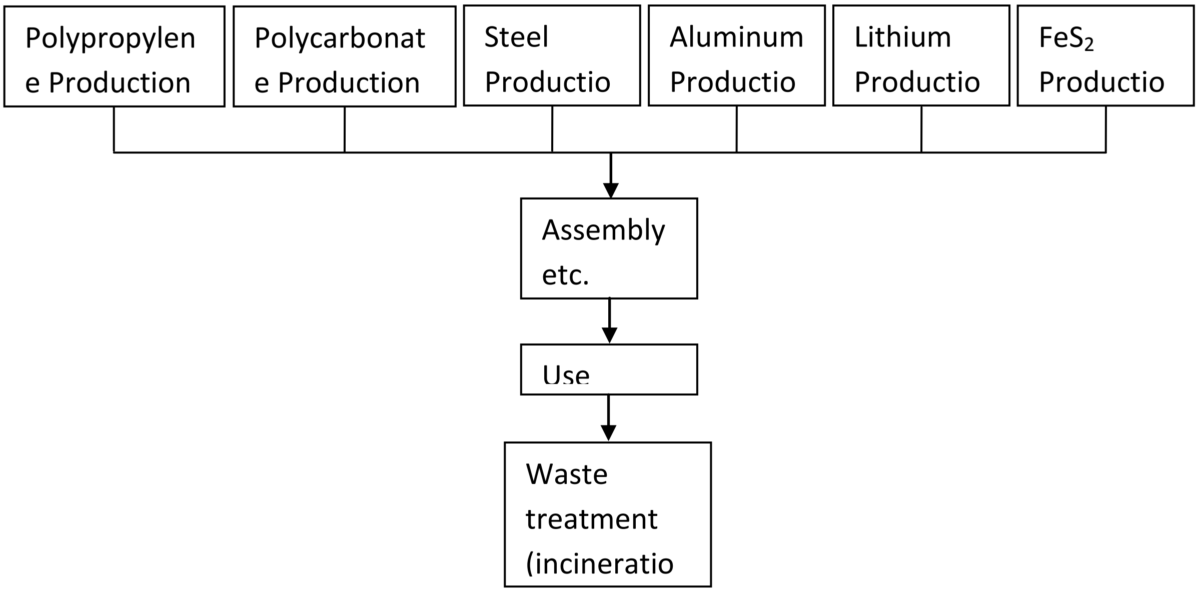


Figure 6.1. Flowchart of Energizer L91 battery life cycle (1) (3).

6.1.2 Fuel cell powered charger

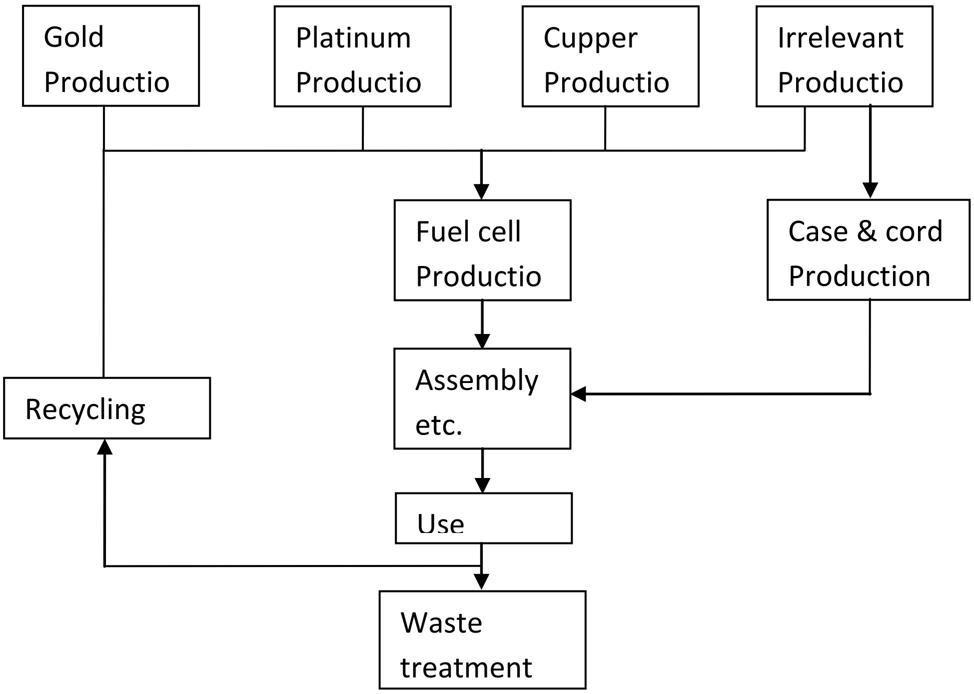


Figure 6.2. ***Flowchart of fuel cell powered fuel cell cell phone.***

6.1.3 Sodium Borohydride (NaBH4)

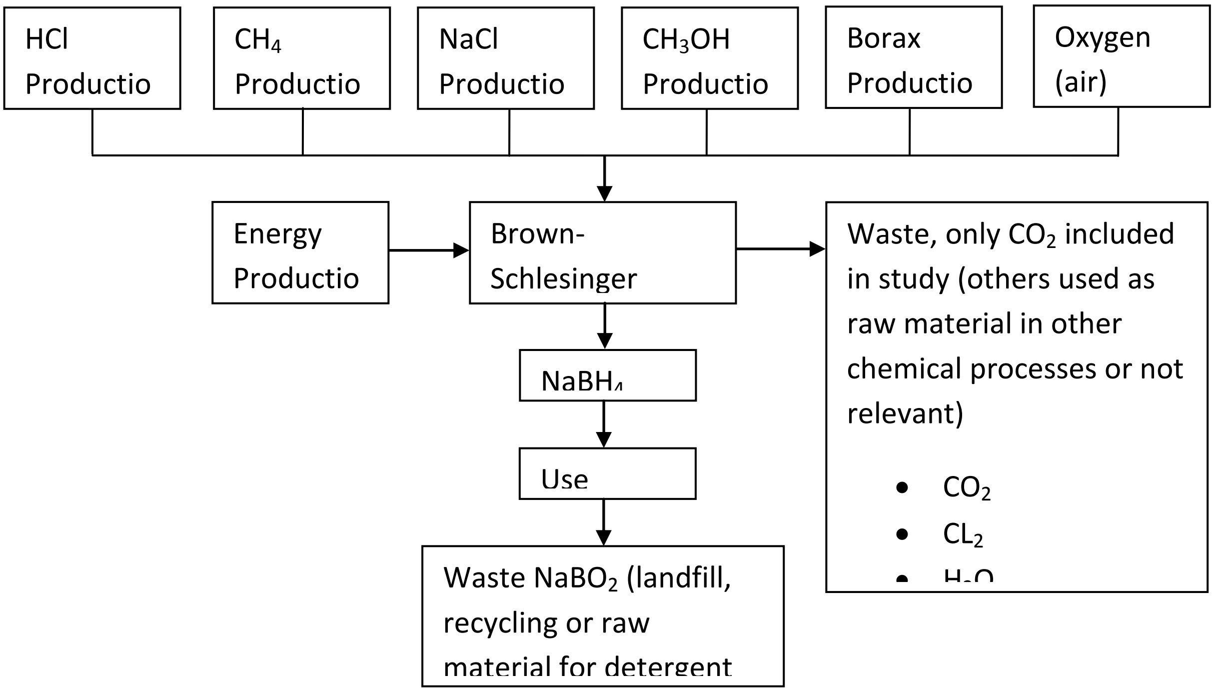


Figure 6.3. Flowchart of sodium borohydride life cycle (4) (14).

6.1.4 Aluminum-alloy (AlGaInSn)

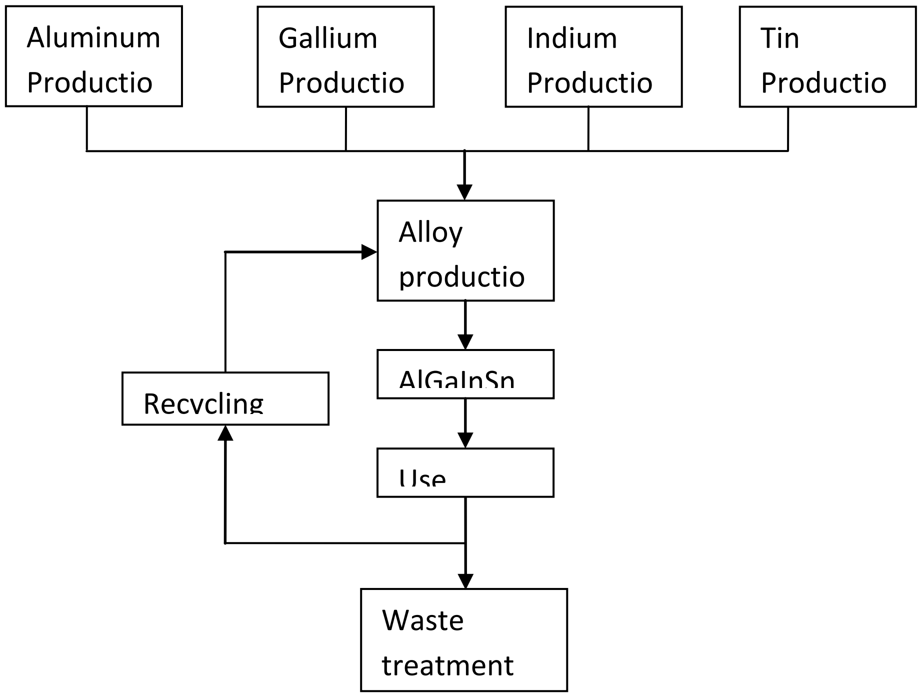


Figure 6.4. Flowchart of Al-alloy life cycle (6).

6.2 Production of energy carrier

The level of recycling is very important for the environmental impact of the energy carrier. It generally takes less energy to recycle a product than it takes to start from the cradle (extracting raw materials through mining etc.). There are statistics on battery recycling (13), and the same numbers are used on the Al-alloy (70 % recycling) since it is used in the same way as small batteries. Small size lithium batteries are currently not recycled but incinerated (emissions and energy obtained from this have not been included in the study). The borax-waste from sodium borohydride can be recycled, but is a stable compound that does not change in the environment, and can be used to produce detergent and soap. Since numbers on borax recycling has not been obtainable, and since the compound is common and not important to the LCA, is has been excluded.

6.2.1 Production of 1.5V lithium batteries (AA)

As far as could be established, only two companies presently (2009-03-24) have production of AA lithium batteries. The battery whose performance was measured by Anders Lundblad was produced by Energizer®. However, as information on the production or even the composition of their battery was not given, the battery produced by Great Power Battery CO., Ltd of China was used for composition information (table 6.1). The two batteries have the exact same performance registered, and the same amount of lithium (0,98g). Information on the production process has not been found here either, and is therefore not included in the study.

Table 6.1. Composition of lithium AA battery (3). The "organic solvent" is likely polycarbonate, and has been included as such. Unfortunately data of emissions during lithium production has not been found, but energy requirements for production of LiCl have been obtained. This, as well as the energy required to produce Li from LiCl, have been included in the LCA.

Substance	Percentage	Weight (g)
FeS_2	34,4	4,99
Lithium	6,2	0,90
Organic solvent	14,8	2,15
Lithium salt	1,6	0,23
Polypropylene	2,3	0,33
Steel	32,9	4,77
Aluminum	7,8	1,13
Total	100	14,5

6.2.2 Production of sodium borohydride ($NaBH_4$)

Sodium borohydride is a reducing agent used in a number of industrial processes, including paper pulp bleaching and wastewater treatment. It has been extensively researched for storing energy in the form of hydrogen, to be used in fuel cells. In November 2007 an independent review panel recommended the US Department of Energy to seize funding research for $NaBH_4$ as a fuel for fuel cell powered cars (14). This is obviously a setback for the technology and will probably have the effect that prices will stay at the present level, while at least a reduction of one order of magnitude would be necessary for a wide implementation as a storage medium of hydrogen (14). There are several ways to produce $NaBH_4$ under development, but presently the Brown-Schlesinger process is the standard. This consists of seven steps (4):

1. Steam reforming of methane to make hydrogen ($CH_4 + O_2 \rightarrow 2H_2 + CO_2$)
2. Electrolysis of sodium chloride to make sodium metal ($2NaCl \rightarrow 2Na + Cl_2$)
3. Refining of borax to make boric acid ($Na_2[B_4O_5(OH)_4]\cdot 8H_2O + 2HCl \rightarrow 2NaCl + 5H_2O + 4B(OH)_3$)
4. Converting boric acid to trimethylborate with methanol ($B(OH)_3 + 3CH_3OH \rightarrow B(OCH_3)_3 + 3H_2O$)
5. Reaction of sodium metal and hydrogen to make sodium hydride ($2Na + H_2 \rightarrow 2NaH$)

6. Combining sodium hydride and trimethylborate to make sodium borohydride ($4NaH + B(OCH_3)_3 \rightarrow NaBH_4 + 3NaOCH_3$)
7. Recycling sodium methoxide by-product to methanol ($2NaOCH_3 + H_2O \rightarrow 2NaOH + CH_3OH$)

Emissions relating to losses during the Brown-Schlesinger process are not included, but the emissions created when producing the substances needed for the process are.

6.2.3 Production of aluminum-alloy mix

No information on the production has been obtained. In this case mixing the metals in a molten state is probably the easiest method to get an even mix throughout the alloy. It is not included in the study.

6.3 Production of chargers

Not included in the study, since the difference of environmental impacts between the Energizer and the fuel cell powered charger (with the exception of the fuel cell) are considered too small to affect the results. The production of the fuel cell have not been included due to difficulty attaining information about this, especially since it is presently only in the development phase.

6.4 Transports

No transportation included in the study, since a similar distribution network is assumed.

7 Inventory results

Presented in Appendix 1.

8 Impact Assessment

Classification and characterization has been performed in a single step. Substances can contribute to different impact categories. As already mentioned in 5.2.10, the impact assessment methods used are very different, and except for abiotic/resource depletion there is no way of directly comparing them to each other until the total environmental impact has been added up. Therefore the characterization numbers have not been compared between the methods. The numbers presented are per Wh electricity charged capacity in the cell phone batteries.

The impact is added up by multiplying the emission weight with the emissions characterization factor. This shows how many kg of a common denominator is needed to reach the same impact as one kg of the substance of a substance, i.e. for global warming “kg CO_2 eq./kg”. The impact category result is then expressed as kg of this denominator.

8.1 CML 2001, Classification and characterization

8.1.1 Abiotic depletion

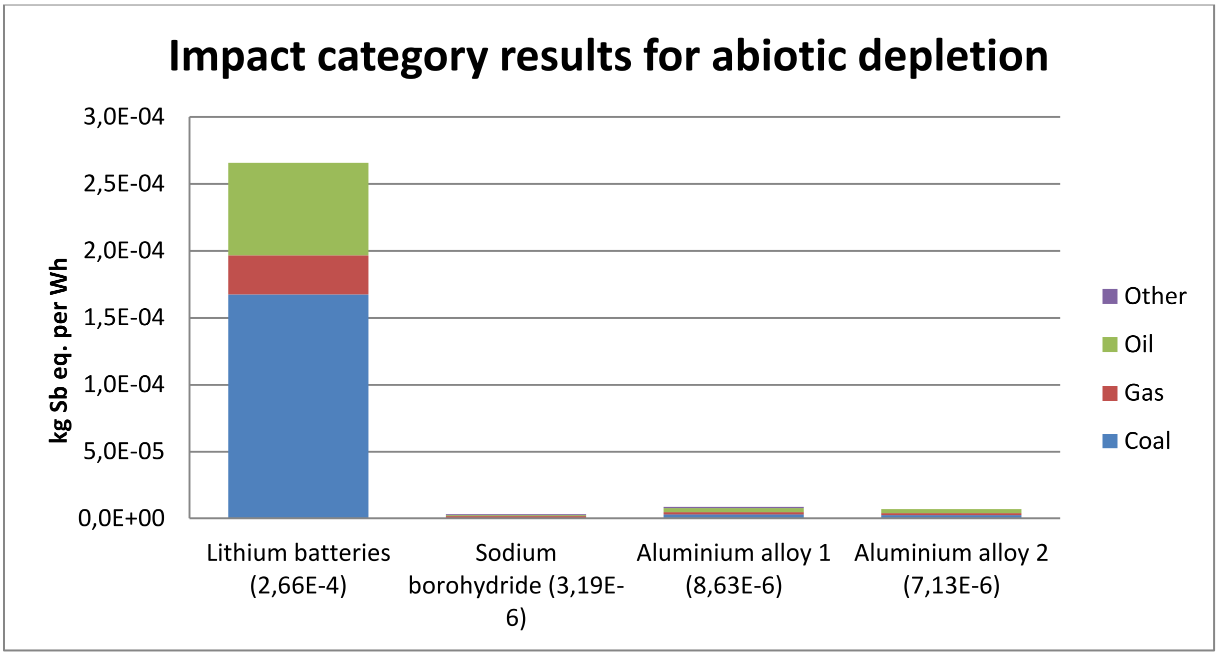


Figure 8.1. The compounds potential for abiotic/resource depletion is formulated as "kg Sb eq. per Wh". All compounds are converted to a comparable amount of Antimony (Sb), because the need to compare different substances to each other demands a common denominator. The valuation is based on concentration reserves and rate of deaccumulation.

In the case of abiotic depletion, fossil fuel use constitutes the bulk of the depletion with the exceptions of 20% impact from Borax in the NaBH4 and 11% impact from Indium and Tin. The true results might be slightly different because of allocation methods for the Al-alloys and since no losses in the Brown-Schlesinger process during NaBH4 are included. There is however no doubt Lithium would still have a considerably larger impact, mainly because of the energy needed to produce Lithium.

It is clear that metal depletion is not considered very important in this case. In the case of the fuel cell charger fossil fuels constitute 87% of the abiotic depletion, while gold constitutes 12%. The amount of platinum is too small to have an impact according to the CML-method. The impact of the charger is 1,58E-3 kg Sb eq, approximately the same as six Wh extracted from lithium batteries.

8.1.2 Acidification

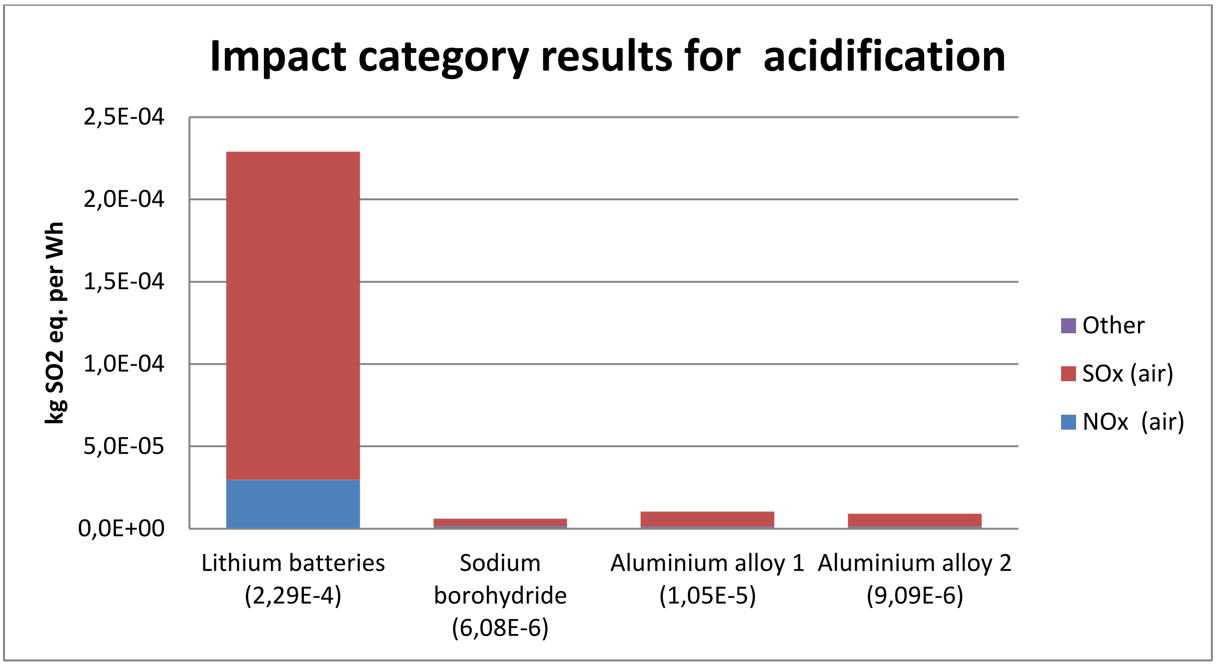


Figure 8.2. All acidifying pollutants form H+ ions, and the unit for a substances acidic potential is "kg SO_2 eq. per Wh".

The major acidifying pollutants are SO_2, NO_X, HCl and NH_3. In this case no HCl or NH_3 are included, although HCl might have a slight influence on $NaBH_4$ since it is used in the production process, which is here calculated without losses. Acidification can occur in several different forms, from acid rain to fallout of dry acidic particles and aerosols which are converted to acids when dissolving in contact with surface water or moist tissues (e.g. in lungs).

Impacts of acidification range from fish mortality in lakes and leaching of toxic metals from soil and rocks, to damage to forests, buildings and coral reefs (9).

In this study, the main contributors for the Li-batteries are lithium production, for $NaBH_4$ the production of HCl and NaCl and for the Al-alloy the production of aluminum.

The impact of the charger is 9,19E-3 kg SO_2 eq, 40 times higher than that of one Wh of electricity from the Li-batteries. The main causes of acidification from the charger are, for NO_X energy for gold production, and for SO_X the platinum production. Gold production might have higher numbers, but no data is available to confirm this.

8.1.3 Eutrophication

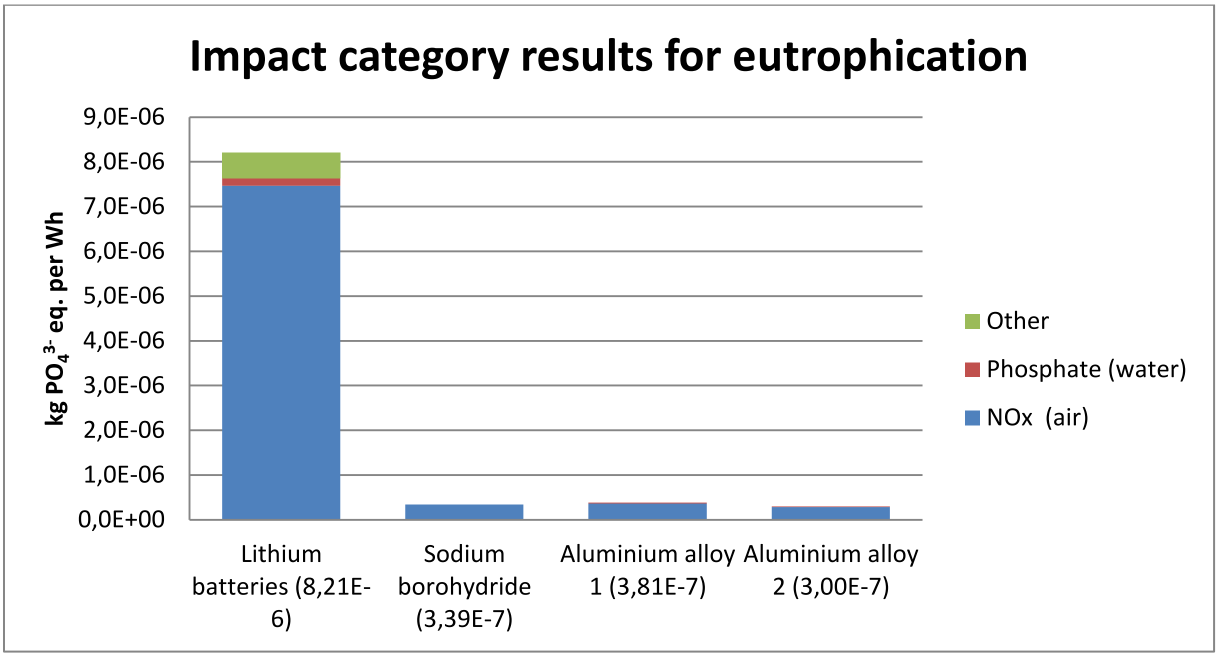


Figure 8.3. Eutrophication potential is expressed as "kg PO_4^{3-} eq. per Wh".

According to Baumann and Tillman (8), eutrophication is generally associated with the environmental impacts of excessively high levels of nutrients that lead to shifts in species composition and increased biological productivity, for example as algal blooms. Actual eutrophication varies greatly geographically, but to simplify the model the geographical variation has been disregarded which means the potential reflect maximum eutrophying effect of a substance, simulating that all airborne nutrients end up in aquatic systems.

The main causes of eutrophication are: for Li-batteries, energy for lithium production; for $NaBH_4$, NaCl production and for Al-alloy, aluminum production.

The fuel cell charger impact is 1,83E-5 kg PO_4^3- eq, which is approximately twice as large as the impact of a Wh electricity from Li-batteries. The energy demand for gold production is the main cause.

8.1.4 Global Warming (100 years)

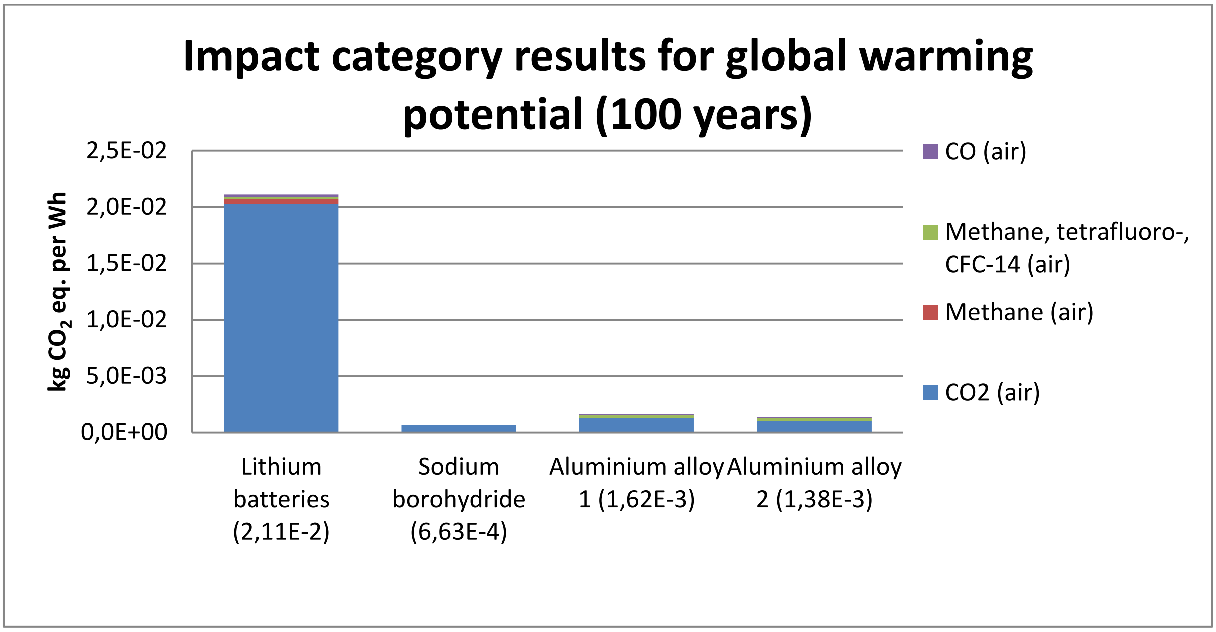


Figure 8.4. Global warming potential is expressed as "kg CO_2 eq per Wh".

Characterization of greenhouse gases (GHG) is based on the capacity to absorb infrared radiation and thereby heat the atmosphere (8). There are many gases that contribute to climate change, e.g. methane, CFCs and N_2O. They are also much more efficient at absorbing heat, but may not be as commonly known since the emissions of these gases are much smaller than that of CO_2. The characterization factors for GHG are developed by the Intergovernmental Panel on Climate Change (IPCC) (9). GWP is often calculated on different time perspectives since the GHG have different effects over time. A time perspective of 100 years has been used in this study.

The main causes of pollution is; for Li-batteries, energy for lithium production; for $NaBH_4$, output of CO_2 from Brown-Schlesinger process and for the Al-alloy, aluminum production.

The fuel cell charger impact is 7,22E-2 kg CO_2 eq, which is approximately three times as large as the impact of one Wh electricity from Li-batteries. The energy demand for gold production is the main cause of emission.

8.1.5 Human Toxicity (100 years)

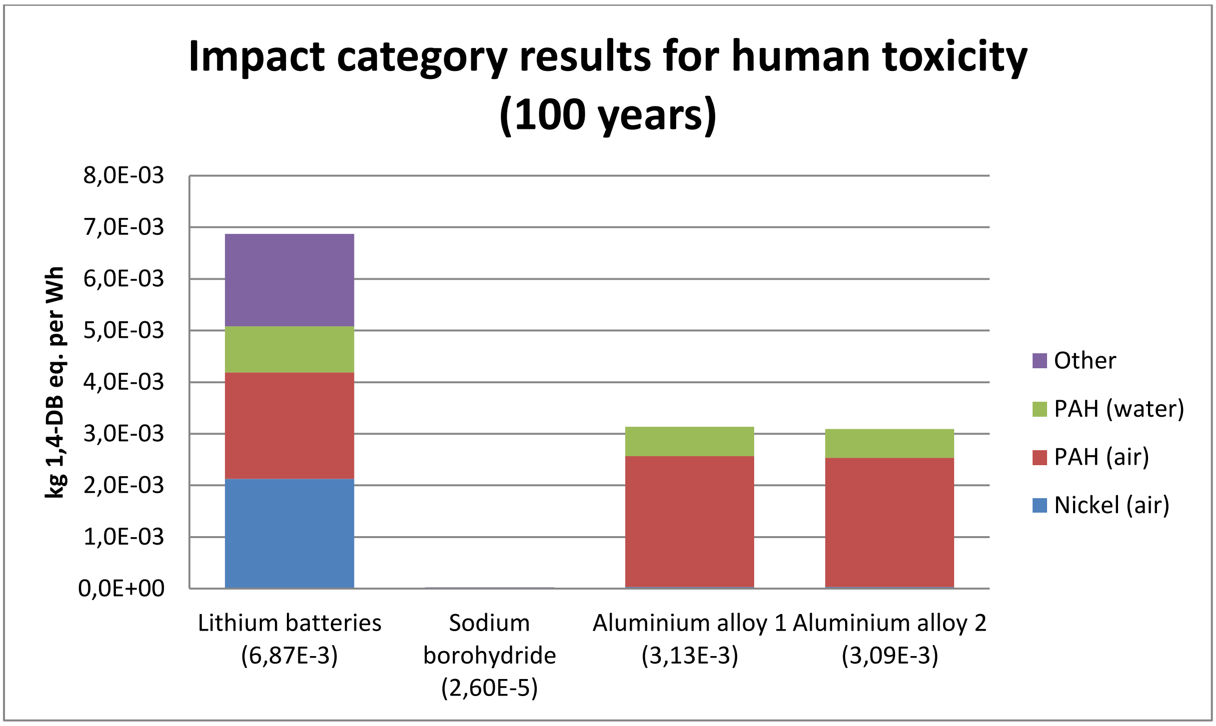


Figure 8.5. Human toxicity is expressed as "kg 1,4-DB eq. per Wh".

The human toxicity characterization factors, expressed as Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon (8). For each toxic substance HTP's are expressed as kg 1,4-dichlorobenzene equivalent/ kg emission.

The main causes of pollution is; for Li-batteries, energy for lithium production and aluminum production; for $NaBH_4$, HCl- and NaCl-production and for the Al-alloy, aluminum production.

The fuel cell charger impact is 4,84E-2 kg 1,4-DB eq, which is approximately seven times as large as the impact of one Wh electricity from Li-batteries. The platinum production is the major cause of emission (mainly copper and nickel to air).

8.1.6 Freshwater aquatic ecotoxicity (100 years)

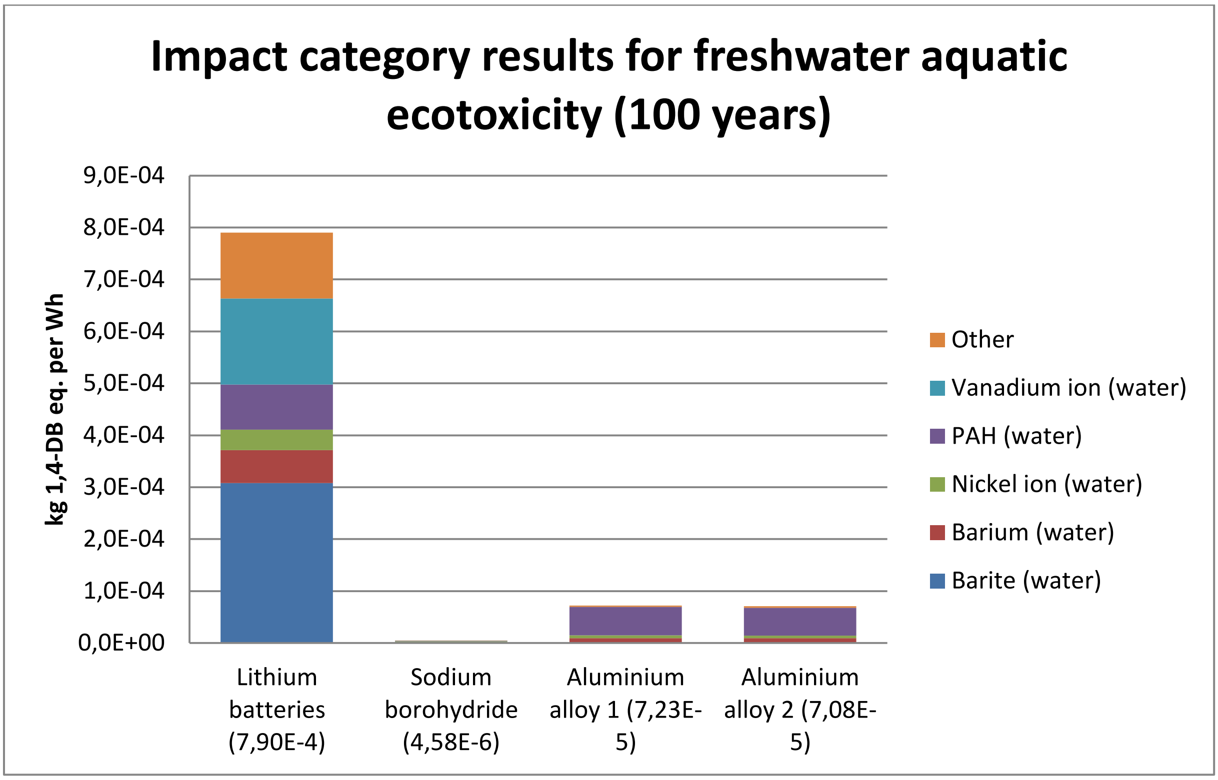


Figure 8.6. Freshwater aquatic exotoxicity is expressed as “kg 1,4-DB eq. per Wh”.

Just as in human toxicity, the freshwater aquatic ecotoxicity is expressed as kg 1,4-dichlorobenzene equivalent/ kg emission (8).

The main causes of pollution is; for Li-batteries, energy for lithium production; for $NaBH_4$, NaCl production and energy for the Brown-Schlesinger process, and for the Al-alloy, aluminum production.

The fuel cell charger impact is 5,05E-3 kg 1,4-DB eq, which is approximately six times as large as the impact of one Wh electricity from Li-batteries. Platinum production and the energy demand for gold production is the major causes of emissions (mainly nickel ion and vanadium ion emissions to water).

8.1.7 Marine aquatic ecotoxicity (100 years)

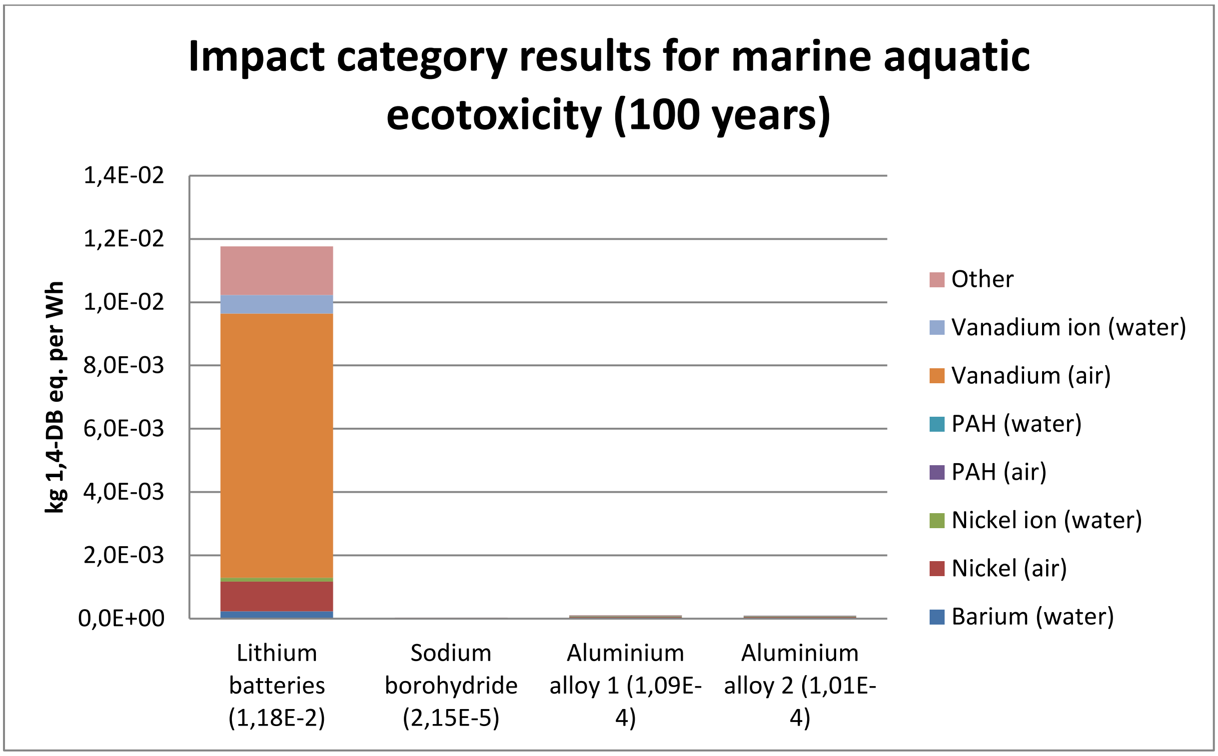


Figure 8.7. Marine aquatic ecotoxicity is expressed as "kg 1,4-DB eq. per Wh".

Similar to the freshwater aquatic ecotoxicity, the marine aquatic ecotoxicity is expressed as kg 1,4-dichlorobenzene equivalent/ kg emission (8).

The main causes of pollution is; for Li-batteries, energy for lithium production; for $NaBH_4$, HCl-, NaCl-production and energy for the Brown-Schlesinger process, and for the Al-alloy, aluminum production.

The fuel cell charger impact is 6,26E-2 kg 1,4-DB eq, which is approximately five times as large as the impact of one Wh electricity from Li-batteries. Platinum production is the major cause of emissions (mainly copper and nickel emissions to air).

8.1.8 Photochemical oxidation

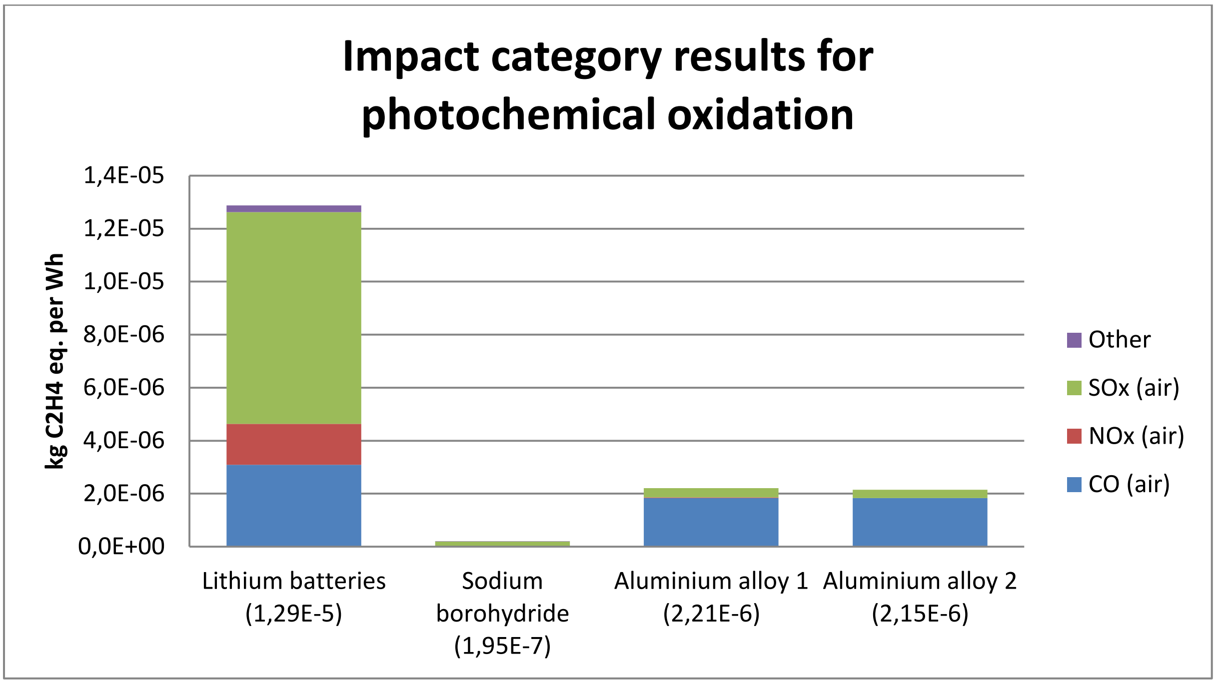


Figure 8.8. Photochemical oxidation is expressed as "kg $C2H_4$ eq per Wh".

Photo-oxidants are secondary pollutants formed in the lower atmosphere in presence of sunlight, mainly from NO_X and hydrocarbons (8). Because of this photochemical smog is more common during summertime. Photochemical smog is a known cause of health problems like irritation to respiratory systems and damage to vegetation. Therefore, the cost of smog to the agricultural community is substantial.

The main causes of emissions are; for Li-batteries, energy for lithium production; for $NaBH_4$, HCl- and NaCl-production, and for the Al-alloy, aluminum production.

The fuel cell charger impact is 3,66E-4 kg $C2H_4$ eq, which is approximately 28 times as large as the impact of one Wh electricity from Li-batteries. Platinum production is the major cause of emissions (mainly SO_X to air).

8.2 EPS 2000, Classification and characterization

8.2.1 Human Health

8.2.1.1 Life expectancy

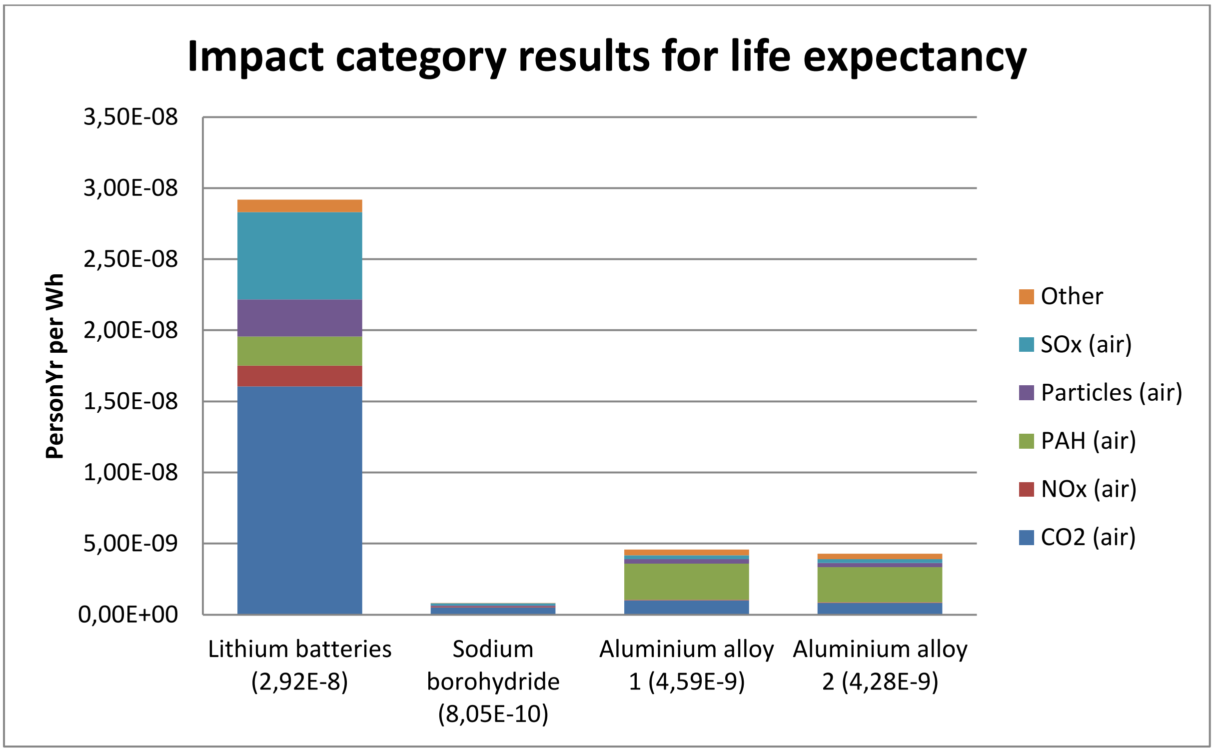


Figure 8.9. Life expectancy expressed in Years of life lost (person year) per Wh.

8.2.1.2 Severe morbidity

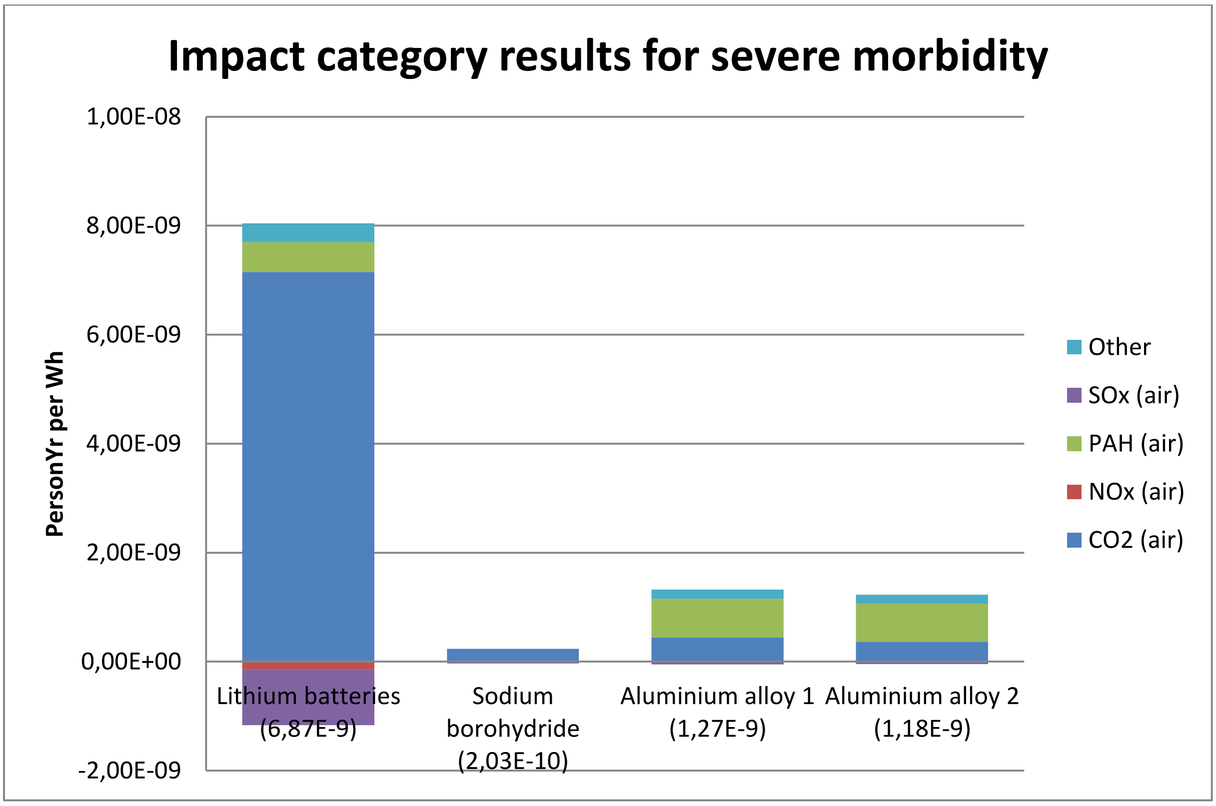


Figure 8.10. Severe morbidity and suffering, in number of Person years per Wh. This includes starvation and serious illness.

8.2.1.3 Morbidity

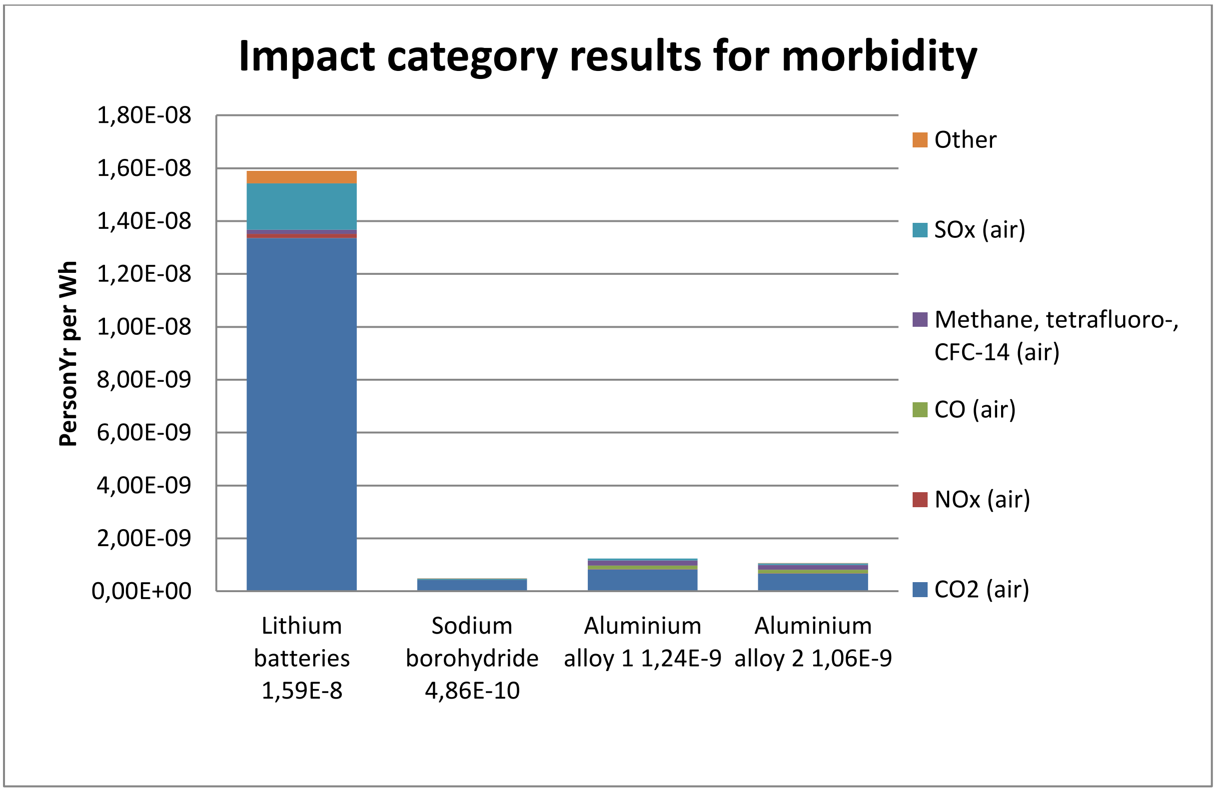


Figure 8.11. Morbidity, in Person years per Wh. Includes things as having a cold or a flue.

8.2.1.4 Severe nuisance

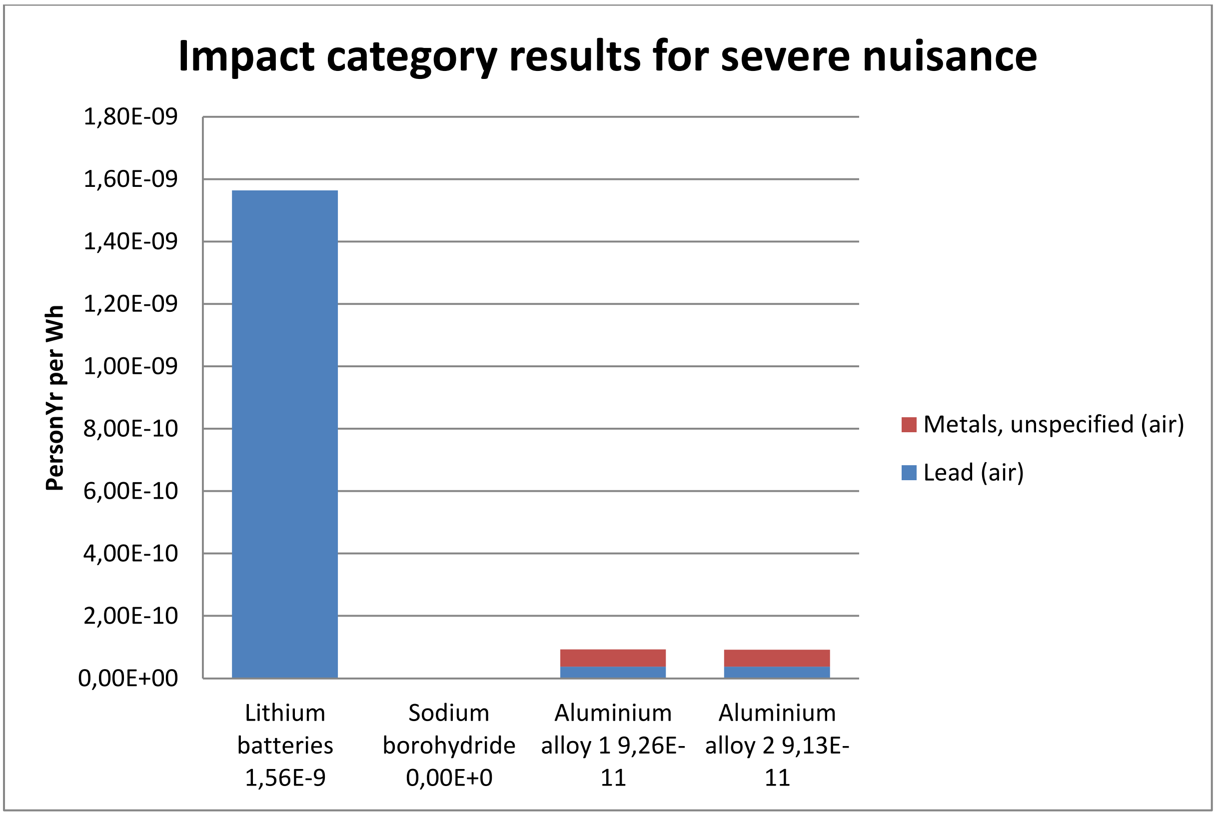


Figure 8.12. Severe nuisance, in person years per Wh. This includes things which would normally cause a reaction to avoid the nuisance.

8.2.1.5 *Nuisance*

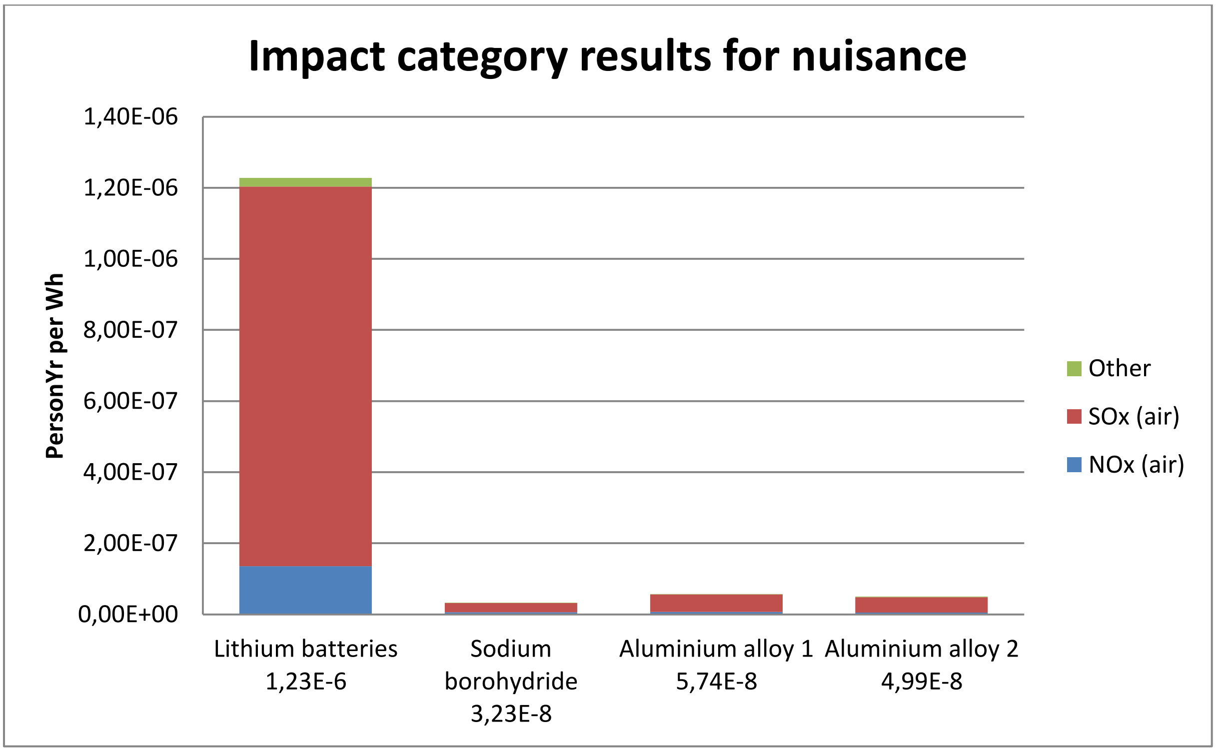


Figure 8.13. Nuisance, in person years per Wh. This includes things that are irritating, but not enough to cause any direct action.

8.2.1.6 *Discussion*

Human health is defined as follows (12):

- Life expectancy, expressed in Years of life lost (person year)
    - Li-battery (2,92E-8 PersonYr/Wh), main cause energy for lithium production.
    - Sodium borohydride (8,05E-10 PersonYr/Wh), main causes HCl-production and output of CO_2 from Brown-Schlesinger process.
    - Al-alloy 1 (4,59E-9 PersonYr/Wh), main cause aluminum production.
    - Al-alloy 2 (4,28E-9 PersonYr/Wh), main cause aluminum production.
    - Fuel cell powered charger (3,52E-7 PersonYr/ Charger, approx. 12 times higher than for one Wh electricity from Li-batteries), main cause platinum production and the energy demand for gold production.
- Severe morbidity and suffering, in person year, including starvation. Worth noticing here is that NO_X and SO_X have positive effects to this category.
    - Li-battery (6,87E-9 PersonYr/Wh), main cause energy for lithium production.
    - Sodium borohydride (2,03E-10 PersonYr/Wh), main causes HCl-production (positive) and output of CO_2 from Brown-Schlesinger process (negative).
    - Al-alloy 1 (1,27E-9 PersonYr/Wh), main cause aluminum production.
    - Al-alloy 2 (1,18E-9 PersonYr/Wh), main cause aluminum production.
    - Fuel cell powered charger (-2,4E-8 PersonYr/ Charger, this means it has a positive effect in this category), main positive cause SO_X-emissions from

  - platinum production and main negative cause CO_2-emissions from the energy demand for gold production.
- Morbidity, in person year, like cold or flue
  - Li-battery (1,59E-8 PersonYr/Wh), main cause energy for lithium production.
  - Sodium borohydride (4,86E-10 PersonYr/Wh), main causes HCl-production and output of CO_2 from Brown-Schlesinger process.
  - Al-alloy 1 (1,24E-9 PersonYr/Wh), main cause aluminum production.
  - Al-alloy 2 (1,06E-9 PersonYr/Wh), main cause aluminum production.
  - Fuel cell powered charger (1,25E-7 PersonYr/ Charger, approx. eight times higher than for one Wh electricity from Li-batteries), main cause platinum production and the energy demand for gold production.
- Severe nuisance, in person year, which would normally cause a reaction to avoid the nuisance
  - Li-battery (1,56E-9 PersonYr/Wh), main cause energy for lithium production.
  - Sodium borohydride (0 PersonYr/Wh)
  - Al-alloy 1 (9,26E-11 PersonYr/Wh), main cause aluminum production.
  - Al-alloy 2 (9,13E-11 PersonYr/Wh), main cause aluminum production.
  - Fuel cell powered charger (2,29E-9 PersonYr/ Charger, approx. 47% higher than for one Wh of electricity from Li-batteries), main cause copper and platinum production.
- Nuisance, in person year, irritating, but not causing any direct action
  - Li-battery (1,23E-6 PersonYr/Wh), main cause energy for lithium production.
  - Sodium borohydride (3,23E-8 PersonYr/Wh), main causes HCl- and NaCl-production.
  - Al-alloy 1 (5,74E-8 PersonYr/Wh), main cause aluminum production.
  - Al-alloy 2 (4,99E-8 PersonYr/Wh), main cause aluminum production.
  - Fuel cell powered charger (4,94E-5 PersonYr/Charger, approx. 40 times higher than for one Wh of electricity from Li-batteries), main cause platinum production.

8.2.2 Ecosystem production capacity

Defines how the biological production capacity is affected of emissions.

8.2.2.1 *Crop growth capacity*

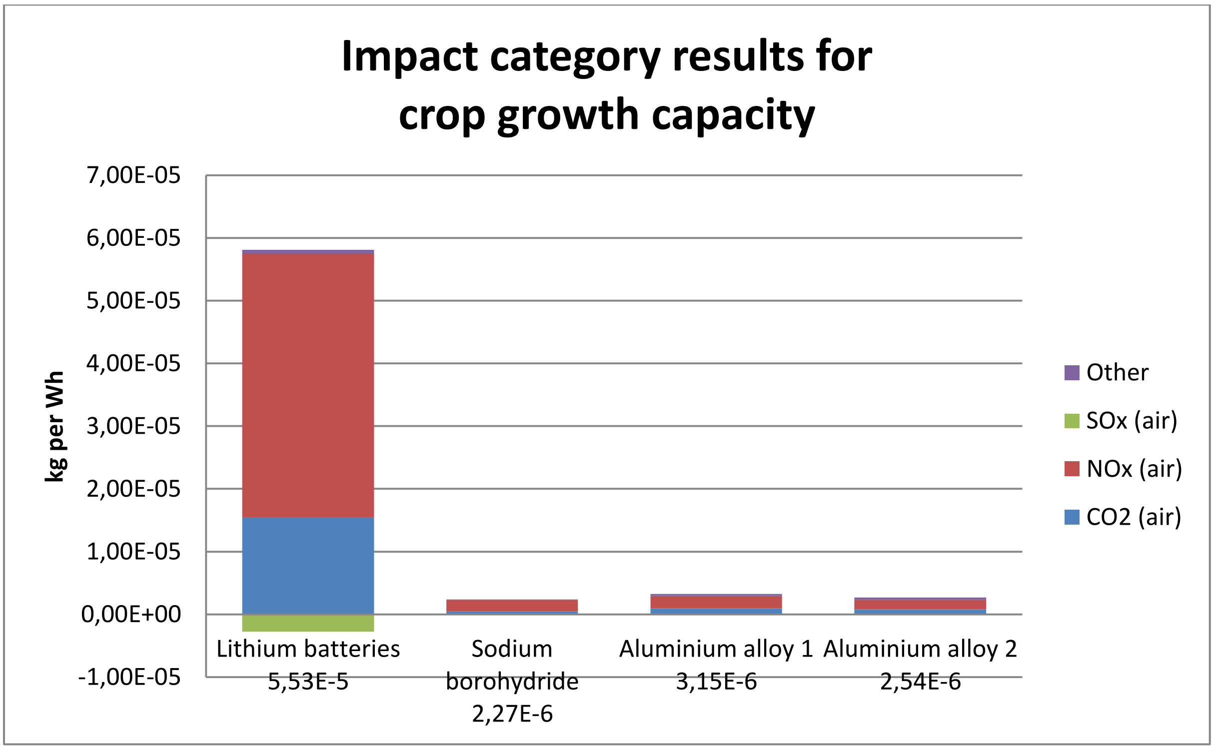


Figure 8.14. Crop production capacity, in kg lost weight at harvest per Wh

8.2.2.2 *Wood growth capacity*

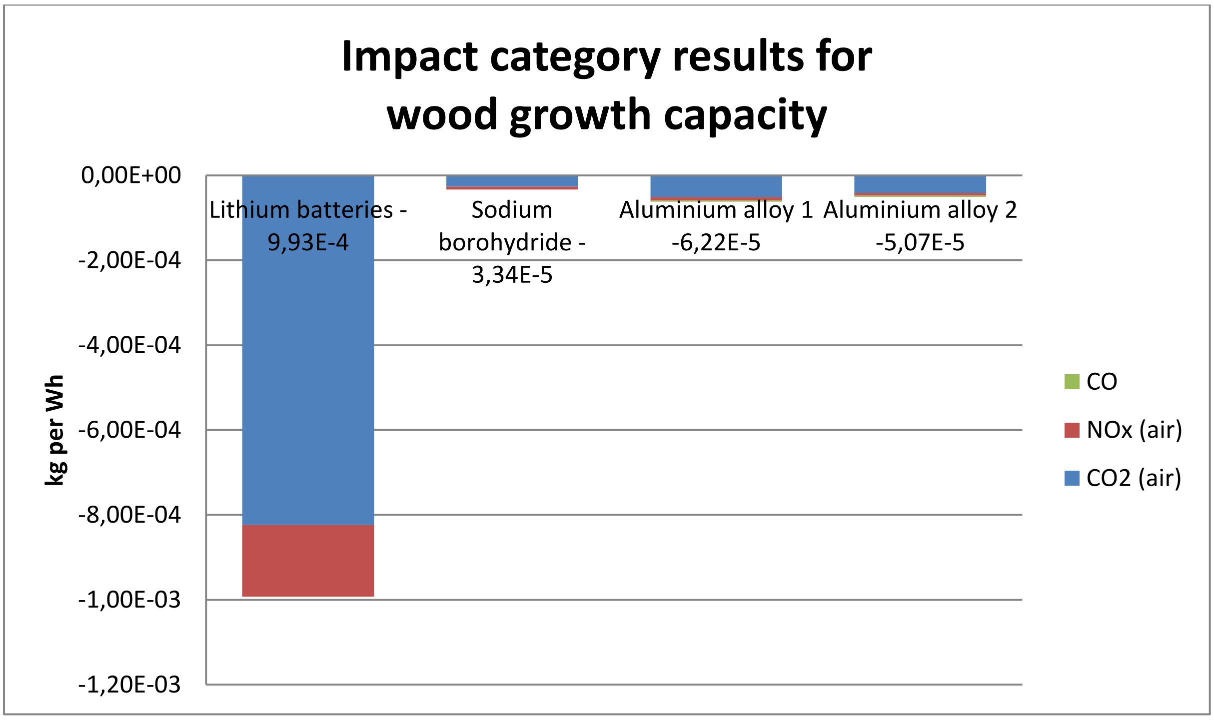


Figure 8.15. Wood production capacity, in kg dry weight lost per Wh.

8.2.2.3 Fish and meat production

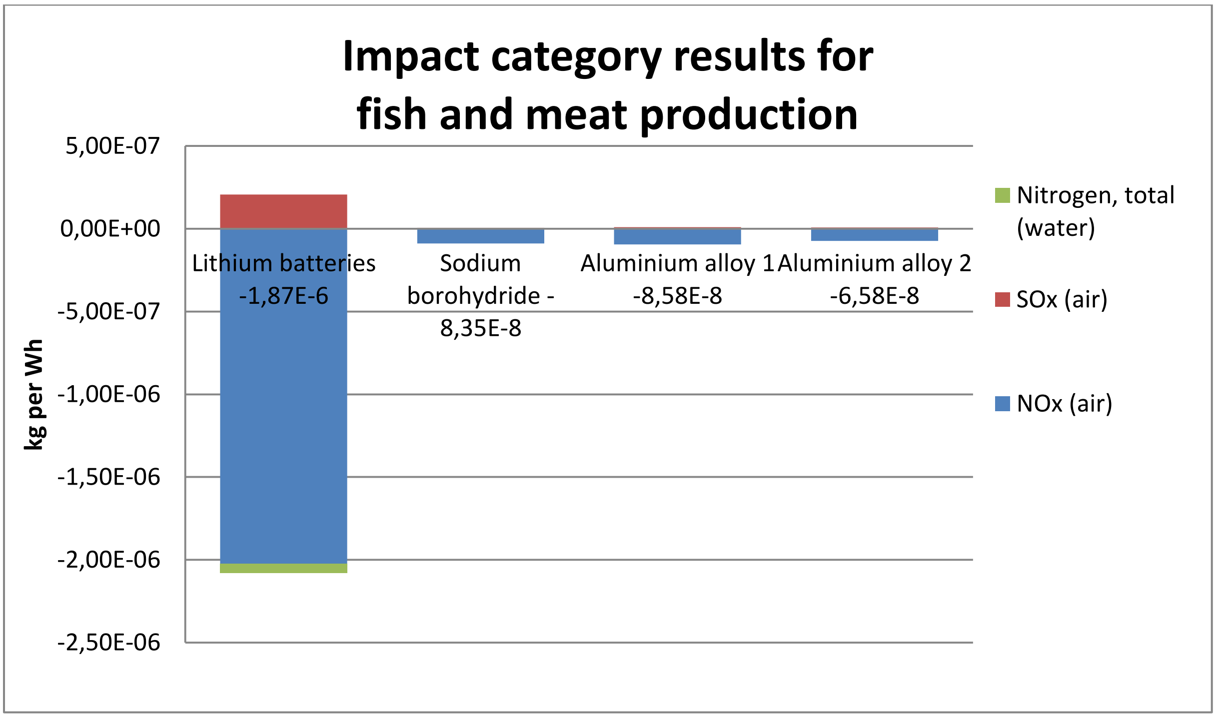


Figure 8.16. Fish and meat production capacity, in kg full weight of animals lost per Wh.

8.2.2.4 Soil acidification

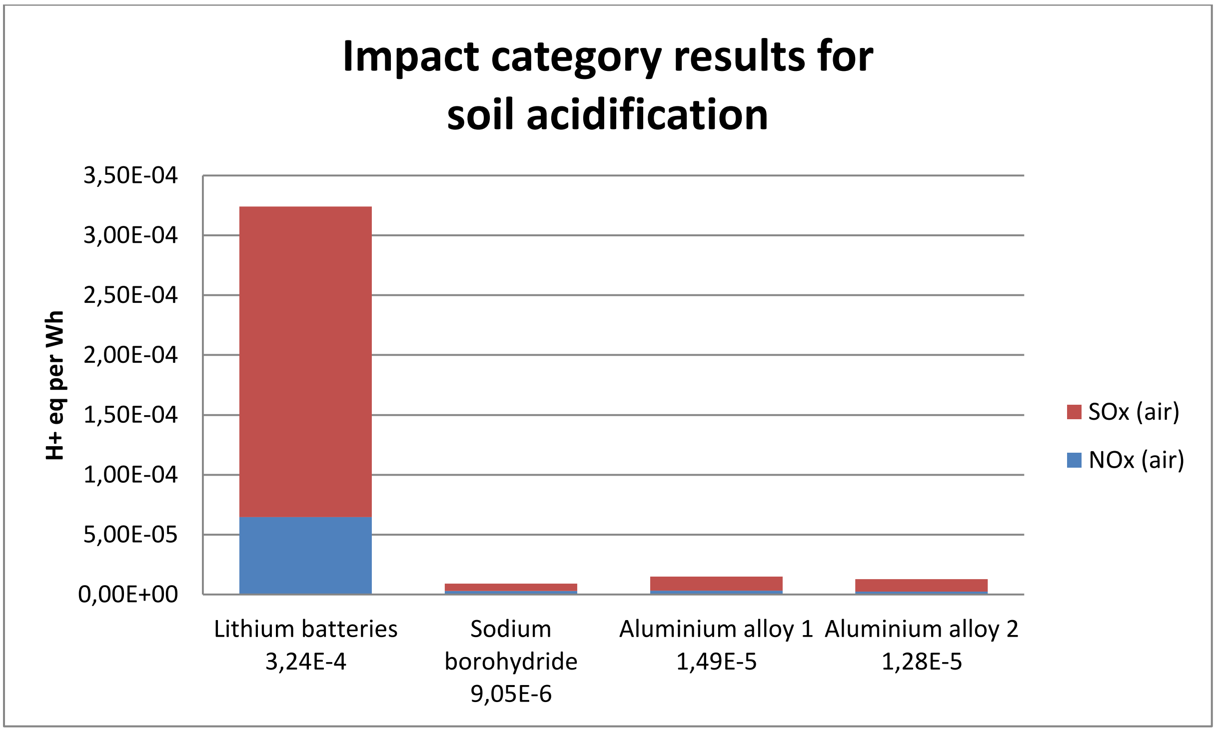


Figure 8.17. Soil acidification or Base cat-ion capacity, in H+ mole equivalents per Wh.

8.2.2.5 Discussion

Production capacity of ecosystems is defined as follows (12):

- Crop production capacity, in kg weight at harvest (worth noticing SO_X has a positive effect)
    - Li-battery (5,53E-5 kg/Wh), main cause energy for lithium production.
    - Sodium borohydride (2,27E-6 kg/Wh), main causes NaCl-production and CO_2 output from Brown-Schlesinger process.
    - Al-alloy 1 (3,15E-6 kg/Wh), main cause aluminum production.
    - Al-alloy 2 (2,54E-6 kg/Wh), main cause aluminum production.
    - Fuel cell powered charger (4,89E-5 kg/Charger), main positive cause platinum production and main negative cause energy for gold production. Total effect positive.
- Wood production capacity, in kg dry weight
    - Li-battery (-9,93E-4 kg/Wh), main cause energy for lithium production.
    - Sodium borohydride (-3.34E-5 kg/Wh), main causes NaCl-production and CO_2 output from Brown-Schlesinger process.
    - Al-alloy 1 (-6,22E-5 kg/Wh), main cause aluminum production.
    - Al-alloy 2 (-5,07E-5 kg/Wh), main cause aluminum production.
    - Fuel cell powered charger (-3,20E-3 kg/Charger), main cause energy for gold production.
- Fish and meat production capacity, in kg full weight of animals
    - Li-battery (-1,87E-6 kg/Wh), main cause energy for lithium production.
    - Sodium borohydride (-8,35E-8 kg/Wh), main positive cause HCl-production and main negative cause NaCl-production.
    - Al-alloy 1 (-8,58E-8 kg/Wh), main cause aluminum production.
    - Al-alloy 2 (-6,58E-8 kg/Wh), main cause aluminum production.
    - Fuel cell powered charger (4,77E-6 kg/Charger), main positive cause platinum production and main negative cause energy for gold production.
- Soil acidification or Base cat-ion capacity, in H+ mole equivalents (used only when models including the other indicators are not available)
    - Li-battery (3,24E-4 H+ eq/Wh), main cause energy for lithium production.
    - Sodium borohydride (9,05E-6 H+ eq/Wh), main positive cause HCl-production and main negative cause NaCl-production.
    - Al-alloy 1 (1,49E-5 H+ eq/Wh), main cause aluminum production.
    - Al-alloy 2 (1,28E-5 H+ eq/Wh), main cause aluminum production.
    - Fuel cell powered charger (1,2E-2 H+ eq/Charger, approx. 37 times higher than for one Wh electricity from Li-batteries), main cause platinum production.

8.2.3 Abiotic stock resource

8.2.3.1 *Depletion of reserves*

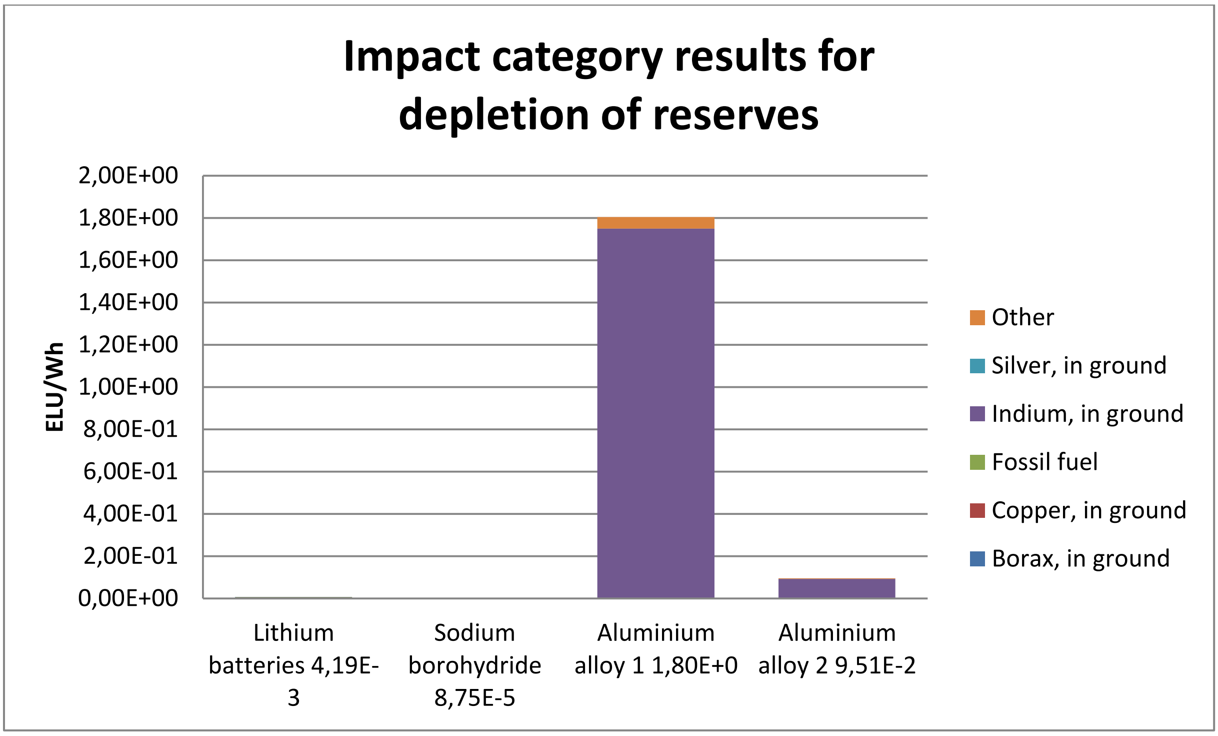


Figure 8.18. The indicator unit is ELU (Environmental Load Unit) per Wh. As mentioned in chapter 5.2.5.2 the weighting factors represent the willingness to pay to avoid changes from the present state of the environment.

8.2.3.2 *Discussion*

Abiotic stock resource indicators are depletion of elemental or mineral reserves and depletion of fossil reserves (12). The depletion for the different energy carriers are as follows:

- Li-battery (4,19E-3 ELU/Wh), main cause fossil fuel depletion during lithium production.
- Sodium borohydride (8,75E-5 ELU/Wh), mainly from borax use in the Brown-Schlesinger process and fossil fuel use during NaCl-production.
- Al-alloy 1 (1,80E+0 ELU/Wh), main cause indium depletion.
- Al-alloy 2 (9,51E-2 ELU/Wh), main cause indium depletion.

The depletion for the fuel cell powered charger is 1,64E+1 ELU/Charger, approx. 3900 times higher than for one Wh of electricity from Li-batteries. The main cause is platinum depletion (84%) and gold depletion (16%).

8.2.4 Biodiversity

8.2.4.1 Species extinction

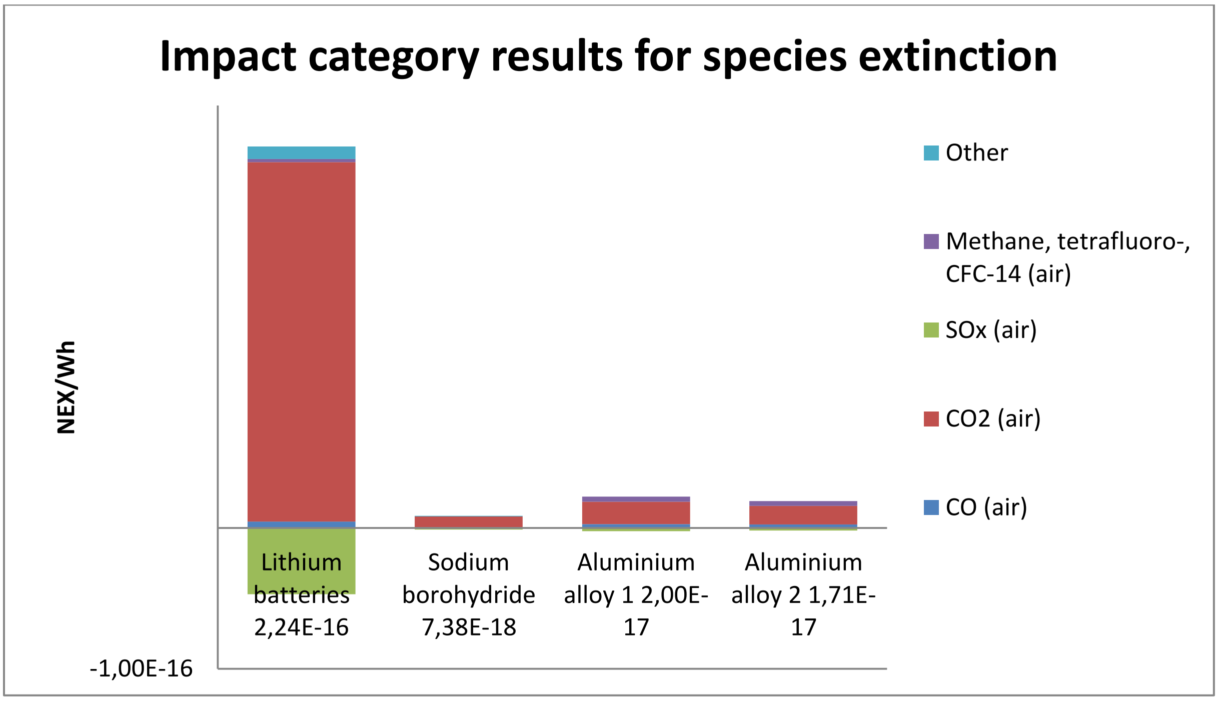


Figure 8.19. Species extinction expressed in Normalized Extinction of species (NEX) per Wh.

8.2.4.2 Discussion

Default impact category for biodiversity is extinction of species, expressed in Normalized Extinction of species (NEX) (12) per Wh. The species extinction for the different energy carriers are as follows:

- Li-battery (2,24E-16 NEX/Wh), main cause energy for lithium production.
- Sodium borohydride (7,38E-18 NEX/Wh), main cause HCl-production (SO_X) and CO_2 output from Brown-Schlesinger process.
- Al-alloy 1 (2,00E-17 NEX/Wh), main cause aluminum production.
- Al-alloy 2 (1,71E-17 NEX/Wh), main cause aluminum production.

The species extinction for the fuel cell powered charger is -1,3E-15 NEX/Charger. The main positive cause is platinum depletion (SO_X) and the main negative cause is energy for gold production (CO_2).

8.3 Sensitivity analysis

In any process, the losses decide how economical and environmentally sustainable it is. So also here, and with a higher recycling rate the results here would look different. The recycling rate used is 80 % for the charger[2] and as already mentioned 70 % for the alloys. The batteries and borax-waste is not recycled.

8.3.1 CML 2001

In the CML the consumption of energy to refine lithium to batteries are the critical issue. The use of oil and coal releases SO_X, CO_2 and Vanadium as air emissions, which increase acidification, global warming and photochemical oxidation (see appendix 1). If the batteries could be recycled instead the emissions would go down substantially. With a recycling rate of 70 % for the batteries the number of Wh produced by the fuel cell powered charger to make it the preferred environmental option would go up more than 300%, to about 30Wh instead of 9Wh. However, this is approximately 8 charges and not very hard to obtain. The results according to the CML-method are therefore representable; even if the number of charges for equal environmental impact may vary it will remain below 10.

8.3.2 EPS 2000

In the EPS-method the abiotic depletion is weighed considerably higher than in the CML-method.

For the aluminum alloys this means >99 % if the environmental impact is due to the depletion of Induim (97 %), Gallium (1 %) and Tin (1 %). This with a recycling rate of 70 %. Even with a recycling rate of 95 %, the impact of these three still represent 96 % of the impact. This would, however, still mean that the alloy with the least environmental impact, alloy number two, had more than twice as high (212 %) impact as the batteries per Wh of electricity. This can therefore never be preferred in the EPS method, as the impact caused by the charger would never be caught up by the impact of the lithium batteries.

The Sodium borohydride has 2.4 % of the impact the Lithium batteries have, calculated per Wh. However, the fuel cell in the charger has an impact equivalent to 2144 Wh being extracted from lithium batteries (approx. 715 charges). This means 2197 Wh (approx. 732 charges) needs to be extracted before the lithium batteries becomes the worse alternative. The fuel cell is the only part of the fuel cell powered charger included in the LCA, and the bulk of the impact from this comes from platinum (83 %), Gold (16 %) and Cupper (1 %), these three cause 99.75 % of the impact. The recycling rate used is 80 %, if this would be increased to 95 % the impact would be reduced with three quarters. This means only 550 Wh needs to be uploaded (equivalent to approx. 183 charges) for the fuel cell powered charger, when using the energy carrier sodium borohydride, to have a smaller

---

[2] Recycling of small batteries in Sweden is 70 % (13), and recycling of PET-bottles and aluminum cans are 88 % respective 91 % (12). Since recycling of the chargers would be in a considerably smaller volume than that of bottles and cans, an 80 % recycling rate has been estimated.

environmental impact than the charger powered by lithium batteries. Other way around, if the fuel cell powered charger only have a 50 % recycling rate 5492 Wh (approx. 1830 charges) needs to be uploaded before having a smaller impact than the lithium battery powered charger.

These numbers are far too high for the fuel cell powered charger to be advantageous for a normal consumer. A phone is usually charged less than 100 times per year, and to exclusively use this charger is not very likely as the cost with lithium batteries or sodium borohydride is likely to be considerably higher than electricity from a socket. And even with 95 % recycling rate for the fuel cell powered charger it has an impact 20 times higher than using a wall socket.

9 Conclusions

Since two different methods are used for the impact assessment and weighting, the results of both has to be considered. In this chapter this is done, in addition to comparing the battery powered Energizer charger against the fuel cell powered charger with its different options for energy carrier.

9.1 Overview

9.1.1 CML 2001

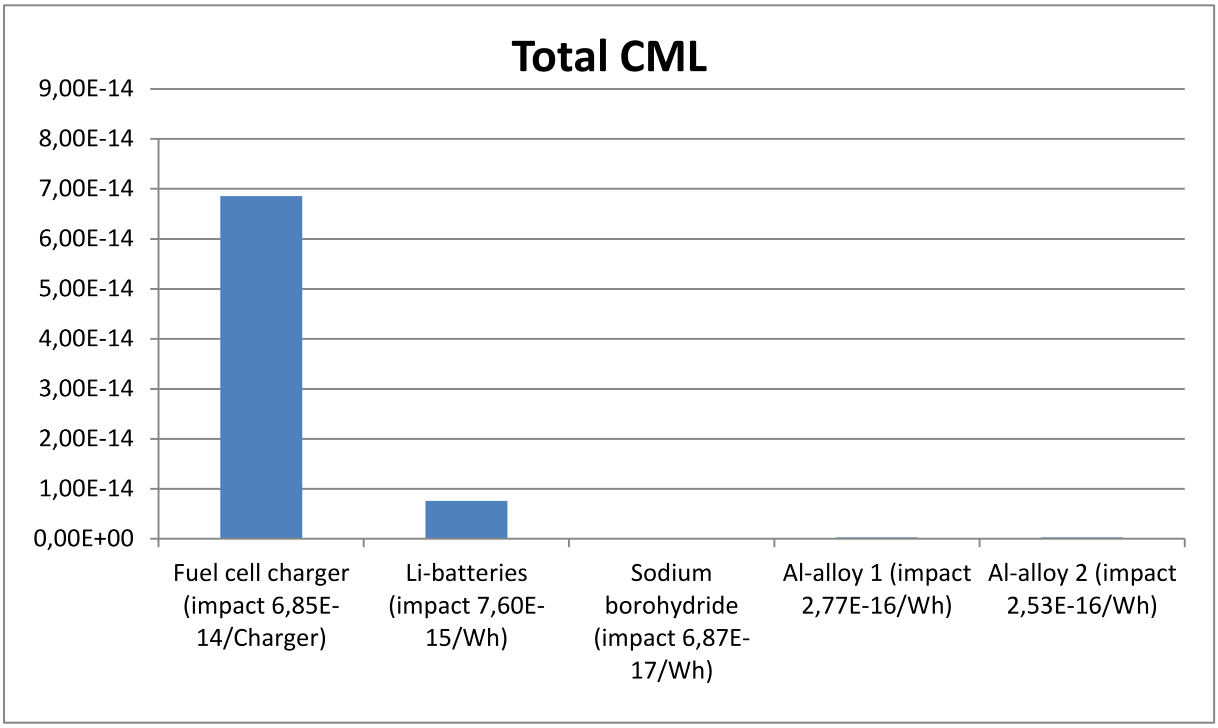


Figure 9.1 Total CML weight per charger or Wh.

As visible in the graph, the starting impact of the fuel cell charger is considerable larger than the impact of lithium batteries, per Wh. However, it is also visible that the lithium batteries have a larger impact than the energy carriers used by the fuel cell charger.

This means that at a certain amount of Wh discharged from the chargers, the environmental impact will be the same (see Figure 9.1). The quantity of Wh is different depending on which energy carrier used, since the impact/Wh are different between the three.

After this point of equal environmental impact the environment would benefit from the use of the fuel cell charger instead of the battery charger, according to the results from the CML 2001 method.

9.1.2 EPS 2000

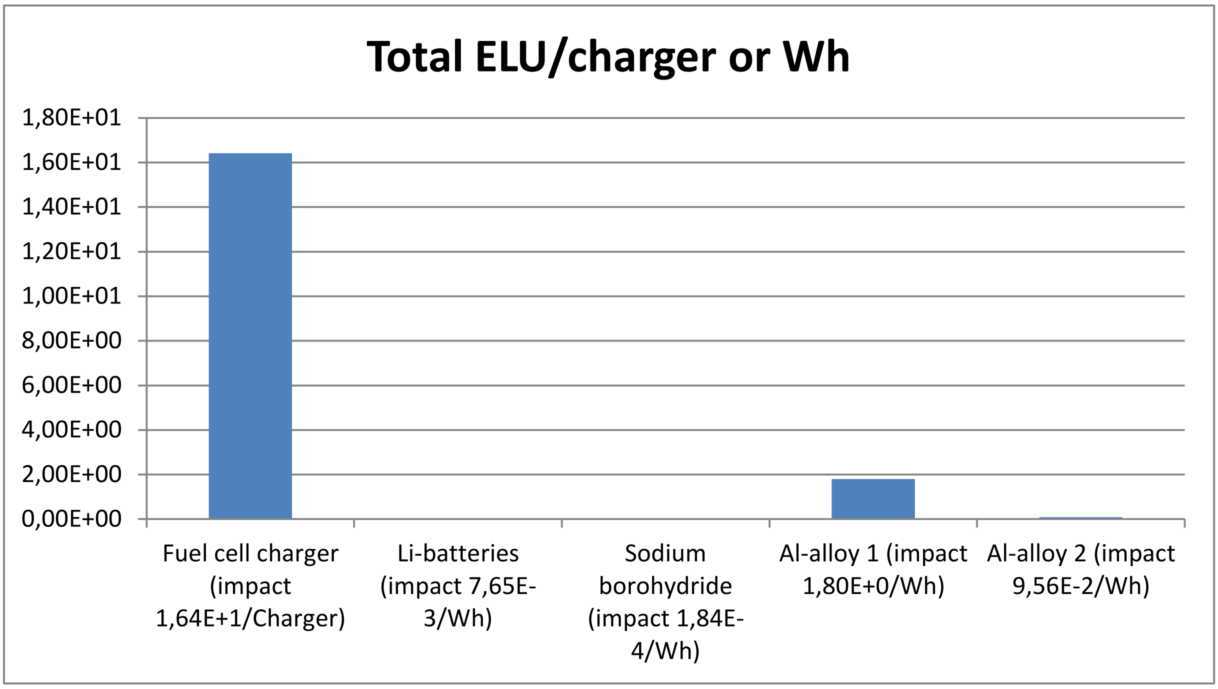


Figure 9.2 ELU per charger or Wh.

As visible in the Figure 9.2 above, like with the CML method, the fuel cell charger has a considerably larger environmental impact than any of the energy carriers. It is also clear that both aluminum alloys have a larger ELU/Wh than the lithium batteries. This means the gap between the battery charger and the fuel cell charger with an aluminum alloy as energy carrier increases with every Wh discharged from the charger. It is therefore not environmentally sound to use the aluminum alloy as energy carrier.

It is, on the other hand, also apparent the sodium borohydride has a lower ELU/Wh than the lithium batteries. This means that with enough use of a charger, the battery charger and the fuel cell charger will have the same total ELUs. The exact number of Wh needed to reach this equal ELU is stated in table 9.1.

9.2 Impact categories contribution to the total environmental impact

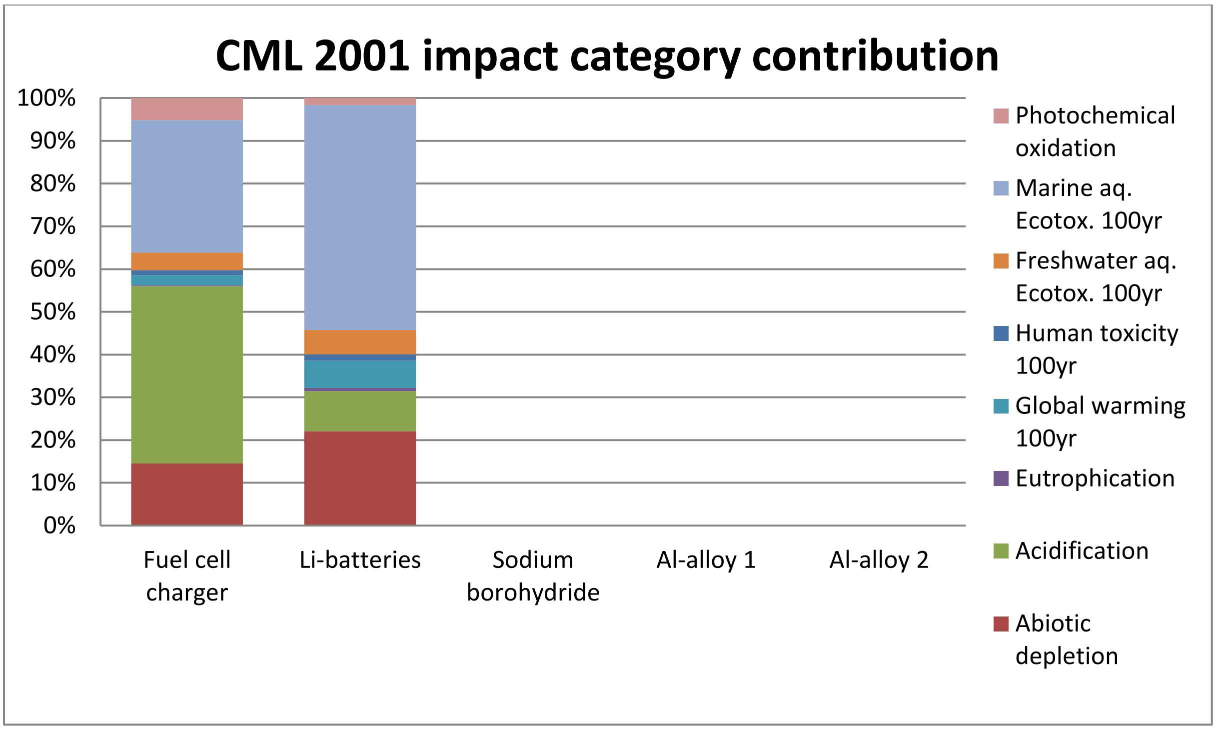


Figure 9.3 Contribution from different impact categories to the total environmental impact.

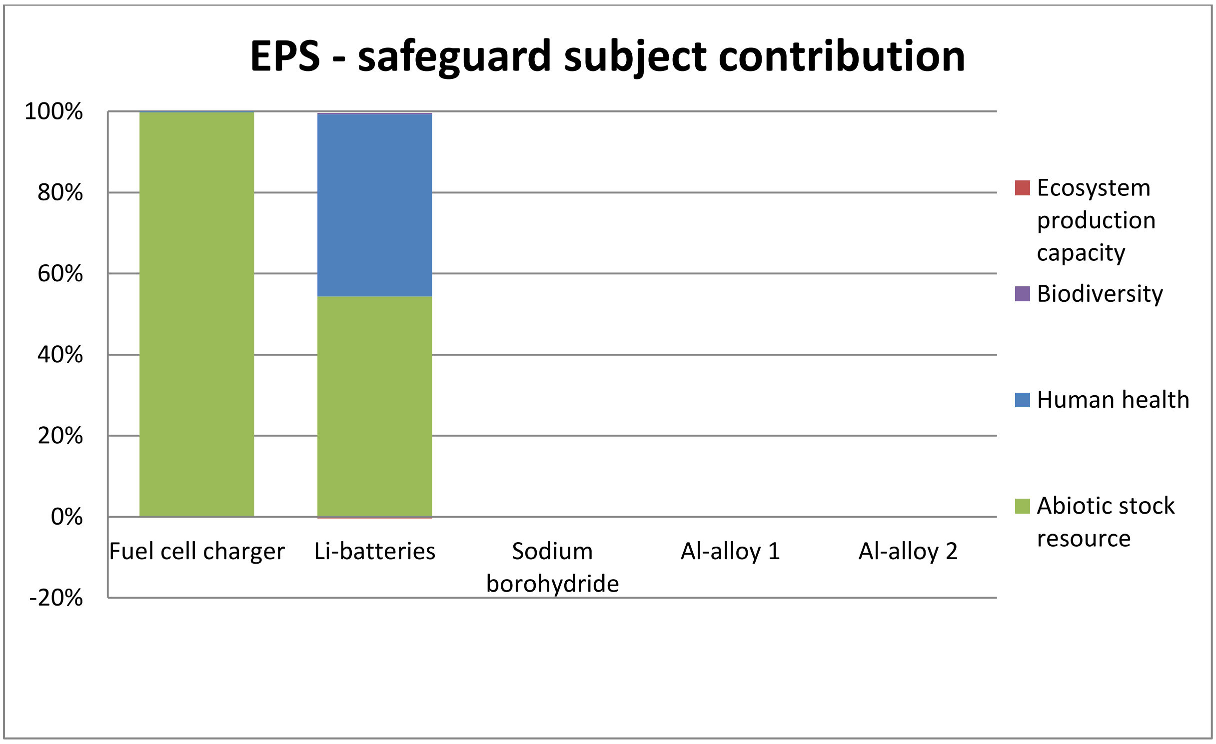


Figure 9.4 Contribution from safeguard subjects to the total environmental impact.

As shown in Figure 9.3 and **Figure 9.4** above, the impact according to the CML method is spread between many impact categories, while the EPS method value the abiotic stock depletion very high, in two cases together with human health. The reason the fuel cell charger and the aluminum alloys have such a high impact from the resource depletion in the EPS method is the economic value of rare metal depletion. This is further discussed in 8.3.1 and 8.3.2.

9.3 Impact contributions from substances

9.3.1 Impact contributions to the fuel cell

Since the chargers are considered equal in impact with the exception of the fuel cell in the fuel cell powered charger, there is not a comparison between the chargers. The environmental impact of the fuel cell therefore causes a starting impact for the fuel cell charger which the battery powered charger does not have. The impact of the charger in comparison to the energy carriers is shown in 9.1.1 and 9.1.2, and the causes of environmental impact are shown below. In figure 9.5 impacts are shown according to the CML-method, and in figure 9.6 according to the EPS-method.

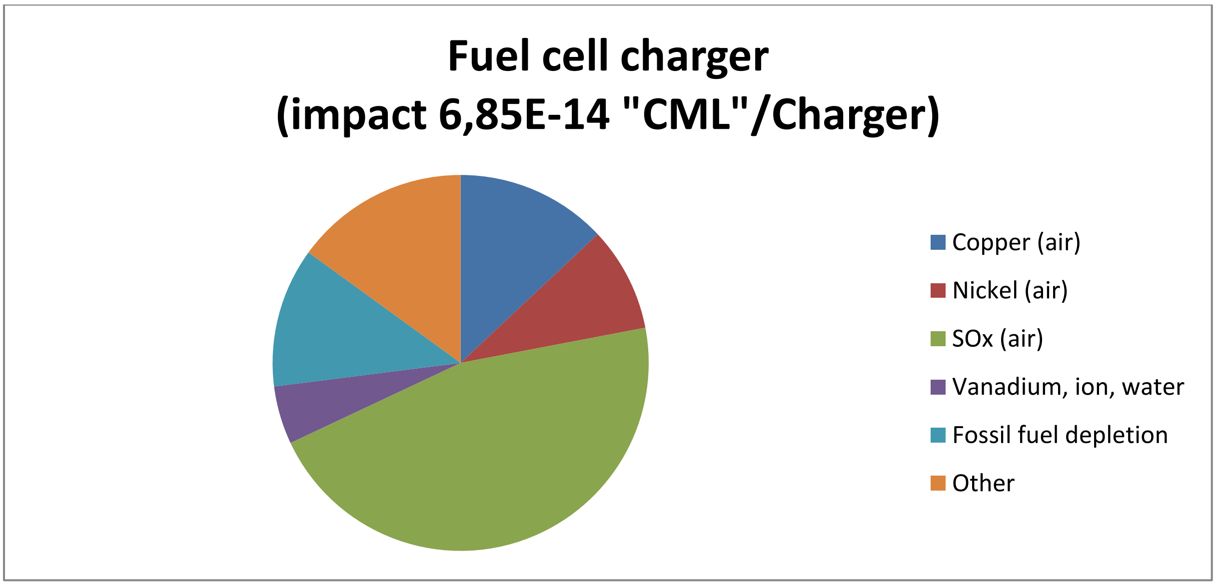


Figure 9.5 Impact of fuel cell charger according to CML

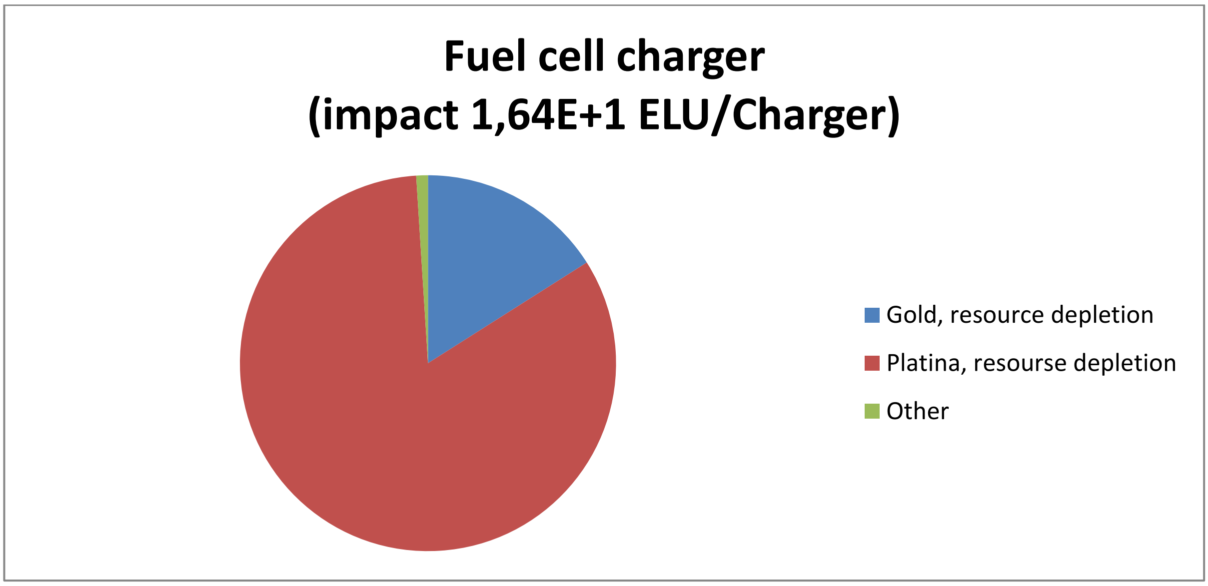


Figure 9.6 Impact of fuel cell charger in EPS

From this it is clear that the EPS model puts a higher emphasis on resource depletion than CML, at least considering rare reserves. This may partly be due to the chosen valuation method for the CML method.

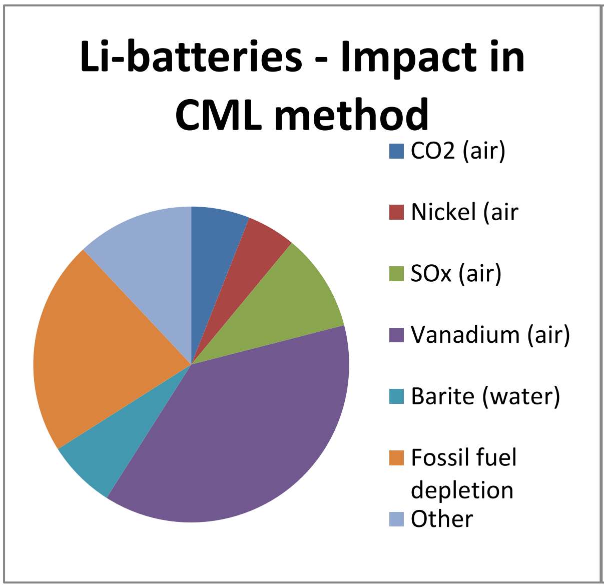
The characterization values of the two methods are however very different, as is visible in the figures above. The CML method weights fossil fuel use much higher than the EPS method, were gold and platinum in the fuel cell have 99% of the total ELU. These metals are very rare, and have therefore a very high ELU in the EPS method, while the impact from fossil fuels in comparison is very small.

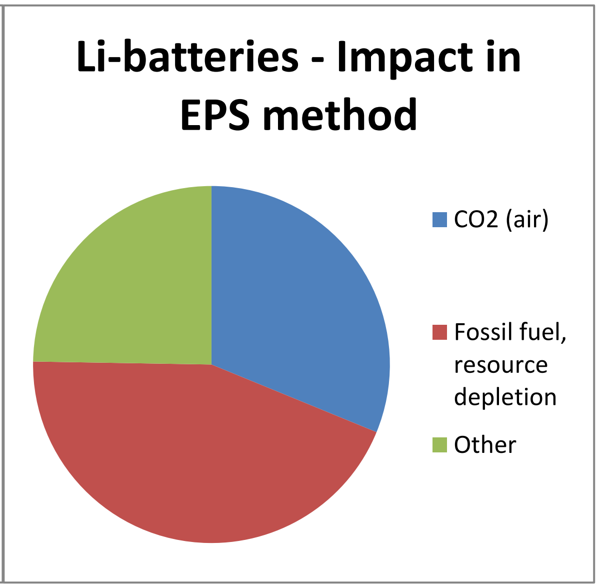
Sulfur oxides are the cause of the largest impact in the CML method. These have an impact on several impact categories, but the main impact is to acidification, and the result is visible in figure 8.2.

9.3.2 Impact contributions to the energy carriers

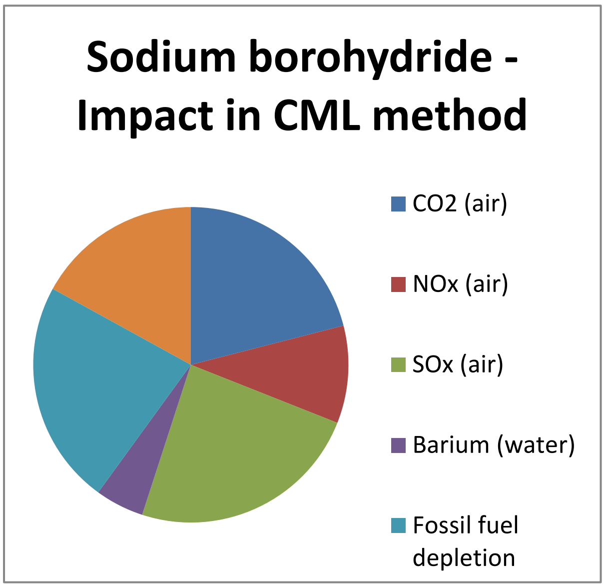
This shows the impact of the energy carriers according to the two methods.

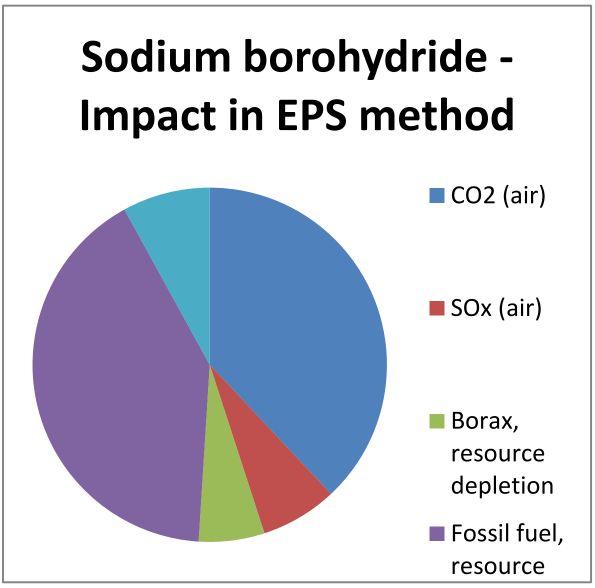
9.3.2.1 Lithium batteries



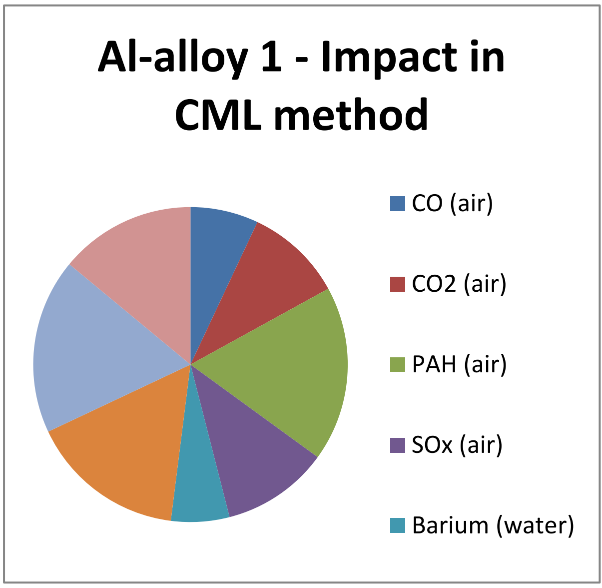


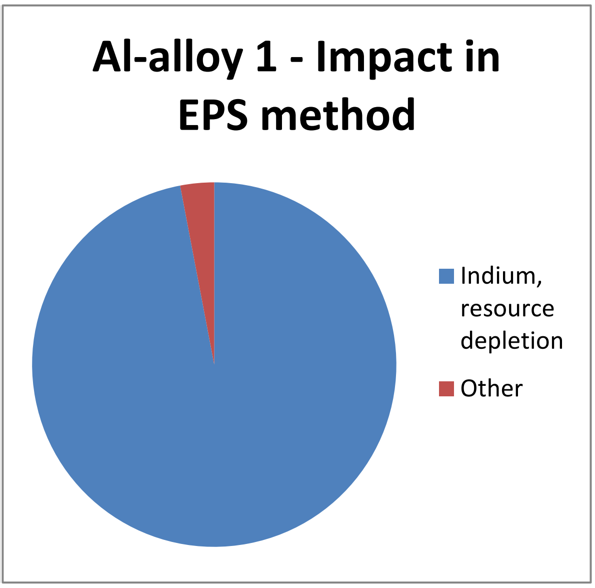
9.3.2.2 Sodium borohydride



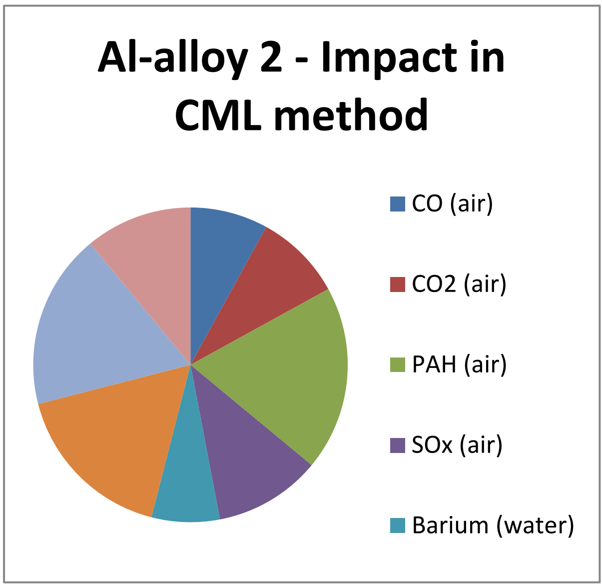


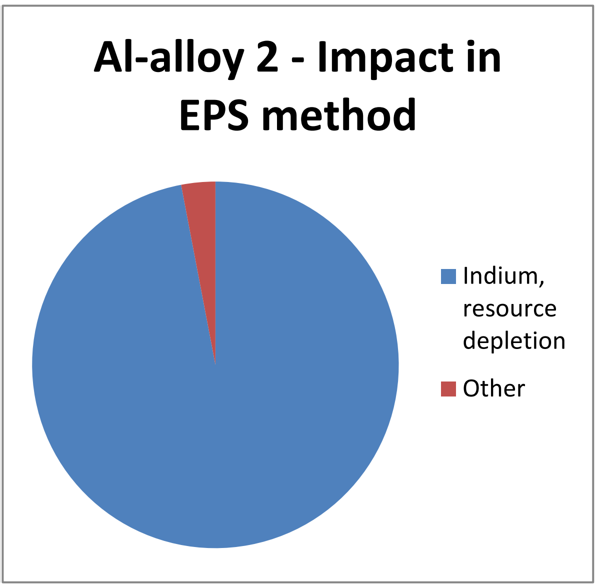
9.3.2.3 Aluminum alloy 1





9.3.2.4 Aluminum alloy 2





9.4 Comparison of total product systems and recommendations

9.4.1 Comparison of total product systems

As stated in 9.1.1 and 9.1.2, the fuel cell powered charger has a large environmental impact, according to both methods used for the LCA. This means that as a one-time disposable product, the fuel cell charger is not a suitable option.

If the target customer of the chargers would be a frequent user, like a security agency, police or military, the situation is different. These users are dependent on working communication, and in a state of long term duty a portable charger might be a very attractive option.

Another type of potential user is businessmen/women. A person with large responsibilities in a company or other organization might need to be certain of being available on a phone in the event of a crisis.

A third type of user is emerging with the technological progress currently happening in the field of cellular technology cell phones. Cell phones are being developed to be much more than just a phone. This opens up a market for other users, like lecturers who uses phones with a projector (like the cell phone "Samsung Show") or just regular travelers who use other small appliances to watch movies, listen to music etc.

For the last two categories of potential customers a distribution system for the energy carriers need to be easily available in a larger area, which is already the case for batteries. The first category of would-be users might be able to order large enough quantities to make the cost and transportation emissions negligible.

The environmental impact depending on product system and number of Wh discharged is shown in Figure 9.7 for the EPS method, and in Figure 9.8 for the CML method.

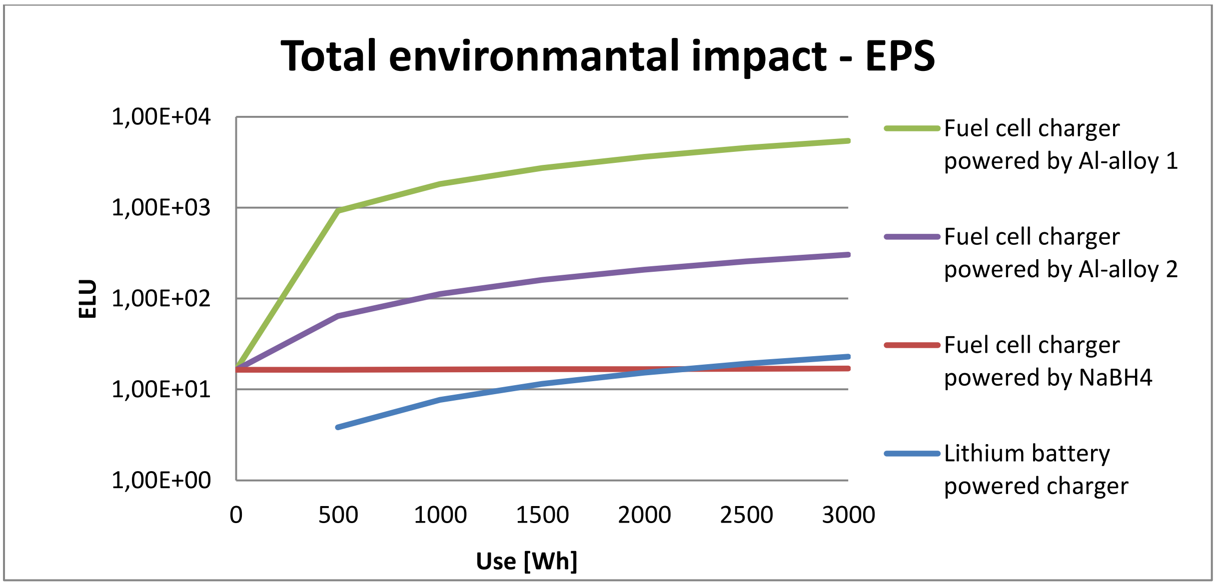


Figure 9.7 Total environmental impact according to the EPS method, expressed in Environmental load units.

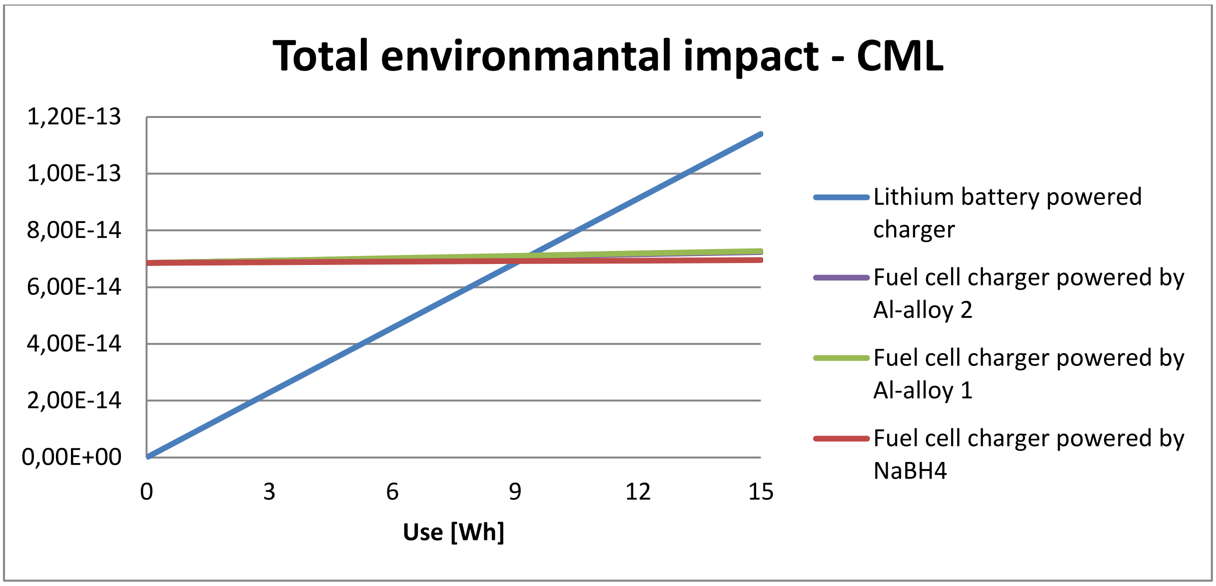


Figure 9.8. Total environmental impact according to the CML-method. As CML does not have a method of summarizing the different impacts, all categories have been valued equally to be able to make a total comparison.

The intersections points in the figures above illustrate the use until the environmental impact is equal between the battery powered charger with lithium batteries and the fuel cell powered charger, with the three options of energy carrier. The exact number of Wh needed for the chargers to have the same impact is shown in Table 9.1.

Table 9.1. Electricity needed to be discharged from the charger for equal environmental impact for the fuel cell charger with energy carrier as the battery powered charger with lithium batteries.

Energy carrier	Wh for equal environmental impact according to the CML method	Wh for equal environmental impact according to the EPS method
NaBH4	9,9	2462,7
Aluminum alloy 1	10,2	Not viable
Aluminum alloy 2	10,2	Not viable

The EPS system has a very clear weighting system, based on willingness to pay to avoid effects from emissions or mineral depletion. The uncertainties with the valuation of impact categories in the CML method are staggering, since the method does not contain a standardized way of weighting e.g. human toxicity against resource depletion. Therefore the results of the EPS method are considered to be more reliable for the evaluation of the different chargers with their energy carriers.

As shown the sodium borohydride has the lowest total environmental impact of the energy carriers for the fuel cell charger in both cases, although with a small margin when using the CML method. This is therefore the preferred option of energy carrier for the fuel cell. For the fuel cell charger to be environmentally favorable 2197 Wh needs to be discharged. This is approximately equal to charging a normal Li-ion cell phone battery[3] 580 times. If charging every third day, it would take more than 4.5 years before this number was reached.

---

[3] A cell phone battery of 950 mAh and 3,7 V assumed. Efficiency during charging is approximately 92-94% for the battery, according to Mats Wolf at Sony Ericsson Mobile Communications AB.

9.4.2 Recommendations

The problem for the fuel cell charger is the large environmental impact of the fuel cell. The main contributors to the high ELU are resource depletion of platinum and gold, causing 83 % respective 16 % of the total ELU for the charger, this with an 80 % recycling rate for the charger.

There are two basic conditions that need to be met for the fuel cell powered charger to be a serious competitor to the Energizer charger for normal users of portable electronics:

- The use of platinum and gold has to be considerably reduced or replaced.
- A widespread distribution system needs to be implemented, with equal availability to consumers as batteries have. This could be slightly depending on price, as a lower price might compensate consumers for a lower availability.
- Losses during use needs to be minimized when using hydrogen producing compounds, as they don't stop reacting when the need for electricity is met, but rather when it runs out of reactive material.

A larger organization with multiple regular users might reach the needed 2197 Wh in a more reasonable time. This would however assume several people using the same charger, which might be possible for law enforcement during personnel intensive actions, but hardly for security agencies or military units, which tend to travel in small numbers or with small possibilities to pass around the charger when in a critical situation.

Therefore the condition of reducing the rare metals in the fuel cell remains for an organization as user, but a large distribution network might not be necessary, since large orders would minimize environmental impacts of transportation. Minimizing losses is imperative to all user groups.

10 References

1. **Energizer Holdings, Inc.** Energizer.com. [Online] [Cited: 06 30, 2009.] http://data.energizer.com/PDFs/l91.pdf.

2. **Energizer Holdings, Inc.** Energizer.com. [Online] [Cited: 06 30, 2009.] http://data.energizer.com/PDFs/ch2aa.pdf.

3. **Cui, Sophia.** [Online] Great Power Battery Co., Ltd., February 18, 2008. [Cited: July 3, 2011.] http://www2.produktinfo.conrad.com/datenblaetter/650000-674999/650420-in-01-en-MaterialSicherheit_EX_PO_LITHIUM_BATT_AA.pdf.

4. **Ying Wu, Michael T. Kelly, Jeffrey V. Ortega.** *Review of Chemical Processes for the Synthesis of Sodium Borohydride.* s.l. : Millennium Cell Inc., 2004.

5. **Jerry Woodall, Purdue University.** Aluminum-rich alloy splits water to produce hydrogen. *ADVANCED MATERIALS & PROCESSES.* May, 2008.

6. *Splitting Water with Al Rich Alloys: Structure and Reaction Kinetics.* **Jeffrey T. Ziebarth, Jerry M. Woodall, Go Choi, C.R. Allen, J-H Jeon, Deborah Sherman, Robert Kramer.** San Fransisco, CA : Purdue University - West Lafayette, IN, 2009.

7. **Swedish Standards Institute, SIS.** Miljöledning - Livscykelanalys - Principer och struktur (ISO 14040:2006). Stockholm : SIS Förlag AB, 2006.

8. **Baumann, Henrikke & Tillman, Anne-Marie.** The Hitch Hikers Guide to LCA - An orientation in life cycle assessment methodology and application. Lund : Studentlitteratur, 2004. ISBN 91-44-02364-2.

9. **Carl Johan Rydh, Mattias Lindahl, Johan Tingström.** *Livscykelanalys - en metod för miljöbedömning av produkter och tjänster.* Malmö : Studentlitteratur, 2002. ISBN 978-91-44-02447-9.

10. Center of Environmental Science of Leiden University. CML 2001 (all impact categories) v. 2.04.

11. **Gabathuler, Heinz.** The CML Story - How Environmental Sciences Entered the Debate on LCA. *The International Journal of Life Cycle Assessment.* 2006, Vol. 11, 1.

12. EPS 2000 default methodology v. 2.03. *SimaPro database.* 09 14, 2009.

13. Batteriinsamlingen. [Online] [Cited: 07 04, 2009.] http://www.batteriinsamlingen.se/fragor.aspx.

14. **Independent Review Panel, National Renewable Energy Laboratory.** *Go/No-Go Recommendation for Sodium Borohydride for On-Board Vehicular Hydrogen Storage.* Golden, Colorado, USA : U. S. Department of Energy Hydrogen Program, 2007.

15. **Returpack.** [Online] [Cited: 09 17, 2009.] http://www.pantamera.nu/start.asp.

16. **Caltech, Solid State Ionic and Electroceramics Research Group.** [Online] [Cited: 06 30, 2009.] http://addis.caltech.edu/images/proton%20fuel%20cell.png.

17. Batteriinsamlingen. [Online] [Cited: 07 04, 2009.] http://www.batteriinsamlingen.se/fragor.aspx.

18. Ecoinvent Centre. [Online] [Cited: 08 20, 2009.] http://www.ecoinvent.ch/.

11 Abbreviation list

1,4-DB	1,4-dichlorobenzene
Al	Aluminum
Al_2O_3	Aluminum oxide
CFC	Chlorofluorocarbon
CML 2001	LCA-methodology developed at Centrum voor Milieukunde Leiden
e.g.	exempli gratia, "for example"
ELU	Environmental Load Unit
EPS 2000	Environmental Priority Strategies, LCA methodology
eq	equivalent
etc.	et cetera, "and more"
Fe	Iron
FeS_2	Iron disulfide
GHG	Greenhouse gas
GWP	Global warming potential
H_2O	Water
HTP	Human Toxicity Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
Li	Lithium
LiS_2	Lithium disulfide
$NaBH_4$	Sodium Borohydride
$NaBO_2$	Borax

NEX	Normalized Extinction of species
NO_X	Generic term for the mono-nitrogen oxides NO and NO_2
PAH	Polycyclic aromatic hydrocarbons
PEFC	Polymer Electrolyte Membrane Fuel Cells, aka Proton exchange membrane Fuel Cell
Sb	Antimony
SO_2	Sulfur dioxide
Wh	Watt hour
WHO	World Health Organization

Appendix 1 - Inventory Results

In this chapter the results from the inventory analysis are presented. This includes emissions to air and water, as well as the reserve demands for the production. Inventory analysis of the different materials was made in Simapro, after which they were added according to their weight to get the results for the end products.

1 Energy carriers

The inventory results for the enrgy carriers; Lithium batteries, Sodium borohydride and aluminum alloys.

11.1 Lithium batteries (AA)

The activities included in the battery production are:

- Production of lithium[4]
- Production of steel[5]
- Production of aluminum[6]
- Production of polypropylene[7]
- Production of polycarbonate[8]

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Arsenic	kg	1,67E-09	Lithium production energy
Benzene	kg	1,37E-09	Steel production
Cadmium	kg	3,21E-09	Lithium production energy
CO	kg	1,16E-04	Steel production
CO_2	kg	2,03E-02	Lithium production energy
Copper	kg	2,70E-09	Steel production
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	1,79E-13	Steel production
Hydrogen fluoride	kg	3,22E-09	Polycarbonate production

---

[4] Resource depletion and energy demand only, calculated with European average electricity production. No complete LCA information available.

[5] LCA for the production of steel at CORUS in the Netherlands, extended with transport according the world average

[6] Aluminum 99% purity. Recycling percentage 15%.

[7] PP granulate average

[8] Production of polycarbonate Europe. Average data for 1992-1994.

Lead	kg	5,37E-09	Lithium production energy
Methane	kg	1,80E-05	Polycarbonate production
Methane, tetrafluoro-, CFC-14	kg	3,40E-08	Aluminum production
Nickel	kg	6,15E-08	Lithium production energy
NO_2	kg	2,06E-06	Steel production
NO_X	kg	5,75E-05	Lithium production energy
PAH	kg	3,59E-09	Aluminum production
Particulates, <10um (stationary)	kg	5,94E-06	Lithium production energy
SO_2	kg	9,99E-06	Steel production
SO_X	kg	1,56E-04	Lithium production energy
Vanadium	kg	2,31E-07	Lithium production energy
Zinc	kg	7,86E-09	Steel production

Table 1-1 Emissions to air from production of materials needed for Li-battery assembly.

. Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Acenaphthylene	kg	5,30E-10	Lithium production energy
Barite	kg	2,33E-06	Lithium production energy
Barium	kg	2,74E-07	Lithium production energy
Copper ion	kg	1,66E-09	Aluminum production
Nickel ion	kg	1,34E-08	Lithium production energy
Nitrogen, total	kg	1,25E-07	Lithium production energy
PAH	kg	3,27E-09	Lithium production energy
Phenol	kg	4,11E-08	Polycarbonate production
Phosphate	kg	1,54E-07	Lithium production energy
Phosphorus pentoxide	kg	1,93E-07	Polycarbonate production

Selenium	kg	1,23E-08	Lithium production energy
Vanadium ion	kg	1,90E-08	Lithium production energy

Table 1-2 Emissions to water from production of materials needed for Li-battery assembly.

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Aluminum, scrap	kg	3,67E-04	Aluminum production
Bauxite	kg	3,15E-04	Aluminum production
Coal, 18 MJ/kg	kg	1,61E-03	Lithium production energy
Coal, 29,3 MJ/kg	kg	1,63E-03	Steel production
Coal, brown, 8 MJ/kg	kg	1,86E-03	Lithium production energy
Copper	kg	1,84E-06	Lithium production energy
Gas, natural, 35MJ/m^3	m^3	1,41E-03	Polycarbonate production
Gas, petroleum, 35MJ/m^3	m^3	1,54E-04	Lithium production energy
Lithium	kg	3,67E-04	Lithium metal production
Oil, crude, 42,6 MJ/kg	kg	3,40E-03	Lithium production energy
Silver	kg	8,13E-09	Lithium production energy
Uranium, 560 GJ/kg	kg	1,26E-07	Lithium production energy

Table 1-3 Raw material demand for production of materials needed for Li-battery assembly.

11.2 Sodium borohydride ($NaBH_4$)

The activities included in the sodium borohydride production are:

- Methane production[9]
- Hydrogen chloride production[10]
- Sodium chloride production[11]
- Methanol production[12]
- Borax reserve depletion[13]
- Brown-Schlesinger process[14]
- Process energy for Brown-Schlesinger process[15]

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Arsenic	kg	1,48E-12	Brown-Schlesinger process energy
Benzene	kg	1,15E-11	Methanol production
CO	kg	1,02E-08	Methanol production
CO_2	kg	6,48E-04	Brown-Schlesinger process waste
Ethane	kg	1,49E-11	Methane production
Methane	kg	6,41E-07	Sodium chloride production
Nickel	kg	3,81E-10	Hydrogen chloride production
NO_X	kg	2,60E-06	Sodium chloride production
PAH	kg	2,63E-12	Sodium chloride production
Particulates	kg	4,87E-07	Sodium chloride production
Particulates, <10um (stationary)	kg	5,73E-09	Brown-Schlesinger process energy

---

[9] Calculated from NG-production, methane content of 90% assumed.

[10] From the production of sodium sulphate and hydrochloric acid in the NaCl process.

[11] Production of NaCl (100%) according to APME (1994), with modifications and additions from Buwal.

[12] Production of methanol using energy forest.

[13] Only included as reserve depletion.

[14] Only CO_2 emission included, as other outputs are materials used in other chemical processes and therefore not considered waste.

[15] Calculated from chemical enthalpy of inputs and outputs, no losses included.

Propane	kg	3,98E-12	Methane production
SO_2	kg	1,33E-08	Methanol production
SO_X	kg	3,97E-06	Hydrogen chloride production
Vanadium	kg	5,25E-11	Brown-Schlesinger process energy
Zink	kg	2,29E-11	Methanol production

Table 1-4 Emissions to air from production of sodium borohydride.

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Acenaphthylene	kg	2,17E-12	Brown-Schlesinger process energy
Barite	kg	1,54E-09	Brown-Schlesinger process energy
Barium	kg	8,19E-09	Sodium chloride production
Cobalt	kg	5,34E-13	Methanol production
Copper ion	kg	1,67E-10	Sodium chloride production
Nickel ion	kg	2,35E-10	Sodium chloride production
PAH	kg	2,37E-11	Sodium chloride production
Phosphate	kg	5,72E-10	Brown-Schlesinger process energy
Selenium	kg	5,00E-11	Brown-Schlesinger process energy
Vanadium ion	kg	7,67E-11	Brown-Schlesinger process energy

Table 1-5 Emissions to water from production of sodium borohydride.

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Borax	kg	6,66E-04	Borax resource depletion
Coal, 18 MJ/kg	kg	3,26E-05	Sodium chloride production
Coal, brown, 8 MJ/kg	kg	7,56E-06	Brown-Schlesinger process energy
Copper	kg	5,38E-09	Brown-Schlesinger process energy
Gas, natural, 35 MJ/m^3	m^3	1,16E-06	Brown-Schlesinger process energy
Gas, natural, 36,6 MJ/m^3	m^3	6,86E-05	Sodium chloride production
Oil, crude, 41 MJ/kg	kg	3,61E-07	Methanol production

Oil, crude, 42,6 MJ/kg	kg	3,62E-05	Sodium chloride production
Silver	kg	4,27E-12	Brown-Schlesinger process energy
Uranium, 560 GJ/kg	kg	5,08E-10	Brown-Schlesinger process energy

Table 1-6 Raw material demand for production of sodium borohydride.

11.3 Aluminum alloy production

The activities included in the alloy production are:

- Production of aluminum[16]
- Production of gallium[17]
- Production of indium[18]
- Production of tin[19]

Metal	Alloy 1, wt%	Alloy 2, wt%
Aluminum	50	95
Gallium	34	3,4
Indium	11	1,1
Tin	5	0,5

Table 1-7 Metal content in Aluminum alloy.

---

[16] 80% recycled material used

[17] Calculated from virgin aluminum production, with 1,08% of emissions allocated to gallium (based on weight and price). Gallium resource depletion added.

[18] Calculated from virgin zinc production, with 2,57% of emissions allocated to indium (based on weight and price). Indium resource depletion added.

[19] Virgin tin production assumed.

11.3.1 Aluminum alloy 1

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Arsenic	kg	1,20E-13	Indium production
Benzene	kg	1,10E-10	Tin production
Cadmium	kg	4,69E-13	Indium production
CO	kg	6,79E-05	Aluminum production
CO_2	kg	1,27E-03	Aluminum production
Copper	kg	2,30E-14	Tin production
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	3,27E-21	Tin production
Formaldehyde	kg	8,86E-11	Tin production
Hydrogen fluoride	kg	1,99E-12	Tin production
Lead	kg	1,29E-10	Aluminum production
Metals, unspecified	kg	2,70E-08	Aluminum production
Methane	kg	1,00E-08	Indium production
Methane, tetrafluoro-, CFC-14	kg	4,42E-08	Aluminum production
Nickel	kg	1,03E-09	Aluminum production
NO_2	kg	4,74E-07	Tin production
NO_X	kg	2,32E-06	Aluminum production
PAH	kg	4,43E-09	Aluminum production
Particulates	kg	2,43E-06	Aluminum production
Particulates, SPM	kg	4,41E-08	Tin production
Particles, <10 um (stationary)	kg	2,26E-08	Gallium production
Particulates, >10 um	kg	3,33E-09	Indium production
SO_2	kg	1,34E-07	Tin production
SO_X	kg	7,45E-06	Aluminum production

Vanadium	kg	9,63E-11	Gallium production
Zinc	kg	3,39E-10	Tin production

Table 1-8 Emissions to air from production of materials needed for aluminum alloy 1.

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Barite	kg	1,76E-09	Gallium production
Barium	kg	4,26E-08	Aluminum production
Cobalt	kg	2,97E-12	Indium production
Copper ion	kg	1,46E-09	Aluminum production
Nickel ion	kg	1,51E-09	Aluminum production
PAH	kg	1,99E-09	Aluminum production
Phenol	kg	3,08E-14	Tin production
Phosphate	kg	1,76E-08	Aluminum production
Selenium	kg	7,79E-12	Indium production
Vanadium ion	kg	3,52E-11	Gallium production

Table 1-9 Emissions to water from production of materials needed for aluminum alloy 1.

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Aluminum, scrap	kg	4,73E-04	Aluminum production
Bauxite	kg	4,10E-04	Aluminum production
Coal, 18 MJ/kg	kg	1,88E-04	Aluminum production
Coal, 29,3 MJ/kg	kg	3,69E-05	Tin production
Copper	kg	2,37E-09	Gallium production
Gallium	kg	1,12E-04	Gallium production
Gas, natural, 30,3 MJ/kg	kg	1,09E-07	Indium production
Gas, natural, 35 MJ/m^3	m^3	1,08E-06	Gallium production
Gas, natural, 36,6 MJ/m^3	m^3	8,20E-05	Aluminum production
Indium	kg	3,61E-05	Indium production
Occupation, industrial area	m^2a	6,57E-08	Indium production
Occupation, traffic area	m^2a	1,35E-08	Indium production
Oil, crude, 42,6 MJ/kg	kg	1,56E-04	Indium production
Oil, crude, 42,7 MJ/kg	kg	1,13E-07	Aluminum production
Silver	kg	4,91E-12	Gallium production
Tin	kg	1,82E-05	Tin production
Uranium, 451 GJ/kg	kg	9,74E-09	Aluminum production

Table 1-10 Raw material demand for production of aluminum alloy 1.

11.3.2 Aluminum alloy 2

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Arsenic	kg	6,34E-15	Indium production
Benzene	kg	5,81E-12	Tin production
Cadmium	kg	2,47E-14	Indium production
CO	kg	6,78E-05	Aluminum production
CO_2	kg	1,03E-03	Aluminum production
Copper	kg	1,21E-15	Tin production
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	kg	1,72E-22	Tin production
Formaldehyde	kg	4,66E-12	Tin production
Hydrogen fluoride	kg	1,04E-13	Tin production
Lead	kg	1,25E-10	Aluminum production
Metals, unspecified	kg	2,70E-08	Aluminum production
Methane	kg	5,26E-10	Indium production
Methane, tetrafluoro-, CFC-14	kg	4,38E-08	Aluminum production
Nickel	kg	1,01E-09	Aluminum production
NO_2	kg	2,50E-08	Tin production
NO_X	kg	2,15E-06	Aluminum production
PAH	kg	4,37E-09	Aluminum production
Particulates	kg	2,43E-06	Aluminum production
Particulates, SPM	kg	2,32E-09	Tin production
Particles, <10 um (stationary)	kg	1,19E-09	Gallium production
Particulates, >10 um	kg	1,75E-10	Indium production
SO_2	kg	7,04E-09	Tin production
SO_X	kg	6,66E-06	Aluminum production

Vanadium	kg	5,07E-12	Gallium production
Zinc	kg	1,78E-11	Tin production

Table 1-11 Emissions to air from production of materials needed for aluminum alloy 2.

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Barite	kg	9,26E-11	Gallium production
Barium	kg	4,19E-08	Aluminum production
Cobalt	kg	1,56E-13	Indium production
Copper ion	kg	1,45E-09	Aluminum production
Nickel ion	kg	1,48E-09	Aluminum production
PAH	kg	1,96E-09	Aluminum production
Phenol	kg	1,62E-15	Tin production
Phosphate	kg	1,73E-08	Aluminum production
Selenium	kg	4,10E-13	Indium production
Vanadium ion	kg	1,85E-12	Gallium production

Table 1-12 Emissions to water from production of materials needed for aluminum alloy 2.

Substance:	Unit/Wh:	Substance/Wh:	Dominating process:
Aluminum, scrap	kg	4,73E-04	Aluminum production
Bauxite	kg	4,06E-04	Aluminum production
Coal, crude, 18 MJ/kg	kg	1,84E-04	Aluminum production
Coal, crude, 29,3 MJ/kg	kg	1,94E-06	Tin production
Copper	kg	1,25E-10	Gallium production
Gallium	kg	5,87E-06	Gallium production
Gas, natural, 30,3 MJ/kg	kg	5,76E-09	Indium production
Gas, natural, 35 MJ/m^3	m^3	5,68E-08	Gallium production
Gas, natural, 36,6 MJ/m^3	m^3	8,20E-05	Aluminum production
Indium	kg	1,90E-06	Indium production
Occupation, industrial area	m^2a	3,46E-09	Indium production
Occupation, traffic area	m^2a	7,13E-10	Indium production
Oil, crude, 42,6 MJ/kg	kg	1,52E-04	Indium production
Oil, crude, 42,7 MJ/kg	kg	5,96E-09	Aluminum production
Silver	kg	2,58E-13	Gallium production
Tin	kg	9,59E-07	Tin production
Uranium, 451 GJ/kg	kg	9,74E-09	Aluminum production

Table 1-13 Raw material demand for production of aluminum alloy 2.

12 Chargers

The only part of the chargers included in the study is the metals of the fuel cell, as mentioned in chapter 5.2.1. An 80% recycling rate assumed as stated in foot note 2 on page 37 in the report. The metals are:

- Platinum[20]
- Gold[21]
- Copper[22]

Substance:	Unit/charger:	Substance/charger:	Dominating process:
Arsenic	kg	2,70E-09	Gold production energy
Benzene	kg	1,48E-09	Copper production
CO_2	kg	7,04E-02	Gold production energy
Copper	kg	1,88E-06	Platinum production
Lead	kg	7,86E-09	Platinum production
Metals, unspecified	kg	2,97E-10	Copper production
Methane	kg	7,71E-05	Platinum production
Nickel	kg	1,03E-06	Platinum production
NO_X	kg	1,24E-04	Gold production energy
PAH	kg	2,44E-09	Gold production energy
Particulates, <10um (stationary)	kg	1,06E-05	Gold production energy
SO_2	kg	3,02E-04	Copper production
SO_X	kg	7,31E-03	Platinum production
Vanadium	kg	1,18E-07	Gold production energy
Zink	kg	2,03E-10	Copper production

Table 12-1 Emissions to air from production of fuel cell metals.

---

[20] World average. Mining, production, transport and recycling included.

[21] Resource depletion and energy demand only, calculated with European average electricity production. No complete LCA information available.

[22] Open mining and sulphide ores (0.6%Cu) assumed. World average data for 2000. 13% old scrap, 98% recovery

Substance:	Unit/charger:	Substance/charger:	Dominating process:
Acenaphthylene	kg	3,96E-09	Gold production energy
Barite	kg	3,65E-06	Gold production energy
Barium	kg	1,72E-06	Gold production energy
Cobalt	kg	4,76E-08	Platinum production
Copper ion	kg	1,33E-07	Platinum production
Nickel ion	kg	2,75E-07	Platinum production
PAH	kg	1,77E-09	Gold production energy
Phosphate	kg	2,21E-06	Platinum production
Selenium	kg	1,87E-07	Platinum production
Vanadium ion	kg	2,38E-07	Gold production energy

Table 12-2 Emissions to water from production of fuel cell metals.

Substance:	Unit/charger:	Substance/charger:	Dominating process:
Coal, 18 MJ/kg	kg	2,31E-02	Platinum production
Coal, 29,3 MJ/kg	kg	1,77E-04	Copper production
Coal, brown, 8 MJ/kg	kg	1,39E-02	Gold production energy
Copper	kg	4,67E-04	Copper production
Gas, natural, 30,3 MJ/kg	kg	1,25E-04	Copper production
Gas, natural, 35 MJ/m^3	m^3	3,69E-03	Gold production energy
Gold	kg	2,16E-06	Gold resource depletion
Occupation, industrial area	kg	2,66E-05	Copper production
Oil, crude, 42,6 MJ/kg	kg	7,48E-04	Copper production
Oil, crude, 42,7 MJ/kg	kg	2,51E-03	Gold production energy
Platinum	kg	1,84E-06	Platinum production

Silver	kg	7,91E-09	Gold production energy
Uranium, 560 GJ/kg	kg	9,43E-07	Gold production energy

Table 12-3 Raw material demand for production of fuel cell metals.