University of Southern Queensland
Faculty of Engineering & Surveying

Total Effect on the Environment of Electric/Hybrid Electric Vehicle Batteries

A dissertation submitted by

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ENG4112 Research Project

towards the degree of

Bachelor of Engineering (electrical)

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Abstract

1.0 Introduction

The depletion of fossil fuels and greenhouse gas emissions are major issues facing the world today. Conventional vehicles, such as combustion driven buses and cars, are major contributors to these issues. Electric or hybrid electric vehicles (part combustion, part electrical) are being offered as an alternative for the future but one of the biggest challenges is the storage of energy in these vehicles. This study is to determine the impact on the environment of the energy storage cells (batteries) used by these vehicles.

2.0 Background

Even though the first electrical powered vehicle was built in the early 19th century, electric or hybrid electric vehicles have not made any real impact in the automotive industry until recently. Several legislative and regulatory actions (involving emissions) in the United States and worldwide have renewed electric/hybrid electric vehicle development efforts. Electric conversions of gasoline powered vehicles as well as electric vehicles designed from the ground up are now available. Unfortunately, the development of batteries for energy storage has been less than desired. There has been some technological advances but have they come at a price to the environment?

3.0 Objectives

1. Research various types of energy storage cells currently available
2. Collect data for energy storage cells (components, types of material, weight etc)

3. Use an appropriate (Life Cycle Assessment) software package to determine total effect on environment of each energy storage cell type
4. Compare energy storage cell types in terms of total effect on the environment

4.0 Methodology

The Life Cycle Assessment software tool "SimaPro" was used to determine and compare the impact on the environment of the batteries. Matlab was also used for evaluation.

5.0 Conclusions

This study has shown that the total effect on the environment of the batteries depend on their application (ie hybrid electric or electric) because these different applications have different requirements of energy etc which, in turn, requires different masses. Therefore, from an environmental and practical point of view, different battery types are better suited to each different application.

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ENG4111/2 *Research Project*

Limitations of Use

Prof F Bullen
Dean
Faculty of Engineering and Surveying

Certification of Dissertation

I certify that the ideas, designs and experimental work, results, analyses and conclusions set out in this dissertation are entirely my own effort, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

C.O'Donnell

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Signature

Date

Acknowledgments

I would like to thank my family, in particular my wife Josephine, for their help and patience. I would also like to thank my employer, East Coast Apprenticeships, for granting me leave to complete this project. Associate Professor David Parsons also needs to be thanked for help with the SimaPro LCA tool.

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University of Southern Queensland
October 2007

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Chapter 1

Introduction

1.1 Chapter 1 Overview

This chapter will introduce the reader to the report, explain why this project was undertaken and give an overview of each chapter for ease of reference for the reader.

1.2 Project introduction

This project was undertaken because the depletion of fossil fuels and greenhouse gas emissions are major issues facing the world today. Conventional vehicles, such as combustion driven buses and cars, are major contributors to these issues. Electric or hybrid electric vehicles (part combustion, part electrical) are being offered as an alternative for the future but one of the biggest challenges is the storage of energy in these vehicles. This study is to determine the impact on the environment of the energy storage cells (batteries) used by these vehicles.

The impact on the environment of the batteries was determined by a Life Cycle Analysis tool (SimaPro), using a cradle-grave approach. The research, analysis techniques, results and conclusions are given in this report.

1.3 Chapter 2 Overview

Chapter 2 is the background and literature review. This chapter includes the following points:

1. As this entire report was written and compiled with the aid of LaTex, a brief explanation and history of LaTex is provided.

2. The SUBAT report was used as a reference for comparison and data information extensively for this project therefore an overview and brief explanation of the SUBAT report is also provided.

3. Why the effects of greenhouse gases and fossil fuel depletion are major issues.

4. Electric vehicle description

5. Electric vehicle history

6. Hybrid electric vehicle description

7. Hybrid electric vehicle history

8. Types of batteries currently being used or researched for electric/hybrid electric vehicles

9. A description of Life Cycle Analysis

10. A description of SimaPro (LCA analysis tool)

1.4 Chapter 3 Overview

Chapter 3 explains the methodology involved in determining parameters which are used to calculate the required data for entry into the SimaPro program. Accurate methodology and data is essential for a meaningful LCA result. This chapter includes the following points:

1. Battery material percentages

2. EV battery masses and how they were determined

3. Other EV battery parameters for the LCA and how they were determined

4. HEV battery masses and how they were determined

5. Other HEV battery parameters for the LCA and how they were determined

1.5 Chapter 4 Overview

Chapter 4 explains the analysis process including all input requirements for SimaPro and the outputs from the program. This chapter includes the following points:

1. EV data entry and output results

2. HEV data entry and output results

1.6 Chapter 5 Overview

Chapter 5 discusses the results and compares the battery types to assess their relative impacts. An approximate vehicle impact is also given for interest. This chapter includes the following points:

1. EV battery analysis results discussion

2. HEV battery analysis results discussion

3. Conventional, EV and HEV comparison

1.7 Chapter 6 Overview

Chapter 6 discusses conclusions to be made from this project, analysis pitfalls and further work.

Chapter 2

Background and Literature Review

2.1 Chapter 2 introduction

As for any research project the research and literature review is a vital part. Information and data needs to be gathered and verified to produce an accurate and effective report. This chapter includes the research and literature review used for the project.

2.2 LaTex

This entire dissertation was written using LaTex so it is only appropriate that some information be supplied about this topic. This is by no means an introductory lesson but merely an overview of the LaTex program.

History

Donald E Knuth(www-cs-faculty.stanford. edu/ knuth) designed a typesetting program called TeX in the 1970s especially for complex mathematical text. LaTeX is a macro package that allows authors to use TeX easily, and uses TeX as its formatting engine. It is available for most operating systems; for example, you can use it on low-specification PCs and Macs, as well as on powerful UNIX and VMS systems. There are many different implementations of LaTeX. The word LaTeX is pronounced lay-tech or lah-tech (ch as in Scottish loch or just hard k), not latex (as in rubber). In plain text, the typography is LaTeX. The latest version is LaTeX2e.

LaTeX is a powerful typesetting system, used for producing scientific and mathematical documents of high typographic quality. Unlike WYSIWYG tools such as FrameMaker and Word, it uses plain text files that contain formatting commands. Its big, open source, stable and used by many technical publishing companies. Its also relatively unknown in the technical writing community. LaTeX is not a word processor! Instead, LaTeX encourages authors not to worry too much about the appearance of their documents but to concentrate on getting the right content. LaTeX is based on the idea that it is better to leave document design to document designers, and to let authors get on with writing documents.LaTeX contains features for:

1. Typesetting journal articles, technical reports, books, and slide presentations.

2. Control over large documents containing sectioning, cross-references, tables and figures.

3. Typesetting of complex mathematical formulas. Advanced typesetting of mathematics with AMS-LaTeX.

4. Automatic generation of bibliographies and indexes.

5. Multi-lingual typesetting.

6. Inclusion of artwork, and process or spot colour.

7. Using PostScript or Metafont fonts.

The best source for news on TeX and LaTeX is the TeX Users Group.(Unwalla 2006)

Basic concepts

An author writes a LaTeX input file in a text editor and then compiles this using LaTeX. An input file contains text and commands for processing the text. There are some conceptual similarities to a markup language such as HTML. However, a fundamental difference is that LaTeX is designed as a page layout language, unlike HMTL which is functional markup. The whole point of LaTeX is to achieve perfect typographic output, which is not the purpose of HTML. LaTeX produces device-independent DVI files, from which you can generate PDF and PostScript files using the utilities that usually come with a LaTeX installation. Typically, you can also create a PDF file directly. There are GUI editors to help with creating input files, but many authors prefer to use highperformance text editors such as UltraEdit from IDM Computer Solutions Inc (www.ultraedit.com). LaTeX is very fussy. A trivial mistake may mean that no output is generated and many error messages are displayed. You will need to check the error logs, fix the problem and recompile. (Dante 2007)

2.3 Subat (Sustainable Batteries)

The SUBAT (sustainable batteries) project was used as a major source of information and comparison for this project. The same parameters were used in this analysis as in the SUBAT project intentionally for comparative purposes. The SUBAT commission was required to provide a report on the possibility to maintain, or not, cadmium, in the exemption list of Directive 2000/53 on End-of-Life Vehicles. The SUBAT proposal's aims were to make a comprehensive and complete assessment of commercially available and forthcoming battery technologies in the world, including Ni-Cd, on the basis of:

1. a technical assessment comparing their performances for full EV and HEV (specific energy, specific power, proven cycle life and calendar life, life cycle cost analysis, operation at extreme temperature, charge acceptance, maintenance issues, safety, energetical efficiency of the battery systems, availability of recycling process at industrial stage, operation during applications). SUBAT also took into account the status of these batteries as to their availability as commercial products.

2. an environmental assessment in order to be able to give them an environmental score which can designate them as being a sustainable solution or not. A life-cycle-analysis approach will investigate availability of primary materials, environmental impact of extraction and manufacturing of the battery, emissions from the battery during use, release of components in case of accident, recycling of active materials, production of non-recyclable waste and environmental impact of recycling processes.

3.an economical assessment with both a micro-economical analysis of production, manufacturing cost of the batteries, forecast cost for the consumers and a macro-economical study to take into account the position of battery manufacturers on the global market, assessing European vs. non-European products and influence on the European trade balance.

Through this multidisciplinary approach, SUBAT will allow to define an overall view of all aspects of the automotive battery market, in order to provide the Commission with a valuable policy support tool that will assist in tracing the pathways for the sustainable transport of the future.

SUBAT was performed by a multidisciplinary international partnership:

VUB Vrije Universiteit Brussel

Vakgroep Elektrotechniek

AVERE Association du vhicule lectrique routier europen

CEREVEH Centre d'tudes et de recherches sur les vhicules lectriques et hybrides

CITELEC Association of cities interested in electric vehicles

CEI Comitato Elettrotecnico Italiano

Commissione Italiana Veicoli Elettrici Stradali

ULB Universit Libre de Bruxelles

Centre d'tudes conomiques et sociales de l'environnement

DESA Universit di Pisa

Department of electrical systems and automation

This alliance of associations were able to obtain information from industry sources which was unable to be released due to the sensitivity of the technology. Therefore, the results obtained from the SUBAT project are taken to be accurate for this report. Even though information could not be provided from the SUBAT report, the methods and results for comparative purposes proved invaluable.

2.4 Greenhouse Gases

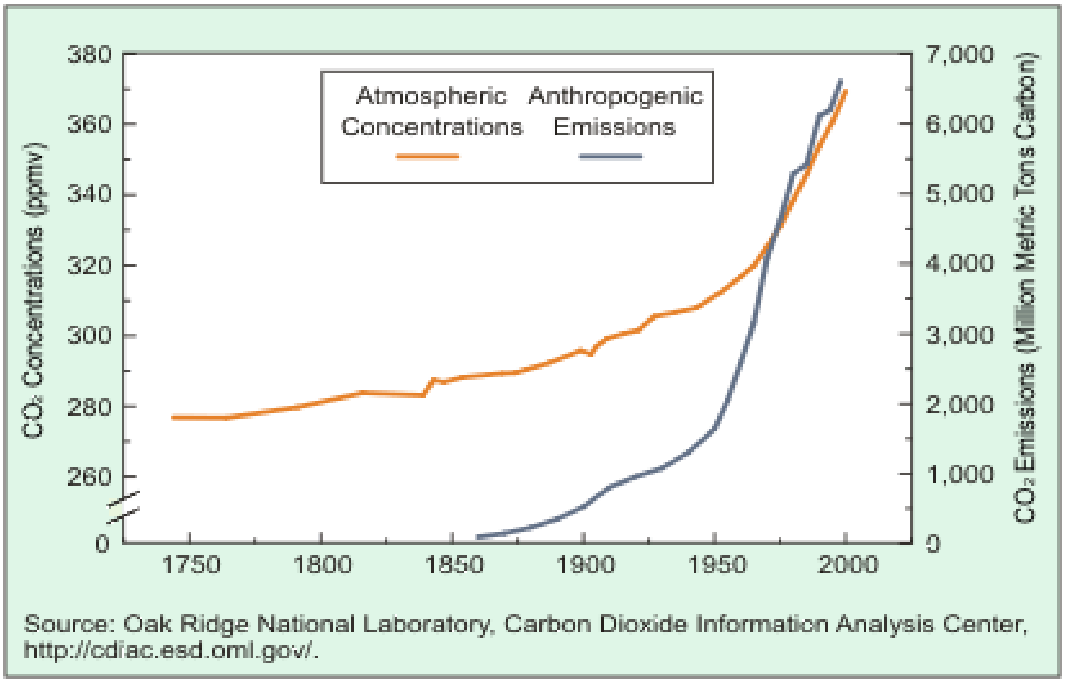
Greenhouse gases and fossil fuel depletion are major issues facing the world today. Many chemical compounds found in the Earths atmosphere act as greenhouse gases. These gases allow sunlight to enter the atmosphere freely. When sunlight strikes the Earths surface, some of it is reflected back towards space as infrared radiation (heat). Greenhouse gases absorb this infrared radiation and trap the heat in the atmosphere. Over time, the amount of energy sent from the sun to the Earths surface should be about the same as the amount of energy radiated back into space, leaving the temperature of the Earths surface roughly constant.

Many gases exhibit these greenhouse properties. Some of them occur in nature (water vapor, carbon dioxide, methane, and nitrous oxide), while others are exclusively human-made (like gases used for aerosols).

Levels of several important greenhouse gases have increased by about 25 percent since large-scale industrialization began around 150 years ago Figure 2.1. During the past 20 years, about three-quarters of human-made carbon dioxide emissions were from burning fossil fuels.

Concentrations of carbon dioxide in the atmosphere are naturally regulated by numerous processes collectively known as the carbon cycle Figure 2.2. The movement (flux) of carbon between the atmosphere and the land and oceans is dominated by natural processes, such as plant photosynthesis. While these natural processes can absorb some of the net 6.1 billion metric tons of anthropogenic carbon dioxide emissions produced each year (measured in carbon equivalent terms), an estimated 3.2 billion metric tons is added to the atmosphere annually. The Earths positive imbalance between emissions and absorption results in the continuing growth in greenhouse gases in the atmosphere.

Given the natural variability of the Earths climate, it is difficult to determine the extent of change that humans cause. In computer-based models, rising concentrations of greenhouse gases generally produce an increase in the average temperature of the Earth. Rising temperatures may, in turn, produce changes in weather, sea levels, and land use patterns, commonly referred to as climate change.



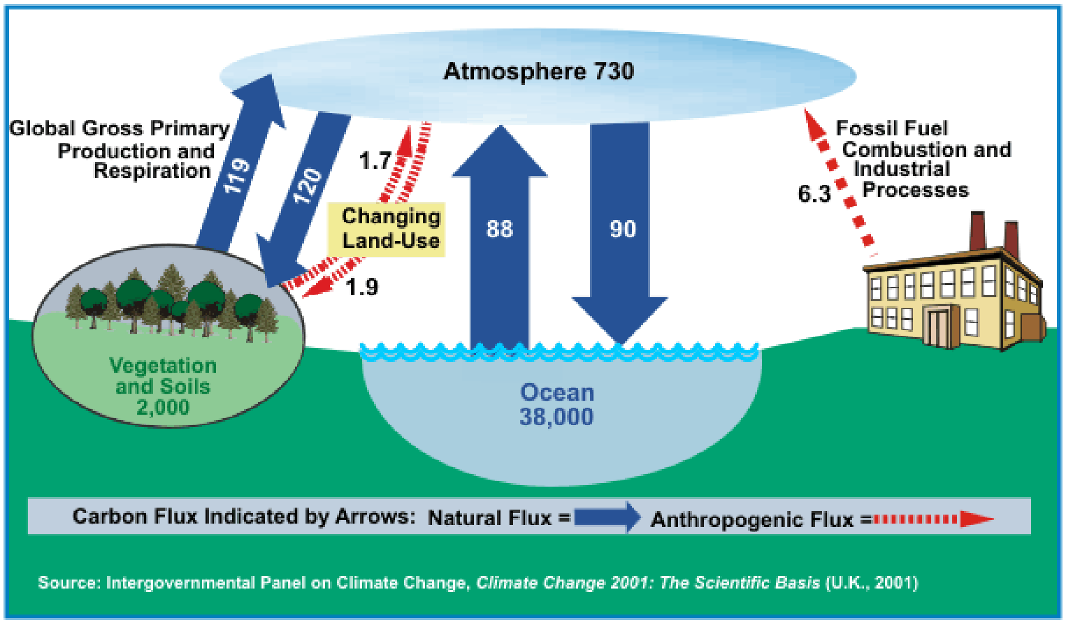
Source: Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center, http://cdiac.esd.ornl.gov/.

Figure 2.1: Atmospheric Concentrations

Assessments generally suggest that the Earths climate has warmed over the past century and that human activity affecting the atmosphere is likely an important driving factor. A National Research Council study dated May 2001 stated, Greenhouse gases are accumulating in Earths atmosphere as a result of human activities, causing surface air temperatures and sub-surface ocean temperatures to rise. Temperatures are, in fact, rising. The changes observed over the last several decades are likely mostly due to human activities, but we cannot rule out that some significant part of these changes is also a reflection of natural variability.

However, there is uncertainty in how the climate system varies naturally and reacts to emissions of greenhouse gases. Making progress in reducing uncertainties in projections of future climate will require better awareness and understanding of the buildup of greenhouse gases in the atmosphere and the behavior of the climate system.

In the U.S., for example, greenhouse gas emissions come mostly from energy use. These are driven largely by economic growth, fuel used for electricity generation, and weather patterns affecting heating and cooling needs. Energy-related carbon dioxide emissions, resulting from petroleum and natural gas, represent 82 percent of total U.S. human-



Source: Intergovernmental Panel on Climate Change, *Climate Change 2001: The Scientific Basis* (U.K., 2001)

Figure 2.2: Emissions flow

made greenhouse gas emissions Figure 2.3.(NEIC 2005) The connection between energy use and carbon dioxide emissions is explored in the box on the reverse side Figure 2.4.

Another greenhouse gas, methane, comes from landfills, coal mines, oil and gas operations, and agriculture; it represents 9 percent of total emissions. Nitrous oxide (5 percent of total emissions), meanwhile, is emitted from burning fossil fuels and through the use of certain fertilizers and industrial processes. Human-made gases (2 percent of total emissions) are released as byproducts of industrial processes and through leakage.

World carbon dioxide emissions are expected to increase by 1.9 percent annually between 2001 and 2025 Figure 2.5. Much of the increase in these emissions is expected to occur in the developing world where emerging economies, such as China and India, fuel economic development with fossil energy. Developing countries emissions are expected to grow above the world average at 2.7 percent annually between 2001 and 2025; and surpass emissions of industrialized countries near 2018.

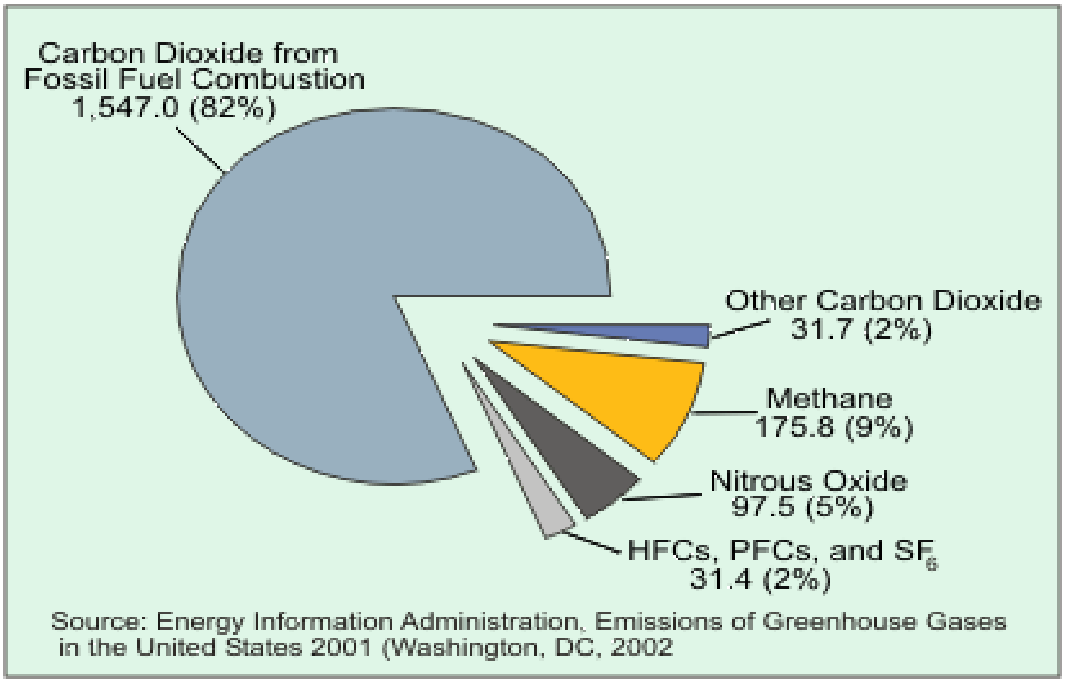


Figure 2.3: Gas emissions

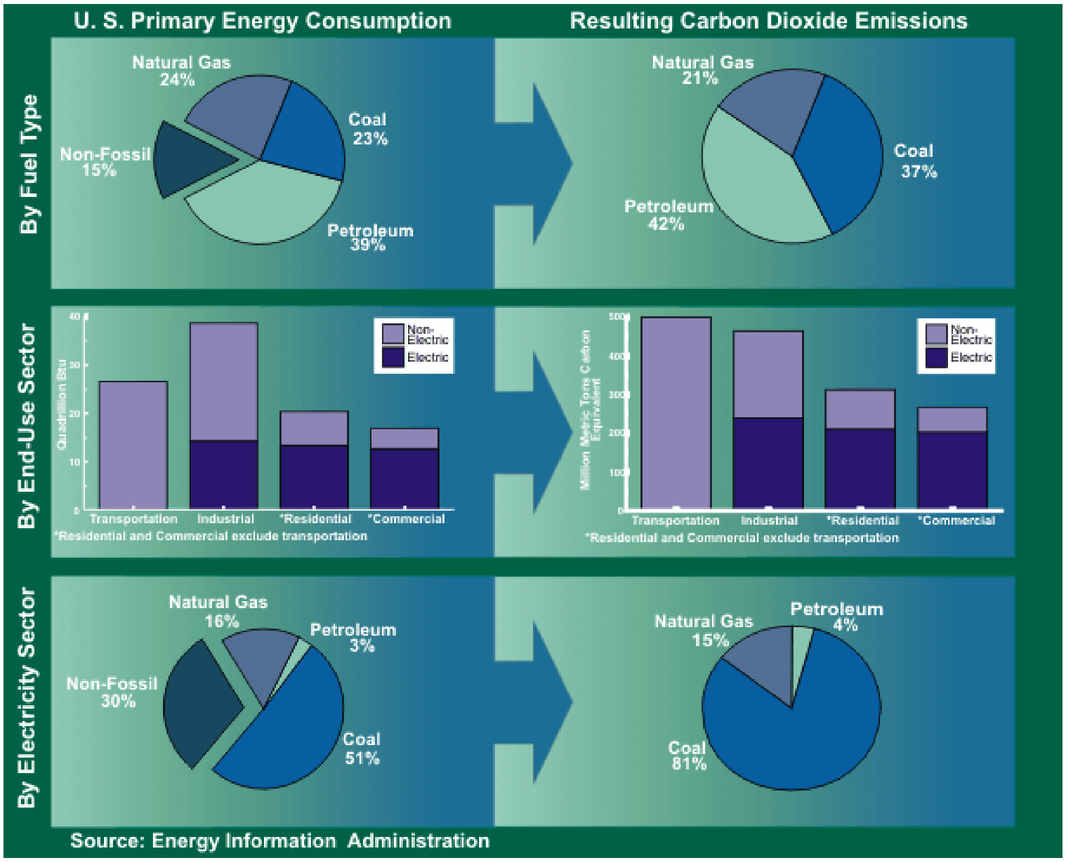
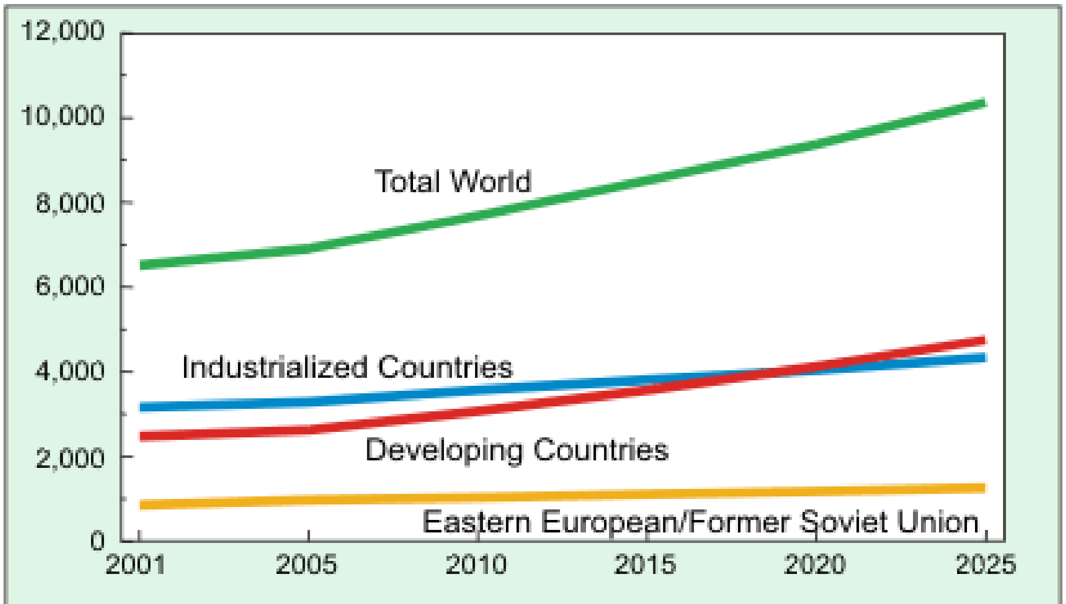


Figure 2.4: US consumption



Source: Energy Information Administration, *International Energy Outlook, 2003* (Washington, DC 2003).

Figure 2.5: World emissions

2.5 Electric Vehicle Description

Electric vehicles, although not currently being produced, may still provide part of the answer to the world's greenhouse gas and fossil fuel deficiency problem. The electric car, EV, or simply electric vehicle is a battery electric vehicle (BEV) that utilizes chemical energy stored in rechargeable battery packs. Electric vehicles use electric motors and motor controllers instead of internal combustion engines (ICEs). Vehicles using both electric motors and ICEs are examples of hybrid vehicles, and are not considered pure BEVs because they operate in a charge-sustaining mode. Hybrid vehicles with batteries that can be charged externally to displace some or all of their ICE power and gasoline fuel are called plug-in hybrid electric vehicles (PHEV), and are pure BEVs during their charge-depleting mode. BEVs are usually automobiles, light trucks, neighborhood electric vehicles, motorcycles, motorized bicycles, electric scooters, golf carts, milk floats, forklifts and similar vehicles.

BEVs were among the earliest automobiles, and are more energy-efficient than internal combustion, fuel cell, and most other types of vehicles. BEVs produce no exhaust fumes, and minimal pollution if charged from most forms of renewable energy. Many are capable of acceleration exceeding that of conventional vehicles, are quiet, and do not produce noxious fumes. It has been suggested that, because BEVs reduce dependence on petroleum, they enhance national security, and mitigate global warming by alleviating the greenhouse effect.

Historically, BEVs and PHEVs have had issues with high battery costs, limited travel distance between battery recharging, charging time, and battery lifespan, which have limited widespread adoption. Ongoing battery technology advancements have addressed many of these problems; many models have recently been prototyped, and a handful of future production models have been announced. Toyota, Honda, Ford and General Motors all produced BEVs in the 90s in order to comply with the California Air Resources Board's Zero Emission Vehicle Mandate, which was later defeated by the manufacturers and the federal government. The major US automobile manufacturers have been accused of deliberately sabotaging their electric vehicle production efforts (Heath 2006).

The price of an EV is set by market factors not cost. For equivalent production volumes battery EVs should be cheaper than internal combustion engine vehicles because they have many fewer parts. This also means they are cheaper to maintain. They are less expensive to operate by a factor of ten over gasoline. Using regenerative braking, a feature which is standard on electric cars, allows hybrids to get about double the fuel efficiency of regular cars.

In general terms a battery electric vehicle is a rechargeable electric vehicle. Other examples of rechargeable electric vehicles are ones that store electricity in ultracapacitors, or in a flywheel.

2.6 Electric Vehicle History

BEVs were among some of the earliest automobiles electric vehicles predate gasoline and diesel. Between 1832 and 1839 (the exact year is uncertain), Scottish businessman Robert Anderson invented the first crude electric carriage. Professor Sibrandus Stratingh of Groningen, the Netherlands, designed the small-scale electric car, built by his assistant Christopher Becker in 1835. The improvement of the storage battery, by Frenchmen Gaston Plante in 1865 and Camille Faure in 1881, paved the way for electric vehicles to flourish. France and Great Britain were the first nations to support the widespread development of electric vehicles (Bellis 2006). In November 1881 French inventor Gustave Trouv demonstrated a working three-wheeled automobile at the International Exhibition of Electricity in Paris (Wakefield 1994).

Just prior to 1900, before the pre-eminence of powerful but polluting internal combustion engines, electric automobiles held many speed and distance records. Among the most notable of these records was the breaking of the 100 km/h (60 mph) speed barrier, by Camille Jenatzy on April 29, 1899 in his 'rocket-shaped' vehicle Jamais Contente, which reached a top speed of 105.88 km/h (65.79 mph).

BEVs, produced in the USA by Anthony Electric, Baker, Detroit, Edison, Studebaker, and others during the early 20th Century for a time out-sold gasoline-powered vehicles. Due to technological limitations and the lack of transistor-based electric technology, the top speed of these early electric vehicles was limited to about 32 km/h (20 mph). These vehicles were successfully sold as town cars to upper-class customers and were often marketed as suitable vehicles for women drivers due to their clean, quiet and easy operation. Electrics did not require hand-cranking to start.

The introduction of the electric starter by Cadillac in 1913 simplified the task of starting the internal combustion engine, formerly difficult and sometimes dangerous. This innovation contributed to the downfall of the electric vehicle, as did the mass-produced and relatively inexpensive Ford Model T, which had been produced for four years, since 1908 (McMahon 2006). Internal-combustion vehicles advanced technologically, ultimately becoming more practical than and out-performing their electric-powered competitors.

Another blow to BEVs in the USA was the loss of Edison's direct current (DC) electric power transmission system in the War of Currents. This deprived BEV users of a convenient source of DC electricity to recharge their batteries. As the technology of rectifiers was still in its infancy, changing alternating current to DC required a costly rotary converter.

Battery electric vehicles became popular for some limited range applications. Forklifts were BEVs when they were introduced in 1923 by Yale (Bellis 2006) and some battery electric fork lifts are still produced. BEV golf carts have been available for many years, including early models by Lektra in 1954 . Their popularity led to their use as neighborhood electric vehicles and expanded versions became available which were partially "street legal".

By the late 1930s, the electric automobile industry had completely disappeared, with battery-electric traction being limited to niche applications, such as certain industrial vehicles.

The 1947 invention of the point-contact transistor marked the beginning of a new era for BEV technology. Within a decade, Henney Coachworks had joined forces with National Union Electric Company, the makers of Exide batteries, to produce the first modern electric car based on transistor technology, the Henney Kilowatt, produced in 36-volt and 72-volt configurations. The 72-volt models had a top speed approaching 96 km/h (60 mph) and could travel nearly an hour on a single charge. Despite the improved practicality of the Henney Kilowatt over previous electric cars, it was too expensive, and production was terminated in 1961. Even though the Henney Kilowatt never reached mass production volume, their transistor-based electric technology paved the way for modern EVs.

After California indicated that it would kill its ZEV Mandate, Toyota offered the last 328 RAV4-EV for sale to the general public during six months (ending on Nov. 22, 2002). All the rest were only leased, and with minor exceptions those models were withdrawn from the market and destroyed by manufacturers (other than Toyota). Toyota not only supports the 328 Toyota RAV4-EV in the hands of the general public, still all running at this date, but also supports hundreds in fleet usage. From time to time, Toyota RAV4-EV come up for sale on the used market, at prices that have ranged up to the mid 60 thousands of dollars. These are highly prized by solar homeowners who wish to charge their cars from their solar electric rooftop systems.

As of July, 2006, there are between 60,000 and 76,000 low-speed, battery powered vehicles in use in the US, up from about 56,000 in 2004 according to Electric Drive Transportation Association estimates.

2.7 Hybrid Electric Vehicle Description

Hybrid electric vehicles are being touted as part of the solution to the greenhouse gas and fossil fuel deficiency problem by the big auto manufacturers. A hybrid electric vehicle (HEV) is a vehicle which combines a conventional propulsion system with an on-board rechargeable energy storage system (RESS) to achieve better fuel economy than a conventional vehicle without being hampered by range from a charging unit like an electric vehicle. The different propulsion power systems may have common subsystems or components.

Regular HEVs most commonly use an internal combustion engine (ICE) and electric batteries to power electric motors. Modern mass produced HEVs prolong the charge on their batteries by capturing kinetic energy via regenerative braking, and some HEVs can use the combustion engine to generate electricity by spinning an electrical generator (often a motor-generator) to either recharge the battery or directly feed power to an electric motor that drives the vehicle. This contrasts with battery electric vehicles which use batteries charged by an external source. Many HEVs reduce idle emissions by shutting down the ICE at idle and restarting it when needed. An HEV's engine is smaller and may be run at various speeds, providing more efficiency.

HEVs are viewed by some automakers as a core segment of the next future automotive market (unknown 2007*a*). In an article for the July-August 2007 issue of THE FUTURIST magazine titled "Energy Diversity as a Business Imperative" (unknown 2007*b*), including plug-in hybrid vehicles, GM vice president for environment and energy Elizabeth Lowery is quoted as saying, "Today, we are embracing multiple energy sources because there is no single answer available for the mass market. In 2007, GM will debut four hybrid modelswith many more in the years to follow."

An overview of the components of a hybrid vehicle is shown Figure 2.6.

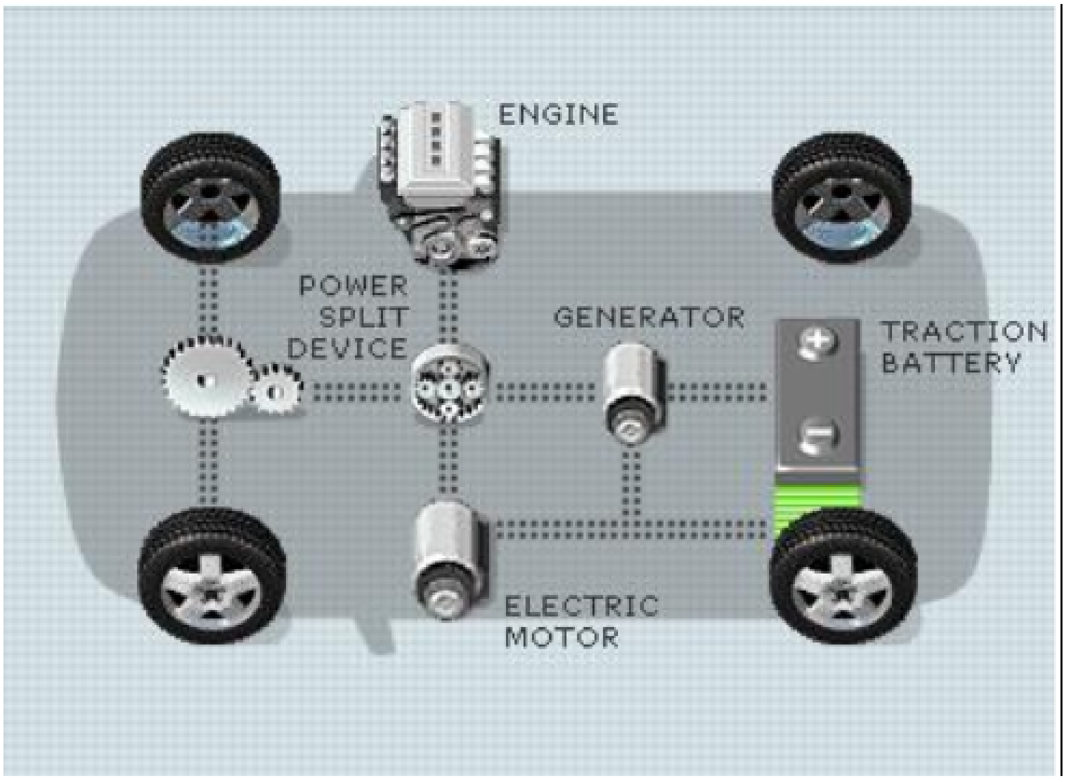


Figure 2.6: Hybrid vehicle overview

2.8 Hybrid Electric Vehicle History

In 1901, while employed at Lohner Coach Factory, Ferdinand Porsche designed the "Mixte", a series-hybrid vehicle based off his earlier "System Lohner-Porsche" electric carriage. The Mixte broke several Austrian speed records, and also won the Exelberg Rally in 1901 with Porsche himself driving. The Mixte used a gasoline engine powering a generator, which in turn powered electric hub motors, with a small battery pack for reliability.

The 1915 Dual Power, made by the Woods Motor Vehicle electric car maker, had a four-cylinder ICE and an electric motor. Below 15 mph (25 km/h) the electric motor alone drove the vehicle, drawing power from a battery pack, and above this speed the "main" engine cut in to take the car up to its 35 mph (55 km/h) top speed. About 600 were made up to 1918 (Georgano 2000).

A more recent working prototype of the HEV was built by Victor Wouk (one of the scientists involved with the Henney Kilowatt, the first transistor-based electric car). Wouk's work with HEVs in the 1960s and 1970s earned him the title as the "Godfather of the Hybrid" (unknown 2006). Wouk installed a prototype hybrid drivetrain into a 1972 Buick Skylark provided by GM for the 1970 Federal Clean Car Incentive Program, but the program was stopped by the United States Environmental Protection Agency (EPA) in 1976 while Eric Stork, the head of the EPA at the time, was accused of a prejudicial coverup (unknown unknown).

The regenerative-braking system, the core design concept of most production HEVs, was developed by Electrical Engineer David Arthurs around 1978 using off-the shelf components and an Opel GT. However the voltage controller to link the batteries, motor (a jet-engine starter motor), and DC generator was Arthurs'. The vehicle exhibited 75 mpgU.S. (3.14 L/100 km / 90.1 mpgimp) fuel efficiency and plans for it (as well as somewhat updated versions) are still available through the Mother Earth News web site. The Mother Earth News' own 1980 version claimed nearly 84 mpgU.S. (2.8 L/100 km / 100.9 mpgimp).

The Bill Clinton administration initiated the Partnership for a New Generation of

Vehicles (PNGV) program on 29 September 1993 that involved Chrysler, Ford, General Motors, USCAR, the DoE, and other various governmental agencies to engineer the next efficient and clean vehicle (Sissine 1996). The NRC cited automakers moves to produce HEVs as evidence that technologies developed under PNGV were being rapidly adopted on production lines, as called for under Goal 2. Based on information received from automakers, NRC reviewers questioned whether the Big Three would be able to move from the concept phase to cost effective, pre-production prototype vehicles by 2004, as set out in Goal 3 (Council 2001). The program was replaced by the hydrogen-focused FreedomCAR initiative by the George W. Bush administration in 2001, (Committee on Science unknown) an initiative to fund research too risky for the private sector to engage in, with the long-term goal of developing effectively emission- and petroleum-free vehicles.

As there are already viable non-fossil fuel dependent vehicles in existence, such as the Mercedes fuel cell cars, hybrid electric vehicles do not represent a long term solution to the problems caused by fossil fuel consumption and should be seen instead as the last desperate throes of an outdated and poisonous technology.

2.9 Battery Types

There are five battery technologies currently considered to be viable or worthy of further consideration for use in the near future. Other technologies are promising but are not considered options for the near future (Autenboer 2005). The five battery technologies being considered, and therefore, analysed in this report are:

1. Lead-acid
2. Nickel cadmium
3. Nickel Metal Hydride
4. Sodium Nickel Chloride
5. Lithium-ion

Information on the other battery technologies has been provided for reference.

Lead-acid batteries

The lead-acid battery was invented by Gaston Plant in 1860. Today, as the oldest and best known electrochemical couple, it is the most widely used traction battery for industrial electric vehicles. In its basic form, the lead-acid battery consists of a negative plate made from lead metal and a positive plate made from brown lead dioxide, submerged in an electrolyte consisting of diluted sulphuric acid. Lead-acid batteries are manufactured in different types and sizes according to their application. For electric vehicle traction purposes the following types are considered: Vented batteries Vented lead-acid batteries are open systems with the electrolyte in liquid form. The vented battery with tubular positive plates is the archetypal traction battery, which is still the most widely used for industrial traction purposes. They may offer a cycle life up to 1500 cycles. This however is only attainable in controlled operating conditions where the batteries receive caring maintenance. The need for maintenance and regular watering makes these batteries less suitable for use in consumer applications; for this reason, their use in electrically propelled road vehicles is limited to heavy-duty fleet vehicles such as buses. In the VRLA (valve-regulated lead-acid) battery, the electrolyte is caught in a gel or in an absorbing glass fibre mat (AGM); water consumption is avoided through the use of hydrogen/oxygen recombination techniques. This battery is maintenance free and does not correct: the battery is not hermetically sealed, but is fitted with a safety valve to release overpressure (e.g. in case of a surcharge). They are more expensive than vented batteries however, and their cycle life is shorter (600- 800 cycles stated by the manufacturers; 300-500 cycles in practical use). Furthermore, they are sensitive to deep discharges and surcharges and should only be used with specially designed battery chargers. The last few years, advanced VRLA designs have been developed combining high current discharge and deep cycling capabilities; such batteries are being proposed as cost-effective solutions for electrically propelled vehicles.

Alkaline batteries

Batteries with alkaline electrolytes have been developed starting from the late 19th century. Most of these batteries use nickel oxide as positive plate material, with negative plates based on cadmium, iron, zinc, or hydrogen (the latter under form of metal hydrides).

Nickel-Iron battery

Nickel-iron batteries were popular in the early 20th century, due to their higher specific energy and longer cycle life compared to lead-acid batteries. They received a renewed interest during the 1980s, but have now been completely abandoned due to their poor lowtemperature performance and poor energy efficiency resulting in unacceptably high water consumption.

Nickel-Cadmium battery

The nickel-cadmium battery also presents a positive electrode made from nickel oxide; the negative electrode however is made of metallic cadmium. The electrolyte consists of a lye solution of potassium hydroxide with an addition of lithium hydroxide, the latter having a stabilizing effect during cycling. The nominal cell voltage is 1.2 Volt. Its historic development was parallel to nickel-iron and it offers the same characteristics as nickel-iron, such as a quite high specific energy compared to lead-acid, a good resistance to abuse and a long cycle life. Its particular advantages however are a better operation at low temperatures, a slower self-discharge and a higher electrical efficiency leading to less maintenance and water consumption. Traditionally, nickel-cadmium batteries have been manufactured with steel jars and pocketplates; in order to decrease weight and thus increase Specific Energy for demanding applications like electric vehicles, advanced plate designs have been proposed. The sintered electrode design makes use of a porous mass of active material (nickel powder) sintered on a steel grid. This process is used by SAFT in France. The elements are packed in polymer jars, either as single cells or as monoblocs, the latter design being the favourite one for electric vehicles. The single cells have widespread applications as railway and aircraft batteries. Another technology makes use of fibrous electrodes consisting of porous conductive fibres which contain active material. These types of batteries have known limited use for electric vehicle applications however. The sintered electrode nickel-cadmium batteries are fitted on most of the electric vehicles now present on the European market. They present quite interesting opportunities for this application: good cycle life and specific power, ability for fast charging and operating in a wide temperature range. The current cost of these batteries remains high however; this fact has caused several electric vehicle manufacturers, particularly in the USA and Japan, not to consider the use of this battery. Furthermore, the toxicity of cadmium has been cited as an aspect affecting the acceptation of this battery.

Nickel Zinc battery

The nickel-zinc battery uses the same type of positive electrode as the nickel-iron and nickelcadmium, this time with a metallic zinc negative plate. One of its advantages is the higher cell voltage (1.6 V) compared with other alkaline battery types. This allows a specific energy 25 per cent higher than nickel-cadmium. Nickel-zinc has been the subject of extensive research focusing on its application in electric vehicles. The main drawback of this electrochemical couple however proved to be its unacceptably short cycle life, which is a result of the formation of zinc dendrites on the negative electrode during charging. These dendrites will eventually perforate the separator and short the cell. A number of research projects on nickel-zinc batteries has been performed in the USA, Korea and the former USSR. A recent research project (PRAZE) funded by the EU aimed at the development of advanced nickel-zinc batteries for use in electric scooters. Although promising results were obtained with the prototype cells, this research has not been continued however due to the French company involved, Sorapec, ceasing its activities. Recent work on nickel-zinc is being performed by SCPS in France. At this moment, they claim promising results as to cycling ability and lifetime; the research is at this time still focused at the cell level however and complete batteries have not yet been experimented for deployment in vehicles. The nickel-zinc battery can thus not yet be considered as a commercial product for electric vehicle applications in a short-term future.

Nickel Metal Hydride battery

The use of hydrogen as negative active material gives a good energy to weight ratio. Storing and maintaining hydrogen gas can be cumbersome however; to this effect, hydrogen can be stored in metal alloys, and thus one obtains the nickel-metal-hydride battery. The alloys used for this purpose are mostly proprietary, and are usually of the types AB5 (e.g. LaNi5) or AB2 (e.g. TiN2). Nickel-metal hydride batteries possess some characteristics making them suitable for use in electrically propelled vehicles. The fact that they are cadmium free is a selling argument in some markets where the use of cadmium is seen as an environmental concern. From a technical viewpoint however, their specific energy is somewhat higher than nickel-cadmium, and; furthermore, they are well suited to fast charging. A disadvantage however is their tendency to self-discharge, due to hydrogen diffusion through the electrolyte. Furthermore, high-current operation during charging (which is an exothermic reaction), makes thermal management and cooling of these batteries essential. Because of this, they have been subject of substantial research and development activities aiming at electrically propelled vehicles. Their use for battery-electric vehicles has been limited however, with only some small series (a few hundred vehicles in the last years) being manufactured and few research efforts being continued. On the other hand, the nickel-metal-hydride is used in advanced hybrids, due to its excellent specific power abilities. It fits commercially available hybrids today like the Toyota Prius. The battery for hybrid use is a power-optimized battery, the design of which reflects the experience gathered with the portable nickel metal hydride battery. This battery is now produced in large series as a commercial product for hybrid vehicles.

Lithium batteries

Lithium is the lightest metal element known and is under full consideration for high energy batteries. Several secondary battery technologies using lithium have been developed.Lithium-ion batteries work through the migration of lithium ions between a carbon anode and a lithium metal oxide alloy cathode. The electrolyte is an organic solution; no metallic lithium is used. Lithium-ion batteries have been proposed for both battery-electric vehicles, where they benefit of their excellent specific energy of up to 200 Wh/kg, and hybrid vehicles, making use of cells specifically designed for high power, where values up to 2000 W/kg can be reached. In the lithium-polymer technology, the electrolyte is a solid conductive polymer, the batteries are completely dry and do not contain liquid electrolytes. Several chemistries are being proposed: the lithium-ion-polymer battery, which does not contain metallic lithium and has a chemistry comparable to the lithium-ion battery;the lithium-metal-polymer battery, where the negative electrode consists of metallic lithium foil. This battery is now being commercially manufactured for stationary purposes, but has also been considered for traction. One main issue to be considered somewhat more acutely with lithium batteries compared to other battery technologies is safety. Lithium is very reactive, and abuse conditions such as crashes, fires and excessive temperature rises may cause uncontrolled energy releases which create hazardous situations. The implementation of cell-level management and control systems is thus a dire necessity for any lithium-based system. Although lithium batteries have taken a considerable share of the portable battery market, one has to recognize that high-power applications such as traction present different challenges. Lithium batteries for traction are now available as prototypes and are on the brink of series production; further optimisation as to life, system safety and stability and production cost is still being performed however, and the lithium systems can today not be considered yet as a fully commercially available product.

Sodium-Nickel-Chloride Battery

The sodium-nickel-chloride battery (known under its brand name Zebra) is characterised by its high operating temperature. It presents interesting opportunities for electrically propelled vehicles due to its high specific energy of typically 100 Wh/kg. The electrodes of this battery consist, in charged state, of molten sodium and molten nickel chloride; the electrolyte is a solid aluminium oxide ceramic. In discharged state, the electrodes are sodium chloride and nickel. Batteries consist of individual cells enclosed in a thermally insulating package. During cycling of the battery, internal resistive losses allow maintaining the operating temperature of 270 C; cooling even becomes necessary when temperature exceeds 330 C. When the battery is standing idle for prolonged periods (exceeding 24 hours), additional heating (typically using 100 W power per battery) is needed to keep the battery warm. Due to this need for additional heating during standstill, the Zebra battery will see its most efficient use in vehicles which are deployed daily and intensively such as public service vehicles and fleet vehicles. These batteries have been successfully implemented in several electric vehicle designs, and present interesting opportunities for fleet applications. The sodium-nickel-chloride battery is fore mostly an energy battery and thus primarily suitable for battery-electric vehicles; its specific power being rather modest for hybrid applications.

Metal-air batteries

Metal-air batteries, such as zinc-air and aluminium-air, are not strictly secondary rechargeable electric batteries, but should rather be considered as fuel cells which are recharged with new metal electrodes. Particularly the zinc-air battery has been experimented in electric vehicle applications. The main advantage of these batteries is their high specific energy, which can exceed 200 Wh/kg, well in excess of conventional battery types. The specific power, at most 100 W/kg, is rather modest however. The main drawback of this battery system is the burden associated with physically replacing spent electrodes in order to recharge the battery. This creates in fact the necessity to establish a logistic circuit involving the collection, regeneration and redistribution of electrodes. Furthermore, the energetic efficiency of the electrolytic regeneration process is limited. All these factors have impeded the widespread deployment of these batteries and make that they cannot be considered as commercial contenders for general use in electrically propelled vehicles.

Redox batteries

Redox batteries are complex electrochemical systems with circulating electrolytes. The heart of the system can be considered as a reversible fuel cell stack, able at both generating electricity from the electrochemical reaction of the electrolytes (discharge), and restoring the original composition of the electrolyte through the injection of electric current (charge). A well-known example of redox battery is the zinc-bromine battery, which has been experimented in electric vehicle systems giving typical values of 80 Wh/kg for specific energy and 100 W/kg for specific power. Despite these values, the complexity of the system and its needs for ancillary equipment have been major drawbacks for further consideration of these couples for actual vehicle traction purposes (Autenboer 2005).

2.10 Life Cycle Analysis

Life cycle assessment (LCA) is a methodology for assessing the environmental aspects associated with a product over its life cycle. The most important applications are:

1. Analysis of the contribution of the life cycle stages to the overall environmental load, usually with the aim to prioritise improvements on products or processes.

2. Comparison between products for internal or external communications.

LCA is a relatively young method that became popular in the early nineties. Initially many thought that LCA would be a good tool to support environmental claims that could directly be used in marketing. Over the years, it has become clear that this is not the best application for LCA, although it is clearly important to communicate LCA results in a careful and well-balanced way. In recent years life cycle thinking has become a key focus in environmental policy making. A clear example is the concept of IPP (Integrated Product Policy) as communicated by the EU. Also in Asia (China: Circular Economy) and the Americas many countries develop strategies that promote life cycle thinking as a key concept. Another development is the sustainability reporting movement. The majority of the Fortune 500 companies now report on the sustainability aspects of their operations. In recent years we have also seen a sharp increase in the development of Environmental Product Declarations or EPDs. LCA provides the more quantitative and scientific basis for all these new concepts. In many cases LCA feeds the internal and external discussions and communications. Being active in LCA means to be able to communicate the environmental impacts of products and business processes.An interesting survey on how LCA is used shows that the most common reasons for the application of LCA are for internal purposes, like product improvement, support for strategic choices and benchmarking . External communication is also mentioned as application, but often this communication is indirect. The LCA report is not published but key findings are reported. The most important pitfall in the implementation of LCA turns out to be the lack of a clear definition of the purpose and application of LCA. In many companies, the marketing department is the initiator, as it would like to show the environmental benefits of products, but usually the marketing department finds out that LCA results are difficult to communicate. Often others, usually the R and D or the environmental department, take over the role of the initiator, and this can create some confusion regarding the exact purpose of the LCA project. The most frequently encountered pattern in the early stages of LCA implementation is the start-up of an ad-hoc project. The most important goal is to learn what LCA is, what one can learn from it and how reliable the results seem. This learning attitude is important. Learning is often more important than the result of the first LCA. According to the study of Frankl and Rubik, an interesting situation occurs if the first LCA gives strange or unexpected results. In some organisations, the result is seen as a reason to disqualify the usefulness of LCA as a tool. Other organisations use the unexpected result as a positive learning experience. After this first study is done companies decide whether they want to continue, and adopt a more structured approach. Success factors of LCA implementation are:

1. A clear description of the reason for using LCA.

2. A clear definition of the way LCAs are to be communicated, both internally and externally.

3. A reasonable budget.

The goal of LCA is to compare the environmental performance of products and services, to be able to choose the least burdensome one. The term 'life cycle' refers to the notion that a fair, holistic assessment requires the assessment of raw material production, manufacture, distribution, use and disposal including all intervening transportation steps. This is the life cycle of the product. The concept also can be used to optimize the environmental performance of a single product (ecodesign) or to optimize the environmental performance of a company. The pollution caused by usage also is part of the analysis. Common categories of assessed damages are global warming (greenhouse gases), acidification, smog, ozone layer depletion, eutrophication, ecotoxic and anthropotoxic pollutants, desertification, land use as well as depletion of minerals and fossil fuels.

Cradle-to-grave

Cradle-to-grave is the LCA of the materials used in making a product, from the extraction of materials and energy to the return of the materials to earth when the product is finally discarded. For example, trees produce paper, which is recycled into low-energy production cellulose (fiberised paper) insulation, then used as an energy-saving device in the ceiling of a home for 40 years, saving 2,000 times the fossil-fuel energy used in its production. All inputs and outputs are considered for all the phases of the life cycle.

Cradle-to-gate

Cradle-to-gate is the LCA of the efficiency of a product or service until it is produced or delivered. It shows the environmental performance as it is. It often is used for environmental product declarations (EPD).

Cradle-to-Cradle

Cradle-to-cradle is a way of thinking about life cycles. If the grave of one cycle can be the cradle of its own or another, the life cycles are called ”cradle-to-cradle”.

2.10.1 The Four Main Phases of Life Cycle Assessment

An LCA study consists of four steps:

1. Defining the goal and scope of the study.

2. Making a model of the product life cycle with all the environmental inflows and outflows. This data collection effort is usually referred to as the life cycle inventory (LCI) stage.

3. Understanding the environmental relevance of all the inflows and outflows. This is referred to as the life cycle impact assessment (LCIA) phase.

4. The interpretation of the study.

The main technique used in LCA is that of modelling. In the inventory phase, a model is made of the complex technical system that is used to produce, transport use and dispose of a product. This results in a flow sheet or PROCESS TREE with all the relevant processes. For each process, all the relevant inflows and the outflows are collected. The result is usually a long list of inflows and outflows that is often difficult to interpret. In the life cycle impact assessment phase, a completely different model is used to describe the relevance of inflows and outflows. For this, a model of an environmental mechanism is used. For example, an emission of SO2 could result in an increased acidity. Increased acidity can cause changes in the soil that result in dying trees, etc. By using several environmental mechanisms, the LCI result can be translated into a number of impact categories such as acidification, climate change etc. A usually highly controversial issue is the weighting of impact categories, as this is a subjective issue.

Goal and scope

In the first phase, the LCA-practitioner formulates and specifies the goal and scope of study in relation to the intended application. The object of study is described in terms of a functional unit. Apart from describing the functional unit, the goal and scope, should address the overall approach used to establish the system boundaries. The system boundary determines which unit processes that are included in the LCA, and must reflect the goal of the study. In recent years, two approaches to system delimitation have emerged. These are often referred to as consequential modeling and attributional modeling. Finally the goal and scope phase includes a description of the method applied for assessing potential environmental impacts and which impact categories that are included.

Life Cycle Inventory

This second phase 'Inventory' involves modelling of the product system, data collection, as well as description and verification of data. This implies data for inputs and outputs for all affected unit processes that compose the product system. The inputs and outputs include inputs of materials, energy, chemicals and 'other' - and outputs in the form of air emissions, water emissions or solid waste. Other types of exchanges or interventions such as radiation or land use should also be included.

The data must be related to the functional unit defined in the goal and scope definition. Data can be presented in tables and some interpretations can be made already at this stage. The results of the inventory is an LCI which provides information about all inputs and outputs in the form of elementary flow to and from the environment from all the unit processes involved in the study.

Life Cycle Impact Assessment

The third phase 'Life Cycle Impact Assessment' is aimed at evaluating the contribution to impact categories such as global warming, acidification etc. The first step is termed characterization. Here, impact potentials are calculated based on the LCI results. The next steps are normalization and weighting, but these are both voluntary according the ISO standard. Normalization provides a basis for comparing different types of environmental impact categories (all impacts get the same unit). Weighting implies assigning a weighting factor to each impact category depending on the relative importance.

Interpretation

The phase stage 'interpretation' is the most important one. An analysis of major contributions, sensitivity analysis and uncertainty analysis leads to the conclusion whether the ambitions from the goal and scope can be met. More important; what can be learned form the LCA? All conclusions are drafted during this phase. Sometimes an independent critical review is necessary, especially when comparisons are made that are used in the public domain.

As with all models of reality, one must understand that a model is a simplification of reality, and as with all simplifications, this means that the reality will be distorted in some way. The challenge for the LCA practitioner is thus to develop the models in such a way that the simplifications and thus distortions do not influence the result too much.The best way to deal with this problem is to carefully define a goal and scope of the LCA study before you start. In the goal and scope the most important (often subjective) choices are described, such as:

1. The reason for executing the LCA, and the questions which need to be answered.

2. A precise definition of the product, its life cycle and the function it fulfils.

3. In case products are to be compared, a comparison basis is defined (functional unit).

4. A description of the system boundaries.

5. A description of the way allocation problems will be dealt with.

6. Data and data quality requirements.

7. Assumptions and limitations.

8. The requirements regarding the LCIA procedure, and the subsequent interpretation to be used.

9. The intended audiences and the way the results will be communicated.

10. If applicable, the way a peer review will be made.

11. The type and format of the report required for the study.

The goal and scope definition is a guide that helps you to ensure the consistency of the LCA you perform. It is not to be used as a static document. During the LCA, one can make adjustments if it appears that the initial choices are not optimal or practicable. However, such adaptations should be made consciously and carefully.

Defining the goal

It is obvious any LCA study should have goal. However, in ISO there are some particular requirements to the goal definition:

1. The application and intended audiences shall be described unambiguously.

This is important, as a study that aims to provide data that is applied internally can be quite differently structured than a study that aims at making public comparisons between two products. For example, in the latter case, ISO states weighting may not be used in impact assessment and a peer review procedure is necessary. Thus, it is important to communicate with interested parties during the execution of the study. The reasons for carrying out the study should be clearly described. Is the commissioner or practitioner trying to prove something, is the commissioner intending to provide information only, etc.

Some LCA studies serve more than one purpose. The results may both be used internally and externally. In that case, the consequences of such double use should be clearly described. For example, it could be that different impact assessment methods are used for the internal or external versions of the study.

Defining the Scope

The scope of the study describes the most important methodological choices, assumptions and limitations, as described below. As LCA is an iterative procedure, the term initial is added to most of the paragraphs below. This means one starts with initial choices and initial requirements that can be adapted later when more information becomes available.

Functional unit and reference flow

A particularly important issue in product comparisons is the functional unit or comparison basis. In many cases, one cannot simply compare product A and B, as they may have different performance characteristics. For example, a milk carton can be used only once, while a returnable milk bottle can be used ten or more times. If the purpose of the LCA is to compare milk-packaging systems, one cannot compare one milk carton with one bottle. A much better approach is to compare two ways of packaging and delivering 1000 litres of milk. In that case one would compare 1000 milk cartons with about 100 bottles and 900 washings (assuming 9 return trips for each bottle). Defining a functional unit can be quite difficult, as the performance of products is not always easy to describe. For example, what is the exact function of an ice cream, a car sharing system, or a holiday?

Initial system boundaries

Product systems tend to be interrelated in a complex way. For example, in an LCA on milk cartons, trucks are used. However, trucks are also products with a life cycle. To produce a truck steel is needed, to produce steel, coal is needed, to produce coal, trucks are needed etc. It is clear that one cannot trace all inputs and outputs to a product systems, and that one has to define boundaries around the system. It is also clear that by excluding certain parts as they are outside the system boundaries, the results can be distorted. It is helpful to draw a diagram of the system and to identify the boundaries in this diagram. As in energy analysis, one can distinguish three orders:

1. First order: only the production of materials and transport are included (this is rarely used in LCA).

2. Second order: All processes during the life cycle are included, but the capital goods are left out.

3. Third order: Now the capital goods are included. Usually the capital goods are only modelled in a first order mode, so only the production of the materials needed to produce the capital goods are included.

What is aboundary in nature? For example, in an LCA on paper it is important to decide if the growing of a tree is included. If it is, one can include the CO2 uptake and the land use effect. In agricultural systems, it is important to decide if agricultural areas are seen as a part of nature or as a production system (technosphere). If this is seen as nature, all pesticides that are applied are to be seen as an emission. If agricultural areas are seen as an economic system, one can exclude the pesticides that remain in the area, and only include the pesticides that leach out, evaporate or that are accidentally sprayed outside the field.

Criteria for inclusion of inputs and outputs Apart from the criteria for system boundaries, one can use a certain threshold below which you consider it useless to collect data for an inflow or an outflow. ISO 14041 recommends using one or more of the following bases for such a threshold:

1. If the mass of the inflow is lower than a certain percentage. The problem is of course that this only works for materials and not for transport distances and energy.

2. If the economic value of an inflow is lower than a certain percentage of the total value of the product system. The problem with this and the previous approach is that

flows with a low value or low mass could have significant environmental impacts.

3. If the contribution from an inflow to the environmental load is below a certain percentage. This seems the most relevant choice, but the problem is that one cannot really know the environmental contribution before the flow is investigated. Once it is investigated, one may wonder why it should not be used. Another problem is the use of the term the environmental load, as ISO has not defined this, and it is not so clear if the use of single scores is permitted. If not, one must determine the contribution of a flow against all relevant data and impact categories, which can be quite complex procedure. Recently the use of input output data has been suggested as a viable way to estimate the missing environmental load. Such tables provide environmental load per unit of costs, so if one knows the costs associated flow (option 2), an estimate of the environmental load can be made, as in option 3.

Allocation

Many processes usually perform more than one function or output. The environmental load of that process needs to be allocated over the different functions and outputs. There are different ways to make such an allocation. ISO recommends the following procedure in order to deal with allocation issues:

1. Avoid allocation, by splitting the process in such a way that it can be described as two separate processes that each has a single output. Often this is not possible, for example wooden planks and saw dust are both an economic outputs of a saw mill, but one cannot split the sawing process into a part that is responsible for the saw dust and one that is responsible for the planks.

2. Another way to avoid allocation is to extend the system boundaries and by including processes that would be needed to make a similar output. For example, if a usable quantity of steam, produced as a by-product, is used in such a way that it avoids the production of steam by more conventional means, one may subtract the environmental load of the avoided steam production. A practical problem is often that it is not always easy to say how the steam would be produced alternatively.

3. If it is not possible to avoid allocation in either way, the ISO standard suggests

allocating the environmental load based on a physical causality, such as mass or energy content of the outputs. For example if the sawdust represents 40 per cent of the mass, one can allocate 40 per cent of the environmental load to sawdust. In the case of allocating steam, we believe the mass of the steam is not a very relevant basis.

4. If this procedure cannot be applied, ISO suggests using a socio-economic allocation basis, such as the economic value. For example if the saw dust represents 20 per cent of the value generated by the saw mill one can allocate 20 per cent of the environmental load to this output. Although ISO mentions the socio-economic basis as a last resort, it is used often. The advantage is that economic value is a good way to distinguish waste (no or negative value) from an output, and it expresses the relative importance of an output.

It is important to determine in advance what type of data you are looking for. In some studies you would like to get an average of all steel producers in the whole world. In other studies you would like to have only data from a single steel producer or from a group of Electro steel producers in Germany. Likewise, you should determine if you want data on average, modern, or worst case technology. Other data quality issues are completeness, consistency and reproducibility.

Inventory

The most demanding task in performing an LCA is data collection. However much data is available in our database you will usually find that at least a few processes or materials are not available, or the available data is not representative. Depending on the time and budget you have available, there are a number of strategies to collect such data. It is useful to distinguish two types of data:

1. Foreground data

2. Background data Foreground data refers to specific data you need to model your system.

It is typically data that describes a particular product system and particular specialised production system. Background data is data for generic materials, energy, transport and waste management systems. This is typically data you can find in databases and literature. The distinction between these data types is not sharp and depends on the subject of your LCA. If you are making an LCA on dishwashers, you will consider the truck that is used to deliver the dishwasher as background data. There is noting special about the truck, and there is no need to collect other data than the transport distance and the load efficiency. The emissions you take from the standard databases. However, if you are making an LCA of trucks you can not use the standard truck, and you will have to investigate the emissions. In the first case one would consider the truck as background data, in the second case the truck becomes foreground data.

Foreground data collection

In many cases you will have to collect foreground data from specific companies. Most frequently one or more questionnaires are to be made to collect such data. It is important to establish good contacts with the persons that are supposed to fill in the questionnaire and to understand what these persons know, in what way data is available and what terminology is used.

Background data

Often 80 per cent of the data you need is background information that you do not have to collect via questionnaires, as they are readily available in databases, or can be found in literature or internet. Using background data requires great care, as you have not personally collected the data. This means you must investigate how well the data in databases are in line with the requirements you defined in the goal and scope. Below we describe the two most important data sources available for the LCA community.

Social aspects

Social aspects relate to issues as working conditions and social security, political oppression, jobs created, and for instance the right to join unions. The problem with assessing social issues is that the issues at stake are wide-ranging and often difficult to quantify in a meaningful way. This explains why there is no ISO standard for these aspects. An important initiative to bring some form of standardisation on how to manage and report on social issues is the Global Reporting Initiative (GRI). This organisation is developing more or less standard lists of social issues to keep track of. Also the GRI acknowledges that there can be big differences between sectors and even individual companies.

Economic aspects

The possibility of adding economic aspects to LCA methodology has been discussed among researchers for over ten year, but often these debates are confused and not really productive. The problems with adding cost and revenues to LCA models are numerous: Important cost factors like investment, research, overheads and marketing are usually not modelled or at least under-represented in an LCA model. LCA does not have a time perspective, so it is difficult to model interest rates The precision requirements for cost and revenue calculations are high. An error in the calculation of a sales margin of a few percent can be fatal. This is why many companies employ a lot of people to keep track of market prices, exchange rates and sales margins. It is not realistic to assume that an LCA expert can improve on this.

Total cost assessment

Probably the most productive approach is to express social and environmental issues in terms of liabilities and intangible costs. For instance, bad publicity about a company caused by the discovery that child labour is involved can be damaging to a companys reputation. Likewise, the environmental damage of a mine in a protected area can be costly. In Total Cost Assessment a systematic procedure is used to estimate such costs and to estimate the probability that the costs occur. Based on these factors a total average cost connected to sustainability issues can be determined.

Impact assessments

Most LCA experts do not develop impact assessment methodologies, they prefer to select one that has been published. Like in the inventory stage, also in impact assessment the Goal and Scope definition is the most important source of guidance for the selection of the method and the impact categories. The most important choice you make is the desired aggregation level of the results. This usually depends on the way you would like to address your audience, and the ability of your audience to understand detailed results.

An important step is the selection of the appropriate impact categories. The choice is guided by the goal of the study. An important help in the process of selecting impact categories is the definition of socalled endpoints. Endpoints are to be understood as issues of environmental concern, like human health, extinction of species, availability of resources for future generation etc. ISO does not recommend using certain endpoints, but requires a careful selection and definition of endpoints first. After that impact categories can be selected, as long as the environmental model that links the impact category to the endpoint is clearly described. It is not necessary to describe this link quantitatively.

Classification

The inventory result of an LCA usually contains hundreds of different emissions and resource extraction parameters. Once the relevant impact categories are determined, these LCI results must be assigned to these impact categories. For example CO2 and CH4 are both assigned to the impact category Global warming, while SO2 and NH3 are both assigned to an impact category Acidification. It is possible to assign emissions to more than one impact category at the same time. For example SO2 may also be assigned to an impact category like Human health, or Respiratory diseases.

Characterisation

Once the impact categories are defined and the LCI results are assigned to these impact categories, it is necessary to define characterisation factors. These factors should reflect the relative contribution of an LCI result to the impact category indicator result. For example, on a time scale of 100 years the contribution of 1 kg CH4 to global warming is 42 times as high as the emission of 1 kg CO2. This means that if the characterisation factor of CO2 is 1, the characterisation factor of CH4 is 42. Thus, the impact category indicator result for global warming can be calculated by multiplying the LCI result with the characterisation factor. (Goedkoop 2007)

2.11 SimaPro

In SimaPro, a special section is available to describe the goal and scope for each project. There are three sections:

1. Text fields, in which you can describe the different aspects required for a goal and scope definition. The texts entered here can later be copied and pasted into your report.

2. A libraries section. Here you can predefine which libraries with standard data you consider appropriate for the project you want to run. For example, if your LCA is to be relevant for Europe, you can switch of the USA-IO database that is supplied with some versions of SimaPro. By switching this library off, you will not see the data while you are running the project. This avoids accidental inclusion of data you do not want.

3. A data quality section. Here you can define the data characteristics you want. After defining your data requirements, you will see that the DQI field in the process indexes will have different colours: Green means that a process matches exactly with your requirements, yellow means there is a small mismatch, orange means there is a considerable mismatch, while red indicates there are big deviations. With these three sections, you have a guide in making a consistent LCA study in line with the ISO guidelines.

If you want to study the effect of different system boundaries, you can use the parameters in SimaPro to switch boundaries. For instance if you are modelling an injection moulding process, you can estimate the amount of steel in the mould (lets say 100 kg), and divide this by the number of products that is expected to be made with that mould (lets say 10.000 products). The result is the steel amount that is allocated to a product (in this example 10 gram). In SimaPro you can enter this amount of steel as an input to the injection moulding process. However, instead of entering 10 gram as an amount, you can enter the simple formula: S*10gram. Before you calculate, you can determine a value for S. If you choose a value of 1, you include the metal, if you choose zero, you ignore the metal. The real power of this application is when you use this switch in many different places, so by controlling one parameter you can change the system boundary throughout your dataset.

The effect of using cut-off criteria can be analysed in the process tree or network window in SimaPro. In many LCAs, process trees become very large. LCAs with over 2000 processes are no exception. These process trees contain many processes that are not contributing much. This can be illustrated by setting the cut-off threshold for displaying processes in the process tree at 0.1 per cent of the environmental load (for a single score or an impact category). In most cases, only 10 to 30 processes turn out to have a contribution that is above this threshold. Now it becomes much easier to see the relevant issues in the process tree. A similar function can be found in the process contribution analysis function in SimaPro. This function gives you the relative contribution per process in a list of processes. A process that is used more than once may have a small contribution in each time it is displayed in the tree (instance), but the total contribution of all instances can still be significant. Contribution analysis shows this total contribution. The SimaPro database contains input output databases that can be used to estimate missing impacts.

In SimaPro each process can have multiple outputs and avoided outputs at the same time. This means you can combine system boundary expansion and direct allocation in any way you like. Behind each multiple output, you can add a percentage that indicates the allocation share. When you allocate the environmental load of a wood saw mill over the main products planks and sawdust, you can allocate 50 per cent to the planks and 50 per cent to the sawdust (ignoring other byproducts). This is when you use mass as allocation basis. If you use an economic allocation basis, you could allocate 80 per cent to planks and 20 per cent to wood, as the value of planks is much higher than the value of sawdust. The sum of the allocation percentage must of course be 100 per cent. It is up to you to decide on which principle you base this allocation percentage. We advise you to document how you determined an allocation percentage.

Allocation percentages can also be expressed using parameters. These parameters can be controlled on a database or project level. This means you can easily change allocation parameters and rerun the LCA to see how the allocation influences the result. In case you use economic allocation, you are often confronted with significant uncertainties in the prices you base the allocation on. If you define the allocation percentages as parameters, you can also define an uncertainty range (see Chapter 10). If you use uncertainty data in allocation parameters, you must of course be sure that the total of all allocation parameters is 100 per cent. If you would just specify the uncertainty in both allocation percentages, you would be unable to guarantee this. A simple solution is to use a formula. If the allocation percentage for product A is defined as a, you can set the allocation percentage for product B as b=(1-a).

In SimaPro you can define a profile of the data you would like to get, the Data Quality Requirements. In that profile, you can define your preference for:

1. Time of data collection
2. Region
3. Representatively and type of technology
4. Allocation
5. System boundaries

If you fill in these characteristics in each process you make, you can keep track of mismatches between what you wanted and what you made.

The (background) data in SimaPro are structured in such a way that you can distinguish between data that is relevant for your current LCA project only, and data that can be useful in any other (future) project. The latter type of data is not stored in projects but in libraries. Professional SimaPro versions (excluding the 2 months temporary licenses) include the comprehensive ecoinvent libraries. These libraries contain over 2700 processes, covering a wide range of processes. The forthcoming release of ecoinvent version 2 will contain some 3500 processes. While performing your LCA, you enter all the new data in the project and not in the library. If you need data from the library, you can make a link to that data. If you want to edit the library data, you copy it into your project and edit the copy only. If you have collected data that could be useful for other projects, you can move it to a library. In this way, you can gradually build up high quality data in your libraries, while you have all the flexibility you need in the projects.

SimaPro contains a detailed input output database that has over 500 commodities, representing the entire USA economy. This so called USA Input Output 98 database has been licensed from CML Leiden. It was compiled by Sangwon Suh, who used a wide variety of US data sources. The database is in many ways unique compared to earlier input output databases, as it also includes estimates for diffuse emissions and small and medium sized industries. These are quite important but often missing. More information can be found in the database manuals. These are supplied as PDF, and can also be accessed via the help menu of SimaPro. Below we show the Input output database for banking services. The output unit is one dollar banking services provided. In the first network, we show the economic flows, without showing any environmental data, so the line thickness represents the dollar value of the commodity flow. Clearly security and commodity brokers, real estate agents and computer processing are important inputs to banking services.

The use of looped datasets required us to change the traditional tree representation. SimaPro can visualise non looped data in two ways:

1. An hierarchical tree structure

2. A network structure

In a tree structure each process is shown with its inputs. If two processes link to the same process, for instance European electricity, this process will be shown twice. If ten processes refer to this electricity record, you will see this record ten times. Tree structures can easily become very large as this way and representing is not so efficient. However, it is a graph that is easily understood. In a network structure, every process is only shown once, so if two or ten processes refer to the same process, you will see this process only once, but you will see two or ten outputs from these processes to other processes. The network structure is much more efficient in using space, but may sometimes look to be more complex. Apart from these differences there are some other aspects that require attention:

1. If a process like electricity appears ten times, you may easily overlook the relative contribution of this process. In a network you can easily recognise the contribution

2. In a tree you can deliberately hide parts of the tree you are not interested in.

In a network this is not possible, as network often do not have separate branches, everything seems to be related to everything The most important difference is however that trees cannot be used if data are looped. If we would allow this, we would see a repetition of the process tree with every loop. This means the number of process would become infinitely large. In case you try to generate a tree visualisation, SimaPro will check for loops, and if they exist, SimaPro will automatically switch to networks With this feature, SimaPro is the only tool available that can indeed visualise the looped structure of the ecoinvent datasets.

SimaPro contains a detailed input output database that has over 500 commodities, representing the entire USA economy. This so called USA Input Output 98 database has been licensed from CML Leiden. It was compiled by Sangwon Suh, who used a wide variety of US data sources. The database is in many ways unique compared to earlier input output databases, as it also includes estimates for diffuse emissions and small and medium sized industries. These are quite important but often missing. More information can be found in the database manuals. These are supplied as PDF, and can also be accessed via the help menu of SimaPro.

SimaPro comes with a large number of standard impact assessment methods. We have selected the most authoritative methods. Each method contains a number (usually 10 to 20) of impact categories, some allow aggregation into a single score, and some do not. Most users will simply select one complete method, instead of selecting individual impact categories. However, SimaPro does allow you to add or delete impact categories from or to a method. We advise you not to change the method as supplied in the impact assessment library, but to copy the method to your project and make the changes there. In this way, you can always revert to the original method. SimaPro also allows you to develop completely new methods. (Goedkoop 2007)

2.12 Chapter 2 conclusions

This chapter covered background and current information available found during the research stage of this project. Despite hours of research and communications with various companies and corporations some current data, particularly for battery materials, was not available. For example, the battery materials were taken from data dating back to 1998. The lack of current data is mainly due to the cutting edge nature of the technologies and the competitiveness of the market.

Chapter 3

Methodology

3.1 Chapter 3 introduction

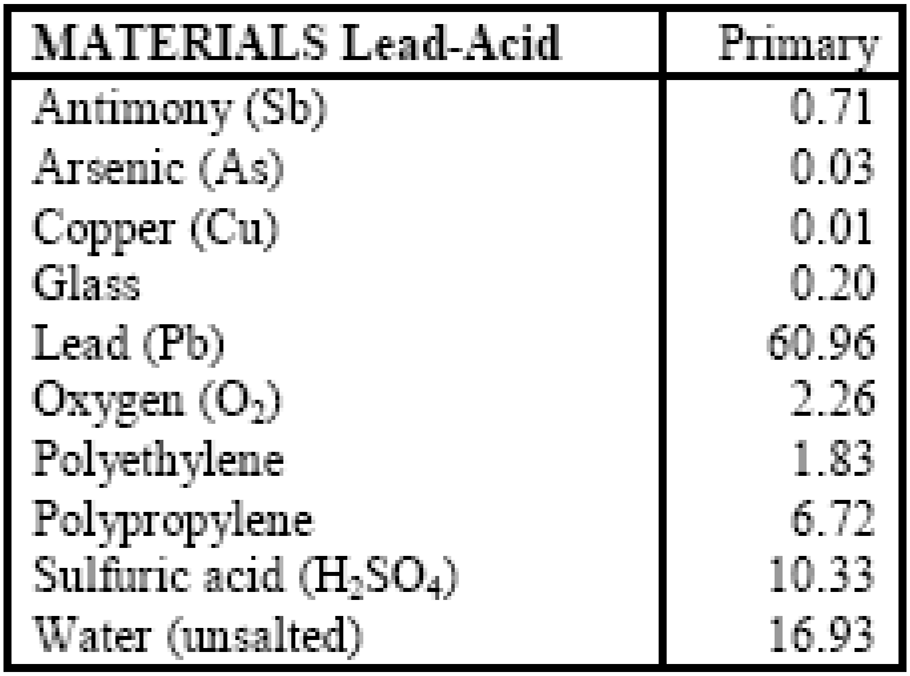
This chapter describes the methods used to determine the functional unit/s for analysis of the battery types with the SimaPro software for both the EV and HEV applications. Masses of each battery type are determined according to the battery type to meet a certain criteria (energy storage for 60km range in the EV case and 21 kW power in the HEV case) so that all battery types are compared equally. Lifespan and efficiency of the battery types are also taken into account during the analysis. Materials data for the Lithium-ion battery technology was not available and therefore could not be analysed in SimaPro. An average value (taken from the SUBAT project (Autenboer 2005)is given to the Lithium-ion battery for comparative purposes and will be explained in more detail later in the report.

3.2 Battery Data

The following information was gathered to use in the software program, SimaPro, to determine the environmental impact of the particular battery technologies.

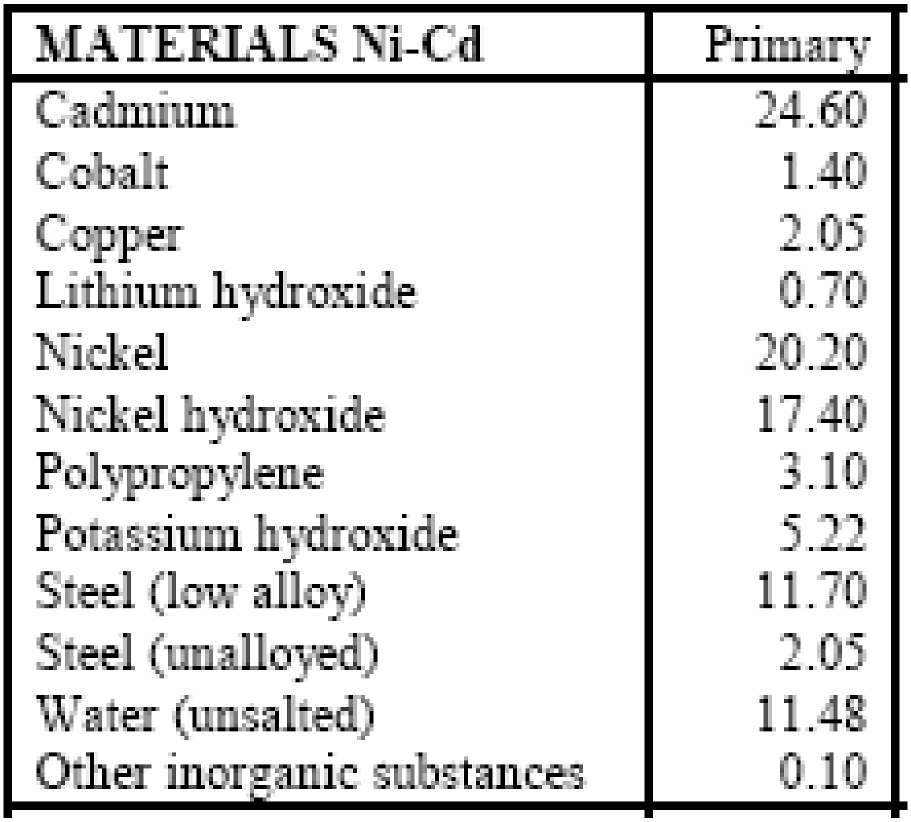
Unfortunately, the following material amounts, in percentages, are from sources dating back to 1996, 1998 etc. Due to the competitiveness and secrecy of developments, for commercial reasons, current data was not available. However, as shown later in the results and conclusions it seems materials have remained similar or, at least, results seem similar.

The material amounts shown in the following tables,in percentages, Figure 3.1, Figure 3.2,Figure 3.3, Figure 3.4, are taken from (Kertes 1996)



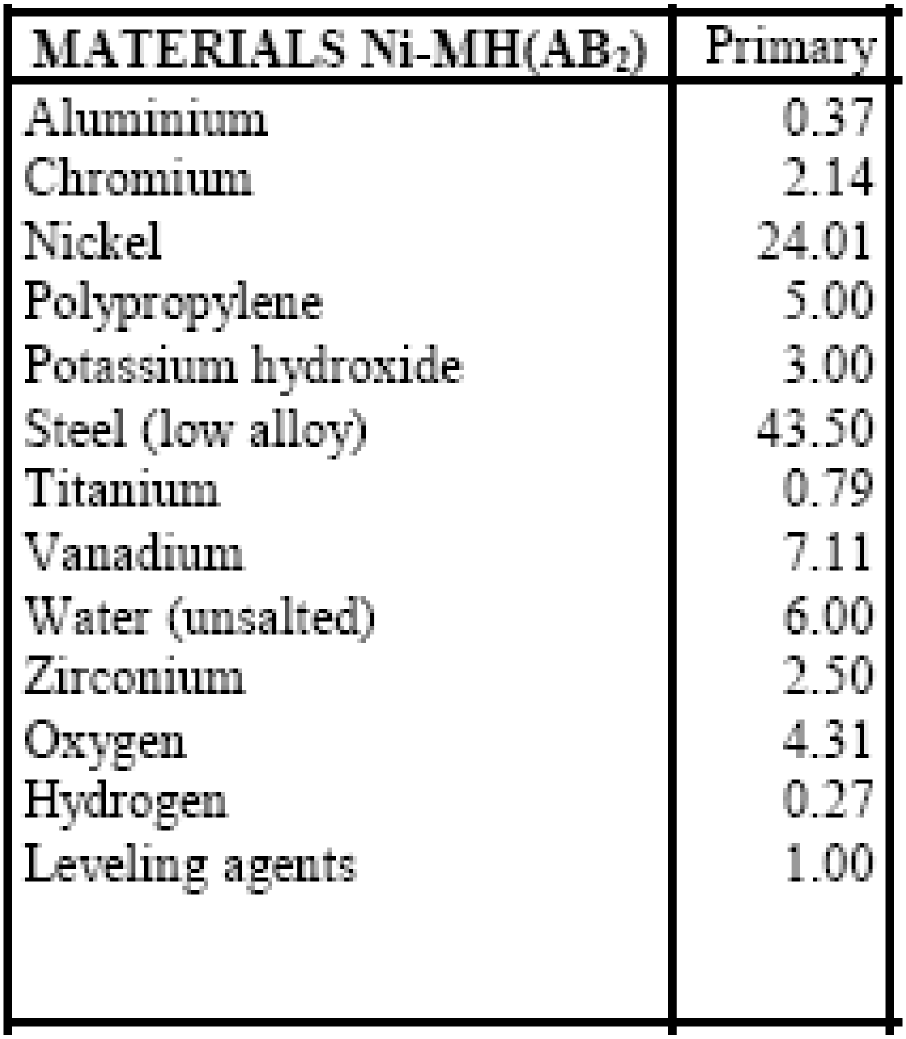
MATERIALS Lead-Acid	Primary
Antimony (Sb)	0.71
Arsenic (As)	0.03
Copper (Cu)	0.01
Glass	0.20
Lead (Pb)	60.96
Oxygen (O_2)	2.26
Polyethylene	1.83
Polypropylene	6.72
Sulfuric acid (H_2SO_4)	10.33
Water (unsalted)	16.93

Figure 3.1: Lead-acid battery material percentages



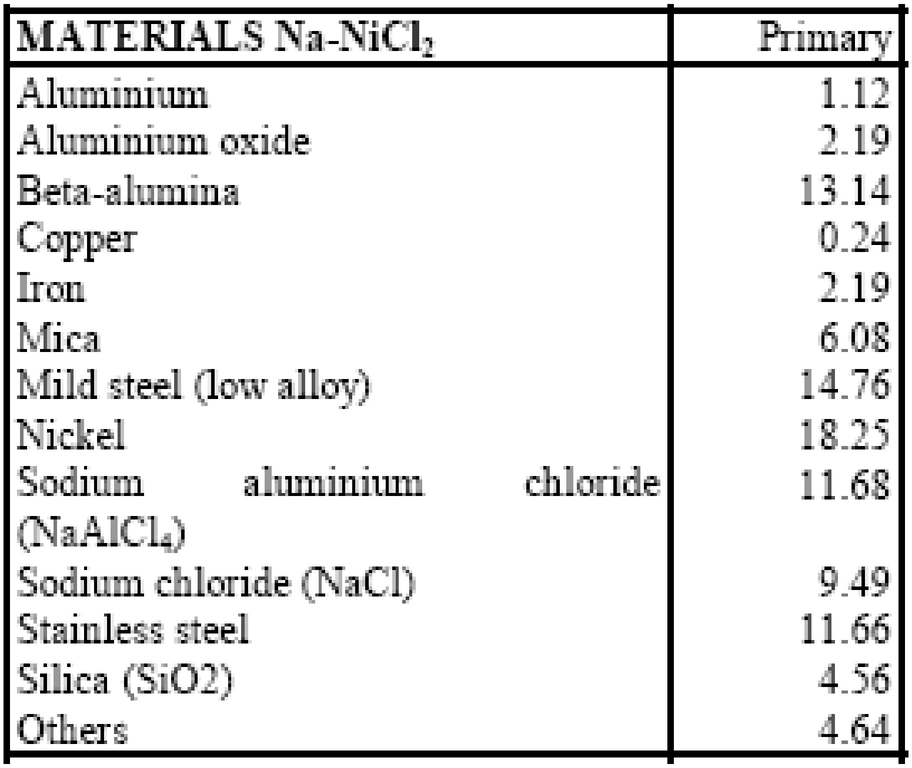
MATERIALS Ni-Cd	Primary
Cadmium	24.60
Cobalt	1.40
Copper	2.05
Lithium hydroxide	0.70
Nickel	20.20
Nickel hydroxide	17.40
Polypropylene	3.10
Potassium hydroxide	5.22
Steel (low alloy)	11.70
Steel (unalloyed)	2.05
Water (unsalted)	11.48
Other inorganic substances	0.10

Figure 3.2: Nickel cadmium battery material percentages



MATERIALS Ni-MH(AB_2)	Primary
Aluminium	0.37
Chromium	2.14
Nickel	24.01
Polypropylene	5.00
Potassium hydroxide	3.00
Steel (low alloy)	43.50
Titanium	0.79
Vanadium	7.11
Water (unsalted)	6.00
Zirconium	2.50
Oxygen	4.31
Hydrogen	0.27
Leveling agents	1.00

Figure 3.3: Nickel metal hydride battery material percentages

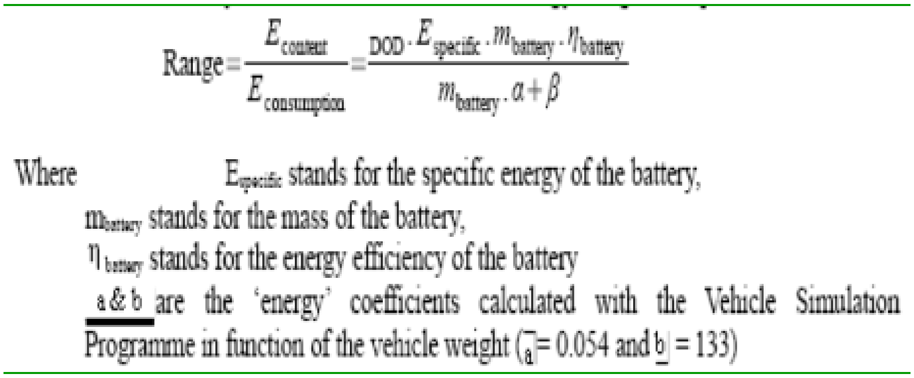


MATERIALS Na-NiCl$_2$	Primary
Aluminium	1.12
Aluminium oxide	2.19
Beta-alumina	13.14
Copper	0.24
Iron	2.19
Mica	6.08
Mild steel (low alloy)	14.76
Nickel	18.25
Sodium aluminium chloride (NaAlCl$_4$)	11.68
Sodium chloride (NaCl)	9.49
Stainless steel	11.66
Silica (SiO2)	4.56
Others	4.64

Figure 3.4: Sodium nickel chloride battery material percentages

3.3 EV Battery Masses

An integral part of this analysis is the determination of a functional unit. As explained earlier a functional unit is required to accurately compare battery technologies otherwise results would be meaningless. For example, if an analysis was conducted on a standard EV lead-acid battery and then compared to a standard EV nickel cadmium battery the results would be meaningless because the analysis was done using only the materials required for one battery of each type. Considering the nickel-cadmium battery has a lifespan roughly three times that of a lead-acid battery the true analysis would require three times the amount of materials for the lead-acid battery. Lifespan must also be taken into consideration as will be shown later in this report. The following equation Figure 3.5, was used to determine the correct battery masses. This formula was sourced from the SUBAT commission (Autenboer 2005). This formula also takes into account battery efficiency.



$$\text{Range} = \frac{E_{\text{content}}}{E_{\text{consumption}}} = \frac{\text{DOD} \cdot E_{\text{specific}} \cdot m_{\text{battery}} \cdot \eta_{\text{battery}}}{m_{\text{battery}} \cdot \alpha + \beta}$$

Where E_{specific} stands for the specific energy of the battery,

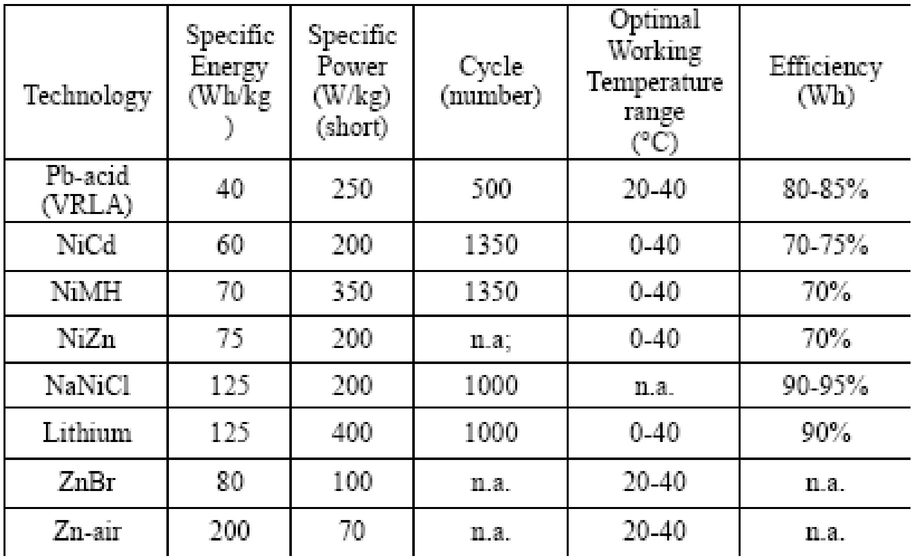
m_{battery} stands for the mass of the battery,

η_{battery} stands for the energy efficiency of the battery

a & b are the 'energy' coefficients calculated with the Vehicle Simulation Programme in function of the vehicle weight (a = 0.054 and b = 133)

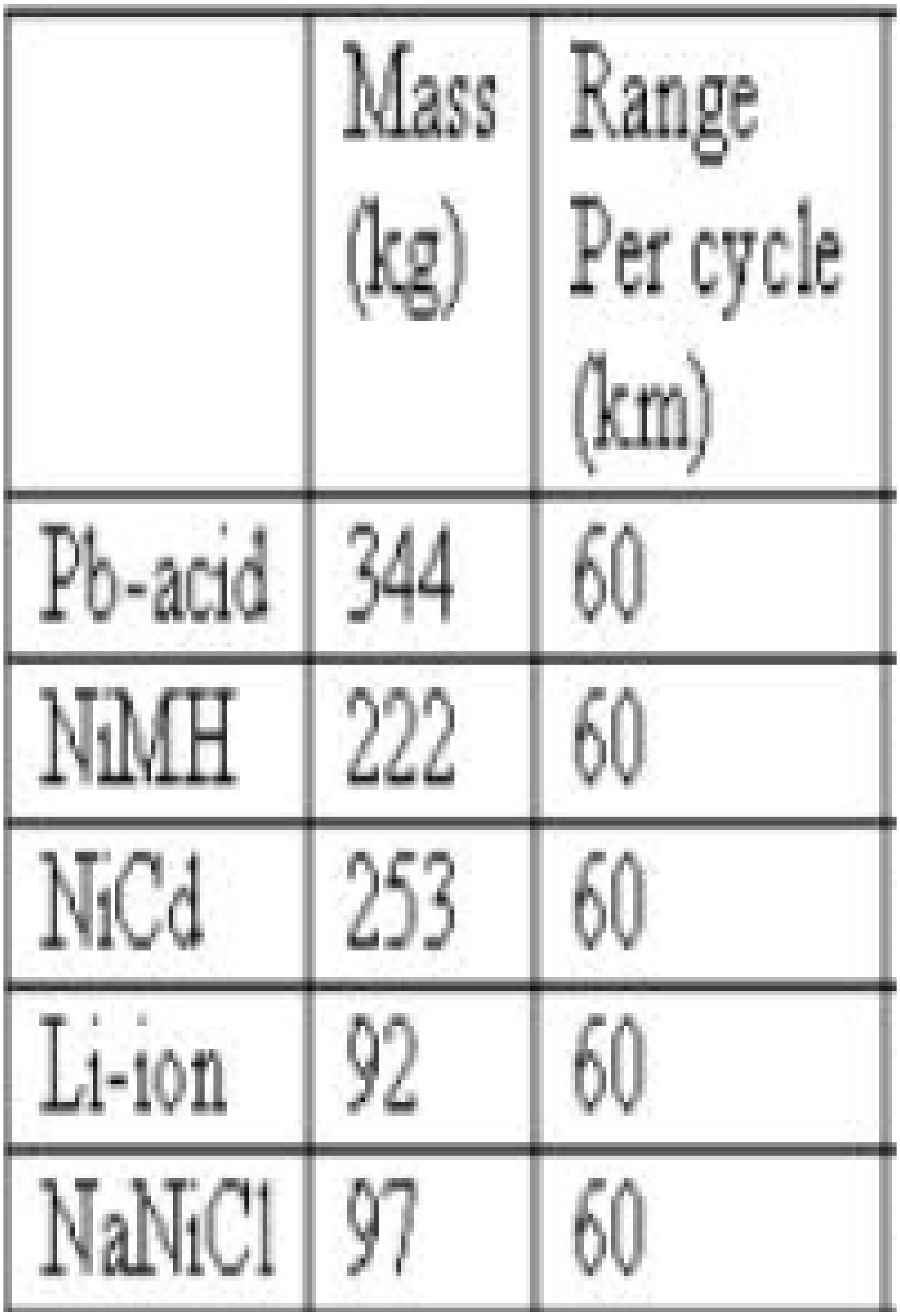
Figure 3.5: Calculation of masses formula

The formula was manipulated to provide an equation for mass. To calculate the mass a range for the vehicle had to be determined. The range was determined to be 60km as this is the average range of a modern electric vehicle (Heath 2006). The range does not need to be precise as long as all battery type masses are calculated using the same range. Data used for the calculation was taken from Figure 3.6 using an 80 percent depth of discharge (DOD) (Heath 2006) which was also sourced from the SUBAT report (Autenboer 2005). The resultant masses are shown in Figure 3.7



Technology	Specific Energy (Wh/kg)	Specific Power (W/kg) (short)	Cycle (number)	Optimal Working Temperature range (°C)	Efficiency (Wh)
Pb-acid (VRLA)	40	250	500	20-40	80-85%
NiCd	60	200	1350	0-40	70-75%
NiMH	70	350	1350	0-40	70%
NiZn	75	200	n.a;	0-40	70%
NaNiCl	125	200	1000	n.a.	90-95%
Lithium	125	400	1000	0-40	90%
ZnBr	80	100	n.a.	20-40	n.a.
Zn-air	200	70	n.a.	20-40	n.a.

Figure 3.6: EV data table



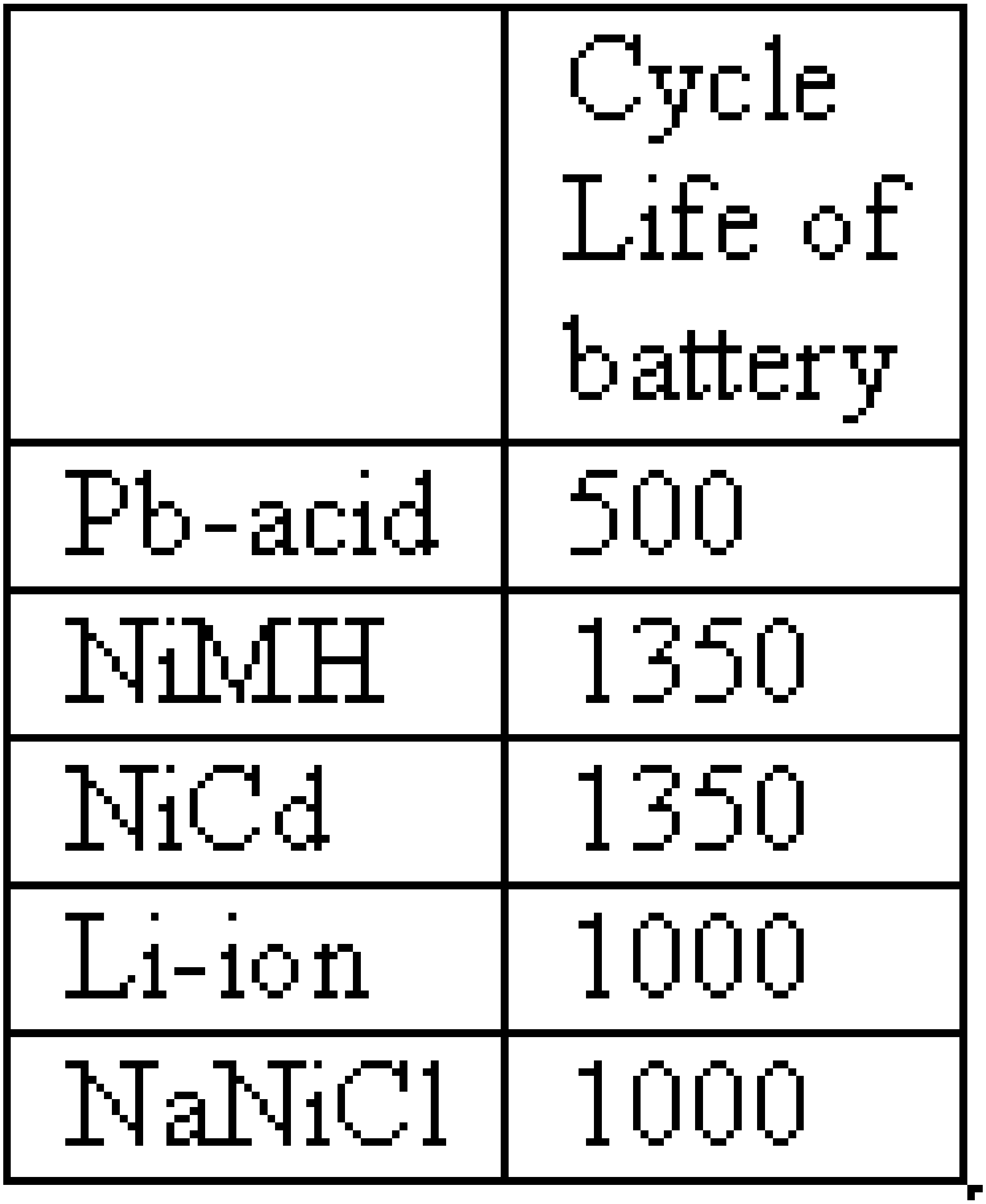
	Mass (kg)	Range Per cycle (km)
Pb-acid	344	60
NiMH	222	60
NiCd	253	60
Li-ion	92	60
NaNiCl	97	60

Figure 3.7: EV masses table

3.4 EV Battery Parameters

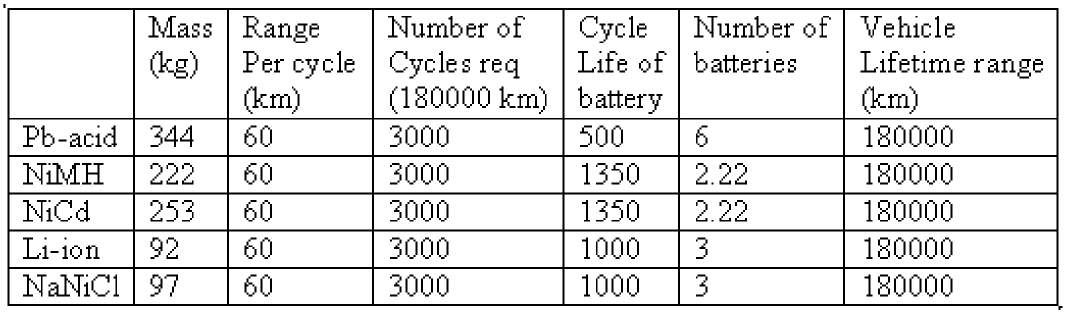
Other battery parameters to be considered were lifespan. The lifespan of each battery type to an 80 percent DOD (depth of discharge) (Heath 2006) is shown Figure 3.8

A universal total lifespan for the vehicle was needed for an accurate comparison. A vehicle lifespan of 180,000km was chosen because this would be approximately the lifespan of an electric vehicle. Also the SUBAT project used a lifespan of 180,000km which enables comparisons between the two reports. The number of batteries required for the vehicle life can now be calculated and are shown Figure 3.9



	Cycle Life of battery
Pb-acid	500
NiMH	1350
NiCd	1350
Li-ion	1000
NaNiCl	1000

Figure 3.8: EV battery cycle life



	Mass (kg)	Range Per cycle (km)	Number of Cycles req (180000 km)	Cycle Life of battery	Number of batteries	Vehicle Lifetime range (km)
Pb-acid	344	60	3000	500	6	180000
NiMH	222	60	3000	1350	2.22	180000
NiCd	253	60	3000	1350	2.22	180000
Li-ion	92	60	3000	1000	3	180000
NaNiCl	97	60	3000	1000	3	180000

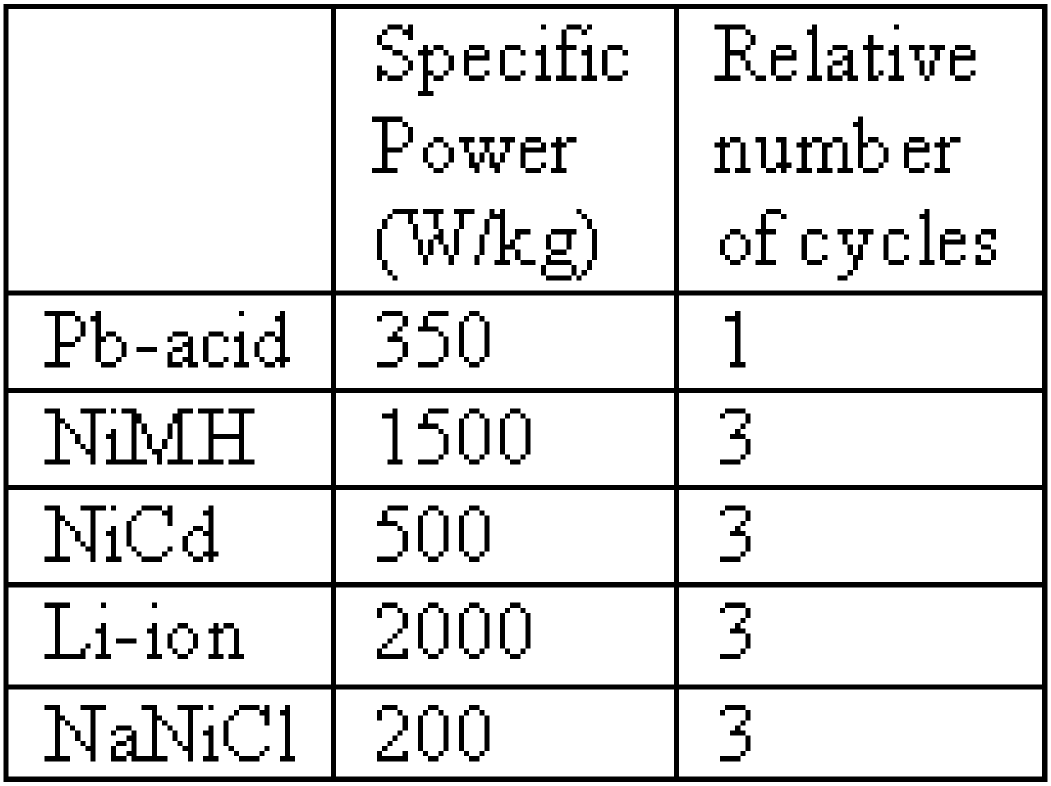
Figure 3.9: EV battery parameters

3.5 HEV Battery Masses

The HEV requires an instantaneous power where as the EV requires more power storage. Due to the different requirements of the batteries for the HEV compared to the EV, different parameters need to be found for an accurate analysis. A power requirement was chosen at 21kW (which is the requirement of the Toyota Prius) (Georgano 2000) to use to determine the required masses. Therefore the masses were determined by the equation:

Mass (kg) = 21kW/specific power (W/kg)

where the specific powers are shown Figure 3.10



	Specific Power (W/kg)	Relative number of cycles
Pb-acid	350	1
NiMH	1500	3
NiCd	500	3
Li-ion	2000	3
NaNiCl	200	3

Figure 3.10: HEV battery specifications

The results are shown Figure 3.11

	Mass (kg)	Specific Power (W/kg)	Number of batteries	Range (km)
Pb-acid	60	350	3	180000
NiMH	14	1500	1	180000
NiCd	42	500	1	180000
Li-ion	10.5	2000	1	180000
NaNiCl	10.5	200	1	180000

Figure 3.11: HEV battery masses

3.6 HEV Battery Parameters

Once again a universal total lifespan for the vehicle was needed for an accurate comparison. A vehicle lifespan of 180,000km was chosen because this would be approximately the lifespan of an electric vehicle. Also the SUBAT project used a lifespan of 180,000km which enables comparisons between the two reports. As the lead-acid battery has approximately one third the relative number of cycles of the other battery types (Autenboer 2005) and it is generally accepted that the other battery types will last 180,000km (Morrison 2001) the required number of batteries is also shown Figure 3.11.

3.7 Chapter 3 conclusions

This chapter was used to calculate the data required for analysis in SimaPro from information collected during the research phase. Although some data collected was not as current as would have been preferred, the data should provide enough accuracy to determine a reasonably accurate outcome.

Chapter 4

Analysis

4.1 Chapter 4 introduction

This chapter will describe how the data was entered into SimaPro (showing a screen shot of an actual data entry page) and how the masses for each particular material of each battery type were calculated for the EV application and the HEV application.

The results from this data input is then manipulated in Matlab to take into account the lifespan of each battery type.

Complete data entry tables and Matlab programmes will be provided in an appendix.

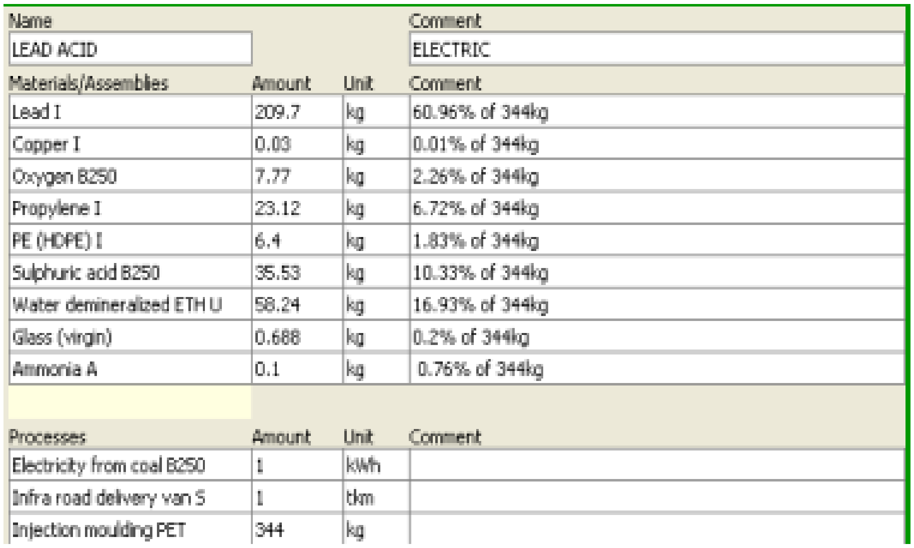
4.2 EV data entry plus output results

Referring to previous tables in Battery Percentages, the masses for each battery type are divided into their material equivalents by multiplying the mass by the percentage.

Example: EV Lead-acid (lead)

60.96 percent of 344kg = 209.7 kg

An example of the data entry for the Lead-acid battery for the EV application is shown Figure 4.1



Name: LEAD ACID

Comment: ELECTRIC

Materials/Assemblies	Amount	Unit	Comment
Lead I	209.7	kg	60.96% of 344kg
Copper I	0.03	kg	0.01% of 344kg
Oxygen B250	7.77	kg	2.26% of 344kg
Propylene I	23.12	kg	6.72% of 344kg
PE (HDPE) I	6.4	kg	1.83% of 344kg
Sulphuric acid B250	35.53	kg	10.33% of 344kg
Water demineralized ETH U	58.24	kg	16.93% of 344kg
Glass (virgin)	0.688	kg	0.2% of 344kg
Ammonia A	0.1	kg	0.76% of 344kg

Processes	Amount	Unit	Comment
Electricity from coal B250	1	kWh	
Infra road delivery van S	1	tkm	
Injection moulding PET	344	kg	

Figure 4.1: Lead-acid (EV) data entry

Data entry for the remaining EV (electric) battery types are shown in an appendix. As is shown in the data entry table Figure 4.1 transport, power source and processes such as injection moulding had to be taken into account. Due to the unwillingness to release information regarding these issues from the companies involved and the lack of real data available assumptions were made and entered into the data entry table. To provide an equal comparison all battery types were given the same data entry for these parameters.

This data was then analysed in the SimaPro software to produce the following results:

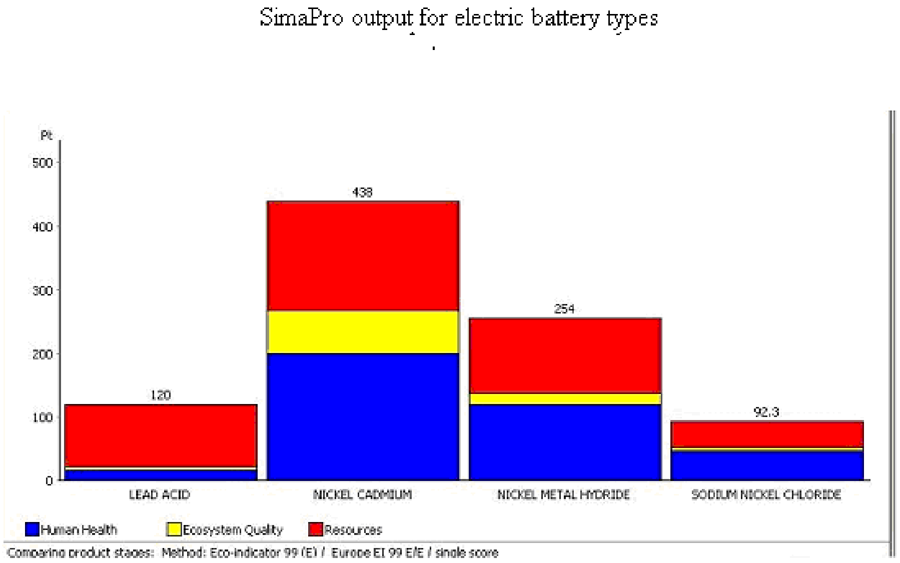


Figure 4.2: SimaPro output for EV application

These results show the environmental impact from the mass of each battery type (excluding Lithium-ion) required for a 60 km range. The number of batteries required for a total vehicle lifespan of 180,000 km must now be taken into account. This was done using Matlab by multiplying the output result from SimaPro by the number of batteries required for 180,000 km (refer figure: EV battery parameters). The output from Matlab can now be shown in Figure 4.3. The scores for each battery type are rated in eco-indicator points where one eco-indicator point is equivalent to one thousandth of the environmental impact of one European person over one year.

The Lithium-ion battery score was calculated by averaging the score from the SUBAT report (Autenboer 2005) output against the Matlab output for the Lead-acid battery. Once again it must be stressed that the Lithium-ion score was only used for reference and was not accurately analysed in this project.

These results will be analysed further and discussed in the next chapter.

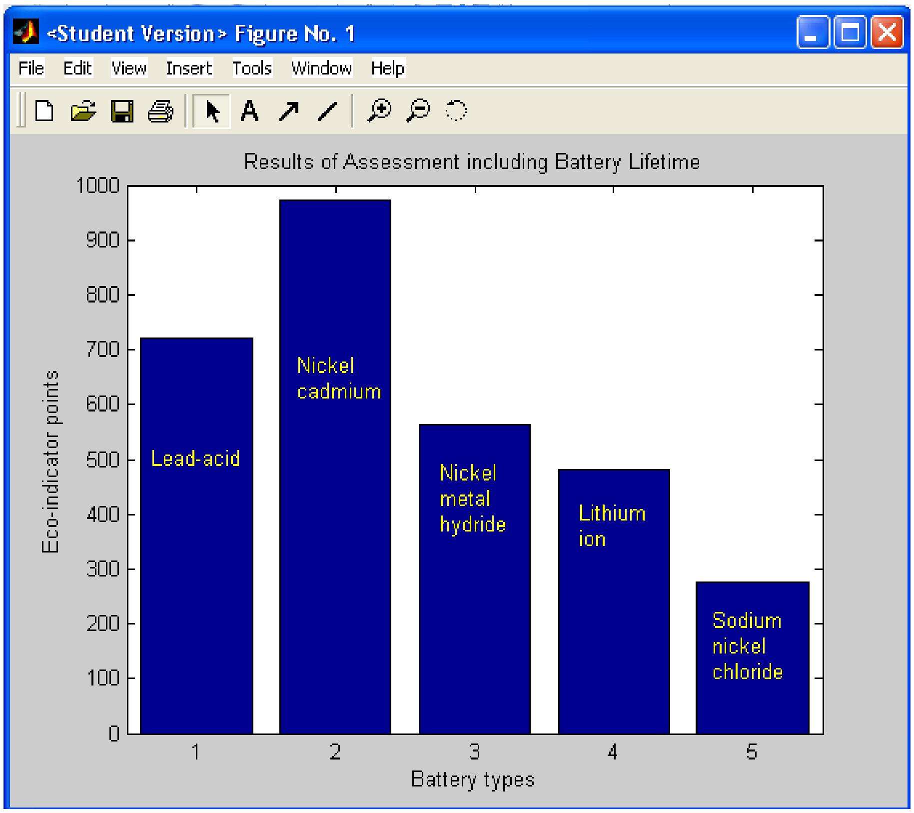


Figure 4.3: EV Matlab output

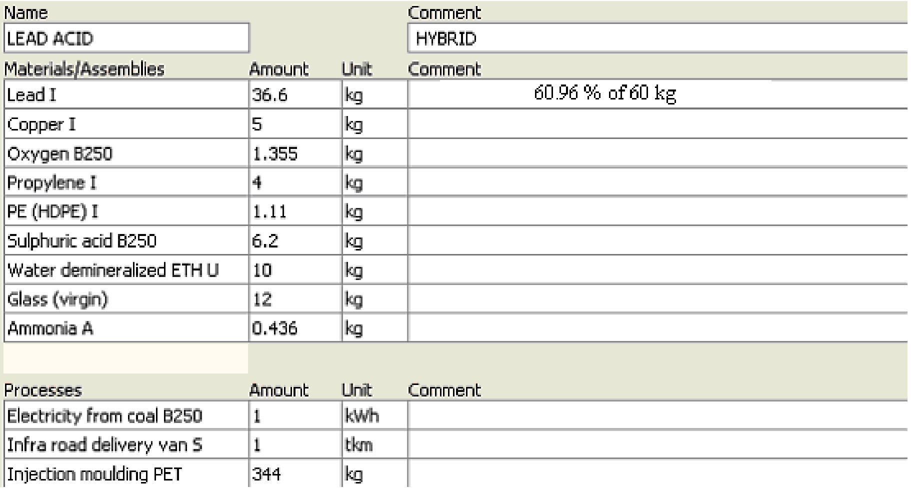
4.3 HEV data entry plus output results

Similar to the EV application, referring to previous tables in Battery Percentages, the masses for each battery type are divided into their material equivalents by multiplying the mass by the percentage.

Example: HEV Lead-acid (lead)

60.96 percent of 60 kg = 36.6 kg

An example of the data entry for the Lead-acid battery for the HEV application is shown Figure 4.4



Name	Comment
LEAD ACID	HYBRID

Materials/Assemblies	Amount	Unit	Comment
Lead I	36.6	kg	60.96 % of 60 kg
Copper I	5	kg	
Oxygen B250	1.355	kg	
Propylene I	4	kg	
PE (HDPE) I	1.11	kg	
Sulphuric acid B250	6.2	kg	
Water demineralized ETH U	10	kg	
Glass (virgin)	12	kg	
Ammonia A	0.436	kg	

Processes	Amount	Unit	Comment
Electricity from coal B250	1	kWh	
Infra road delivery van S	1	tkm	
Injection moulding PET	344	kg	

Figure 4.4: Lead-acid (HEV) data entry

Data entry for the remaining HEV (electric) battery types are shown in an appendix. As is shown in the data entry table, Figure 4.4, transport, power source and processes such as injection moulding had to be taken into account. Due to the unwillingness to release information regarding these issues from the companies involved and the lack of real data available assumptions were made and entered into the data entry table. To provide an equal comparison all battery types were given the same data entry for these parameters.

This data was then analysed in the SimaPro software to produce the following results:

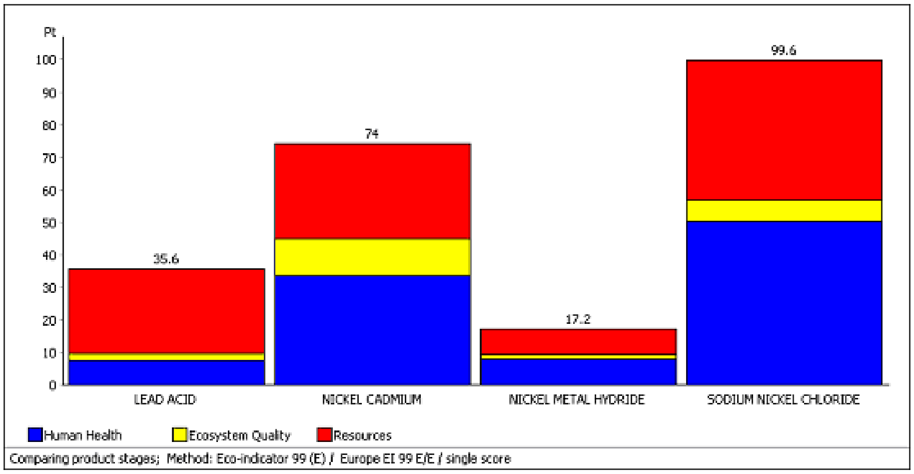


Figure 4.5: SimaPro output for HEV application

These results show the environmental impact from the mass of each battery type (excluding Lithium-ion) required for a 60 km range. The number of batteries required for a total vehicle lifespan of 180,000 km must now be taken into account. The SimaPro output is multiplied by the number of batteries required (refer figure: HEV battery masses) in Matlab. The output from Matlab can now be shown in Figure 4.6. The scores for each battery type are rated in eco-indicator points where one eco-indicator point is equivalent to one thousandth of the environmental impact of one European person over one year.

The Lithium-ion battery score was calculated by averaging the score from the SUBAT report (Autenboer 2005) output against the Matlab output for the Lead-acid battery. Once again it must be stressed that the Lithium-ion score was only used for reference and was not accurately analysed in this project.

These results will be analysed further and discussed in the next chapter.

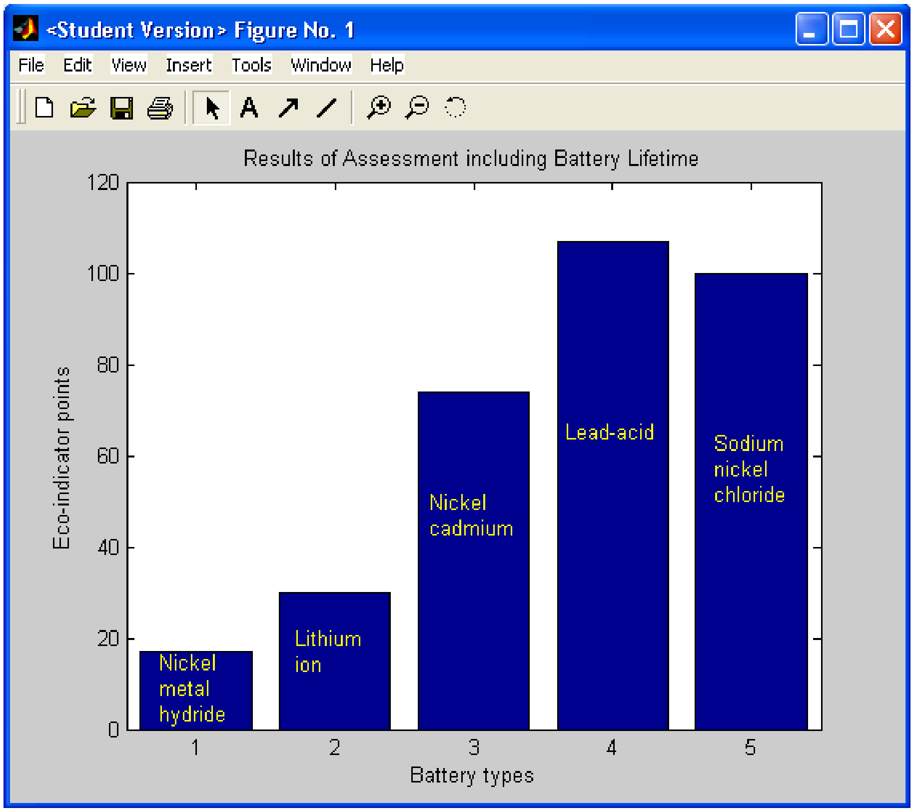


Figure 4.6: HEV Matlab output

4.4 Chapter 4 conclusions

This chapter included the data input calculation and entry methods for SimaPro and Matlab for the different battery types. The Lithium-ion battery was not analysed due to a lack of data but results from a previous project have been adjusted to this application by means of averages and is used as a comparison to the other battery technologies. Input data such as transport, power source and processes are not deemed accurate but are entered the same for each battery type and therefore should provide a result siutable for this application.

Chapter 5

Results

5.1 Chapter 5 introduction

This chapter shows the results from the previous chapter separated into individual environmental impact analysis (ie impact on human health, impact on ecosystem quality, impact on resources). A graph of a comparison of the different vehicle types is also shown for interest.

5.2 EV results

The following graph 5.1 is the matlab output graph with the different environmental impacts superimposed.

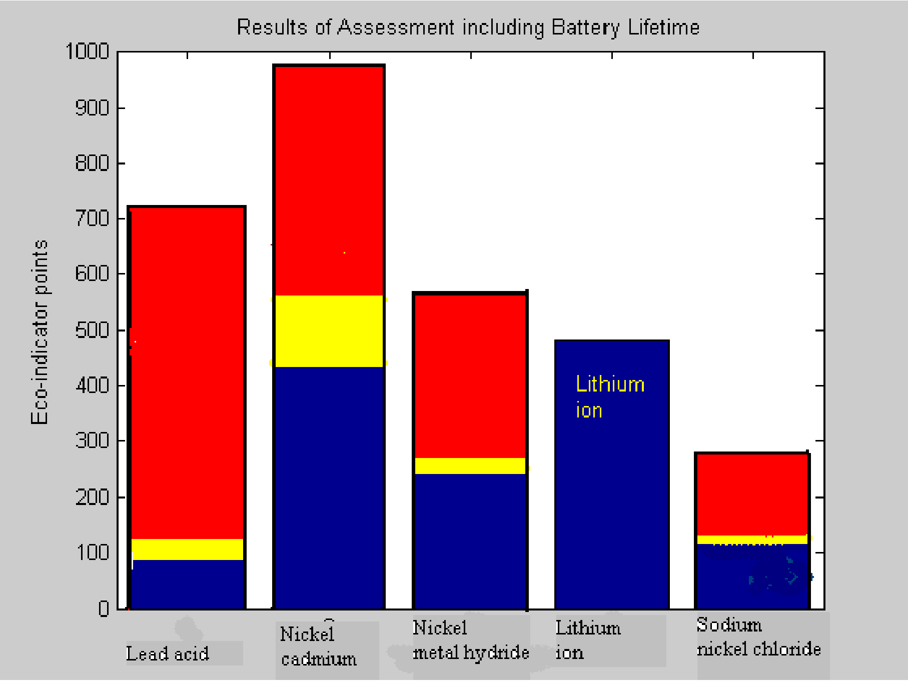


Figure 5.1: EV environmental impact

Where:

blue = impact on human health

yellow = impact on ecosystem quality

red = impact on resources

Note: Lithium-ion was not analysed and therefore no definite impact was assessed.

At this stage a comparison was made with results from a previous study (Autenboer 2005) to determine whether the results from this project were realistic or not. As can be seen in Figure 5.2 the results appear to be reasonably accurate although there are discrepancies with eco-points and individual impact assessments. This may be attributed to the inaccuracy of the process inputs or outdated data.

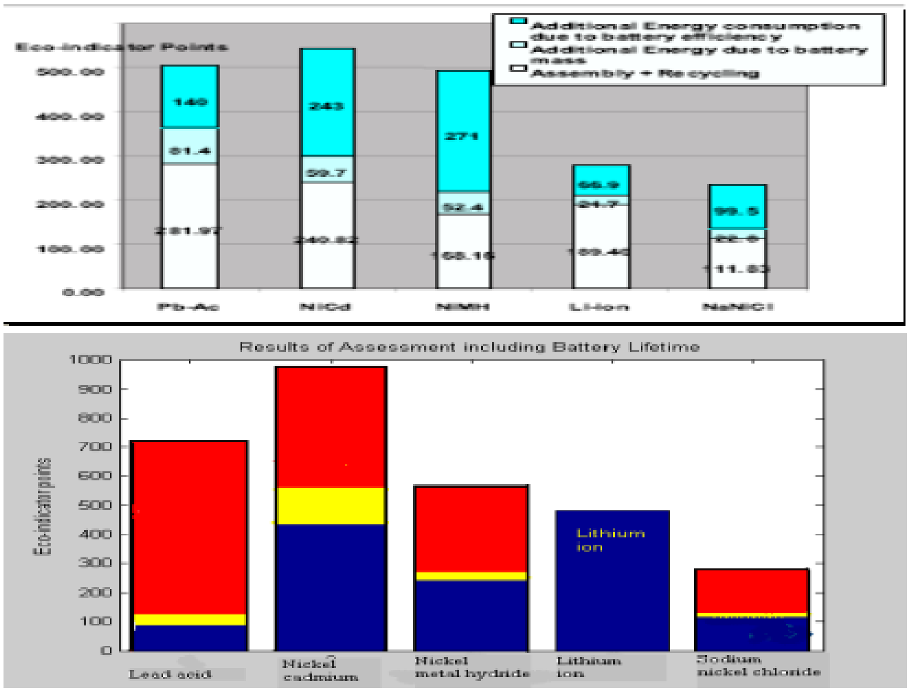


Figure 5.2: EV subat comparison

5.3 HEV results

The following graph Figure 5.3 is the matlab output graph with the different environmental impacts superimposed.

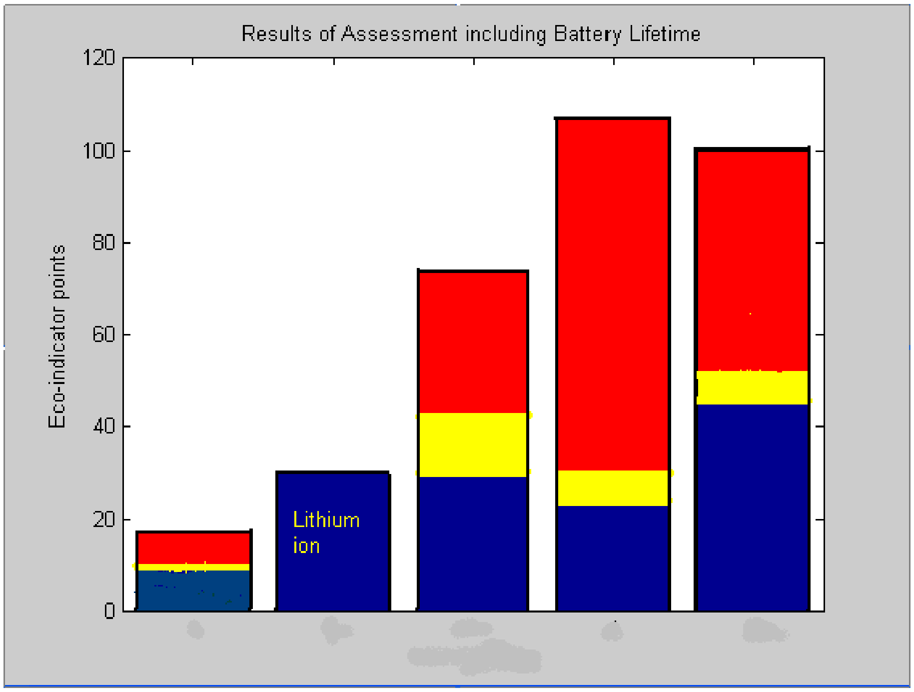


Figure 5.3: HEV environmental impact

Where:

blue = impact on human health

yellow = impact on ecosystem quality

red = impact on resources

Note: Lithium-ion was not analysed and therefore no definite impact was assessed.

At this stage a comparison was made with results from a previous study (Autenboer 2005) to determine whether the results from this project were realistic or not. As can be seen in Figure 5.4 the results appear to be reasonably accurate although there are discrepancies with eco-points and individual impact assessments. This may be attributed to the inaccuracy of the process inputs or outdated data.

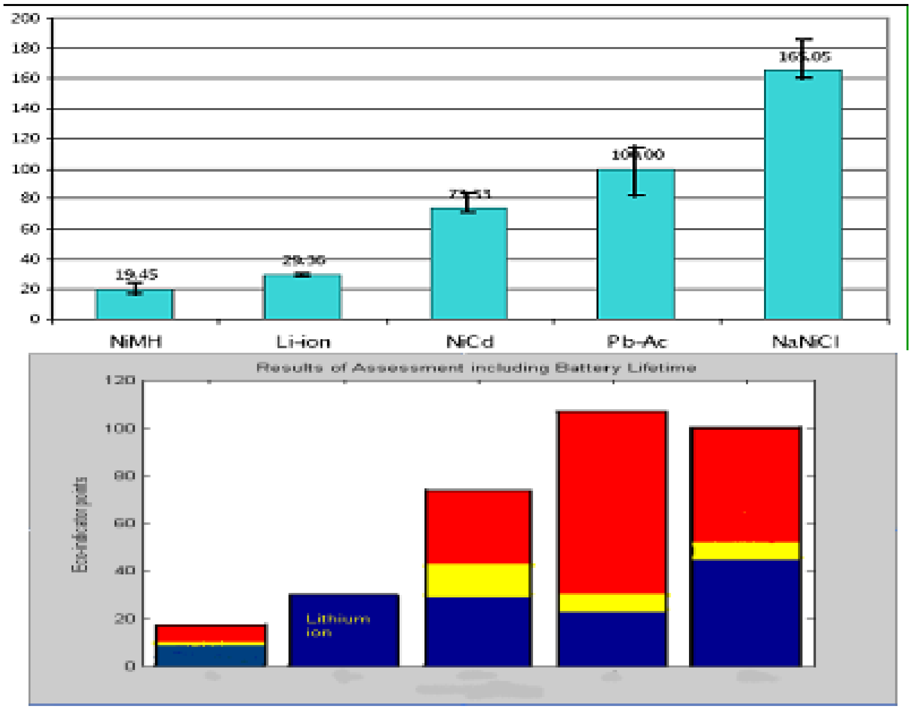


Figure 5.4: HEV subat comparison

5.4 Vehicle comparison

Although not strictly part of this project, a comparison of the different vehicles was made from information researched during this project (Autenboer 2005), (Committee on Science unknown). The following graph in Figure 5.5 shows the figures for each vehicle type in terms of impact on the environment. The impact from the electric vehicle may be reduced dramatically (to approximately 10 percent impact of the conventional combustion vehicle) by the use of a more environmentally friendly power source such as solar or wind (the power source used for this analysis was coal).

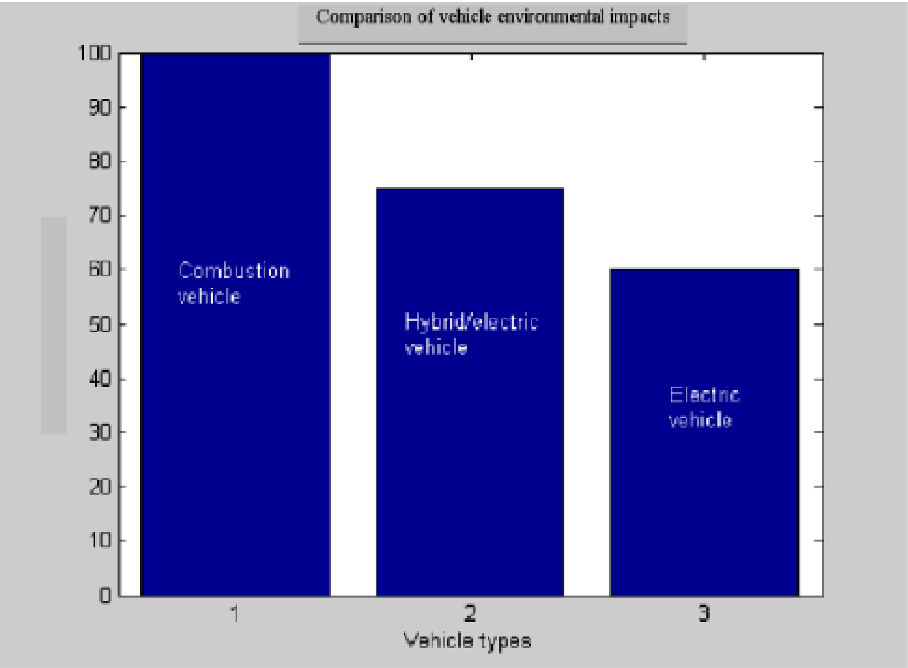


Figure 5.5: Vehicle comparison

5.5 Chapter 5 conclusions

Unfortunately the analysis did not include the Lithium ion battery technology, however , for comparitive purposes Lithium ion was included. The comparison from this project to the previous project shows reasonable accuracy although there are discrepancies which may be attributed to inaccurate data or outdated information. The results show that human health and resources are impacted the most from these technologies.

Chapter 6

Conclusion

6.1 Conclusion

Overall this project has been reasonably successful producing an outcome which appears to compare reasonably with previous studies conducted. The results show that for each different application (EV and HEV) different battery types are more suitable from an environmental point of view. For the EV application Lithium ion and Sodium nickel chloride appear to be the most environmentally friendly whereas for the HEV application Lithium ion and nickel metal hydride appear to be better for the environment. It should be noted that this is only from an environmental point of view. Other factors such as cost and practicality must be taken into account to test the feasibility of each battery type.

It should also be noted that due to inaccuracies of data these results should only be used for a comparative purpose and not to be taken on the value of eco-point indicators shown.

The main problem encountered for this project was the lack of current technology data including materials and processes used. The SimaPro software required some time and effort to master well enough to be able to analyse the batteries with reasonable accuracy.

Further work would include reanalysing the battery technologies as more up to date information is released and also researching any new battery technologies as they are developed. The analysis would also be simplified if the complete analysis was done in SimaPro only. The total analysis in SimaPro is possible but requires additional SimaPro software skills which, due to time constraints, was not mastered at this time.

The actual impact on the environment from the batteries are only minimal compared to the overall impact of the vehicle. The energy consumption (fuel and power for recharge) of the vehicles has by far the biggest impact on the environment but in the current world predicament all aspects of environmental impact need to be taken into account.

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Appendix A

Project Specification

University of Southern Queensland

Faculty of Engineering and Surveying

ENG4111/2 Research Project

PROJECT SPECIFICATION

FOR: CLAYTON O'DONNELL

TOPIC: Total Effect On The Environment Of Electric/Hybrid Electric Vehicle Batteries.

SUPERVISOR: PROFESSOR DAVID ROSS

PROJECT AIM:

This project aims to provide a comprehensive analysis of batteries currently available for modern electric/hybrid electric vehicles with respect to total effect on the environment of the batteries.

PROGRAMME: Issue A, 15/5/2007

1. Research various types of batteries currently available

2. Collect data for batteries (components, types of material, weight etc)

3. Use an appropriate (Life Cycle Assessment) software package to determine the total effect on the environment of each battery type

4. Compare battery types in terms of total effect on the environment

As time permits:

5. Determine energy input requirements during recharge of each battery type

6. Determine energy output of each battery type per recharge

7. Determine life cycle of each battery type in terms of energy output

8. Compare battery types by Life Cycle Assessment including recharge

AGREED:

(Student)

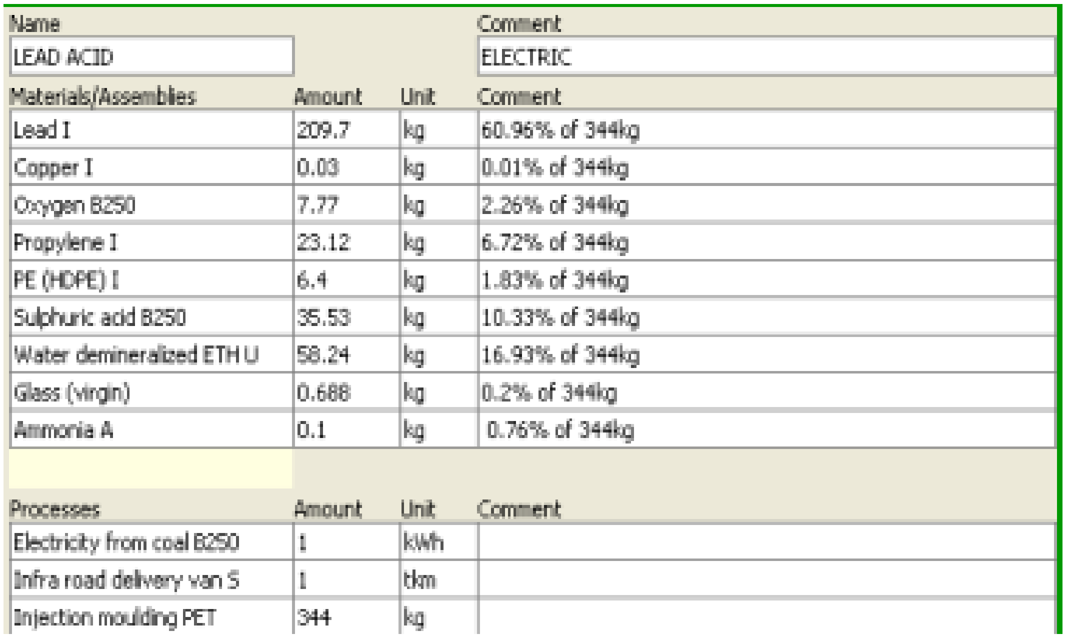
(Supervisor)

Date

Appendix B

EV Data Entry

The following figures are the EV SimaPro data entry snapshots.

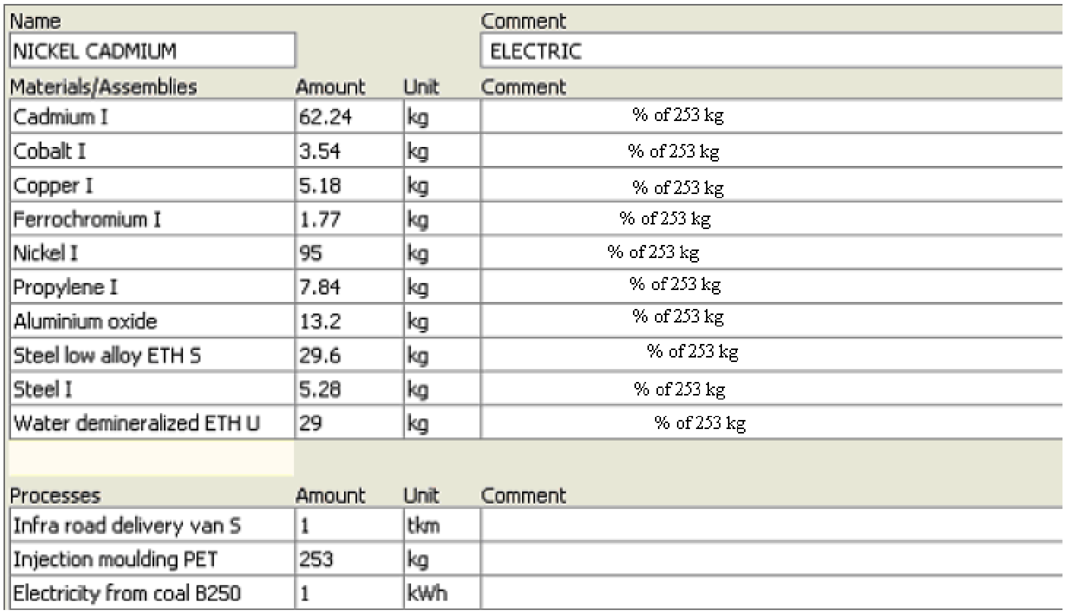


Name	Comment
LEAD ACID	ELECTRIC

Materials/Assemblies	Amount	Unit	Comment
Lead I	209.7	kg	60.96% of 344kg
Copper I	0.03	kg	0.01% of 344kg
Oxygen B250	7.77	kg	2.26% of 344kg
Propylene I	23.12	kg	6.72% of 344kg
PE (HDPE) I	6.4	kg	1.83% of 344kg
Sulphuric acid B250	35.53	kg	10.33% of 344kg
Water demineralized ETH U	58.24	kg	16.93% of 344kg
Glass (virgin)	0.688	kg	0.2% of 344kg
Ammonia A	0.1	kg	0.76% of 344kg

Processes	Amount	Unit	Comment
Electricity from coal B250	1	kWh	
Infra road delivery van S	1	tkm	
Injection moulding PET	344	kg	

Figure B.1: EV lead-acid entry

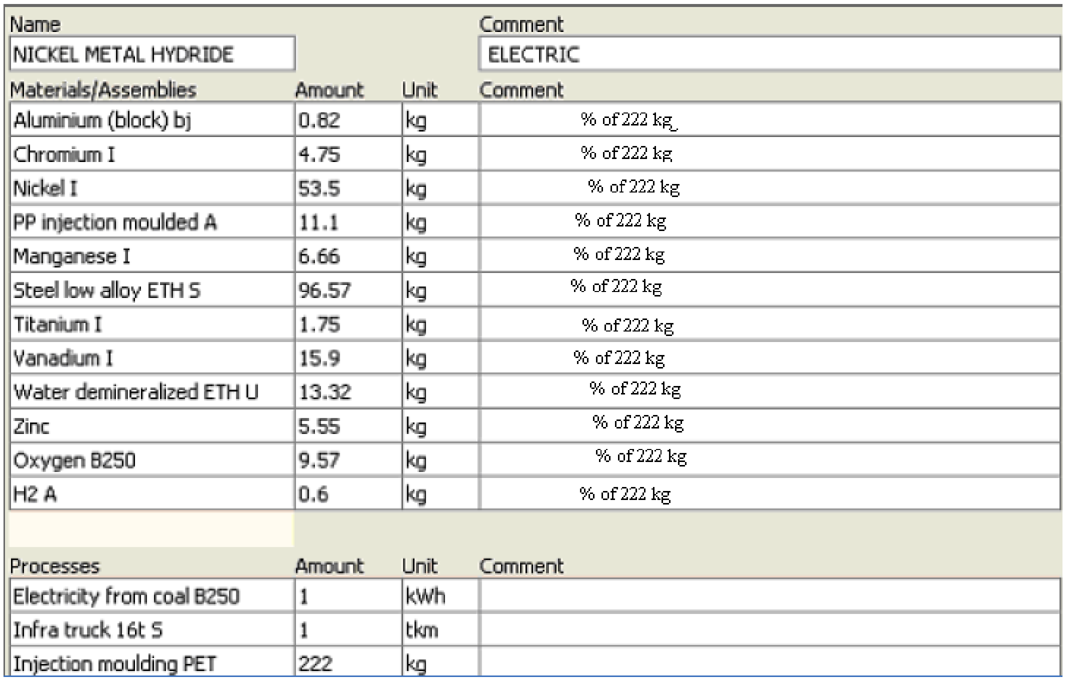


Name	Comment
NICKEL CADMIUM	ELECTRIC

Materials/Assemblies	Amount	Unit	Comment
Cadmium I	62.24	kg	% of 253 kg
Cobalt I	3.54	kg	% of 253 kg
Copper I	5.18	kg	% of 253 kg
Ferrochromium I	1.77	kg	% of 253 kg
Nickel I	95	kg	% of 253 kg
Propylene I	7.84	kg	% of 253 kg
Aluminium oxide	13.2	kg	% of 253 kg
Steel low alloy ETH S	29.6	kg	% of 253 kg
Steel I	5.28	kg	% of 253 kg
Water demineralized ETH U	29	kg	% of 253 kg

Processes	Amount	Unit	Comment
Infra road delivery van S	1	tkm	
Injection moulding PET	253	kg	
Electricity from coal B250	1	kWh	

Figure B.2: EV nickel cadmium entry

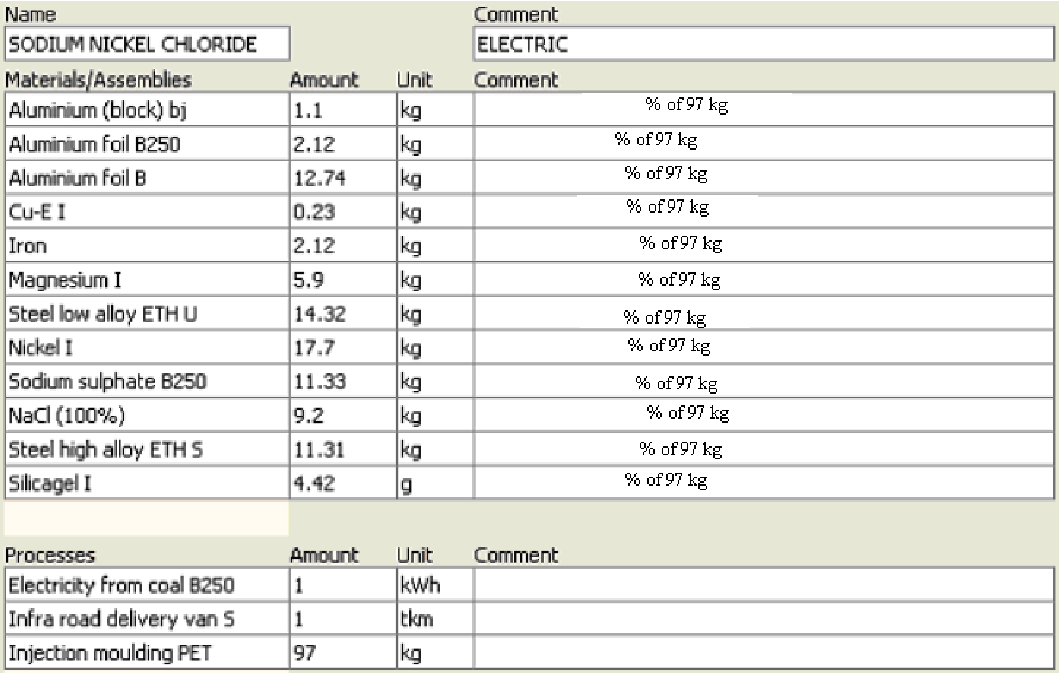


Name	Comment
NICKEL METAL HYDRIDE	ELECTRIC

Materials/Assemblies	Amount	Unit	Comment
Aluminium (block) bj	0.82	kg	% of 222 kg
Chromium I	4.75	kg	% of 222 kg
Nickel I	53.5	kg	% of 222 kg
PP injection moulded A	11.1	kg	% of 222 kg
Manganese I	6.66	kg	% of 222 kg
Steel low alloy ETH S	96.57	kg	% of 222 kg
Titanium I	1.75	kg	% of 222 kg
Vanadium I	15.9	kg	% of 222 kg
Water demineralized ETH U	13.32	kg	% of 222 kg
Zinc	5.55	kg	% of 222 kg
Oxygen B250	9.57	kg	% of 222 kg
H2 A	0.6	kg	% of 222 kg

Processes	Amount	Unit	Comment
Electricity from coal B250	1	kWh	
Infra truck 16t S	1	tkm	
Injection moulding PET	222	kg	

Figure B.3: EV nickel metal hydride entry



Name	Comment
SODIUM NICKEL CHLORIDE	ELECTRIC

Materials/Assemblies	Amount	Unit	Comment
Aluminium (block) bj	1.1	kg	% of 97 kg
Aluminium foil B250	2.12	kg	% of 97 kg
Aluminium foil B	12.74	kg	% of 97 kg
Cu-E I	0.23	kg	% of 97 kg
Iron	2.12	kg	% of 97 kg
Magnesium I	5.9	kg	% of 97 kg
Steel low alloy ETH U	14.32	kg	% of 97 kg
Nickel I	17.7	kg	% of 97 kg
Sodium sulphate B250	11.33	kg	% of 97 kg
NaCl (100%)	9.2	kg	% of 97 kg
Steel high alloy ETH S	11.31	kg	% of 97 kg
Silicagel I	4.42	g	% of 97 kg

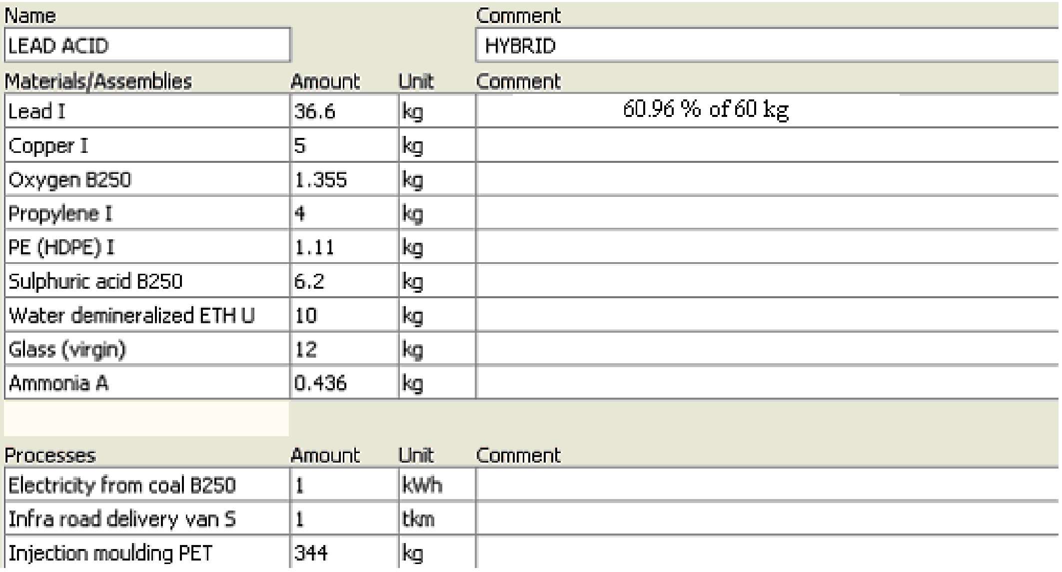
Processes	Amount	Unit	Comment
Electricity from coal B250	1	kWh	
Infra road delivery van S	1	tkm	
Injection moulding PET	97	kg	

Figure B.4: EV sodium nickel chloride entry

Appendix C

HEV Data Entry

The following figures are the EV SimaPro data entry snapshots.

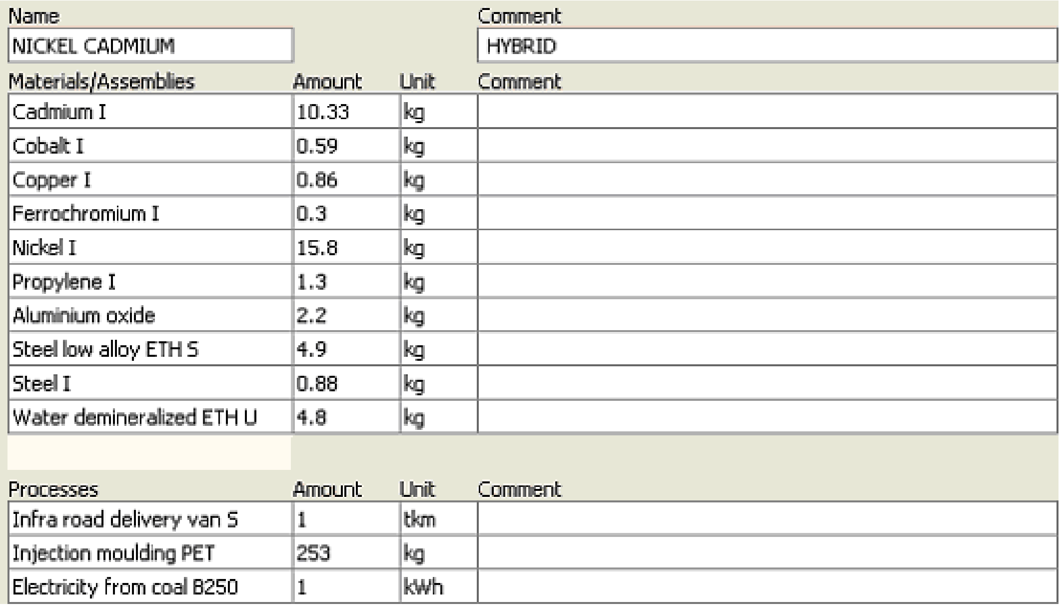


Name	Comment
LEAD ACID	HYBRID

Materials/Assemblies	Amount	Unit	Comment
Lead I	36.6	kg	60.96 % of 60 kg
Copper I	5	kg	
Oxygen B250	1.355	kg	
Propylene I	4	kg	
PE (HDPE) I	1.11	kg	
Sulphuric acid B250	6.2	kg	
Water demineralized ETH U	10	kg	
Glass (virgin)	12	kg	
Ammonia A	0.436	kg	

Processes	Amount	Unit	Comment
Electricity from coal B250	1	kWh	
Infra road delivery van S	1	tkm	
Injection moulding PET	344	kg	

Figure C.1: HEV lead-acid entry



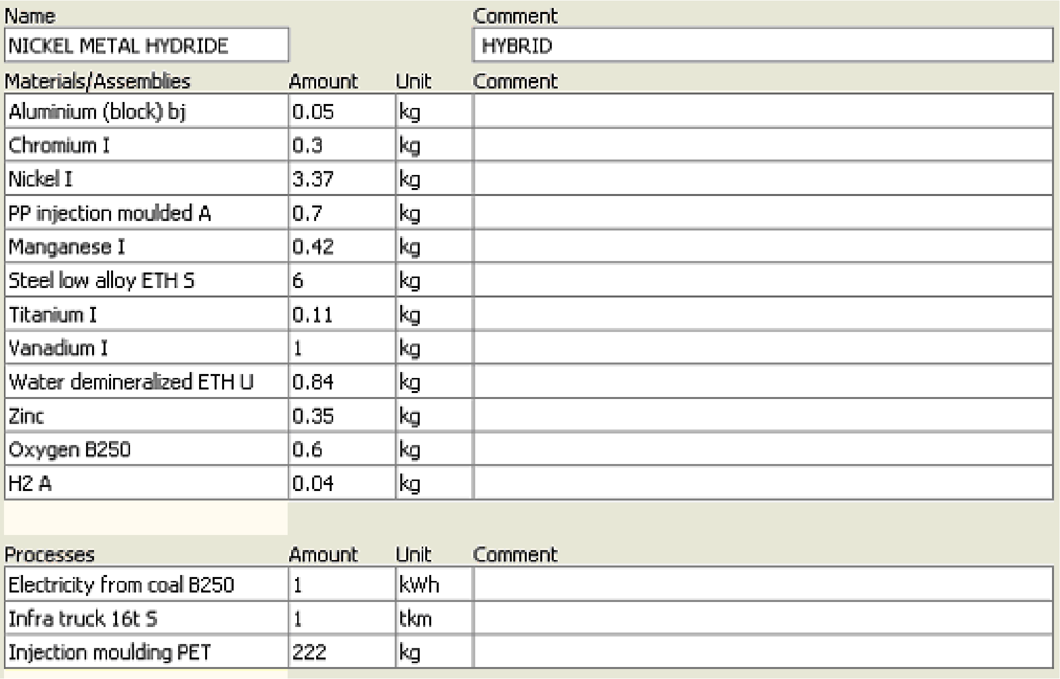
Name: NICKEL CADMIUM

Comment: HYBRID

Materials/Assemblies	Amount	Unit	Comment
Cadmium I	10.33	kg	
Cobalt I	0.59	kg	
Copper I	0.86	kg	
Ferrochromium I	0.3	kg	
Nickel I	15.8	kg	
Propylene I	1.3	kg	
Aluminium oxide	2.2	kg	
Steel low alloy ETH S	4.9	kg	
Steel I	0.88	kg	
Water demineralized ETH U	4.8	kg	

Processes	Amount	Unit	Comment
Infra road delivery van S	1	tkm	
Injection moulding PET	253	kg	
Electricity from coal B250	1	kWh	

Figure C.2: HEV nickel cadmium entry



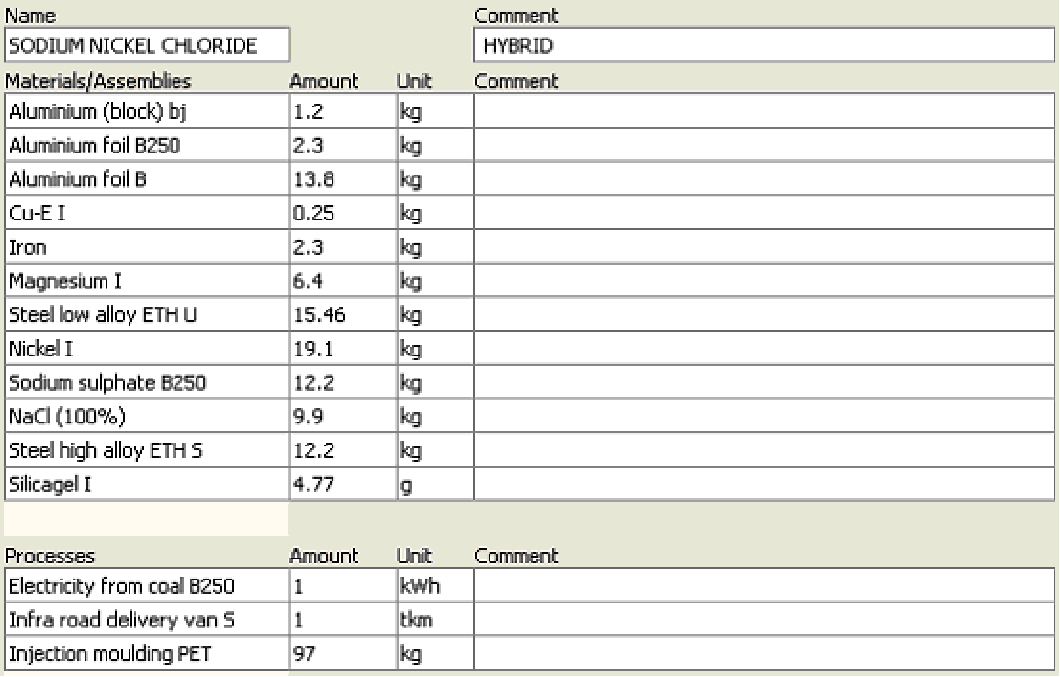
Name: NICKEL METAL HYDRIDE

Comment: HYBRID

Materials/Assemblies	Amount	Unit	Comment
Aluminium (block) bj	0.05	kg	
Chromium I	0.3	kg	
Nickel I	3.37	kg	
PP injection moulded A	0.7	kg	
Manganese I	0.42	kg	
Steel low alloy ETH S	6	kg	
Titanium I	0.11	kg	
Vanadium I	1	kg	
Water demineralized ETH U	0.84	kg	
Zinc	0.35	kg	
Oxygen B250	0.6	kg	
H2 A	0.04	kg	

Processes	Amount	Unit	Comment
Electricity from coal B250	1	kWh	
Infra truck 16t S	1	tkm	
Injection moulding PET	222	kg	

Figure C.3: HEV nickel metal hydride entry



Name	Comment
SODIUM NICKEL CHLORIDE	HYBRID

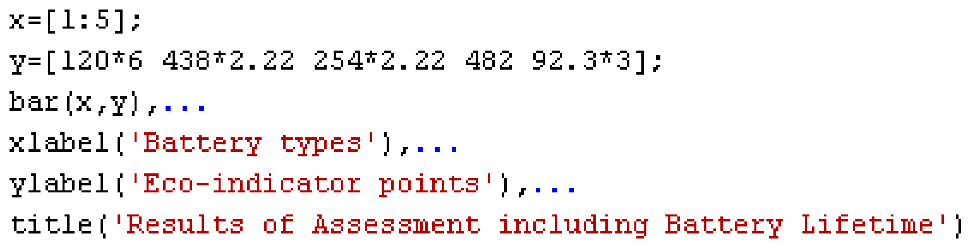
Materials/Assemblies	Amount	Unit	Comment
Aluminium (block) bj	1.2	kg	
Aluminium foil B250	2.3	kg	
Aluminium foil B	13.8	kg	
Cu-E I	0.25	kg	
Iron	2.3	kg	
Magnesium I	6.4	kg	
Steel low alloy ETH U	15.46	kg	
Nickel I	19.1	kg	
Sodium sulphate B250	12.2	kg	
NaCl (100%)	9.9	kg	
Steel high alloy ETH S	12.2	kg	
Silicagel I	4.77	g	

Processes	Amount	Unit	Comment
Electricity from coal B250	1	kWh	
Infra road delivery van S	1	tkm	
Injection moulding PET	97	kg	

Figure C.4: HEV sodium nickel chloride entry

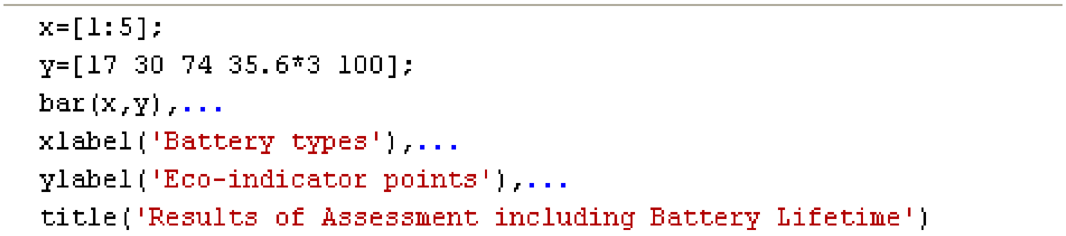
Appendix D

Matlab files



```
x=[1:5];
y=[120*6 438*2.22 254*2.22 482 92.3*3];
bar(x,y),...
xlabel('Battery types'),...
ylabel('Eco-indicator points'),...
title('Results of Assessment including Battery Lifetime')
```

Figure D.1: EV matlab file



```
x=[1:5];
y=[17 30 74 35.6*3 100];
bar(x,y),...
xlabel('Battery types'),...
ylabel('Eco-indicator points'),...
title('Results of Assessment including Battery Lifetime')
```

Figure D.2: HEV matlab file