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Comparative LCA of Electrification Alternatives for Long Haul Trucks

The Case of Iron Ore Powder Transportation from the Pajala Mine

Master of Science Thesis in the Master Degree Program Sustainable Energy Systems

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Cover: Scania's Catenary Hybrid

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Abstract

The transport sector is facing a major challenge in meeting future demands for increased energy efficiency. In the future, most likely new technologies such as hybridization, electrification and use of alternative fuels will play an increasing role.

The main purpose for carrying out this study has been to investigate how the environmental load of the road bound trucks transporting iron ore powder from the mine in Kaunisvaara, Pajala, to Svappavaara would be altered by a possible electrification. This has been done through an attributional comparative LCA study of three different drivetrain alternatives for heavy duty trucks, during 16 years of mining operation. The first alternative is a conventional truck with an internal combustion engine, constituting the reference alternative which the other two are compared with. The second alternative is a parallel hybrid electric version of the same truck without external charging and the third is a parallel hybrid electric version of the same truck receiving electricity from an overhead conductive catenary.

A handful of components in the parallel hybrid and catenary hybrid drivetrain have been identified, including a lithium-ion battery and an electric motor of different sizes. These components were studied throughout their life cycle: raw material extraction, production of components, drivetrain assembly, use phase, recycling and disposal. For the catenary hybrid alternative also the production of the extra needed infrastructure has been taken into account.

In order to quantitatively assess the environmental impact of these different phases, five different environmental impact categories have been used: global warming potential, abiotic depletion, and emissions of hydrocarbon, emissions of particles and emissions of nitrogen oxides.

The results show that both the parallel hybrid and catenary hybrid are better solutions than the conventional truck in general. However, the catenary hybrid is the more favorable choice in both impact categories as well as for the studied emissions. The use of electricity instead of diesel provides enormous savings in environmental impact.

Furthermore, it is shown that the largest contribution to the environmental load for the parallel hybrid clearly comes from the Li-ion battery. This is due to the amount of advanced materials included in the battery and that raw material extraction of these materials is very energy consuming. For the catenary hybrid it is the infrastructure which has the largest environmental impact. This is due to the large amount of material that is used and, again, the environmental impact comes mainly from the raw material extraction.

The life cycle phase that has the largest environmental impact is clearly the use phase with its enormous savings in fuel and thus also in environmental impact. However, even large changes in energy consumption do not change the final choice of the most favorable solution. Also when changing the electricity mix to a lot dirtier production the catenary hybrid is still outperforming both the reference vehicle and parallel hybrid.

This life cycle assessment does not provide values with exact precision for the final results. However, more important is that the final results and conclusions are very robust.

Sammanfattning

Transportsektorn står inför en stor utmaning att möta framtidens krav på ökad energieffektivitet. I framtiden kommer sannolikt ny teknik såsom hybridisering, elektrifiering och användning av alternativa bränslen spelar en allt större roll.

Det huvudsakliga syftet för att genomföra denna studie har varit att undersöka hur miljö-belastningen för lastbilar som transporterar järnmalm från gruvan i Kaunisvaara, Pajala, till Svappavaara skulle påverkas av den en eventuell elektrifiering. Detta har gjorts genom en orsaksinriktad (attributional) och jämförande LCA-studie av tre olika alternativ för drivlinor till tunga lastbilar, under 16 års gruvdrift. Det första alternativet är en konventionell lastbil med en förbränningsmotor och den referens som de andra två alternativen jämförs med. Det andra alternativet är en parallellhybrid, dvs. en elektrifierad version av samma bil men utan möjlighet till extern laddning och den tredje är en helelektrisk parallellhybrid, en elvägshybrid, av samma bil, men då elektricitet fås från en luftburen kontaktledning.

En handfull komponenter i parallellhybridens och elvägshybridens drivlinor har identifierats, däribland ett litium-jon-batteri och en elmotor i olika storlekar. Dessa komponenter har studerats under hela deras livscykel: utvinning av råmaterial, tillverkning av komponenter, montering av drivlinan, användningsfas, återvinning och avfallshantering. För elvägshybriden beaktas också produktionen av den nödvändiga tillkommande infrastrukturen.

För att kvantitativt kunna bedöma miljöpåverkan av dessa olika livscykelfaser har fem olika miljöpåverkanskategorier använts: potentialer för global uppvärmning och abiotisk resursanvändning, samt emissioner av kolväten, partiklar och kväveoxider.

Resultaten visar att både parallellhybriden och elvägshybriden är bättre lösningar än den konventionella lastbilen. Elvägshybriden är dock ett mycket fördelaktigare val sett till både miljöpåverkanskategorierna och de studerade emissionerna. Användning av el istället för diesel ger enorma besparingar i miljöpåverkan.

Dessutom visas det att det största bidraget till miljöbelastningen för parallellhybriden kommer från Li-jon batteriet. Detta beror på att mängden av avancerade material som ingår i batteriet och dess energikonsumerande råvaruutvinning. För elvägshybriden är det infrastrukturen som har den största miljöpåverkan. Detta beror på den stora mängd material som används och att miljöpåverkan även då kommer främst från råvaruutvinning.

Den livscykelfas som har störst påverkan på miljön är användningsfasen med sina enorma besparingar i bränsle och därmed också i miljöpåverkan. Även stora förändringar i energiförbrukningen förändrar inte det slutliga valet av den mest gynnsamma lösningen. Även vid byte av elmix till en smutsigare produktion är elvägshybriden fortfarande den mest gynnsamma lösningen.

Denna livscykelanalys ger inga slutresultat med hög numerisk noggrannhet. Däremot, och mycket viktigare, de slutliga resultaten och slutsatserna är mycket robusta.

Acknowledgements

I would like to thank Scania and the department of Energy and Environment at Chalmers University of Technology for commissioning this study. In particular Håkan Gustavsson, which has been my supervisor at Scania, and also all the coworkers at the department of hybrid system development which have been very helpful, kind and caring during my time working at Scania. I would also give my special thanks to my supervisor at Chalmers, Anders Nordelöf, for being very helpful, patient and showing his commitment to my project.

Confidentiality

Some information used in this project has been declared confidential by Scania. For this reason specific data for components have been left out this public report. Suppliers are not mentioned by name and manufacturing locations are randomized and this specific data has been included in a second appendix only presented to the supervisor and examiner at Chalmers, in addition to Scania.

However, all data necessary for the LCA calculations have been available for evaluation by all participating parties in order to assure the validity and quality of the LCA.

Table of Contents

1. Introduction

The transport sector is facing a major challenge in meeting future demands for increased energy efficiency. To achieve a significant reduction in energy consumption development and/or changes in many areas are required. Today, for example, a lot of work is done to train drivers to drive more energy efficient, to optimize the existing drivetrains and to vehicle aerodynamics. In the future, most likely new technologies such as hybridization, electrification and use of alternative fuels will play an increasing role.

The focus of this project is set on issues related to the drivetrain in a life cycle perspective. The aim is to increase the knowledge about environmental aspects of plausible future technologies for energy-efficient transportation with heavy commercial vehicles. Thereby the project also aims to provide support for decisions and strategies for vehicle electrification and the ability to meet energy efficiency targets and at the same time decrease the overall environmental load of the product in a larger systems perspective.

1.1 Background of the Iron Ore Mine Pajala Project

The global demand of iron is increasing, with the consequence that iron ore mines in operation will increase their activity, and that mines that today are in fallow will be resumed. Also, exploration of new iron ore deposits can be expected. (Trafikverket, 2012)

As a result, Northland Resources AB is planning to start mine operation in Kaunisvaara in Pajala in 2013, creating a need for a transportation solution for the iron ore powder. The current plan is to transport it by truck from the mine in Kaunisvaara to Svappavaara and then by train to the port of Narvik. Preliminary 1,5 million tons of iron ore powder will be transported from the mine annually, increasing to around 4,6 million tons from 2015. Because of the new mining establishment, the Swedish Government gave Trafikverket the mission to investigate the conditions for upgrading the standard of roads between Kaunisvaara in Pajala and Svappavaara in Kiruna municipality, and the ability to meet the arisen transport need and its effects.

The increased traffic will become a major burden on the existing road network, which today is not good enough for transport of this kind of weight, and large improvements of the current infrastructure must be made. The assignment to Trafikverket also included an analysis of the possibilities to carry out the transportation with trucks that run on electricity from the road. (Trafikverket, 2012)

There are three main stakeholders for electrification of heavy trucks for the transportation solution in Pajala, and their main interests are:

1. The *mining company* – Expects a significantly reduced cost due to both anticipated reduced maintenance on the trucks' engines and significantly reduced energy cost.
2. The *automotive industry* – Receives a demonstration facility. If it proves to be successful, it could contribute to development of the electrification system that could become a major export product for both the automotive industry and other stakeholders.

3. The *society* – The government strives for a lower environmental impact from the transport sector. In addition, Sweden confirms its position as one of the leading nations in the field of logistics and automotive technology.

1.2 Scania's incentive

For Scania, it is important to develop a better understanding of the factors that are central in the debate concerning energy efficient transport. For example, does it make sense to go for an all-electric drivetrain with batteries as energy storage, or is it better to keep the internal combustion engine and only run partly on electricity with smaller batteries? Or is it better to get electricity directly from the road? These questions are essential for Scania to answer, so the company can be a competitive supplier to the transportation industry in the future.

2. Life Cycle Assessment Methodology

In this chapter the life cycle assessment (LCA) concept is going to be explained and presented. It is an overviewing summary based on *The Hitch Hiker's Guide to LCA* (Baumann & Tillman, 2004) with additional remarks of the ISO standard 14040 series (ISO, 2006).

2.1 Introduction to LCA

LCA is used to analyze the environmental impact of products and services. The whole life cycle of a product is followed, from its "cradle to grave". The process starts with the extraction of raw material from natural resources, the "cradle", continues with production and use, and ends when the product reaches the disposal, the "grave".

Natural resource use and pollutant emissions are described in quantitative terms as showed in the Figure 2-1 below.

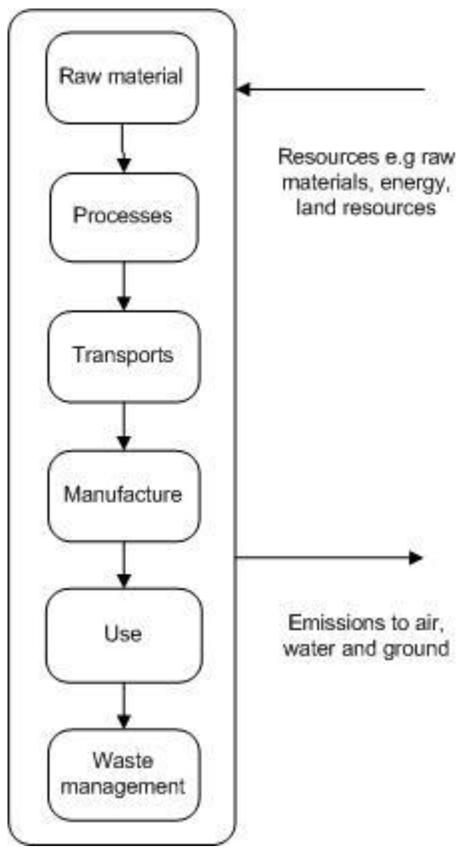

Figure 2-1 The life cycle model (Baumann and Tillman, 2004)

The LCA methodology contains a whole framework for how such studies are done and interpreted, as showed in Figure 2-2 below. First, the purpose and the object of study for the LCA are specified in the goal and scope definition. Second the inventory analysis implies the construction of the life cycle model and that emissions and resources used are calculated. In the third phase, the impact assessment, relations between emissions, resources used and various environmental problems are established through the act of impact classification and characterization. In the end of this phase the different environmental impacts may be put on the same scale through weighting, making it easier to compare the results.

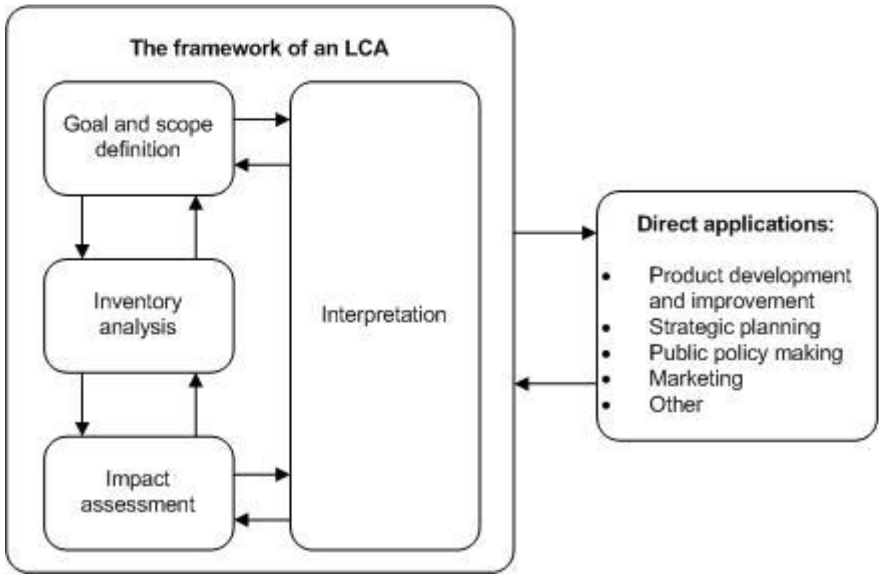

Figure 2-2 The framework of an LCA according to the ISO standard 14040 (2006)

The strength of LCA is that it takes the whole product system in consideration. This avoids the sub-optimization that may occur if only a few processes are focused on. It allows comparisons between alternative products since the results are related to the function of the product, rather than the product itself.

The data collected for an LCA can either represent some type of geographical average or be site specific depending on the type of process that specific data represent as well as the purpose of the study. For example, in the case of a raw material, which may have many different suppliers, an average value is often preferable and if it is traded on a global market it is best represented by a global average. It is rather seldom necessary to go too deep in the level of detail, when an indication of the environmental load often is preferable. Another reason is that the data collection is very time consuming and rather complex.

LCA includes normally only environmental aspects. However, in the impact assessment, different optional weighting procedures may include both economic and social considerations, when the relative importance of various environmental impacts is given values on one single scale.

LCA is also an important tool when learning about the relationships between the processes or when exploring the environmental properties of the studied product system.

2.2 Goal and Scope Definition

In the goal and scope definition phase of the LCA study, the purpose and the content of the study are decided upon. This part is crucial – it is important that the goal and scope definition are stated correctly and the questions asked are as precise as possible. This is because different purposes require different methodology and different methodological choices give different results.

2.2.1 Goal of the Study

The goal of an LCA study should clearly state the reasons for doing the study, the intended application and to whom the results should be presented to.

It is important that the goal is stated and explained in the beginning of the study, but as seen in Figure 2-2, LCA is an iterative process. This means that the purpose of the study can be redefined and additional purposes can be added along the way. Preferably, purposes are stated as questions, and some examples of how they may be phrased questions are given below (Baumann & Tillman, 2004):

- Where are the improvement possibilities in the life cycle of this product?
- Which are the activities in the life cycle that contributes the most to the environmental impact associated with this product?
- What would be the environmental consequences of changing certain processes in the life cycle in such and such a way?
- What is the environmentally preferable choice of products A, B and C for a designated application?

2.2.2 Scope of the Study

The scope will define the system boundaries of the LCA study that are needed to answer the stated goal, according to the ISO standard (2006). Again, as LCA is an iterative process and also the scope of the study can therefore be redefined along the way.

2.2.2.1 Flowchart

To get a general idea about the system studied, an initial flowchart normally is constructed at this stage of study. It does not need to be very detailed, since it is intended to provide an understanding of what is going to be covered in the study.

2.2.2.2 Functional Unit

The functional unit is a reference unit, used to normalize all the inputs and outputs included in the study. This is done to be able to compare all the aspects included in the study.

A process could have more than one possible function. However, the selected one should be dependent on the goal and scope and be measurable. Also the function, corresponding to the functional unit, describes the product or process purpose.

For stand-alone LCA studies, studies of single products or processes, the choice of the functional unit is seldom critical. In comparative studies, however, it may be a more difficult task since the functional unit is then used for comparison between the different alternatives. Then the functional unit must represent the function of the compared alternatives in a rational way, and all the different alternatives must fulfill the function rather well.

2.2.2.3 Impact Categories

It is important to consider which environmental impacts to take into account in LCA studies. The ISO standard (2006) prescribes three main groups of categories which should be covered: resource use, ecological consequences and human health. These are then often divided into subcategories, for example global warming, acidification and resource depletion to mention some of them. However, not all studies take all possible categories into account – it is a part of the scope definition and depends on the earlier stated purpose and intended audience of the study. Also, which data to collect follow the choice of impact categories as not all emissions contribute to all types of environmental impacts and vice versa.

2.2.2.4 Different Types of LCA

There are two main types of LCA studies which are called attributional and consequential. The first one answers questions like “What environmental impact can this product be held responsible for?” or “What is the difference in environmental impact between different alternatives?”. It examines the effects of or difference in effect between products or services when they are in operation, reflecting the causes of the system. The consequential type answers questions of the type “What would happen if …?” and it compares the foreseeable environmental consequences of a decision by modeling the effects of change. The attributional type of LCA has normally a retrospective approach in time, since it compares the causes of a system and consequentially has a prospective approach in time, due to the fact that it models the effects of a future change.

When deciding what type of LCA to use it helps to analyze how the outcome of the LCA will be used. As seen in Table 2-1 below, a summary of which type of methodology goes with which type of LCA.

Table 2-1 Characteristics of accounting type and change-oriented LCA models (Tillman 2000)

Type of LCA/ Characteristics	Attributional	Consequential
System boundaries	Additivity Completeness	Parts of system affected
Allocation procedure	Reflecting causes of a system Partitioning	Reflecting effects of change System enlargement
Choice of data	Average	Marginal (at least in part)
System subdivision	-	Foreground & background

2.2.2.5 System Boundaries

System boundaries are defined during the goal and scope part of the LCA. However, exact details can often not be decided until enough information has been collected during inventory analysis.

According to Baumann and Tillman (2004) the system boundaries need to be specified in several dimensions:

- Boundaries in relation to natural systems,
- Geographical boundaries,
- Time boundaries,
- Boundaries within the technical system:
    - Boundaries related to production capital, personnel, etc.
    - Cut-off criteria, means that flows with negligible influence on the main results can be ignored – they are "cut-off".
    - Boundaries in relation to other products' life cycles. Requires allocation procedures.

2.2.2.6 Allocation problems

Several products or functions can share the same process during their life cycles as products are linked in networks. This can cause an allocation problem, i.e. how should the environmental load be distributed between the products.

There are three basic cases when allocation problems are encountered:

1. Multi-output. Processes that result in several products. An example is a refinery process.

2. Multi-input. Waste treatment processes, e.g. landfill, that have input consisting of several products.

3. Open loop recycling. When one product is recycled into a different product. Quality losses are often a result of open loop recycling. Some examples of this type of process are recycling of food packaging into other types of packaging and recycling of energy from waste incineration.

Allocation problems can sometimes be avoided through increasing the level of detail in the model. However, this is only true for multi-output and multi-input, but not for open loop recycling.

2.2.2.7 Data Quality Requirements

Data quality requirements should be defined so that the goal and scope of the LCA study are reached. Depending on which data that is used the LCA will give different results and also provide different reliability of the results. When talking about data quality Baumann and Tillman (2006) discusses relevance, reliability and accessibility as main features.

Relevance describes whether the used data actually represent what it should. When the availability of suitable data is limited and approximate data are borrowed from other LCA studies, the relevance might become a problem. Furthermore, Baumann and Tillman (2004) explain that precision is an aspect that is connected to reliability of data. It concerns the numerical accuracy and uncertainty of data. However, reliability also depends on the consistency with which it has been collected and documented and also on the competence of the person or organization that collected the data. Data are more credible if they can be reviewed and that is only possible if they are documented transparently. Transparent documentation also supports the reproducibility of the results and the reproducibility is connected to the accessibility of the data.

Major assumptions and limitations of the study should be described and explained in the goal and scope definition. However, some limitations can be a result of problems that comes up along the study. One problem could be the project resources, for example if there is not enough time to go deep enough in the level of detail. Then the limitations of the study will be updated. This is another example that shows that LCA is an iterative proves.

2.3 Procedural Aspects and Planning of an LCA Study

Before setting up an LCA some important activities need some considerations. These are described in this subchapter.

2.3.1 Critical Review

Critical review is a method to verify whether an LCA study has met the requirements for methodology, data and reporting according to the ISO standard (2006), although generally regarded as optional by the standard. However, if the results of the LCA study should be revealed to the public, the ISO standard states that it must be conducted.

Different types of critical reviews can be made, from internal or external experts, or by interested parties.

2.3.2 Actors in an LCA Project

The practitioner is the one conducting the LCA study; it can be a single person or a group of people. Often there is also a commissioner separate from this group, who requests the LCA study to be made. The commissioner has the task to state the goal of the LCA, but it often becomes too vague to use as a basis for the study. For this reason the goal and scope definition should be seen as an interaction between commissioner and practitioner so that the general goal is rephrased to a more specific purpose, preferable in the form of a question. Another part that is discussed between the two is the planning of the study so it will stay within the time and budget constraints.

Since the largest amount of work is the data collection, it is important to plan the data collection in detail. For example which data sources to use for which parts of the life cycle.

2.4 Inventory Analysis

Life cycle inventory analysis, LCI, involves data collection and calculation procedures to quantify relevant inputs and outputs of a product system according to the ISO standard (2006).

The inventory analysis includes the construction of a detailed flow model of the technical system. It is an incomplete mass and energy balance, where only the environmentally important and relevant flows are taken into consideration. LCI models are simplified to become static and linear, and do not use time as a variable.

The activities of an LCI include (Baumann and Tillman, 2004):

1. Construction of the flow chart according to the system boundaries decided on in the goal and scope definition.

2. Data collection for all the activities in the product system followed by documentation of collected data.

3. Calculation of the environmental loads (resource use and pollutant emissions) of the system in relation to the functional unit.

As data is collected during this part it is sometimes necessary to revise decisions taken during the goal and scope definition, and as mentioned earlier this leads to an iterative process between these two parts.

2.4.1 Construction of a Flow Chart

In the goal and scope definition a general flow chart was constructed. In the inventory analysis the flow chart is made much more detailed. It shows all modeled activities and the flows between them. As mentioned before, the inventory analysis is an iterative process which means that when more information is collected about the processes it will lead to revisions in the flowchart with more details.

2.4.2 Data Collection

The most time consuming part of the LCA study is the data collection. It can be very difficult to find data about some activities in the studied process and then assumptions and limitations are inevitable.

2.4.2.1 Which Data

Numerical data on the inputs and the outputs to all modeled activities need to be collected. These are inputs of raw material and energy, inputs and outputs of products and emissions to air, water and land and other environmental aspects. Also descriptive and qualitative data need to be collected to support allocation.

2.4.2.2 Data Sources

There are many different technical procedures taking place in a life cycle and it is almost impossible for the practitioner to be an expert on all the fields represented. Therefore, experts within specific subjects need to be consulted and communication between the expert and the practitioner is then very important. Of course there are other data sources as well, e.g. different data bases, other companies and so on.

2.4.2.3 Planning for Data Collection

Before collecting data the practitioner needs to know in advance how the processes work to be able to ask the right questions and be prepared for dialogue with various experts. Also the practitioner must decide for which processes average data is preferred and where site-specific data need is necessary.

Another aspect of importance is to have a strategy for addressing and handling confidentiality issues with suppliers and decide if the suppliers will be given the opportunity to see how their data is used and interpreted.

2.4.2.4 Validation of Data

The ISO standard (2006) requires a check of the validity of the collected data. Such checks can be done by comparisons with other data sources, or by performing mass and energy balances. The practitioner shall also check if the data quality requirements formulated in the goal and scope are fulfilled, and if the data sets collected are within the system boundaries.

2.4.3 Calculation Procedures

When all the data is collected and the flow chart is drawn completely an LCI is calculated in the following steps (Baumann and Tillman, 2004):

1. Normalize data for all the activities where data have been collected.
2. Calculate the flows linking the activities in the flow chart, using the flow representing the functional unit as a reference.
3. Calculate the flows passing the system boundaries, again related to the flow representing the functional unit.
4. Sum up the resource use and emissions for the whole system.
5. Document the calculations.

2.4.4 Allocation procedures

In previous subchapter allocation problems are described. The solution is referred to as an allocation procedure and there are two main methods: allocation through partitioning or by system expansion. Partitioning means that the up-stream resource consumption and emissions associated with the multiple processes are divided between them based on for example weight. System expansion means that the system boundaries are enlarged, for example that an industrial system is credited with the environmental load from the heat production that is avoided in the district heating system when it receives surplus heat.

The ISO standard (2006) sets out following procedure for dealing with allocation:

1. Whenever possible, allocation should be avoided by:
    a. Increasing the level of detail of the model
    b. System expansion

2. Where allocation cannot be avoided, the environmental loads should be partitioned between the system's different products or functions in a way which reflects the underlying physical relationship between them.

3. Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them.

Baumann and Tillman (2004) support a different method for allocation procedures based on the reason for the product's existents. This puts focus more on the economic aspects than the ISO standard (2006). One example could be extraction of gold, where the largest part of the extracted mass is another mineral. Therefore, if the ISO standard rules are followed, the largest percent of the environmental load should be allocated to the mineral and not to gold. However, the reason for extracting anything at all from that mine is that it consists of gold, and this can be taken into account in the study by using the economic values of the mine products as the basis for the allocation. Baumann and Tillman (2004) also say that the allocation method should depend on which type of LCA that is carried out. They think that partitioning is applicable to attributional LCAs and system expansion is more relevant for consequential LCAs. This is also shown in Table 2-1.

2.5 Impact Assessment

Life cycle impact assessment (LCIA) aims to describe the environmental consequences of the environmental loads in the LCI. The LCIA is achieved by using the results from the LCI and translate the loads into impacts, such as acidification, ozone depletion, global warming, toxicological impacts on human health, effect on biodiversity, etc. These impacts are sub-categories to three general categories of environmental impacts often considered in LCA studies: resource use, human health and ecological consequences.

One reason for making this translation is that it is easier to communicate the results from an LCIA than an LCI. People not familiar with LCA or environmental systems analysis, probably relate easier to the potential for acidification than to SO_2.

Another reason is to improve the readability of the results; the number of parameters from the LCI can be up to 200 or more, but it can be reduced significantly to about 15 when using LCIA, or even down to one by weighing across the impact categories.

In this sub-chapter the methods of doing an LCIA are described and discussed.

The LCIA are divided into mandatory elements and some optional element, as seen in Figure 2-3 the below (ISO 2006).

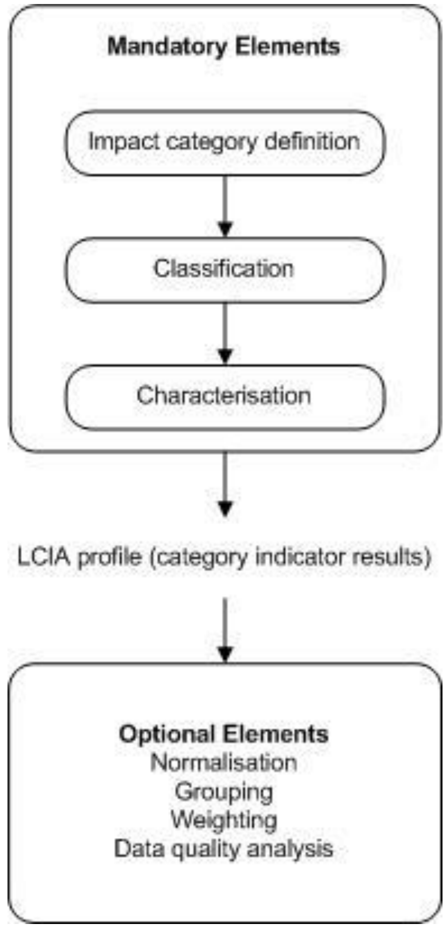

Figure 2-3 The LCIA are divided into mandatory elements and optional element (Baumann and Tillman, 2004)

The core sub-phases of LCIA are classification, characterization and weighting and they are often used when carrying out an LCA. When using ready-made LCIA methods many of the sub-phases are already included inside the method. There are several of ready-made LCIA methods and the practical advantage of them is that the environmental information for various pollutants and resources are aggregated to a characterization indicator or even a single number, an index including weighting. The procedure of the impact assessment is already inside the ready-made LCIA methods.

2.5.1 Impact Category Definition

In this part the set of impact categories will be described in more detail than in the goal and scope definition. When deciding which impact categories to include several things should be considered as completeness, practicality, independence, possibility to integrate in the LCA calculations, environmental relevance and scientific method (Baumann and Tillman, 2004*)*. Some conflicts may occur when considering all of these aspects, and then a decision on the best solution must be made by the practitioner.

2.5.2 Classification

In this sub-phase of the LCIA the LCI result parameters are sorted and assigned to the various impact categories. The easiest way to find out which parameter that should be assigned to which impact category is through published lists. In these there are various substances together with their equivalency factors listed per impact category.

For example CML-IA is a database that contains characterizations factors for LCIA (Institute of Environmental Sciences, CML). In some cases certain environmental loads corresponds to more than one impact category and need to be listed in all affected categories. However, this can only be done when the impact categories are independent of each other, otherwise it will lead to double counting.

2.5.3 Characterization

This sub-phase is a quantitative step. When calculating the magnitudes of potential environmental impacts per category, the equivalency factors, which are defined by expert sources such as IPCC, are used while modeling the cause-effect chains. For example, if acidification is the impact category, all the emissions causing acidification (SO_x, NO_x, HCl, etc.) in the LCI are added up based on their equivalency factors. The sum of all these emissions is an indication of the potential acidification impact.

2.5.3.1 Methods for Characterization

Characterization methods translate environmental load into impact, based on scientific methods, from chemistry, toxicology, ecology, etc. For pollutants a combination of their physicochemical properties and their effect in the environment are considered. For resources, land use, noise, casualties, etc. other modeling principles, based on occurrence or frequencies, are used.

Since the environmental system is rather complex, some impact categories have several alternative characterization models. There are also categories where characterization factors are lacking or have incomplete sets of equivalency factors.

The emission-caused impacts such as acidification, eutrophication and global warming, have more developed characterization methods than those mentioned above. When such methods are lacking, conditional assessment factors can be developed for the specific study in order to evaluate the results from the inventory analysis. Otherwise the impact assessment points out certain environmental impacts and neglects others (Baumann and Tillman, 2004). These assessment factors could be developed by LCA practitioners with good environmental knowledge. However, it is more common to separate the results which is lacking on the characterization method from the others and present them under different heading, for example *flows to other technical systems*.

2.5.4 Normalization

In this step the results from the characterization are connected to the actual or predicted magnitude for each impact category. Normalization is carried out when a comparison between the results in relation to one specific studied system can give more transparency. The aim of normalization is to gain better understanding of the size of the environmental impacts that is caused by the studied system.

2.5.5 Grouping

In this sub-phase the characterization results are sorted into one or more sets. However, this is a noncompulsory step, and it is occasionally unnecessary, but it can make the results more transparent. It can also be very useful for the analysis and presentation of the results. For example the characterization results can be sorted into global, regional, local impacts or impacts with high, medium and low priority.

2.5.6 Weighting

This sub-phase can be defined as the qualitative or quantitative process where the relative importance of the different environmental impacts is weighted against each other. Furthermore, the relative weights are expressed by their weighting factors.

The environmental harm of a pollutant or a resource is indicated relative to other pollutants or resources in ready-made LCIAs. Characteristic for the weighting methods is that all environmental problems are measured on a single scale, and therefore it is possible to calculate the total impact of a system into one number. It is obtained by multiplying all environmental loads of the system by their corresponding indices and summing them up.

$$Total\ environmental\ impact = \sum_{i=0}^{n} load_i\ x\ index_i$$
$$where\ i = all\ pollutants\ and\ resources\ used$$

According to the Baumann and Tillman (2004) the methods for generating the weighting factors are mainly based in the social sciences and on several kinds of principles, for example the European Network for Strategic Life-Cycle Assessment Research and Development (LCANET) and European Environmental Agency (EEA). These are:

- *Monetarisation*. With this method our values concerning the environment are described as the cost of various kinds of environmental damage or as the prices of various environmental goods. One important aspect is how values are described for goods for which there is no market (therefore no price). However, a price can be derived from peoples willingness-to-pay (i.e. one question asked can be how much they are willing to pay to avoid extinction of a species, for example) or revealed by their behavior (e.g the difference in price of similar houses close and far away from an airport reveals the cost of noise coming from the airport).

- *Authorized targets.* This method uses the difference between current levels and target levels of pollution, and it can be used to derive weighting factors. The target levels can be formulated by national authorities as well as by companies. This approach could be said to be based on a so called distance-to-target thinking.

- *Authoritative panels*. In this approach panels are used. They can be made up of, for example, scientific experts, government representatives, decision makers in a company or residents in an area. The panels typically describe and rank various types of impacts so that weighting factors representative for their view can be derived.

- *Proxies.* With a proxy method, one or a few parameters are stated to be indicative for the total environmental impact. Energy consumption and weight are some examples of proxy parameters.

- *Technology abatement.* The possibility of reducing environmental loads by using different technological abatement methods (e.g. filters, etc.) can be used to set weighting factors. This method can be said to be based on a distance-to-technically-feasible-target thinking.

There will never be a consensus in the weighting element in LCIA, since both ethical and ideological values are involved. Many engineers therefore have an awkward relationship to weighting, and the use of weighting factors often lead to discussion about whether they are "scientifically correct" or not, whether the values are representative or not, etc.

Many LCIA methods are described in principle, but lists with indices for various substances have been developed for a small number of them. Those methods use different means, i.e. weighting principles, to obtain the one-dimensional indices. Each method reflects different social values and preferences, since the determination of the relative harm of different environmental impacts is a value-laden procedure.

2.5.7 Data Quality Analysis

To better understand the significance, uncertainty and sensitivity of the LCIA results additional analysis may be needed, for example relevant sensitivity analysis. This is a part of the interpretation phase of the LCA where findings from the LCI and LCIA are combined together in order to reach conclusions and recommendations. These findings can also be used for reviewing and revising the goal and scope of the LCA as it is an iterative procedure. According to Baumann and Tillman (2004) these techniques are used in order to identify:

- the most polluting activities in the life cycle.
- the most responsive inventory data, i.e. a sensitivity analysis, where the data describing the activities in the life cycle for which minor changes in value change the ranking between compared alternatives.
- the most responsive impact assessment data, i.e. a sensitivity analysis.
- the significance of alternative methodological choices, e.g. different types of allocation, also a type of sensitivity analysis, and
- the degree of uncertainty in the results (uncertainty analysis). Uncertainty is introduced to the calculations when input data are estimates, intervals or probabilities.

3. Drivetrain Technology

In this chapter the three alternative drivetrain solutions are going to be explained more in detail. The first alternative is a drivetrain from a conventional truck with an internal combustion engine (ICE) and a transmission system. The second alternative is a parallel hybrid electric vehicle with the same ICE and transmission system as the conventional truck but with additional electric components described in this chapter.

The last studied alternative is a truck which uses electricity supplied through conductive transfer from overhead electric wires. The drivetrain in this alternative consists of the same parts as in the conventional alternative plus an extra large electric machine and a pantograph. In this last alternative there is also infrastructure needed to deliver the electricity to the vehicle which must be included in the LCA.

3.1 Drivetrain of a Conventional Truck

Internal combustion based motor vehicles have been built for more than a century and engines are an affordable and well-established power source. Below the drivetrain of a conventional truck is going to be presented.

3.1.1 Drivetrain Architecture

The drivetrain of a truck often have the following torque-transmitting elements (Basshuysen and Schäfer, 2004):

- A internal combustion engine.
- A torque converter
- A gearbox. Consisting of an initial movement element and the actual speed-reduction gearing system.
- A final drive gearing systems.
- Possibly an integrated starter-motor/alternator (ISG).
- In the case of four-wheel drive a power divider will also be included.

Other functions are balancing the engine and vehicle traction requirements, reduction of engine rotation irregularities and distribution power to the wheels.

The distribution of power is achieved by an exchange of torque between the front and rear axles. The gearbox adapts the movement of the engine to a significantly larger, and required, torque. (Basshuysen and Schäfer, 2004).

3.1.1.1 Internal Combustion Engine

Internal combustion engines are energy conversion devices which extract stored energy in a fuel through the combustion process and deliver mechanical power (Husain, 2011).

ICEs for conventional vehicles are designed to operate over a wide range of power and torque, and compromise is often necessary to deliver acceptable efficiency and performance throughout its operating regime.

ICEs used in automobiles, trucks and buses are of the reciprocating type, where the reciprocating motion of a piston is converted to linear motion through a crank mechanism.

There are two types of reciprocating ICEs, and they are the spark-ignition (SI) engine and the compression-ignition (CI) engine. The two types are more commonly known as gasoline/petrol engine and the diesel engine depending on the fuel used for combustion. The main difference between the two is the method of initiating the combustion. (Husain, 2011).

To start with the SI engine, a mixture of air and fuel is drawn in and a spark plug ignites the intake of the engine, which are called the charge. To help to measure the right amount of fuel in response to driver demand, electronic control devices are used. The SI engines are relatively light, lower in cost and used for low power applications, as in conventional cars. (Husain, 2011)

In the CI engine, which is more suitable for heavy duty vehicles, air is drawn in and compressed to such high pressure and temperature that combustion starts spontaneously when fuel is injected. These engines are more suitable for applications in the high power range, such as trucks. Problems with NO_x emissions in CI engines can be solved through catalytic conversion and emission after-treatment components. (Husain, 2011)

However, since all three drivetrain alternatives will have the same internal combustion engine, and since it is a comparative LCA study, the effect on the environment for producing the engine will not be included.

3.2 Topology of Hybrid Electric Vehicles

The definition of a hybrid electric vehicle (HEV) is that it uses two different types of sources to deliver power to the wheels for propulsion. The most common setup is to combine an ICE with one or more electric machines. The main reasons of using hybridized vehicles are to improve fuel economy, reduce fuel consumption and reduce emissions (Husain, 2011).

Compared with conventional drivetrains, HEVs generally provide better fuel economy through regenerative braking, less engine idling and more efficient engine operation. The drivability gets better since the electric motor characteristics better match the road load. Also, emissions of greenhouse gases are decreasing with HEVs and since the fuel economy is better the fossil fuel consumption is reduced (Mi et al, 2011).

3.2.1 Drivetrain of Hybrid Electric Vehicles

There are different classifications of HEVs based on the configuration of the drivetrain, for example series hybrid, parallel hybrid, series-parallel hybrid and plug-in hybrid (Mi et al, 2011). Below in the Figure 3-1 and Figure 3-2 examples of a series and a parallel hybrid drivetrain are showed. The analyzed hybrid alternative in this LCA study is a parallel hybrid.

Scania has chosen to go with a parallel hybrid for efficiency reasons. The parallel hybrid has better fuel economy than series hybrid, but series variants have other advantages, for example it is easier to pack and it has a better noise profile[1].

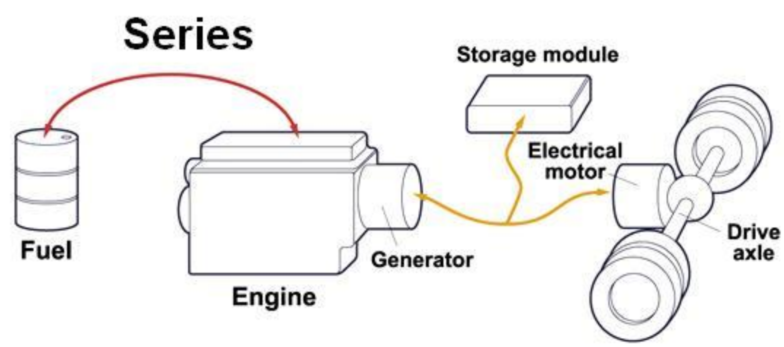

Figure 3-1 Series hybrid drivetrain (Scania)

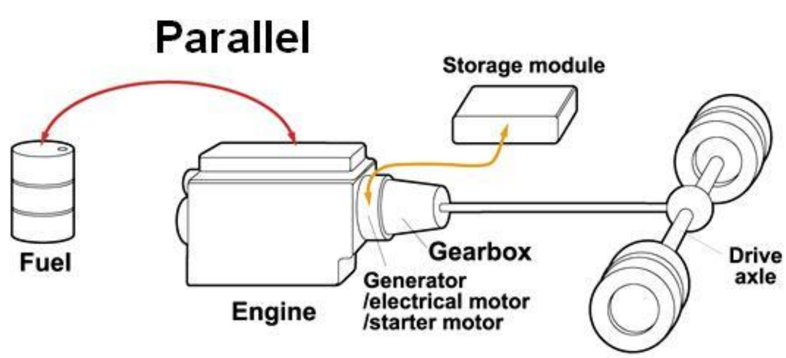

Figure 3-2 Parallel hybrid drivetrain (Scania)

[1] According to Johan Lindström at Scania

3.2.1.1 Modes of the Parallel Hybrid

In a parallel hybrid drivetrain, the engine and the electric machine can be used in the following modes (Mi et al, 2011):

- *Electric machine-alone mode*. When the battery has sufficient energy, and the vehicle power demand is low, then the engine is turned off, and the vehicle is powered by the battery only. The electric energy in the battery is converted to kinetic energy by the electric machine operating as a motor with positive torque.

- *Combined power mode*. At high power demand, both the ICE and the electric machine supplies mechanical power. The necessary engine torque is reduced in purpose to save fuel.

- *Engine-alone mode*. During highway cruising and at moderately high power demands the engine provides all the power and the electric machine is unused.

- *Power split mode*. When the engine is on, but the vehicle power demand is low and the battery SOC is also low, then some of the engine power is converted to electricity by the electric motor acting as a generator to charge the battery.

- *Stationary charging mode*. The battery is charged by running the electric motor as a generator driven by the engine, without the vehicle being driven.

- *Regenerative braking mode*. The electric machine is operated as a generator during vehicle braking to convert the vehicle's kinetic energy into electric and store it in the battery. The electric machine here acts a part of the vehicle brake system to collect energy during braking.

3.2.2 Important Components of the Parallel Hybrid

The components of the Scania parallel hybrid system, included in the life cycle assessment, are explained in this sub-chapter.

3.2.2.1 Electric Machine

An electric machine is an electromechanical device used for electrical to mechanical energy conversion and also vice versa. It is both a motor and a generator. The electric machine can process supplied electric energy and deliver torque to the propulsion system, but it also processes the power flow in the reverse direction during regeneration when the vehicle is braking (Husain, 2011).

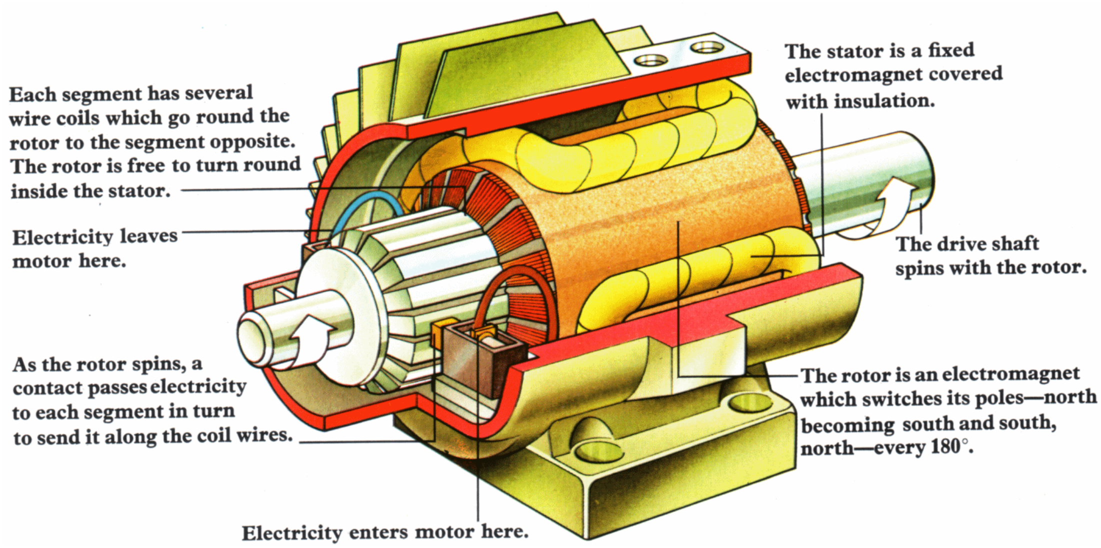

Figure 3-3 An example of an electric machine (Arthur's Engineering Clipart)

Thus, the electric machine is called motor when it converts electrical energy to mechanical, and it is called generator when the power flow is in the opposite direction. The braking mode in electric machines is referred to as regenerative braking. Above in Figure 3-3 an example of an electric machine is seen.

Losses occur in electrical, mechanical and magnetic forms during the conversion process, which affects the electric machine's efficiency. However, the efficiency of electric machines is quite high compared to other types of energy conversion devices.

The major advantage of an electric machine compared to an ICE is that the electric machine can provide full torque at low speeds and the instantaneous power provided can be two or three times the rated power of the motor. (Husain, 2011).

There are both DC and AC electric motors. The DC motors are too big and require a lot of maintenance; therefore electric and hybrid vehicles often use AC motors, in this case a type based on permanent magnets called permanent magnet synchronous motor (PMSM).

3.2.2.2 Inverter

An inverter is a device that converts direct current, DC, from the battery to alternating current, AC, to drive and control the electric motor. The inverter also converts AC to DC when it takes power from the generator to recharge the batteries. The required voltage can be constructed with the use of appropriate transformers, switching and control circuits. Below in Figure 3-4 an example of how an inverter is shown.

Figure 3-4 One example off an inverter (Real Work Trucks)

3.2.2.3 DC/DC

A DC/DC converter, as seen in Figure 3-5, changes the system voltage from one level to another. The input is a filtered DC voltage, although it may be unregulated. The output is a regulated DC voltage, and multiple outputs can be designed for many applications. There are both isolated and non-isolated converters. The 12V electronics in the electric and hybrid vehicles are supplied with a high- to low-voltage DC/DC converter, and this needs to be of the isolated type (Husain, 2011).

Figure 3-5 An example of DCDC converter (Pues EV)

3.2.2.4 Battery

Hybrid and electric vehicles in general need some type a portable supply of electrical energy. The electrical energy is typically obtained through conversion of chemical energy stored in devices such as batteries and fuel cells for example (Husain, 2011).

Batteries are the most convenient and developed choice of energy storage available for electric and hybrid vehicles. High specific power, high specific energy, high charge acceptance rate for both recharging and regenerative braking, and long calendar and cycle lives are wanted features of batteries to use for hybrid and electric vehicles. However, although most of these requirements can be met in some combinations technically, the cost of batteries is often still too high to be commercially applicable. (Husain, 2011)

There are two types of batteries, primary and secondary batteries. The main difference is rechargeability – primary batteries are not rechargeable while secondary batteries are. The batteries used for hybrid and electric vehicles are for obvious reasons of the secondary type.

The main types of batteries used or being considered for hybrid applications are, according to Husain (2011):

- Nickel-metal-hydride (NiMH)
- Lithium-ion (Li-ion)
- Lithium-polymer (Li-poly)
- Sodium-sulfur

The most promising battery among the four are the Li-ion, but there are several of different types of Li-ion battery technologies being developed. An example of a Li-ion battery is seen in Figure 3-6.

Figure 3-6 A Li-ion battery (DIY Trade)

To obtain as long life time as possible the battery state of charge (SOC) is often limited for discharging and charging, for example to 25% of the total possible capacity. This means that a large share of the battery capacity is not used. An alternative to batteries for some hybrid truck applications are super capacitors which do not rely on chemical reactions and therefore have a much longer lifetime. They can be operated between a SOC of 0% and 100% without degrading the lifetime, and at the same time withstand a large number of charge/discharge cycles. (Fuhs, 2008).

3.2.2.5 Hybrid Power Unit Housing

The housing of the hybrid power unit is a box made of aluminium and steel[2] that contains the battery, inverter and the DC/DC unit, but also the cooling and warming unit. However, the two last parts are not included in this study.

3.3 Drivetrain of a Vehicle with Electricity from the Road

Electrified heavy vehicles are not new. From 1920 to 1960 trolleybuses was quite common in Swedish cities. However, this was before the diesel engine came into production and after its introduction the overhead contact wires was dismantled. Nevertheless, trolleybuses are still used in south of Europe and other parts of the world.

A lot of resent interest for electrifying heavy vehicles has focused on solutions with continuous electricity supply during driving instead of battery-powered solutions. The reason is that in the foreseeable future it is not considered feasible to implement battery solutions for heavy transports driving long distances due to the limited amount of energy and power batteries can supply. (Trafikverket, 2012)

According to Trafikverket (2012) there are today three main technologies for continuous electricity supply from infrastructure to the vehicles during driving:

- Conductive transfer through overhead catenaries,
- Conductive transfer via some form of tracks or leaders in the road,
- Inductive transmission via electromagnetic fields from the road structure.

The first alternative, as seen in Figure 3-7, is today the most developed technology and also the one studied in this LCA study. However, there are some important differences between the earlier mentioned trolley busses compared to electrified long-haulers, for example the environment in which the transportation work is made, the average speed and what is being transported. Another important difference is that in cities, where trolleybuses naturally are implemented, the buildings could be used to mount the electric wires. (Trafikverket, 2012)

[2] Interview with Alexei Tsychkov at Scania

Figure 3-7 Conductive power transfer from overhead catenaries (Scania)

Figure 3-8The second and third concept, which is seen in Figure 3-8 and Figure 3-9 below, are new in this context. Therefore the knowledge behind these concepts is to a larger extent protected by the inventing companies and their patent rights, which complicates comparisons. For this reason only the first concept is used and analyzed in this study.

Figure 3-8 Conductive power transfer from the road (Scania)

Figure 3-9 Inductive power transfer from the road (Scania)

The requirements on reliability to transport the iron ore from the mine to the customer are very high. Therefore, considering the conductive tracks and the inductive technology, it is more reasonable to implement demonstration plants before full-scale implementation is made, motivated by not least the technology immaturity and operational uncertainty but also the economic and time aspects for the Pajala mine project. (Trafikverket, 2012)

3.3.1 Important Components of the Catenary Hybrid

The components which will be used in the Scania catenary hybrid system, as included in the life cycle assessment, are explained in this sub-chapter.

3.3.1.1 Electric Machine

The electric machine in the electrified truck has the same technology as in the hybrid alternative except that it is larger, so see the previous chapter for an explanation of the technology.

3.3.1.2 Pantograph

The electricity supplied to the vehicle is collected from the overhead wires by a pantograph, as it can be seen in Figure 3-7 above. Since the transfer is conductive, the pantograph must maintain good contact under all running conditions of the vehicle in order to provide power. The higher speed is, the more difficult it is to maintain good contact between the pantograph and the electric wires.

In today’s technology the contact is maintained between the pantograph and the electric wires by spring or air pressure. However, compressed air pressure is preferred for higher speed operations. To maintain the pantograph in raised position, the pantograph is connected to a piston cylinder which remains the required air pressure. (Trafikverket, 2012)

The pantograph itself consists of a contact strip or similar, which is lagging the electric wires and transfers the electricity to the vehicle. The contact strips are supported by a mechanical structure which is attached to the vehicle and is adjustable. At least two contact lines must be used to transmit the electrical energy, and more degrees of freedom to the pantograph is needed in order the connection to the electrical wires in momentum is safe (Ranch, 2011).

However, it is important to point out that the installation and system integration of the pantograph on the truck is still under development.

3.3.1.3 Infrastructure

The added infrastructure consists of a large power system consisting of an auxiliary and catenary system. The catenary system supplies the trucks with propulsion power and the auxiliary system supplies the signaling, telecom, switch heating, illumination and other systems. Also an automatic transformer system is used for distributing the power in the catenary system.

As mentioned, the infrastructure includes a telecom system. The telecom system is used to facilitate communication along the road. It consists of telecom cables, telephone systems, transmission facilities, radio equipment, detectors, radio towers and buildings for electrical equipment. All construction, operation and maintenance are included in the assessment of the infrastructure.

4. Definition of Goal and Scope for this Study

In this chapter the goal and scope of this LCA study will be defined and explained.

4.1 Goal of the Study

The main purpose for carrying out this study has been to investigate the effect on the environmental load of a possible electrification of the road bound trucks transporting iron ore powder from the mine in Kaunisvaara, Pajala, to Svappavaara. This has been done through an attributional comparative LCA study of three different drivetrain alternatives for heavy duty trucks, during 16 years of mining operation – this equals the whole lifetime of the mine minus the estimated construction of necessary infrastructure. In essence, the ***vehicle cycle***, or cradle to grave**,** impact of a set of additional components have been compared to the effect of the reduced total energy use of fuel and electricity in the well to wheel phase when a conventional truck has been solely hybridized or hybridized with external power supply from the road.

Three questions have been evaluated:

1. What is the difference in environmental impact of the three alternatives for transporting iron ore powder?

2. Which added component in the drivetrain has the largest environmental impact?

3. Which phase in the life cycle has the largest environmental impact?

4. Assuming the same extraction rate per year, how long time must the mine be operated before break-even is reached for the two alternatives, with the reference and with each other?

This study was commissioned by Hybrid Systems Development department at Scania CV AB and they have also been the intended recipients. Their motive for initiating this study has been to increase their knowledge about the potential environmental impacts of electrifying the drivetrain of heavy duty trucks.

4.2 Scope of the Study

Three different alternatives for the drivetrain have been compared. All other parts of the trucks have been assumed to be exactly the same for all three alternatives and for this reason been left out of the study.

4.2.1 Options

The three alternatives are:

1. A conventional truck with an internal combustion engine
2. A parallel hybrid electric version of the same truck without external charging

3. A parallel hybrid electric version of the same truck receiving electricity from an overhead conductive catenary

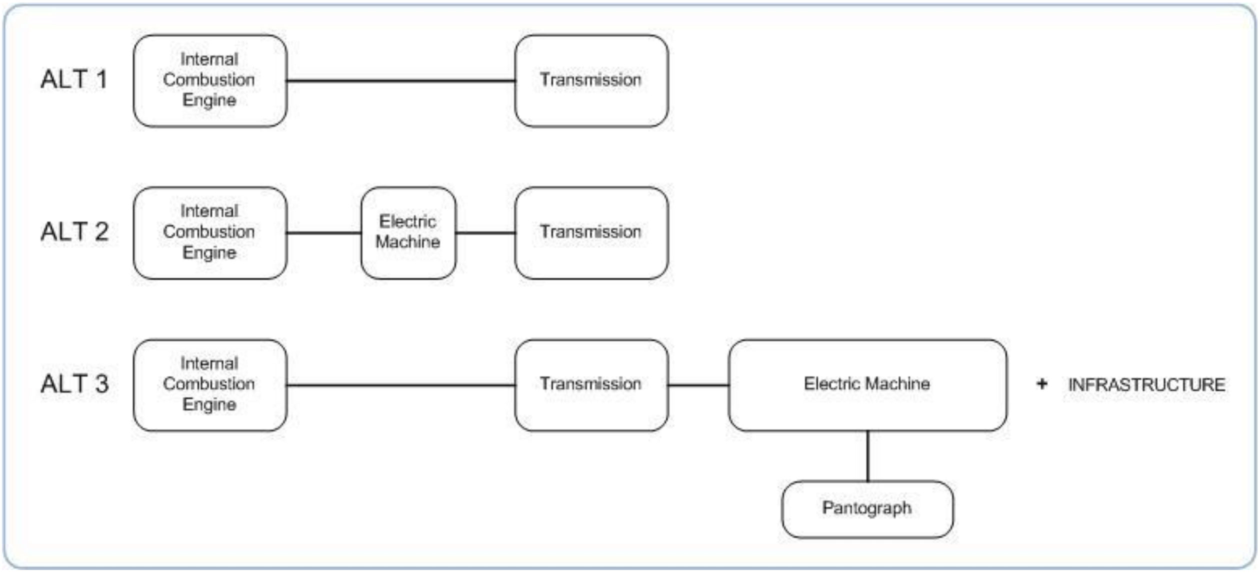

Figure 4-1 The three different alternatives studied

In this report the first alternative will be referred to as the reference alternative, the second alternative will be mentioned as the parallel hybrid alternative and the third as the catenary hybrid alternative.

The reference alternative, as seen in Figure 4-1, was the conventional truck which constituted the baseline for the comparison – all components in this truck were also included the other two alternatives. They have the same internal combustion engine and from an LCA perspective equivalent transmission systems. This conventional truck is able to load 65 tons of iron ore powder and the total weight of the truck is 90 tons, which is also the maximum allowed weight for all three alternatives.

The second alternative was the parallel hybrid truck which has been electrified to make the drivetrain more efficient and use less fuel, but without being externally charged. As the internal combustion engine and the transmission has been kept the same as in the conventional truck, only a set of additional main components have been identified by Scania for the study. The complete cradle-to-grave life cycle of these components have been included from raw material extraction and production, component manufacturing and assembly in the vehicle, their effect on the fuel consumption in the use phase, to the waste handling and recycling of materials when they are scrapped.

The following components were selected: the power electronic controller in the form of an inverter, the electric machine, the DCDC converter, the lithium ion battery and the hybrid power unit housing. Furthermore, as the addition of these extra components to the drivetrain increased the unloaded vehicle weight, it also implied that the weight of the iron ore powder possible to load had to be reduced in order to keep the maximum weight of the loaded vehicle. This lead to an increase in the number of trucks needed to transport the same amount of load, however only five extra trucks in continuous operation over the 16 year period.

In the third alternative, the catenary hybrid truck, a larger electric machine has been installed compared to the second alternative, as seen in Figure 4-1. It has been assumed to be factor of three larger regarding material, size and effect calculations compared to the electric motor in the hybrid alternative. However, for the installation of the electric machine on the assembly of the driveline the amount of energy used is assumed to be the same[3]. Also, an additional component, the pantograph, has been added to the truck and the lithium-ion battery has been removed.

Furthermore, the infrastructure of the conductive transfer of electricity through overhead catenaries has been included in the study. As well in the catenary alternative, as in the parallel hybrid alternative, an increased number of five trucks were needed due to the extra weight of the added components.

4.2.2 Driving Pattern

Only transportation of iron ore powder by truck from the mine in Kaunisvaara to Svappavaara has been considered in the study, and the distance has been assumed to be 140 km after the new road has been constructed. In addition, in Svappavaara the iron ore powder has been assumed to be transshipped over to train and further transported on railway to the port of Narvik.

4.2.3 Flowcharts

In Figure 4-2, a simple flowchart is representing the life cycle phases of the parallel hybrid alternative.

In Figure 4-3 the flowchart of the infrastructure for the catenary hybrid alternative is seen (Nielsen, 1999) and
Figure 4-4 shows the complete flowchart for the catenary hybrid including the infrastructure.

[3] Interview with Håkan Gustavsson at Scania

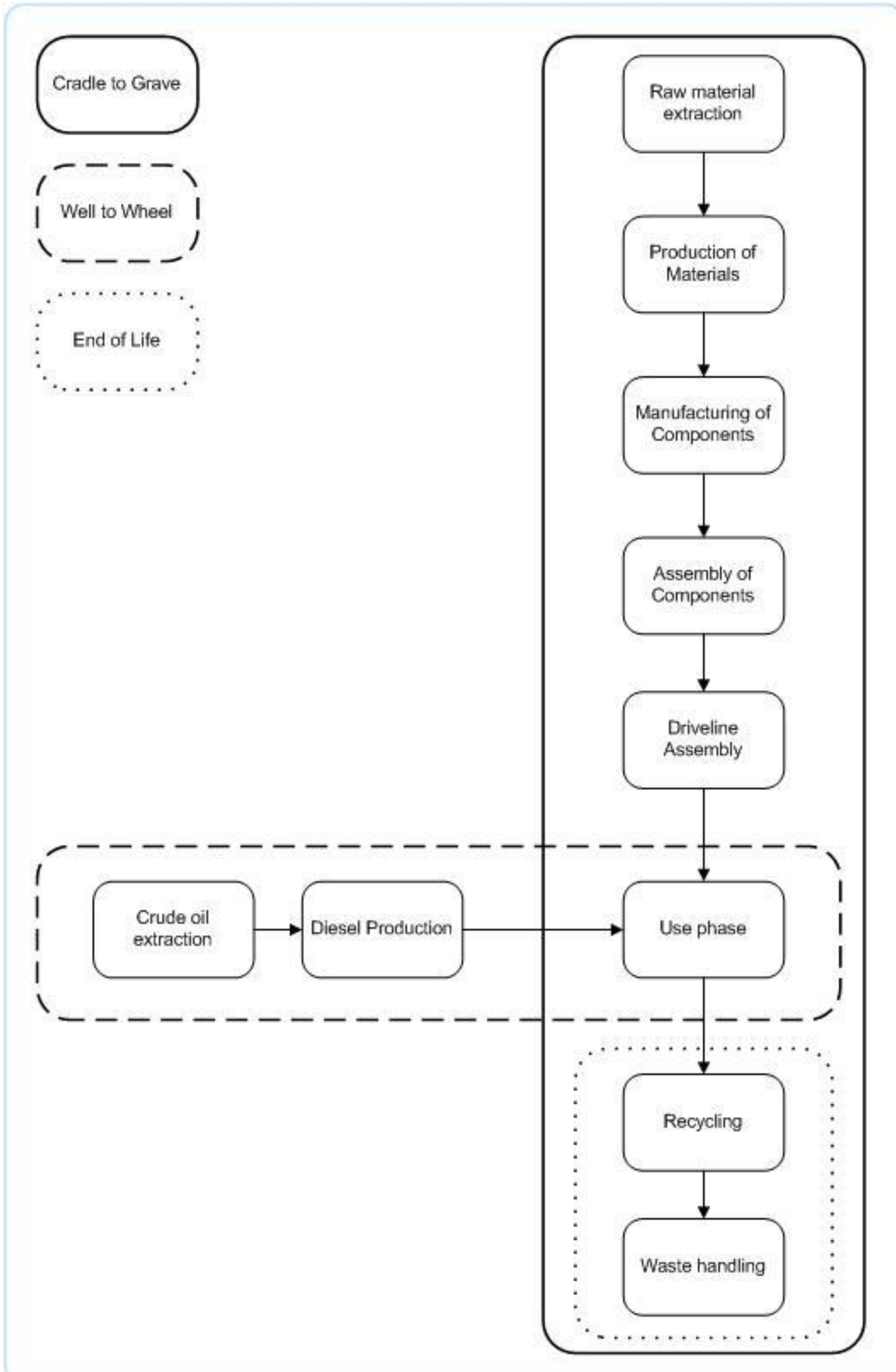

Figure 4-2 A flowchart of the life cycle for the parallel hybrid alternative, cradle to grave, and the well to wheel cycle.

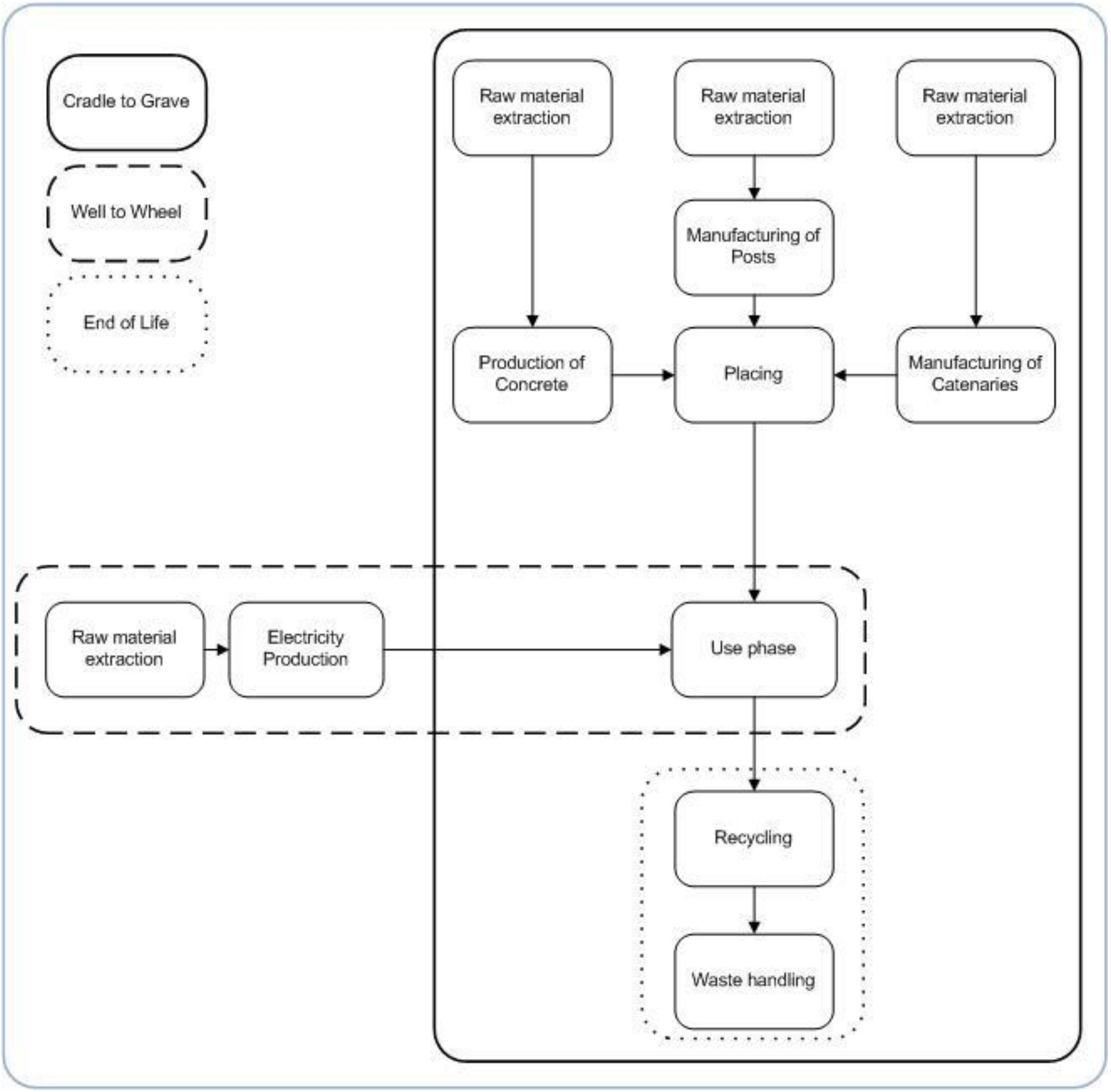

Figure 4-3 Flowchart of the life cycle of the infrastructure

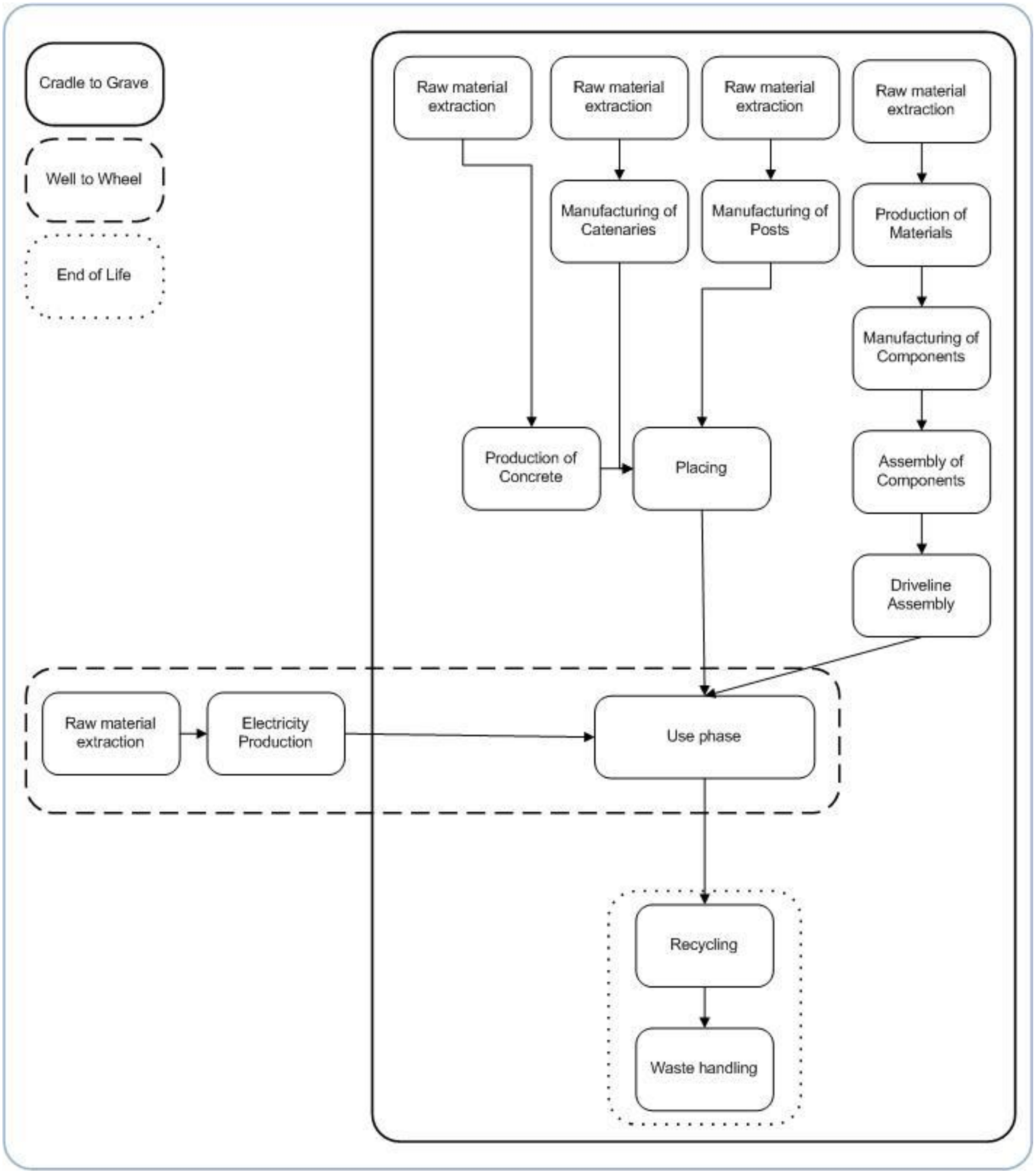

Figure 4-4 The flowchart of the life cycle for the catenary hybrid alternative, cradle to grave and the well to wheel cycle

4.2.5 System Boundaries

As stated earlier the study covered the whole life cycle of the drivetrain of the different alternatives from the cradle to grave. However, in the well-to-wheel phase, seen in Figure 4-2, the data for the fuel consumption and energy use refers to the complete vehicle.

The study has focused on the technology available today and it has been assumed that no new development or drivetrain changes were implemented during the life time of the mine. As stated earlier the internal combustion engine has been the same in all three alternatives. Note that all other parts of the vehicle, except the drivetrain, has been regarded as identical and were not included in the study.

Environmental impacts from the manufacturing of capital goods, such as machines used when producing the different components for the drivetrain, were not considered, nor the impacts from activities of the employees.

As mentioned earlier in Chapter 3, the following components were decided together with Scania as relevant to include in the study for the parallel hybrid alternative:

- DCDC converter
- Electric Machine (EM)
- Li-ion Battery
- Inverter
- Hybrid power unit housing (HPUH)

For the catenary hybrid alternative the Li-ion battery has been taken away and these were the components included:

- DCDC converter
- A larger Electric Machine (EM)
- Inverter
- Hybrid power unit housing (HPUH)
- Pantograph
- Infrastructure for electric power transfer

Two important assumptions have been made in discussion with Scania which should be pointed out. First, no battery change was needed for the trucks during their 2 years of operation at the Pajala mine[4], and, second, the vehicle has been used up to 70 % of its distance life during this operation[5]. The rest of its life time it assumed to be reused for another purpose.

[4] Interview with Johan Lindström at Scania
[5] Interview with Håkan Gustavsson at Scania

4.2.6 Geographical and Time Boundaries

In consultation with Scania the operation time at the Pajala mine of one vehicle was decided to be 2 years, corresponding to 500 000 km of driving distance for the two studied alternative and the reference vehicle assuming the driving pattern described in the previous chapter. The life cycle of the iron ore mine was set to 16 years with a starting point in 2015. This year the construction of the infrastructure is assumed to be completely finished and from this year and onwards 4,6 million tons of iron ore powder are expected to be produced and transported annually.

Raw material production has been taken place globally or in Europe, and in the modeling of material production, data from Ecoinvent has been used for global averages data or European regional data depending on the availability (Ecoinvent, 2007).

Manufacturing of studied components has been assumed to take place in the countries listed below in Table 4-1 for the parallel hybrid alternative and in Table 4-2 for the catenary hybrid alternative.

Table 4-1 The components and manufacturing location for the parallel hybrid alternative

Component	Manufacturing location
DCDC	Sweden
Battery	China
Inverter	Germany
Electric Machine	Germany
Hybrid Power Unit Housing	Sweden

Table 4-2 The components and manufacturing location for the catenary hybrid alternative

Component	Manufacturing location
DCDC	Sweden
Inverter	Germany
Electric Machine	Germany
Hybrid Power Unit Housing	Sweden
Pantograph	Germany
Infrastructure	Sweden

The assembly of the driveline has been done in Södertälje, Sweden.

The electricity used for the catenary hybrid vehicle has been modeled with the projected average Swedish electricity mix in 2020. This was chosen as the operational phase will take place the north of Sweden and because 2020 is the midpoint year of the assumed 15 year mine life length in full operation.

The entire use phase was taken place in the Pajala area. The vehicle end-of-life has been assumed to take place in Sweden.

The transport road between the transshipping and the mine has been assumed to be the same in all three alternatives.

4.2.7 Functional Unit

The functional unit of the LCA study was chosen to be transportation of one ton iron ore powder, i.e. this was the chosen unit for the use phase, identified as the reference process in the study. In other words, the results of the study will be presented per ton of transported iron ore powder, which is the function that the trucks provide.

4.2.8 Limitations

Transportation of components between manufacturing sites and Scania have been excluded in the study based on the assumption that it would have very small or negligible additional impact. Also the transport of the trucks from Scania and up to Pajala has been excluded in the study.

Also the information about the different materials has also been simplified to keep within the time boundaries of the project. For example only one type of steel has been used in the study to approximate the environmental impact for different steel types.

4.2.9 Types of Impacts Being Considered

The impact categories were decided upon in cooperation with Scania. They are listed below and explained more in Chapter 6 in this report.

- Global warming potential
- The emissions: NOx, HC, PM
- Abiotic resource depletion potential

The global warming has been chosen since it is a current problem in the world and widely discussed how to solve the emissions.

The NOx, HC and particle emissions are of interest since these are the emissions from the operational phase using diesel as fuel for the reference case and the parallel hybrid case.

Abiotic resource depletion was considered as an impact category since the reference vehicle and the parallel hybrid are consuming large volumes of fossil fuels. However, the catenary hybrid uses no fossil fuels but far more of others materials due to the demanding infrastructure. It will therefore be an interesting trade-off between the use of fossil fuels in the parallel hybrid and use of material in the catenary hybrid for this impact category.

4.2.10 Allocations

Allocations in material production, production of components and end of life treatment have been mainly based on weight, since this has been the best available information. Since this is a comparative study attributional LCA, partitioning has been used in accordance with Baumann and Tillman (2004).

Allocations with regards to the infrastructure have been made based on time, more specifically the lifetime of the mine. This is due to the fact the mine in Pajala has a lifetime of 16 years and the data used to represent the infrastructure has an assumed lifetime of 60 years (Bothniabanan, 2010).

4.2.11 Data Collection

Data for this LCA study has been collected from different sources. The data for raw material extraction has been taken from Ecoinvent. Ecoinvent was created by the Ecoinvent Centre in Switzerland and contains life cycle inventory data for various services and products.

To analyze the production of the components invested, data has been collected from other LCA studies on similar products and from suppliers of the different components. Also, some assumptions and estimations have been made by technology experts at Scania.

The data for the use phase has been collected from Scanias own Environmental Product Declaration (Scania, 2012), from the report of Trafikverket (2012) about the mine in Pajala and in discussion with Scania.

The data for end of life phase has been assumed in discussion with Chalmers and is also collected through different studies on recycling of materials.

4.2.12 Critical Review

The LCA study was critically reviewed by the supervisors, Anders Nordelöf and Ann-Marie Tillman from Chalmers University of Technology and Håkan Gustavsson from the department of Hybrid Systems Development at Scania CV AB.

5. Inventory analysis

This chapter describes the different processes in the life cycle and the procedures of data collection, modeling and calculation of life cycle inventory (LCI).

5.1.1 Life Cycle Phases of the Drivetrains

The life cycle of the drivetrain was divided into four different phases:

- Production
- Use
- Maintenance and repair
- End-of-life

The processes in the life cycle are taking place in various locations around the world. In all major processes their corresponding locations are seen below in Table 5-1. These geographical locations have been used when choosing the electricity mix for manufacturing of the different components.

Table 5-1 Overview of the processes, their locations and time horizon

Proces	Representative location	Time
Raw material extraction	Global average or European average is used, in special cases specific region are used.	2012
Manufacturing of Electric Machine	Sweden	2012
Manufacturing of Inverter	USA	2012
Manufacturing of DCDC	USA	2012
Manufacturing of HPHU	Sweden	2012
Manufacturing of Battery	China	2012
Manufacturing of Infrastructure	Sweden	2012
Assembly of Drivetrain	Sweden	2012
Use phase	Sweden	Midpoint 2020
End of Life	Sweden	2031

To be in line with the geographical and time boundaries projected future state and country specific electricity mixes have been used. In Table 5-3 the projected average electricity mix for Sweden 2020 and 2031 are presented. Data for 2031 has been approximated by using data for 2030. In line with the goal and scope formulation, average data has been used for all electricity mixes.

Table 5-2 Projected average Swedish electricity grid mixed in 2020 (Gustavsson, Särnholm et al. 2011)

Primary energy demand, shares by fuel [%]	Hydro	Wind	Solar	Nuclear	Electricity production at district heating plants	Electricity production in industry (assumed oil)
Sweden 2020	38.5	11.7	2.3	40.8	3.4	3.3
Sweden 2031	40.4	18.3	4.9	30.6	3.1	2.7

The electricity mixes for 2012 for the United States and China has been assumed to correspond to the data from 2009 (IEA, 2012) and is seen in Table 5-3 below.

Table 5-3 Electricity mix for the United States and China (IEA, 2012)

Primary energy demand, shares by fuel [%]	Coal	Gas	Oil	Hydro	Wind	Solar	Nuclear	Biofuels	Waste
United States	45.4	22.8	1.2	7.2	1.8	0.1	19.9	1.2	0.5
China	78.8	1.4	0.4	16.7	0.7	0	1.9	0.1	0

5.2 Production

In the production phase there are raw material extraction, production of components and vehicle assembly. The data collected for these steps are explained more in detail below.

5.2.1 Raw Material Production

The drivetrain consists of many different materials and data from the production phase for these were gathered from Ecoinvent. The data used for extraction of raw material has been either global averages (GLO) or European averages data (RER). This assumption has been made since the raw material is extracted on different locations around the world and the global and European average data was found the most representative.

5.2.1.1 Aluminium

European average data has been used for production of aluminium. Including processes has been cast aluminium ingot production, transports of materials to the plant and the disposal of the waste (Classen et al, 2009).

5.2.1.2 Copper

In the extraction of copper global average data is used. It includes the pre-treatment of the ore, the reduction and the refining; the product is used as pure metal or as alloying element in various technical applications (Classen et al, 2009).

5.2.1.3 Steel

In the production of steel, carbon steel has been assumed with a process that used average global and European production mix (Classen et al, 2009).

5.2.1.4 Neodymium

The data of extraction of neodymium has been assumed to take place China (Classen et al, 2009). Since this was representative due to the fact that China produces 97 % of the world's neodymium supply (Milmo, C. 2010).

5.2.1.5 Cast Iron

For the cast iron a composition of 35% scrap and 65% virgin iron has been used. Also, the process represents a mix of global average and European production mix (Classen et al, 2009).

5.2.1.6 Nylon

In the production of nylon, average European production has been assumed (Hischler, 2007).

5.2.1.7 Brass

Brass was assumed to contain 70% copper and 30% zinc, and the melting and casting of brass ingots are included. The only data available was from production in Switzerland and it was therefore used as the best available representation of the global average (Classen et al, 2009).

5.2.1.8 Nickel

Global average data were used for the production of nickel. Included processes were mining, necessary infrastructure and disposal of overburden and tailings. It also includes the metallurgy step with the disposal of slag, the infrastructure and the separation of the co-product copper and production, application and emissions of most agents and additives used in beneficiation and metallurgy (Classen et al, 2009).

5.2.1.9 Printed Wiring Board

Global average data has been assumed in the production of printed wiring boards. The data represent a mix of two mounting technologies, surface mount and through-hole mount. Assuming a mix of 50:50 mix between the two technologies. It includes processes of components mounting using lead and lead free solder technology (Hischler et al, 2007).

5.2.1.10 Tin

European data has been assumed, including the cradle to gate inventory of world-wide primary tin production. Transports are also included from the major producers in Europe (Classen et al, 2009).

5.2.1.11 Synthetic Rubber

This type of rubber is used in technical products and was chosen since it was assumed to be the most accurate rubber available. European data has been assumed and the included processes are production of the rubber and also the transport of raw material to the production plant (Hischler, 2007).

5.2.1.12 Polymethyl methacrylate, PMMA

PMMA are a thermoplasts which is used in the industry as insulators and it has been assumed to correspond to the plastic parts in the different components, since the lack of information on what kind of plastic material which has been used. European data has been assumed and the included processes are all processes from raw material extraction until delivery at plant (Hischler et al, 2007).

5.2.1.13 Carbon
Global average data has been used and the included processes are raw material extraction and production of chemicals used for production of carbon. The transport of material to manufacturing plant is included. (Hischler et al, 2007)

5.2.1.14 Graphite
This data includes the production of an anode for a lithium-ion battery where the graphite acts as a Li^+-ion accumulator. The data are based on patents and the transportation are based on Ecoinvent standard estimates. A European dataset are used for global processes. (Hischler et al, 2007)

5.2.1.15 Lithium
Global average data were used for the production of lithium. The lithium was produced from Lithium chloride electrolysis which delivers the co-products lithium and chloride. The allocation in this case has been based on stoichiometric calculations according to Ecoinvent. (Classen et al, 2009)

5.2.1.16 Oxygen
European average data has been used. The technology used is cryogenic air separation, and the products are liquid oxygen, liquid nitrogen and liquid crude argon and no gaseous products are considered. Allocation factors were calculated from the heat of vaporization and the specific heat capacity multiplied with the temperature difference from 20 ^oC to the boiling point. Included processes are the electricity for the process, cooling water and waste heat. (Hischler et al, 2007)

5.2.1.17 Phosphorus
Phosphorus has been produced with the technology oxidation of phosphorous trichloride. Raw materials are modeled with a stoichiometric calculation, and energy consumption and transports are estimated. The transports have been calculated with standard values. The data used has been based on European averages. (Hischler et al, 2007)

5.2.1.18 Tube insulation
The data for tube insulation used in the study was chosen for its representativeness of technical applications. The included processes are raw material extraction and the production stages to a finished product. The dataset used comes from Germany and were assumed to be representative for the European average data. (Hischler et al, 2007)

5.2.1.19 Electrolyte
The production of the electrolyte for Li-ion batteries covers all processes from raw material extraction to finished electrolyte. Global average data has been used and the process data. (Hischler et al, 2007).

5.2.2 Production of Components

For this part of the life cycle data have been collected for material compositions of the different components along with the energy, electricity and heat, used to manufacture them from these raw materials. A waste percentage of 1% in the production for the different components has been assumed in discussion with Scania.

The electricity mix used to calculate the emissions for the production of the different components have been taken from the manufacturing country showed in Table 5-1.

5.2.2.1 Electric Machine

The material data for the electric machine in the parallel hybrid alternative has been collected from Scania. It has a maximum power output of 150 kW and total weight of 83 kg.

The total weight of the permanent magnets in the electric machine was 1.9 kg and the material composition were 0.5 kg neodymium, 0.25 kg dysprosium, 0.02 kg boron and the rest of the material was assumed to be iron[6]. However, data on dysprosium and boron was not available in Ecoinvent and was therefore assumed to have the same environmental effects as neodymium.

For the assembly energy of the electric machine for the parallel hybrid data was taken from an EPD of an electric machine made by ABB. The selected reference motor is a flameproof 400 V AC motor with 22 kWh rated power output and with a total weight of 279.2 kg (ABB, 2002). After rescaling based on weight and assuming that the manufacturing energy in the EPD approximately corresponded to the assembly energy of the Scania electric machine, the result was calculated to be 19 kWh of electricity and 16 kWh heat.

The electric machine for the catenary hybrid does not exist today, and the material data for the catenary hybrid has been assumed to have a power output of 250 kW in nominal rating. A rescaling on the same electric machine from ABB, as in the parallel hybrid, was made and the material data has been made based on the power output and with the same material configuration. The total weight of the electric motor was calculated to be 278 kg. The assembly energy was calculated as in the case of the parallel hybrid and was found to be 31 kWh of electricity and 26 kWh of heat.

The linear rescaling of the machines weight and material content based on the power output only is consistent with reality if it is assumed the electric machine has been prolonged only[7]. However, if the larger power output instead would reach with larger radius, the rescaling is instead the squared value of the material to get the same power output.

5.2.2.2 Inverter

The inverter was assumed to be manufactured in USA. The material data for the inverter for the parallel hybrid was collected through disassembly and weighting at Scania. The inverter has a

[6] Interview with Jörgen Engström at Scania
[7] Interview with Jörgen Engström at Scania

maximum alternating current of 300 Ampere which matches the electric machine of 150 kW and it has a total weight of 18 kg[8].

The inverter for the catenary hybrid was assumed to be identical with the one in the parallel hybrid, even with higher power output of the larger electric machine, based on information from Scania.[9]

For the assembly of the inverter, an approximation from an EPD made by ABB was studied and a converter with the most similar material content was chosen, the ACS 100/140 frequency converter (ABB, 2002). The manufacturing energy consumption was assumed to correspond to the assembly energy for the inverter. After rescaling according to weight the assembly energy was calculated to be 70 kWh of electricity and 39 kWh heat.

The inverter included in the study is based on old technology and has therefore been larger than necessary. Today smaller inverters with more up to date technology are available.[10]

5.2.2.3 DCDC

The DCDC converter was assumed to be manufactured in Sweden. The maximum power output is 7.5kW and total weight is 21.5 kg. The material data has been provided by the supplier.

For the production and assembly of the DCDC converter, an EPD from ABB (2002) has been used to approximate the used energy. The DCS 400 has been rescaled based to weight, and the manufacture energy is assumed to correspond to the assembly energy for the DCDC converter. After rescaling the assembly energy was calculated to be 12 kWh of electricity and no heat is used.

The DCDC converter used in this study are over dimensioned and based on old technology, but it was the only available data. Today there is better performing technology is available which also will be used in the future at Scania[11].

5.2.2.4 Hybrid Power Housing Unit

The HPHU has been assumed to be manufactured in Sweden with a total weight of 297 kg. The value for energy used in the production has been estimated by Scania[12]. The total length of the laser cutting has been assumed to be 58 m, and the speed of the laser cutting is around 5 m/min since the thickness of the steel is average 3 mm thick (LTU, 2012).

5.2.2.5 Battery

The battery was assumed to be manufactured in China and the material data was collected from the article Life-Cycle Analysis of Production and Recycling of Lithium Ion Batteries (Gaines,

[8] Interview with Jörgen Engström at Scania.
[9] Interview with Jörgen Engström at Scania.
[10] Interview with Jörgen Engström at Scania
[11] Interview with Jörgen Engström at Scania
[12] Interview with Alexei Tsychkov at Scania

et.al, 2012). The battery data from the article was, according to Pontus Svens at Scania, very consistent with the battery Scania is using and therefore assumed to correspond very well. However, in the production of the battery only the energy for the material transformation phase has been included and not the part manufacturing and assembly energy due to lack of data. However, this has been assumed not to affect the final results.

For more detailed information about the battery see Appendix A.6.

5.2.2.6 Infrastructure

For the infrastructure part of the catenary hybrid alternative, the data has been collected from an EPD, which is based on a LCA study, made on Bothniabanan (Bothniabanan, 2010), where the available data was the environmental impact of 1 km of power, signaling and telecom systems. The operation and maintenance data was based upon 60 years of activity. Therefore, a factor was multiplied to these phases to get relevant data for 16 years, which has been the estimated lifetime of the iron ore mine.

Since the pantographs used by trains on Bothniabanan only have one current collector and the pantograph on a catenary hybrid is designed to have two, the length of the overhead catenaries were doubled.

5.2.2.7 Pantograph

The pantograph intended for the catenary hybrid only exists today as a prototype and how it will be manufactured is still very uncertain. It was also considered too time consuming to try and find relevant data for a similar product and therefore it has been excluded in the LCA. However, a mark-up for the pantograph has been made in the sensitivity analysis later in the report.

5.3 Drivetrain assembly

When collecting data for the vehicle assembly, the energy needed has been assumed to be equal between buses and trucks, since only the total energy use was available. An average between trucks and buses was calculated by the total energy from 2011 divided by the numbers of produced buses and trucks (Appendix A.3).

5.3.1 Transports

In the raw material extraction and production of material phases of the life cycle all the transports has been included in Ecoinvent, when calculating the environmental load. Also for the construction of the infrastructure, transports have been included. However, the transports between the other life cycle phases have been excluded in the study. For the step after the drivetrain assembly, to the vehicles in place for operation, all alternatives would anyway be driven conventional in mode from Södertälje to Pajala.

5.4 Well to Wheel

In the well to wheel phase the vehicle operation have been considered together with the production of diesel and electricity to calculate the savings in fuel consumption and emissions for the two hybrid alternatives compared to the reference vehicle. An average speed of 65 km per hour has been assumed for all vehicles. The reference was found to have an average fuel consumption of 0.50 liters per km based on the stated fuel consumption per hour given by Scania. The parallel hybrid alternative is expected to save 1.50 liter diesel per hour according to Scanias calculations, which gives an average fuel consumption of 0.48 liters per km. The catenary hybrid values have been based on the Swedish projected average electricity mix for the 2020. The average electricity consumption has been calculated to 2.7 kWh per km.

The extra added components in the two different alternatives will decrease the load capacity, and in turn instead increase the number of trucks used to be able to transport the same total amount of iron ore powder per year. In Table 5-4 the total numbers of trucks used during the lifetime of the iron ore mine are presented.

Table 5-4 The total number of trucks used in the different alternatives

Alternative	Number of trucks
Reference Vehicle	646
Parallel Hybrid	651
Catenary Hybrid	651

5.5 Maintenance and repair

It has been assumed that the difference in maintenance and repair are negligible among the different alternatives. This was decided together with the Hybrid Systems Development department at Scania.

No battery change has been assumed in the parallel hybrid alternative, due to the short lifetime of 2 years for the trucks and therefore a change will not be needed.[13].

5.6 End of Life

After the truck's lifetime for transporting iron ore powder from the mine in Pajala has expired, it has been assumed that both hybrid alternatives will be used for other purposes with less heavy operation as in the mine. In the case of the parallel hybrid this means that it may still be used as a hybrid vehicle whereas the catenary hybrid then only can be operated in the engine-alone mode, as a conventional mode. Therefore, an assumption was made together with Scania that the trucks could be in operation 30 % longer than the 2 years in Pajala, and in the case of the parallel hybrid the effect of this reuse was examined for the hybrid powertrain components.

[13] Interview with Johan Lindström at Scania

The end-of-life stage has been divided into a recycling phase and waste management phase. Swedish waste incineration data has been used in the waste management phase since the use phase has been located in Sweden. The heat produced when incinerating the materials has been assumed to replace other heat production and was therefore credited for the corresponding global warming emissions, since this is the major emissions when producing heat (Environmental Energy Agency, 2011). Landfill has been assumed to be the most accurate waste management process when recycling was not possible.

The actual recycling process for can be expected to be of an open loop type. Open loop recycling is when a product is recycled into a different product and quality losses are quite common. As the activities in the open loop system are shared between two products an allocation problem often On the other hand, closed loop recycling method assumes that no significant losses in quality occur when recycling the material. Each product is hereby responsible for its environmental load associated with virgin material production, recycling and the final waste treatment. Therefore, an average impact allocated equally among the products depending on the number of times recycling occurs (Nicholson, A.L. et al. 2009).

Today virgin raw materials are extracted and stockpiled in society in the form of products. Even in cases when recycled materials would satisfy the quality requirements, virgin material is often used to be able to produce products with high quality and because the infrastructure for extraction makes it easily available. Nevertheless, the assumption in this study has been that all recycled material comes into use in another new product as in the open-loop setup but at the same time it is still replacing virgin material extraction by the recycled amount, as if modeled by a closed loop. The idea is that there is a large share of the societal raw material demand which use virgin resources but which could be met using a mix of virgin and recycled material with lower but acceptable quality. Different materials have then also been assigned different recycling rates due to dispersion in various processes and in some cases too large quality losses. These assumptions are explained further down. Accordingly, with this calculation method the recycling process resembles more a closed loop recycling method than the supposed open loop, and the positive effects of the recycling process has been credited the different studied alternatives.

Electronics have been assumed to be dismounted and disassembled by hand to separate larger metal and plastic casings. Small metal fractions and alloys have been assumed to be fragmented and not recycled, and then placed in a landfill. The plastic materials have been assumed to be incinerated with energy recovery. Today there is no effective process in recycle the printed wiring boards, so they have been assumed not to be recycled and also go to landfill.

The larger metal scrap has been assumed to be recycled according to the following rates: aluminium and copper with 100 % (Leifsson, 2009) and steel and iron with 70 % due to waste and quality losses. The remaining 30 % has been assumed to go to landfill.

Lithium from the battery has not been recycled at all. Since the battery recycling market is largely price driven and with current technology recycled lithium costs as much as five times more than newly produced lithium. Though, lithium could be recycled to 100% and it is expected to be the future main source of lithium supply (Waste management world, 2011).

6. Impact assessment

After the LCI, a life cycle impact assessment (LCIA) is performed. It is described in this chapter.

6.1 Characterization method

To get a better understanding of the environmental impact and to decrease the number of parameters generated in the LCI, the data was aggregated into the two impact categories. As stated in the Goal and Scope Definition, it was decided together with Scania that the study was going to present results for these selected impact categories and some direct emissions. They are explained below:

Global Warming Potential (GWP): Greenhouse gases (GHG) are characterized by their ability to absorb infrared radiation and thereby heat the atmosphere. Different GHGs have varying life time in the atmosphere, and therefore the so called global warming potential is calculated for different time horizons. In this study a 100 years perspective has been used and the results from the global warming potential are presented as grams or kg CO_2-equivalents. Examples of substances contributing to GWP are carbon dioxide, methane and nitrous oxide.

Abiotic Resource Depletion Potential (ADP): The ADP is calculated in kg Sb-equivalents (antimony) and it reflects the use of non-renewable substances, such as crude oil and metals. Resource depletion is a relevant category since both the parallel hybrid and the catenary hybrid drivetrains contains many additional components using various metals compared to the reference vehicle. The catenary hybrid also requires large amounts of metals for its infrastructure, and both the reference vehicle and the parallel hybrid consume large quantities of fossil liquid fuel.

Emissions of particles, hydrocarbons and nitrogen oxides were also taken into account in the impact assessment and they were summarized directly from the LCI data. These emissions are subject to regulation and therefore well-known in the automotive industry and relevant to Scania.

6.2 Results of the Impact Assessment per Category

The results are presented below in figures for the above mentioned impact categories and emissions. The results are in most figures presented as delta values compared to the reference vehicle, which is represented as the zero line in the graphs. Positive values in the graphs show that the alternatives are adding extra environmental impact compared to the reference vehicle. Negative values show that the alternatives are saving environmental impact compared to the reference vehicle.

The exact values of the different categories are presented in Appendix A.4.

6.2.1 Results for Global Warming Potential

The first graph, Figure 6-1, illustrates how big the global warming emissions are in the well to wheel cycle for the different studied alternatives. As seen a large saving has been done in the catenary hybrid compared to the reference vehicle, but also compared to the parallel hybrid. This is due to the change of the energy source from diesel to Swedish projected average electricity mix in 2020.

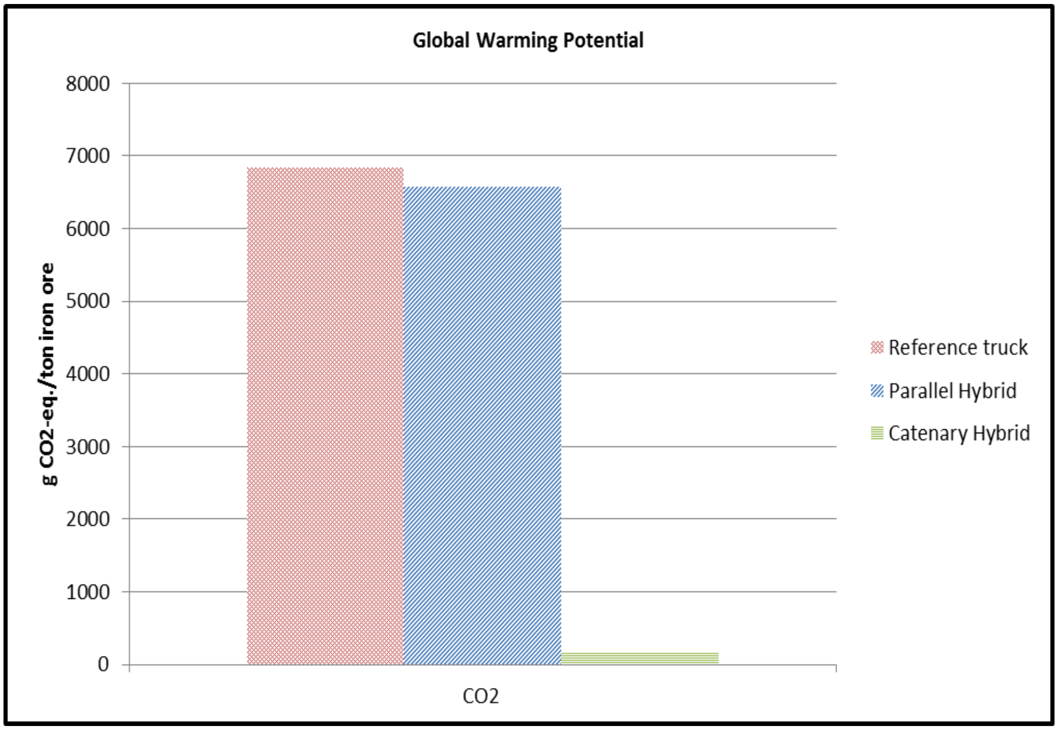

Figure 6-1 Global Warming Potential of the Well to Wheel cycle for the different alternatives in turns of g CO_2-eq./ton iron ore

The second graph,
Figure 6-2, shows the global warming emissions for the entire life cycle of the drivetrain, the cradle to grave cycle. The values in this graph are delta values compared to the reference vehicle, which is always at the zero line. If the emissions have positive values, the studied alternatives emit more than the reference vehicle and when the alternatives have negative values the alternatives provide savings in emissions. Thus, a negative total bar indicates that the alternative is a better solution than the reference vehicle.

As seen in Figure 6-2, the savings in the well to wheel phase for the catenary hybrid is very large compared to the saving in the parallel hybrid. However, both alternatives are favorable solutions compared to the reference vehicle. The catenary hybrid has larger global warming emissions compared to the reference vehicle in the extraction of raw material phase. However, these added emissions are clearly counterbalanced and outweighed by the saving in the well to wheel phase.

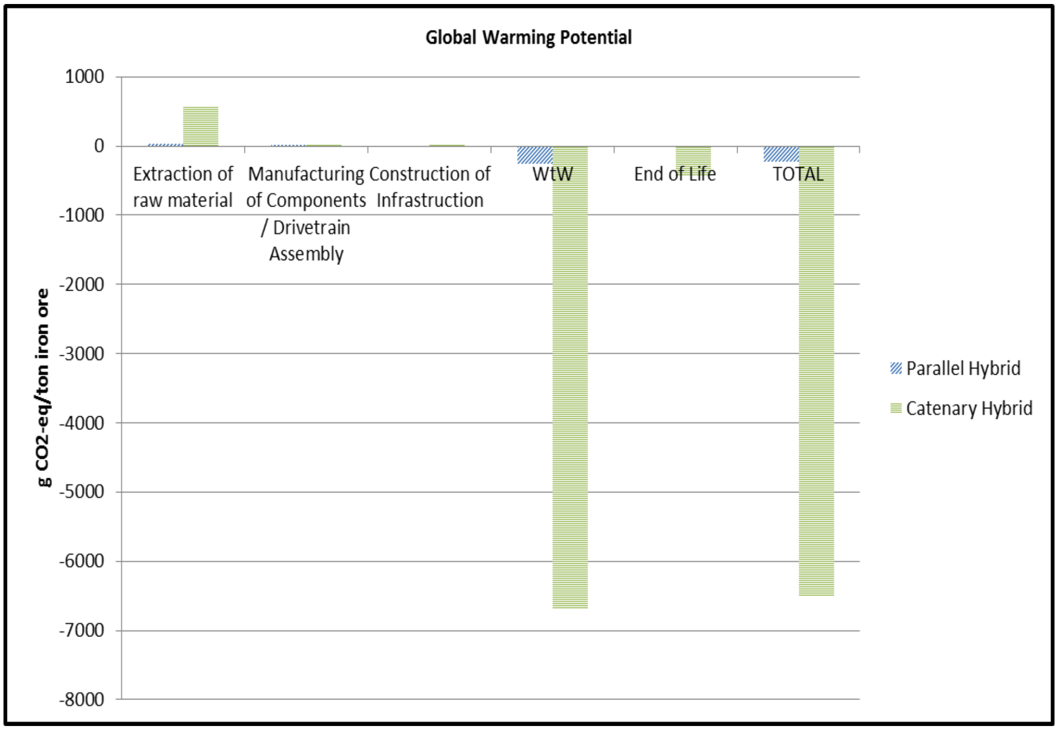

Figure 6-2 Global Warming Potential for the parallel hybrid and the catenary hybrid compared to the reference vehicle in turns of g CO_2-eq./ton iron ore

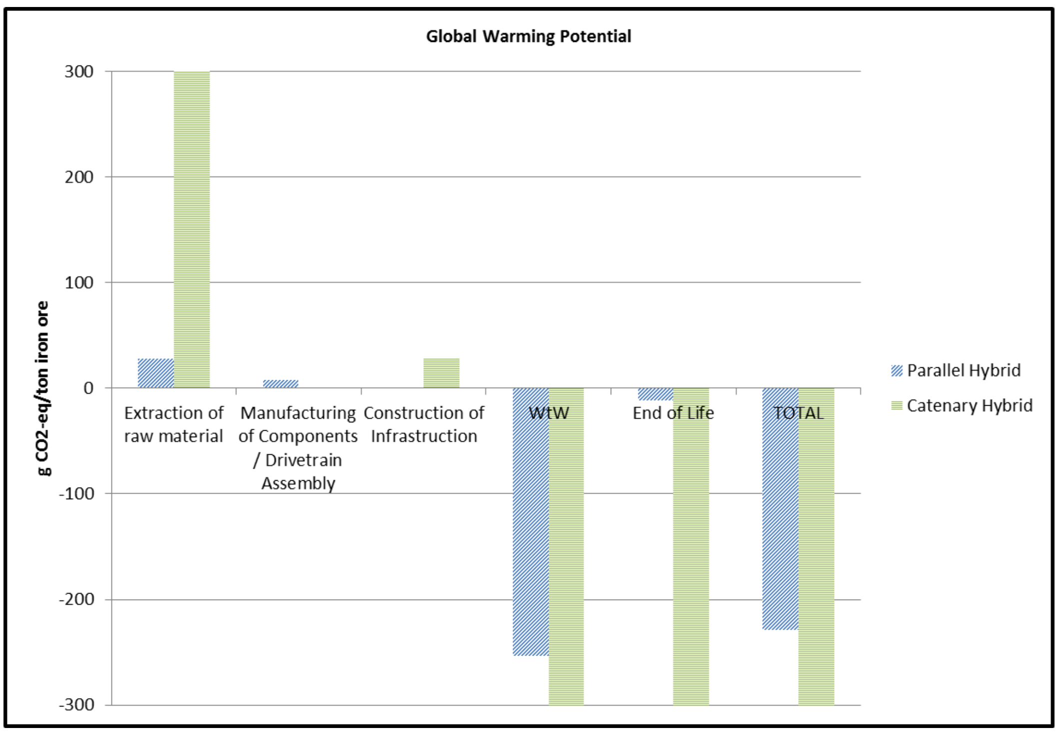

Figure 6-3 A zoom in on Figure 6-2 for the Global Warming Potential in the Cradle to Grave cycle in turns of g CO_2/ton iron ore

To show the values for the parallel hybrid more clearly a zoom in on Figure 6-2 has been made, showed in Figure 6-3. Here as well large savings are made in the well to wheel cycle. However, the savings are not very large compared to the catenary hybrid.

6.2.2 Results for Abiotic Resource Depletion

The second graph, Figure 6-4, show the results from the second studied impact category, the abiotic resource depletion potential. Also in this impact category only the catenary hybrid is a lot better than the reference vehicle and it has the same format as the global warming potential.

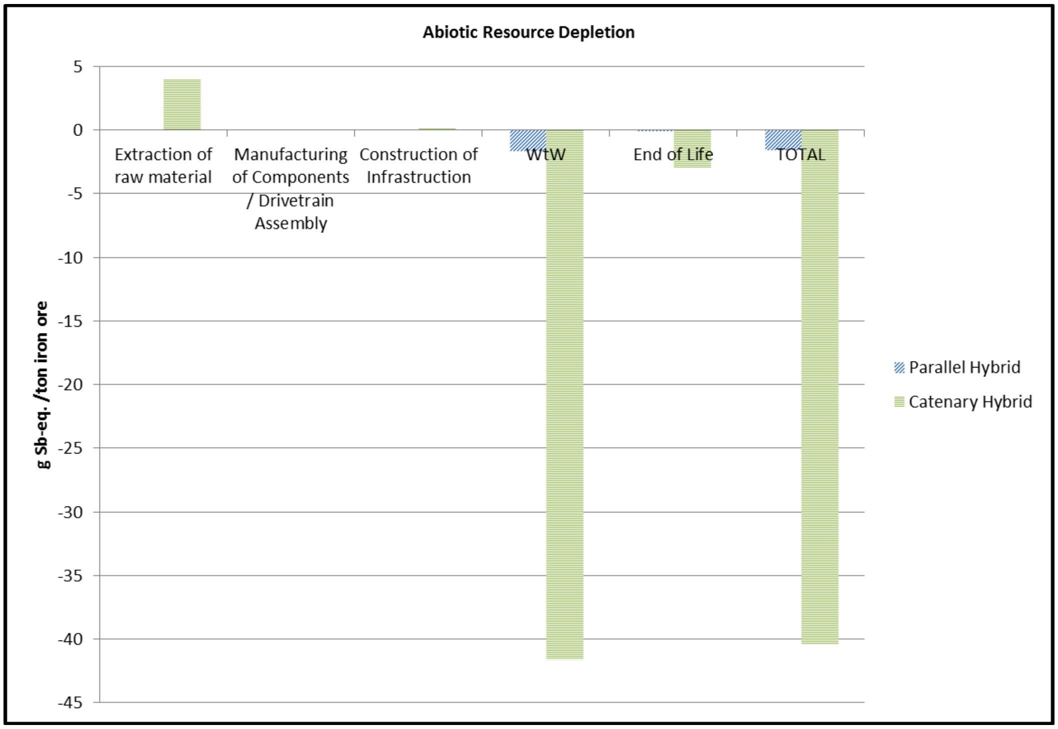

Figure 6-4 Abiotic Resource Depletion for the parallel hybrid and the catenary hybrid compared to the reference vehicle in turns of g Sb-eq./ton iron ore

6.2.3 Results for Selected Emissions

As seen below, in
Figure 6-5 and Figure 6-6, the emissions of hydrocarbons and nitrogen oxides are following the same pattern as the global warming and the abiotic resource depletion results.

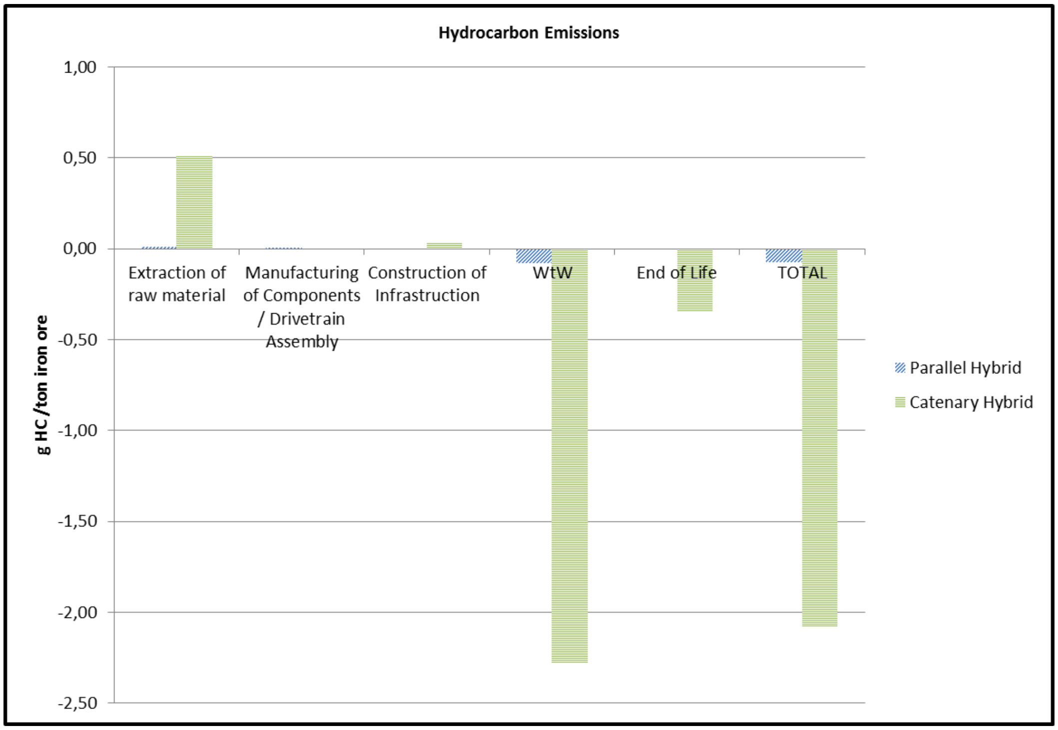

Figure 6-5 Emissions of hydrocarbons for the studied alternatives compared to the reference vehicle in turns of g HC/ ton iron ore

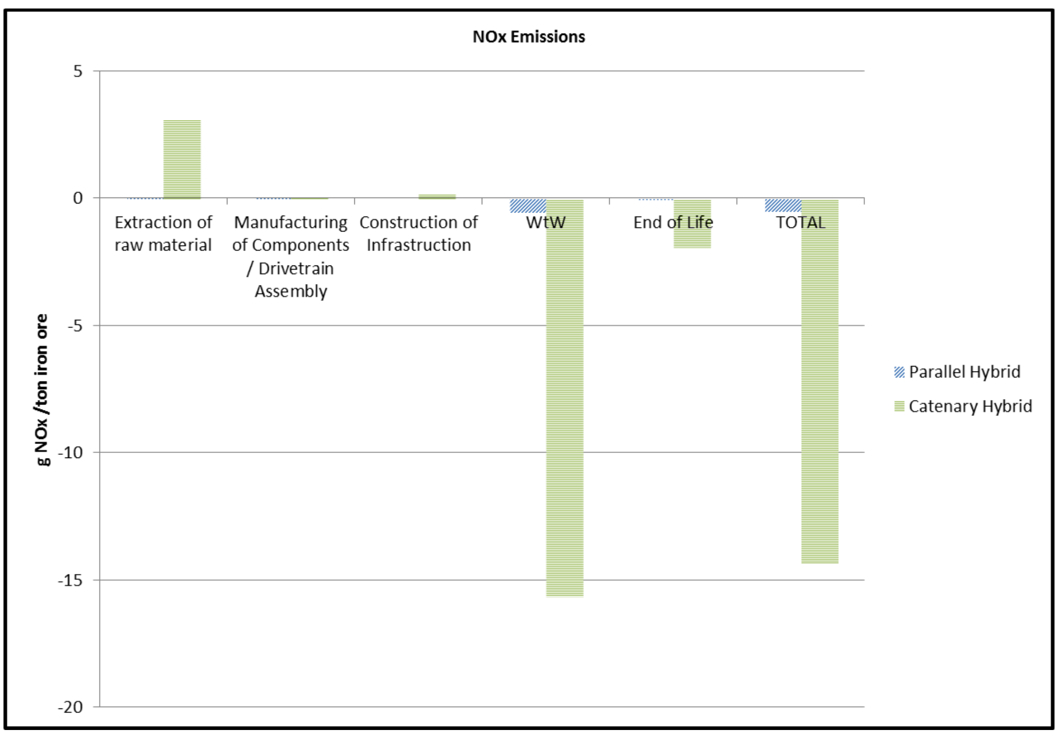

Figure 6-6 Emissions of nitrogen oxides for the studied alternatives compared to the reference vehicle in turns of g NO_x/ ton iron ore

However, the emissions of particles, seen in Figure 6-7, do not follow the same pattern as the rest of the studied categories.

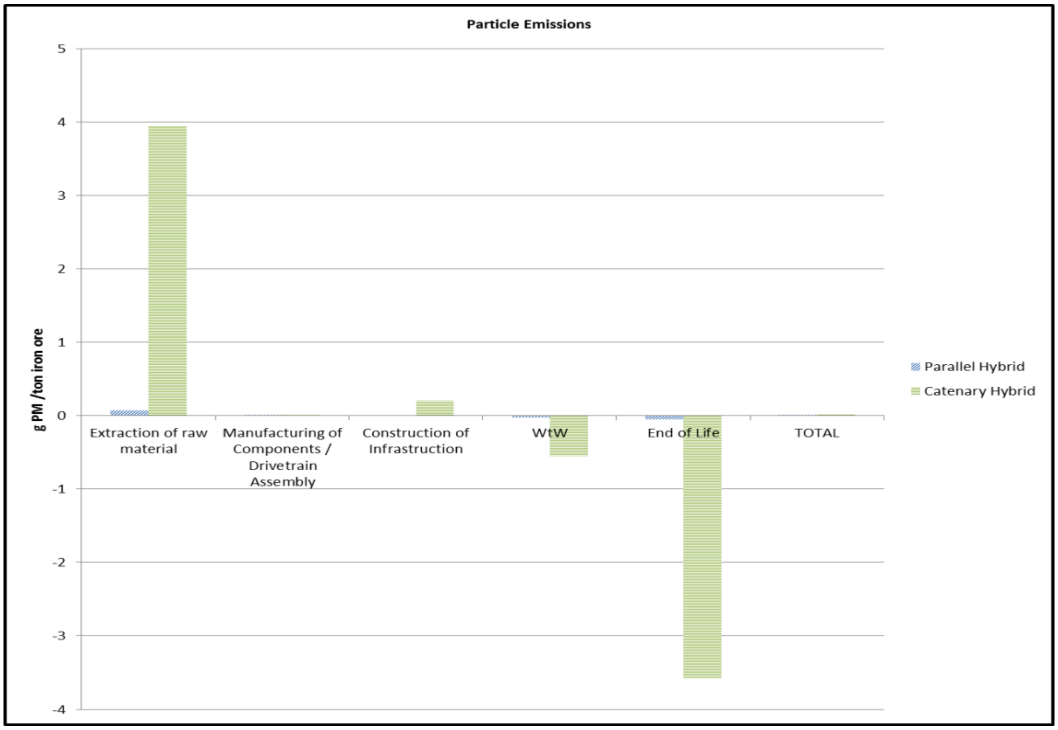

Figure 6-7 Emissions of particles for the studied alternatives compared to the reference vehicle in turns of g PM/ ton iron ore

A zoom in of the total results for the particle emissions is shown in Figure 6-8 below. Here an actual increase of particle emissions are shown compared to the reference vehicle. This is a result of the decreased load capacity that leads to an increase of the number of trucks for the two alternative powertrains. Also production of the infrastructure and the battery has large emissions of particles which are not outperformed from the savings in the well to wheel phase.

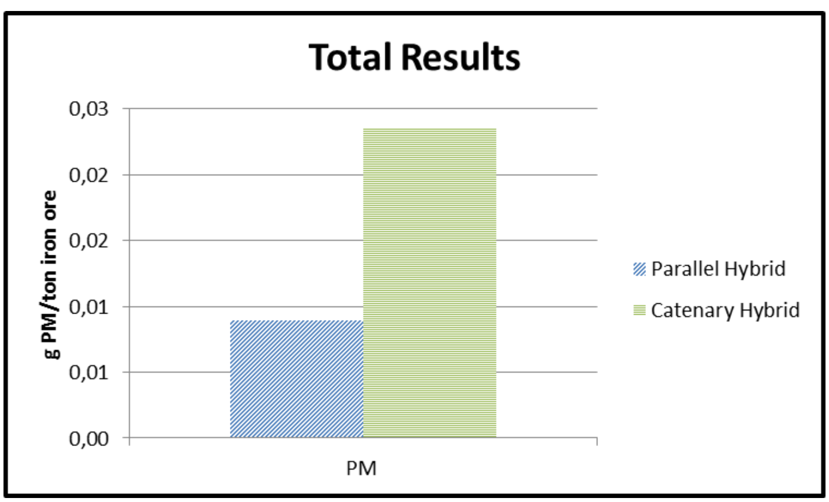

Figure 6-8 A zoom in of the total results for the particle emissions in turns of g PM/ton iron ore

6.2.4 Summary of the Results

The results show that both the studied alternatives are favorable solutions compared to the reference vehicle. The life cycle phase that has the largest environmental impact is without doubt the well to wheel phase, i.e. when the vehicles are in operation.

The alternative powertrains are a lot better than the reference in almost all studied impact categories, except for the emissions of particles. In this category the emissions are slightly worse.

Comparing the alternatives with each other, the catenary hybrid is the more favorable choice for transporting iron ore powder in Pajala.

6.3 Results Divided Into Life Cycle Stages

In order to investigate which of the added components that has the largest environmental impact pie charts have been produced showing each component's share of contribution to the different impact categories and emissions. The included life cycle phases were raw material extraction, production of component and end of life. The results for the parallel hybrid are shown in Figure 6-9.

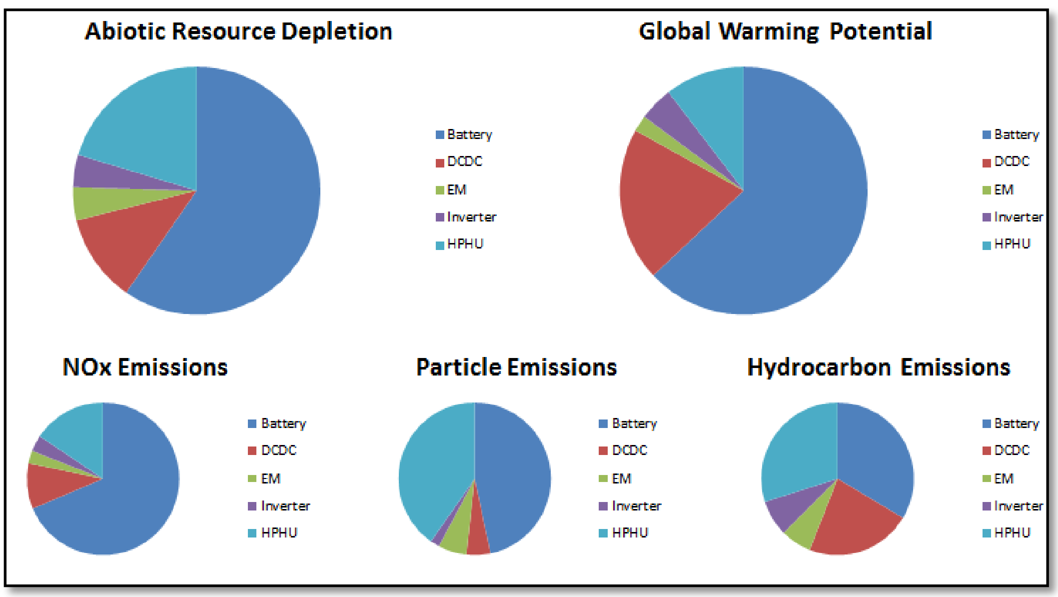

Figure 6-9 Relationships between the components in the Parallel Hybrid alternative

As seen in the Figure 6-9 above, the battery has the largest environmental impact in both impact categories, but also in the emissions of nitrogen oxides and particles. An interesting result is that the Hybrid power unit housing had such big percentage of the hydrocarbon and particle emissions. This is due to the large amount of material used in the HPHU.

In the catenary hybrid the constituent with the largest environmental impact is more obvious. As seen in Figure 6-10, is the environmental impact of the infrastructure an order of magnitude larger than the components added in the vehicle. The blue part of the first bar in the parallel hybrid stack is the environmental impact from the battery and the orange part represents the remaining added components. The green bar is the global warming potential of the infrastructure and the purple bar is the components in the catenary hybrid without the infrastructure.

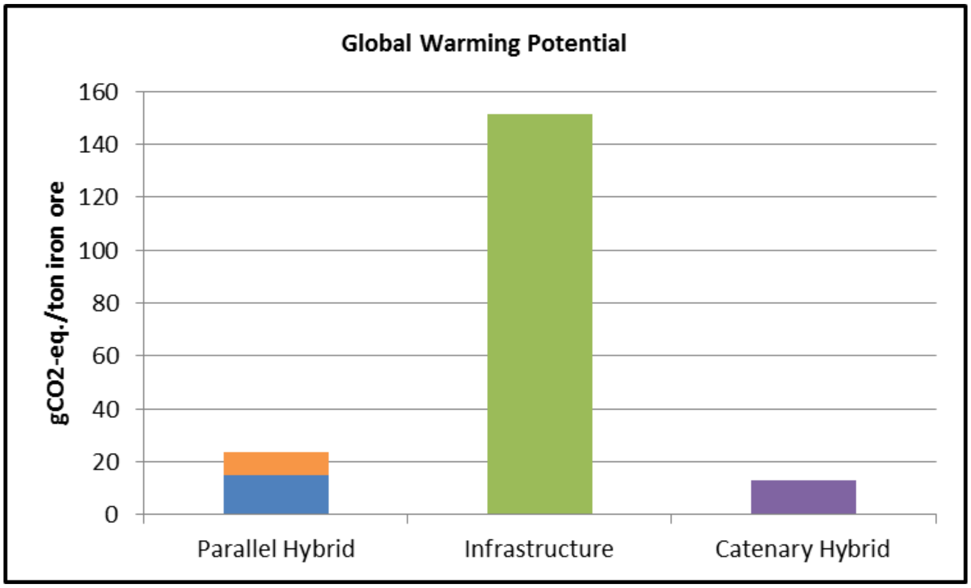

Figure 6-10 Environmental impact of the parallel hybrid components, the infrastructure and the catenary hybrid components excl. the infrastructure in turns of gCO_2-eq/ton iron ore

6.4 Break-even Analysis

In the reference case the trucks have been leaving the mine fully loaded every 7:th minute. Assuming the same extraction rate of 4.6 million tons iron ore powder per year, it has been examined how long time the mine must be operated before break-even is reached for the two alternatives, with the reference and with each other for the two impact categories, global warming potential and abiotic depletion potential.

As seen in Figure 6-11 the break-even point for the catenary alternative is at roughly four months with both the hybrid and the reference for the global warming emissions. In order words, if the mine is going to be used for more than four months the catenary hybrid becomes the most favorable choice to transport the iron ore powder. The values are still delta values compared to the reference vehicle, meaning that negative values are savings in environmental impact.

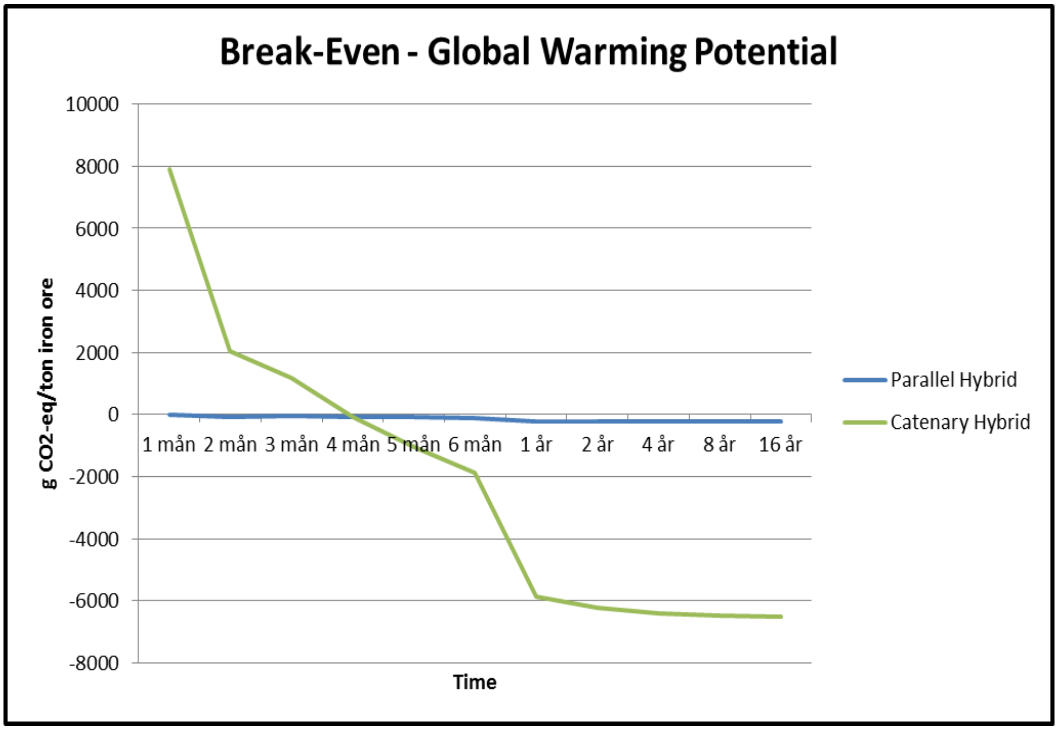

Figure 6-11 Break-even analysis for global warming potential in turns of gCO_2-eq/ton iron ore

For the second impact category, the abiotic resource depletion, the break-even point was approximately at four and a half month, seen in Figure 6-12.

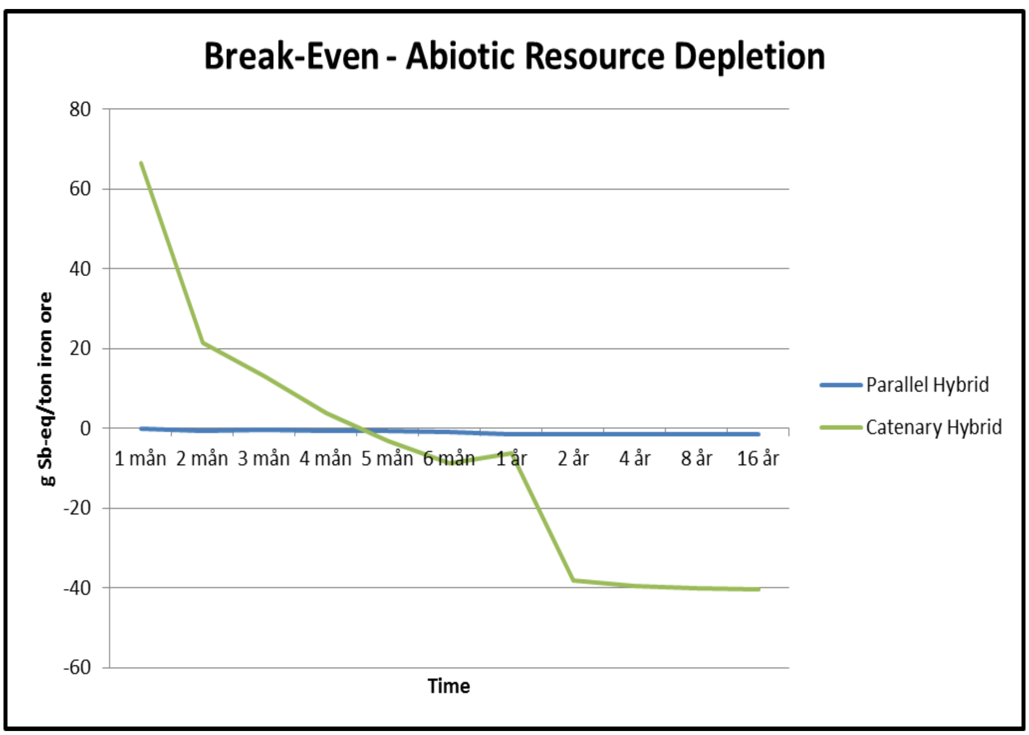

Figure 6-12 Break-even analysis for abiotic resource depletion in turns of gSb-eq/ton iron ore

7. Uncertainty and Sensitivity Analysis

An investigation of the robustness of the final results was conducted for some identified key assumptions and limitations of the project. The result of this investigation is presented here.

7.1 Mark-up for the Pantograph

The pantograph was never included in the LCA calculations for the catenary hybrid alternative as explained above. Together with Scania it was decided that a mark-up calculation was the most accurate method to evaluate the uncertainty caused by excluding the pantograph from the study.

Three different mark-up calculations have been conducted: 25 %, 50 % and 100% of the raw material extraction and the production of components phases of the catenary hybrid, excluding the infrastructure, was used.

The results for the mark-ups for the pantograph for the Global Warming Potential are presented below in Figure 7-1. As seen, even if the pantograph is included in the drivetrain it does not contribute to any major difference in the final results.

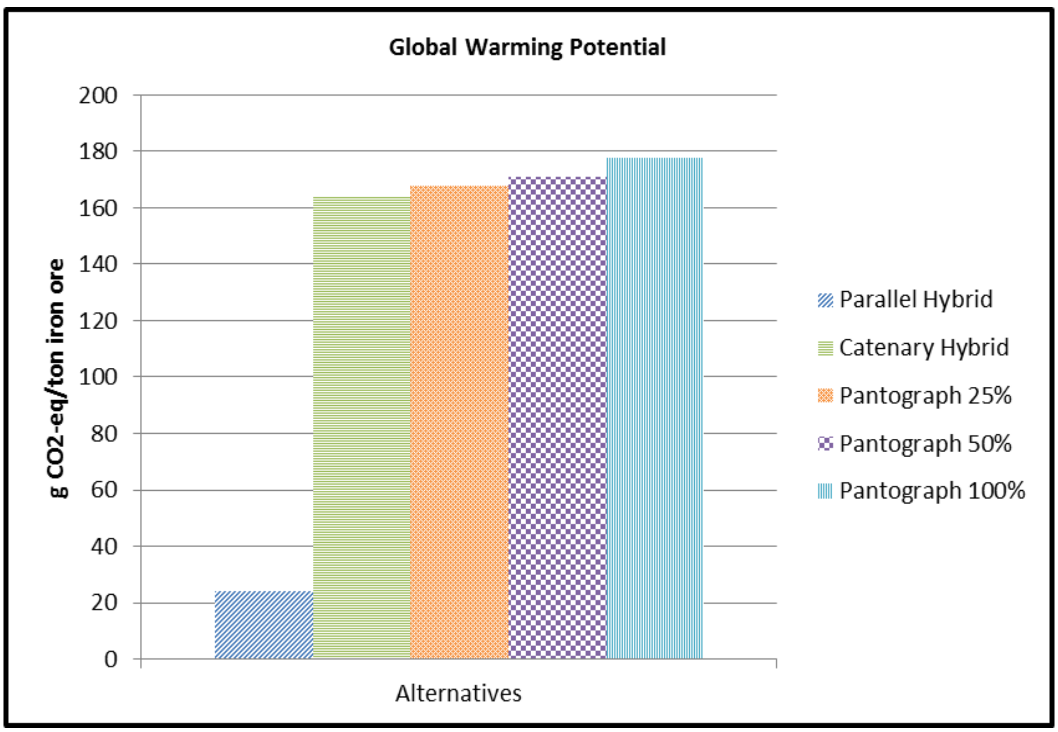

Figure 7-1 Mark-up for the Pantograph in Global Warming Potential in turns of gCO_2-eq/ton iron ore

7.2 Changes in Energy Consumption

Since the well to wheel phase of the catenary hybrid has undoubtedly the largest environmental impact, changes in fuel consumption data used was made to see if it made any changes of the results.

A 10 % change in fuel consumption of diesel was tested, both positive and negative changes. Also, a 10 % variation in electricity consumption of the catenary hybrid was made. In both cases the changes in the final results were very small. Below, in Figure 7-2 the results from a 10% lower fuel consumption of diesel combined with a 10 % higher electricity consumption was assumed and are presented as the "worst case". To clarify, no other life cycle phase was changed.

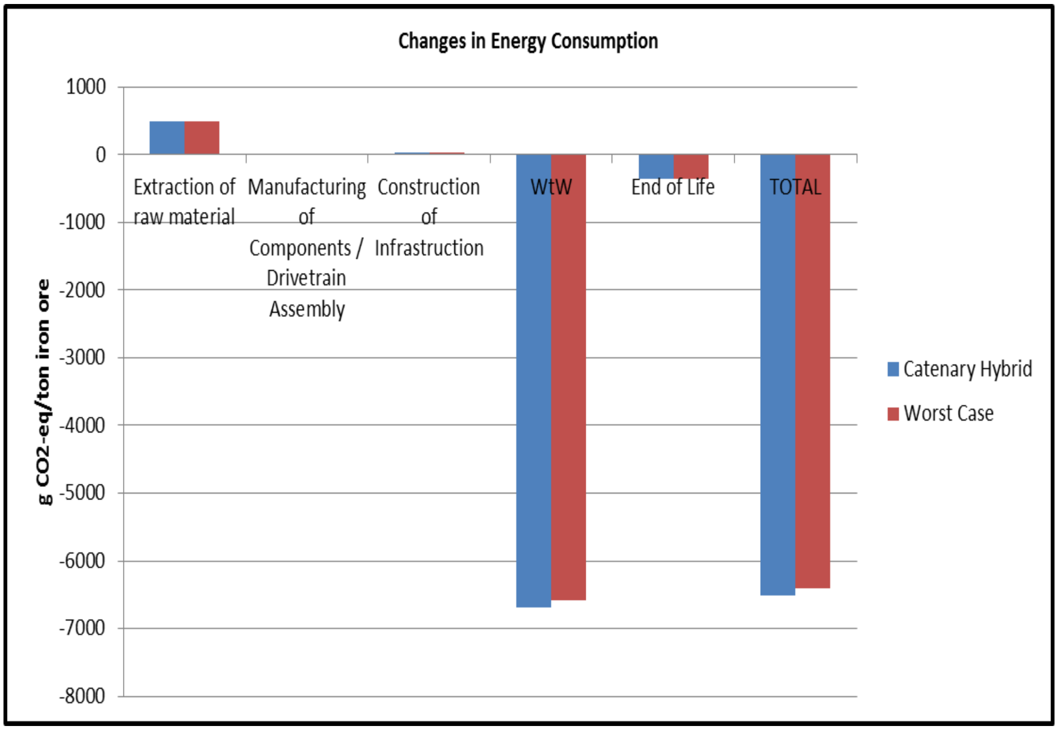

Figure 7-2 Changes in the Energy Consumption was made with a 10% lower fuel consumption of diesel and a 10 % higher electricity consumption in turns of gCO_2-eq/ton iron ore

7.3 Importance of Recycling and Reuse

The recycling rates for aluminium, steel, iron and copper are set to be quite high in the study and it helps to reduce the environmental impact of both the studied alternatives. It has also been assumed that the vehicles are reused after the mine operation. A worst case scenario, for the end of life phase, would be if no reuse or recycling was made at all and all the material was assumed to go to landfill.

First the importance of reuse is presented in Figure 7-3 below. Here the parallel hybrid trucks have no reuse phase after the operation in the iron ore mine in Pajala.

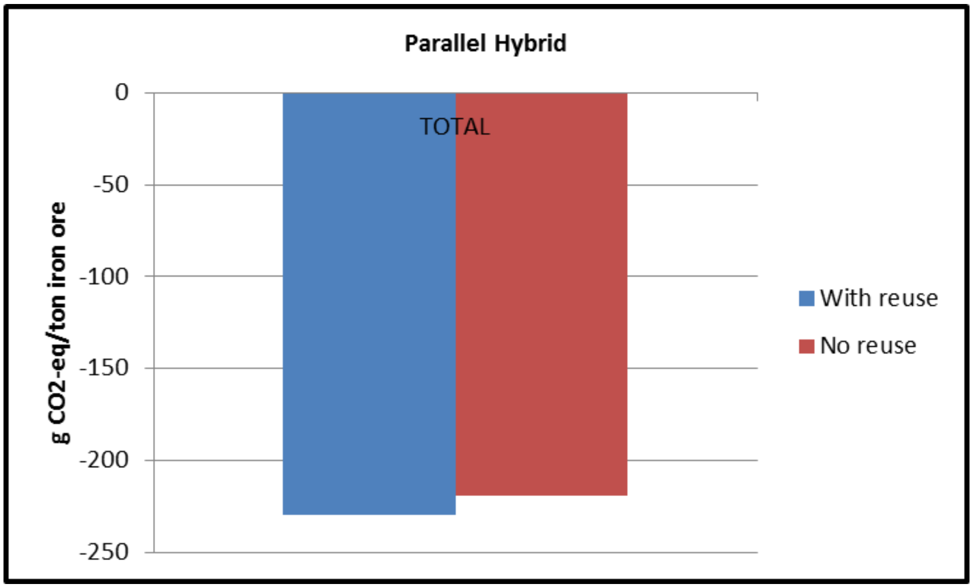

Figure 7-3 The total results for the parallel hybrid when assuming no reuse after the iron ore mine operation in turns of gCO_2-eq/ton iron ore

Below in Figure 7-4 the importance of recycling is presented. Here all the material from both the studied alternatives has been assumed go directly to landfill. As seen the negative bars in the end of life phase are gone and the total results for both the alternative have decrease a bit. However, the total results have not decreased more than a smaller fraction and the final results are still very robust, even if the recycling has been taken out of the model.

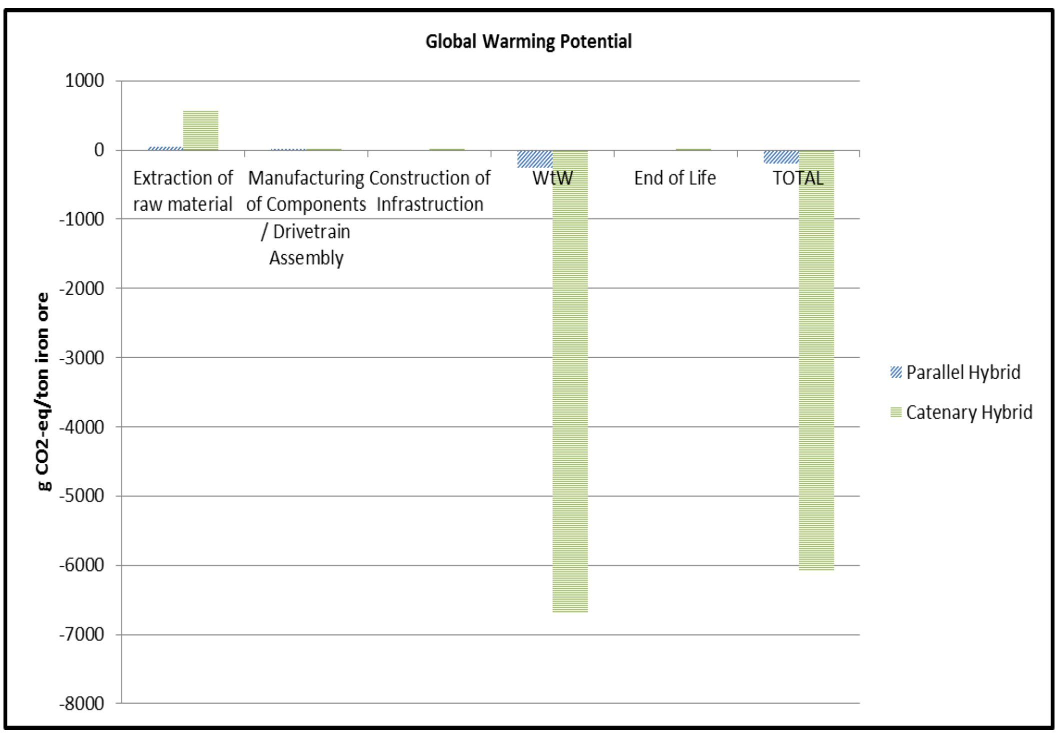

Figure 7-4 The results for cradle to grave cycle for the studied alternative without recycling in the end of life phase in turns of gCO_2-eq/ton iron ore

The final results did not change very much and the catenary hybrid is still the most favorable solution.

7.4 Electricity Produced from Coal

To see if the choice of electricity mix would change the final results, a worst case scenario for the electricity use has been calculated. All the electricity used in the catenary hybrid has been assumed to be produced from coal.

Seen in Figure 7-5 the saving for the catenary hybrid decreased with 58 %, which is a huge decline. However, the change is not big enough to make the parallel hybrid alternative a better choice but the catenary hybrid is still clearly the most favorable solution even with a much dirtier electricity production.

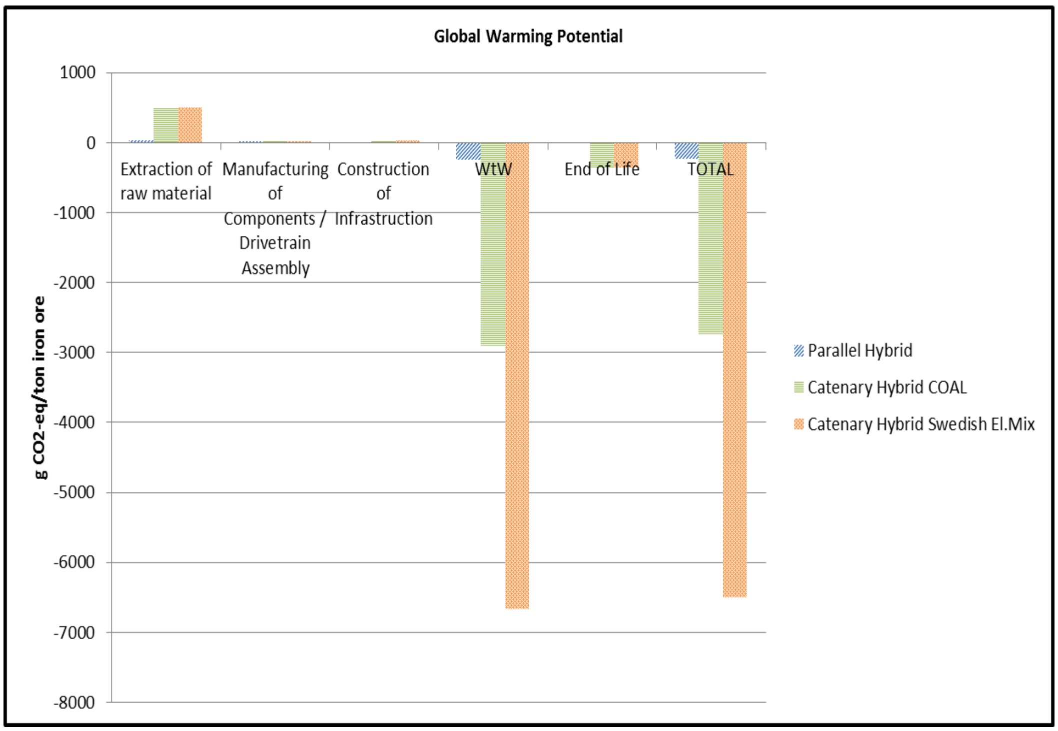

Figure 7-5 The cradle to grave results for global warming potential with the US electricity mix

8. Interpretation

In this chapter of the report the results are discussed and final conclusions are drawn. Also some thoughts and recommendations about the made LCA are presented.

8.1 Discussion

Changing the energy supply from diesel to electricity is the most important explanation for overall final results. As a consequence, the methodological choice of the electricity mix plays an important role, but the sensitivity analysis shows that a change of the electricity mix will not alter which of the alternatives that becomes the most favorable final solution. This is an interesting conclusion, since a lot of debate today concerns that the European electricity mix possibly will make the catenary hybrid solution an unfavorable solution compared to reference truck.

This life cycle assessment has, in some cases, used rough approximations and simplified, but reasonable, assumptions and cannot therefore provide values with exact precision for the final results. This is partly a consequence of the selected calculation method (spreadsheet software) as well as the data availability for collection. However, as indicated both by the results themselves and the uncertainty and sensitivity analysis, the results are both clear and very robust.

Studying the life cycle of the different drivetrain, for all impact categories, production of components and drivetrain assembly has been shown to have a minor impact compared to other phases. On the contrary, the well to wheel phase has without doubt the largest effect on the savings for both the alternatives, but mostly for the catenary hybrid. The construction of infrastructure has also quite large effect, but with recycling rates that are quite high, the contribution to the environmental impact in the end turned out to be quite small.

Both alternatives are a better solution than the reference vehicle in all impact categories except the emissions of particles. This might be due to the poor level of detail when collecting data to the use phase from Scania’s EPD. Therefore, this rather small increase of emission must be regarded as uncertain.

The component with the largest contribution to environmental impact for the parallel hybrid is clearly the battery when studying the raw material extraction, production of components and end of life. And this is the case although that only part of the energy in the production of the battery has been included due to lack of data. However, this data lack can be assumed to be small and have no effect on the overall results of the parallel hybrid, with an uncertainty similar to the mark-up of the pantograph section 7.1, at the same time as would only strengthen the role of the battery in the parallel hybrid drivetrain. The main reason for the large impact of the battery is use of advanced materials in quite large quantities, such as in the active electrode materials, which are both energy and resource intensive when produced.

Another interesting result was that the hybrid power unit housing had such a large percentage of the emissions of particles and hydrocarbons.

Another comment about the environmental impact of the different components is that the difference between the inverter and DCDC is relatively large. They are consisting of approximately the same materials and ought to be more similar. However, the collection of data for the inverter was conducted through disassembly and weighting of the different materials, i.e. with less precision than other parts which may be an explanation.

For the catenary hybrid the infrastructure has, as mentioned earlier, the largest contribution. Also, if it is compared with the most contributing part of the parallel hybrid, the battery, then it becomes obvious that there is an order of magnitude difference. However, the savings are then also much larger in the WTW phase for the catenary hybrid.
When assuming no recycling and reuse at all the catenary hybrid still remains the better option, despite the large use of materials in the infrastructure. It was expected that recycling would have a greater impact than it showed – the explanation is again that the savings in the WTW phase are a lot bigger than the savings in the end of life phase. However, with another, more fossil intensive electricity mix the end of life phase would have a larger influence on the final results.

As seen in the mark-up for the pantograph of the catenary hybrid alternative, it does not contribute to any larger difference in the final results. Therefore, the presented results could be rather representative even without the pantograph.

A final observation is the result for the break-even point. If the iron ore mine only has a lifetime longer than five months the catenary hybrid is the more favorable solution in an environmental perspective.

8.2 Conclusions

Based on the results and discussion the answers to the questions asked in Goal and Scope are the following:

1. What is the difference in environmental impact of the three alternatives for transporting iron ore powder?

   The Catenary Hybrid is the more favorable choice for both impact categories and for the selected emissions. This is because the use electricity instead of diesel provides enormous savings in environmental impact.

2. Which added component in the drivetrain has the largest environmental impact?

   For the parallel hybrid it is clearly the Li-ion battery that gives the largest additional environmental load. This is due to the amount of advanced materials included in the battery. For the catenary hybrid it is the infrastructure which has the largest environmental impact. This is due to the large amount of material that is used. In both cases the environmental impact comes derives from the raw material extraction.

3. Which phase in the life cycle has the largest environmental impact?

   For all studied alternatives, including the reference, it is the use phase and the WTW cycle that that is most important in terms of environmental impact. Both hybrid vehicles have their largest contribution in this phase and it the amount of savings made here that determine the overall final results.

4. Assuming the same extraction rate per year, how long time must the mine be operated before break-even is reached for the two alternatives, with the reference and with each other?

   For the global warming potential the break-even point was at four months and for the abiotic depletion the break-even point was at four and a half month. This means that if the mine is in operation longer than four and a half month the catenary hybrid is the better choice.

8.3 Recommendations

Based on this LCA study the following recommendations regarding choice of drivetrain for transportation of iron ore powder from the mine in Pajala, and future LCA work are given.

The catenary hybrid shows larger environmental savings than the parallel hybrid. Therefore the catenary hybrid drivetrain, including infrastructure, is the recommended drivetrain solution.

For future LCA studies it is also recommended to collect material and process data from the suppliers continuously to an internal LCI database. However, in the case when no data is available, literature data or assumptions regarding processes can be used to estimate energy consumption, material transformation, etc. from similar studies.

8.4 Future work

Some recommendations for future work to complement this study:

- The role of other electricity mixes could be more explored.
- Explore the role of new or different materials in the components.
- Investigate if downsizing of the ICE is possible and if it could lead to more load capacity.
- Investigate the accuracy for using Bothniabanan as an approximation to the Pajala road infrastructure.
- Continuous data collection for future LCA studies.
- Look at other technologies of continuous electricity supply.
- Investigate the particle emissions more closely.
- Explore how the results change if other fuels than diesel are used.

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Appendix A

A.1. Summary of Material Data

In the table below a summary of all material used for one drivetrain in both the studied alternatives are presented.

	Parallel	Catenary
Aluminium	64,2903	92,43377
Copper	25,7742	35,5134
Steel	353,4097	478,3948
Nd	0,77	2,566667
Plastic	5,97978	2,22618
Circuit board	1,7663	1,7663
Nylon	0,0021	0,0021
Brass	0,007	0,007
Rubber	0,04562	0,04562
Graphite	12,4848	
Li	0,8976	
Oxygen	7,344	
Iron	7,9398	1,575
Phosphorus	3,5904	
Carbon	1,7136	
Binder	2,7744	
Electrolyte solvent	11,5872	
Thermal insulation	1,0608	
Electronic parts	0,2448	
Ni	0,04	0,04
Tin	0,04	0,04
	501,7624	614,6108

A.2. Material Data for Infrastructure

In the table below all material for the total infrastructure used for transportation of iron ore in the mine in Pajala are presented (Bothniabanan, 2011).

Materials	**Infrastructure Pajala**	
Iron	6 089 840,29	kg
Gravel	3 423 384,79	kg
Aluminium	1 703 090,93	kg
Copper	1 651 482,11	kg
Solid rock	1 410 640,97	kg
Calcite	1 014 973,38	kg
Sand and gravel	842 943,99	kg
Limestone	688 117,55	kg

A.3. Material Data for the Battery

In the table below the material data of the selected lithium iron phosphate ($LiFePO_4$) battery are presented (Gaines et al. 2012).

Cathode	$LiFePO_4$
Anode	Graphite
Battery mass [kg]	81.6
Material Composition [mass %]	
Cathode active material	22.2
Anode active material	15.3
Electrode elements	
Lithium	1.1
Oxygen	9.0
Iron	7.8
Phosphorus	4.4
Graphite	15.3

Material Composition [mass %], continued	
Carbon	2.1
Binder	3.4
Copper parts	13.8
Aluminium parts	13.3
Aluminium casing	9.4
Electrolyte solvent	14.2
Plastics	4.6
Steel	0.1
Thermal insulation	1.3
Electronic parts	0.3

Below is the table for the exact values of the battery used in the study.

Battery [kg]	
Graphite	12,4848
Li	0,8976
Oxygen	7,344
Iron	6,3648
Phosphorus	3,5904
Carbon	1,7136
Binder	2,7744
Copper parts	11,2608
Aluminium parts	10,8528
Aluminium casing	7,6704
Electrolyte solvent	11,5872
Plastics	3,7536
Steel	0,0816
Thermal insulation	1,0608
Electronic parts	0,2448

A.4. Drivetrain Assembly Energy 2011[14]

Total number of trucks: 9951 p
Total number of buses: 3114 p
Total number of vehicles: 13065 p

Total electricity consumption: 9427 MWh
Total heat consumption: 8866 MWh

[14] E-mail correspondence with environmental coordinator Peter Öhman at Scania

It can be estimated that around 10 % of the stated total amount of vehicles do not complete the assembly line as customer vehicles.[15] This value has been subtracted r in the calculation of the following table:

Alternative	Percentages of electricity / heat	Consumption of electricity / heat [kWh]
Reference vehicle	3 %	19,5 / 18,3
Parallel Hybrid	4 %	26,0 / 24,4
Catenary Hybird	5 %	32,5 / 30,5

A.5. Results from the LCIA

The table below shows the exact delta values of the GWP100.

Table A-1: The exact values of the GWP100 in g CO2-eq/f.u.

Alternative/ Phase	Raw material extraction	Manufacturing of Components and Drivetrain Assembly	Construction of Infrastructure	WtW	End of Life	TOTAL
Parallel Hybrid	28	8	x	-254	-12	-230
Catenary Hybrid	580	0, 15	28	-6681	-438	-6510

In Table A-2, the real delta values of both the alternatives and the different life cycle phases are presented for the abiotic resource depletion potential.

Table A-2: The exact values of the Abiotic resource depletion in g Sb-eq/f.u.

Alternative/ Phase	Raw material extraction	Manufacturing of Components and Drivetrain Assembly	Construction of Infrastructure	WtW	End of Life	TOTAL
Parallel Hybrid	0,1	0,05	x	-2	-0,08	-1,5
Catenary Hybrid	4	0,001	0,2	-42	-3	-40

[15] Interview with Håkan Gustavsson at Scania.

As seen in Table A-3, the difference between the parallel hybrid and the reference is very small, compared to the catenary hybrid.

Table A-3: The exact values of emissions of hydrocarbon in g HC/f.u.

Alternative/ Phase	Extraction of Raw Material	Manufacturing of Components and Drivetrain Assembly	Construction of Infrastructure	WtW	End of Life	TOTAL
Parallel Hybrid	0,008	0, 0002	x	-0,1	-0,005	-0,10
Catenary Hybrid	0,5	0,00003	0,03	-2	-0,3	-2

Table A-4 The exact values of emissions of NOx in g NOx/f.u.

Alternative/ Phase	Extraction of Raw Material	Manufacturing of Components and Drivetrain Assembly	Construction of Infrastructure	WtW	End of Life	TOTAL
Parallel Hybrid	0,05	0,02	x	-0,5	-0,03	-0,5
Catenary Hybrid	3	0,0003	0,2	-16	-2	-14

Table A-5 The exact values of emissions of particles in g PM/f.u.

Alternative/ Phase	Virgin raw material extraction	Manufacturing of Components and Drivetrain Assembly	Construction of Infrastructure	WtW	Waste Handling	TOTAL
Parallel Hybrid	0,07	0,01	x	-0,02	-0,05	0,01
Catenary Hybrid	4	0,0001	0,2	-0,5	-3	0,03

A.6. Selected End-of-life Treatment

Materials	Ecoinvent	End-of-life
Aluminium	Aluminium, primary, at plant RER	Recycle
Copper	Copper, primary, at refinery GLO	Recycle
Steel	Chromium steel, at plant, RER	Recycle
Neodymium	Neodymium oxide, at plant, CN	Landfill
Cast Iron	Cast iron, at plant, RER	Recycle
Nylon	Nylon 6, at plant, RER	waste incineration
Brass	Brass, at plant, CH	Landfill
Nickel	Nickel, at plant, GLO	Landfill
Printed wiring board	Printed wiring board, mixed mounted, GLO	Landfill
Tin	Tin, at regional storage, RER	Landfill
Synthetic Rubber	Synthetic Rubber, at plant, RER	waste incineration
Tetraflourethene	Tetraflourethylene, at plant, RER	waste incineration
Carbon	Carbon black, at plant, GLO	waste incineration
Graphite	Graphite, at plant, CN	waste incineration
Lithium	Lithium, at plant, GLO	Landfill
Oxygen	Oxygen, liquid, at plant, RER	Landfill
Phosphorus	Phosphorus, liquid, at plant, RER	Landfill
Tube insulation	Tube insulation, elastomere, at plant, DE	waste incineration
Electrolyte	Electrolyte, KOH, LiOH additive, at plant, GLO	Landfill
Gravel	Gravel, unspecified, at mine, CH	Landfill
Limestone	Limestone, milled, loose, at plant, CH	Landfill