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Identification of environmental impacts for the Vectus PRT system using LCA

Identifikation av miljöpåverkan för Vectus spårtaxisystem genom LCA

Anders Eriksson

ABSTRACT

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Emissions from passenger transport causes impacts to the environment and human health. With increasing demand for urban transportation caused by population growth and urbanization new transport solutions are needed. Vectus Intelligent Transport develops a new transport solution with the Personal Rapid Transit (PRT) technology which provides individual, automated and on demand transportation. Vectus is currently building their first commercial system at the Suncheon wetlands in South Korea. One of the purposes with the Suncheon PRT system is to reduce the environmental impact on the unique eco-system of the wetlands. The PRT technology is considered a sustainable transport solution due to the fact that it is electrically powered. However, there has not until now been any detailed environmental analysis of a complete PRT system.

In this thesis a life cycle assessment (LCA) for the Vectus PRT was performed to identify the parts of the system that contributed to the largest environmental impact and in which phase of the life cycle these impacts occurred, as well as the impact of some system changes. The Suncheon PRT system was used as a ground scenario. All processes needed to construct, operate and dismantle the system were included in the assessment and were used to build a material and energy flow model for the complete life cycle.

For the overall system the track stood for the largest impact followed by the vehicles. These impacts occurred at different phases of the life cycle, the tracks during construction due to its large mass and vehicles during operation due to the energy demand. A track made of steel had a lower environmental impact compared to a concrete track due to its lighter structure. By using certified electricity mix the impact during the operation phase could be reduced by over 95 % for most of the impact categories studied. The choice of electricity mix during operation was the single most efficient way to affect the overall environmental impact of the system. Using power collection instead of batteries was the preferred alternative as the vehicle power system due to short lifetime for batteries and increase in number of vehicles to maintain passenger capacity due to charging time. By combining these configurations for the Suncheon PRT system the overall environmental impact could be lowered by about 50 %.

According to the LCA a slight decrease in greenhouse gas emissions and increase of emissions of acidifying substances will occur compared to competing modes of transport, such as transportation with cars and buses, due to the construction of the Suncheon PRT. However, during operation minimal emissions will occur at the Suncheon wetlands thus fulfilling the purpose of the PRT. There is also a large potential to substantially lower the impact by choosing renewable power, an alternative not available for gasoline driven vehicles.

Keyword: Personal rapid transit, life cycle assessment, passenger transport, Vectus, Suncheon PRT.

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REFERAT

Identifikation av miljöpåverkan för Vectus spårtaxisystem genom LCA

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Utsläpp från persontransporter påverkar både miljön och människors hälsa. Med ökad efterfrågan av stadstrafik på grund av befolkningstillväxt och urbanisering krävs nya transportlösningar. Vectus Intelligent Transportation utvecklar en ny transportlösning med konceptet spårtaxi (PRT) som erbjuder individuell och automatiserad passagerartransport på begäran. Vectus uppför för närvarande sitt första kommersiella system vid Suncheons nationalpark i Sydkorea. Ett av syftena med spårtaxisystemet i Suncheon är att minska miljöpåverkan vid nationalparken. PRT-tekniken anses vara en hållbar transportlösning tack vare det faktum att driften sker med el. Någon detaljerad miljöanalys av ett komplett spårtaxisystem har dock inte tidigare utförts.

I detta examensarbete utfördes en livscykelanalys (LCA) för Vectus PRT för att identifiera vilka delar av systemet som bidrog till störst miljöpåverkan och i vilken del av livscykeln dessa effekter inträffade samt effekter av olika ändringar i systemutformning. Spårtaxisystemet i Suncheon användes som grundscenario. Alla processer som krävdes för att bygga, driva och avveckla systemet ingick i analysen och användes till att bygga en material- och energiflödesmodell för hela livscykeln.

För det totala systemet stod spåret för den största miljöpåverkan följt av fordonen. Dessa effekter uppstod under olika faser av livscykeln, spåret under konstruktion på grund av dess stora massa och fordonen under drift på grund av dess energiförbrukning. Ett spår bestående av stål hade en lägre miljöpåverkan jämfört med ett spår i betong tack vare dess lättare struktur. Genom att använda certifierad elmix kunde effekterna under driftsfasen minskas med över 95 % för flertalet av de studerade miljöeffekterna. Valet av elmix under drift var det enskilt mest effektiva sättet att påverka systemets totala miljöpåverkan. Användandet av strömavtagare i stället för batterier var att föredra som alternativ till fordonens energikälla. Detta på grund av kort livslängd för batterier och en ökning av totala antalet fordon i systemet för att upprätthålla passagerarkapacitet på grund av laddningstiden. Genom att kombinera dessa konfigurationer för Suncheons spårtaxisystem kunde den totala miljöpåverkan sänkas ca 50%.

Enligt LCAn kommer en liten utsläppsminskning av växthusgaser men en ökning av utsläpp av försurande ämnen ske jämfört med konkurrerande vägtransporter, så som bilar och bussar, genom uppförandet av spårtaxisystemet vid Suncheon. Däremot kommer minimala utsläpp ske vid Suncheons nationalpark under drifttiden vilket uppfyller syftet med spårtaxisystemet. Det finns också en stor potential att avsevärt sänka effekterna genom att välja förnyelsebara energikällor, ett alternativ som inte skulle vara möjligt för bensindrivna motorfordon.

Nyckelord: Spårtaxi, livscykelanalys, passagerartrafik, Vectus, Suncheon PRT.

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초록

VECTUS 시스템 LCA사용에 따른 환경적 영향 도출

Anders Eriksson

여객 운송에서 방출되는 배기가스 가 환경과 인간의 건강에 영향을 미치고 인구증가에 따른 대중교통수단에 대한 수요가 증가 함에 따라 새로운 운송수단이 필요하다.

VECTUS Intelligent Transport 는 개인, 친환경 , 자동화, 주문형 (on demand)제공하는 새로운 대중교통수단 대안, PRT (소형경전철), 개발한다
VECTUS 는 현재 그들의 첫 상업시스템을 대한민국, 순천만 습지에서 제작중이다.
순천 PRT 시스템 의 목적중 하나는 순천만 습지의 독특한 에코 시스템에 미치는 환경적인 영향을 줄이기위해서이다. PRT (소형경전철)기술은 전기 동력에 기반하기 때문에 지속가능한 대중교통수단의 대안으로 간주된다.그러나 완전한 PRT 시스템에 대한 상세한 환경적인 분석은 없다.

이 논문에서는 VECTUS PRT의 LCA (전과정 평가, 라이프사이클 분석기법, 생애주기분석기법)이 어떤 부분의 시스템이 환경적으로 큰 영향을 미치는지 그리고 라이프사이클의 어떤 단계에서 이런 영향들이 일어나는지 대해 알아보기위해 시행된다.다른 시스템의 레이아웃은 트랙과 동력시스템 그리고 다른 전력 혼합으로 간주된다.
순천 PRT 시스템은 이런 레이아웃들을 평가하기위해 이용되었다.
순천에 PRT 시스템을 건설함으로써 PRT 시스템으로 인하여 버스들과 승용차들의운송수단이 전환이 일어날것이다. (전환교통: modal shift)
LCA 따르면 이것은 약간의 온실가스 방출을 줄이고 산성화 물질 방출은 증가할게 될것이다.
그러나 이런 방출은 순천만 습지에서 일어 나지는 않을것이다. 따라서 PRT 의 목적을 달성할것이다.
또한 휘발유로 가는 차량으로써는 대체 할수 없는 더 나은 전력혼합을 선택함으로써 상당히 적은 영향을 미칠 큰 잠정성이 있다

전반적으로 시스템이 가장큰 환경적인 영향을 미치고, 그 다음으로는 차량들이다.
이런 영향들은 라이프사이클의 다른 단계에서 나타나는데 트랙은 공사기간중 그리고 차량들은 주행중에 나타난다.
트랙은 콘크리트 트랙과 비교해 철로 구성된 트랙이 더 적은 환경적인 영향을 미쳤다.
대부분의 영향 조사에 따르면 공인 전력혼합을 사용함으로써 주행단계에서 미치는 영향을 95 % 이상을 줄일수가 있다.
주행중의 전력혼합의 선택은 시스템의 전반적인 환경영향에 영향을 미칠수 있는 단 하나의 가장 효율적인 방법이다.
배터리의 수명이 적고 베터리 교체 시간때문 승차인원을 유지하기위해 차량의 수를 늘려야하기때문 배터리사용대신 power collection(집전)을 사용한것은 차량 동력 시스템에 이제까지 가장 좋은 대체 방안이였다.
순천 PRT 시스템에서 이런 설정들을 연계하여 전체적인 환경적인 영향을 약 50% 까지 줄일수도 있다.

키워드 소형경전철, 라이프사이클분석기법, 여객운송, Vectus 순천 PRT

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PREFACE

This thesis is the final part of the Master Programme in Environmental and Water Engineering at Uppsala University. The work comprises 30 ECTS-credits and has been performed at Vectus Intelligent Transportation, Uppsala. Gunnar Larsson at the Department of Energy and Technology at the Swedish University of Agriculture Science has been the reviewer and supervisor at Vectus has been Jörgen Gustafsson.

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POPULÄRVETENSKAPLIG SAMMANFATTNING

Identifikation av miljöpåverkan för Vectus spårtaxisystem genom LCA

Anders Eriksson

Passagerartransport är en viktig del av det moderna samhället och olika transportmedel har dramatiskt förändrat hur människor reser. Då världens befolkning växer, växer också behovet av passagerartransport. Transportsektorn är dock en av de största källorna till utsläpp av växthusgaser och andra föroreningar som påverkar miljön. Med dessa problem uppmärksammade gällande utsläpp från persontransporter och ökat transportbehov på grund av befolkningsökning är inte optimering av befintliga transportmedel tillräckliga utan nya koncept och tekniker behövs.

Vectus Intelligent Transport utvecklar nya transportlösningar inom konceptet spårtaxi. De grundläggande principerna för spårtaxi är automatiserade persontransporter med korta väntetider, direktresor, högre medelhastighet, tillgänglighet dygnet runt och lägre driftkostnad. Systemet omfattar fordon, stationer, spår och ström- och kontrollsystem. Fordonen är små till storlek med kapacitet för vanligtvis 2 - 6 passagerare och går på en upphöjd bana. Konceptet syftar till att kombinera den individualitet och flexibilitet som bilen erbjuder med de miljömässiga fördelarna och säkerheten som är synonymt med järnvägstransporter.

Vectus bygger för närvarande ett spårtaxisystem i Suncheon, Sydkorea. Suncheons nationalpark anses som en våtmark av internationell betydelse tack vare dess unika ekosystem, och därför är det mycket viktigt att bevara naturen så mycket som möjligt. Genom att konstruera Vectus spårtaxisystem flyttar Suncheon stad nationalparkens parkeringsplatser och andra anläggningar ca 5 km mot inlandet. Detta begränsar transporter med bil och buss i nationalparken och därmed begränsas direkta föroreningar och skador på miljön.

Spårtaxi anses vara en hållbar transportlösning då systemet drivs på el. Det har dock ej gjorts någon detaljerad miljöanalys av ett komplett spårtaxisystem och för att ändra på det genomfördes en livscykelanalys (LCA) av Vectus system.

När man jämför transportalternativ ur miljösynpunkt är energiförbrukning och utsläpp från avgasrör de konventionella metoderna för att kvantifiera ett fordons miljöpåverkan. Bilar, bussar, tåg och flygplan jämförts med varandra utan hänsyn till tillverkning, konstruktion, underhåll med mera.

Ett annat sätt att jämföra transportmedel är genom LCA där direkta och indirekta processer och tjänster som krävs för att driva fordonet betraktas. Detta inkluderar råvaruutvinning, tillverkning, drift, underhåll och demontering. Detta tillvägagångssätt ger en bättre helhetsbild, men ofta försummas ändå den kringliggande infrastrukturen som behövs för att köra fordon, så som vägar eller järnvägar, när LCA genomförs för olika transportmedel. I denna LCA är även infrastruktur för spårtaxisystemet inkluderat.

Genom att uppföra ett spårtaxisystem i Suncheon sker en trafikövergång från bussar och bilar till förmån för spårtaxi. Enligt studien kommer detta att leda till en liten minskning av utsläpp av växthusgaser medan en ökning av försurande ämnen sker. Under drift kommer dock minimala utsläpp att ske vid Suncheons våtmarker tack vare eldriften vilket uppfyller syftet med uppförandet av spårtaxi i nationalparken. Det finns också en stor potential att avsevärt sänka påverkan genom att välja el från förnyelsebara källor, ett alternativ som inte är tillgängligt för bensindrivna motorfordon. Studien visade att genom att använda förnyelsebar energi för att driva fordonen kan miljöpåverkan minskas med över 95 % under driftsfasen.

Studien visade att för Suncheons spårtaxisystem står banan för den största miljöpåverkan följt av fordonen. Dessa effekter uppträder vid olika faser av livscykeln, spårens påverkan under konstruktion och fordonens påverkan under drift. Detta beror på det faktum att spåret står för merparten av systemets totala vikt medan fordon står för merparten av systemets energibehov.

Genom att konstruera ett spår bestående av stål i stället för betong och genom att använda förnyelsebar el till Suncheons spårtaxisystem kan den totala miljöpåverkan minskas med ca 50 %.

Studien visade också att Suncheon spårtaxisystem har ungefär samma miljöpåverkan som snabbspårväg och detta visar att det är möjligt att konstruera upphöjda spårtaxisystem med samma totala påverkan som motsvarande system beläget på marken. Spårtaxins påverkan från infrastruktur jämfört med trafikpåverkan är relativt hög jämfört med andra transportsystem och genom att integrera annan infrastruktur i spåret eller genom att dela stationer med andra transportmedel kan miljöpåverkan minskas ytterligare.

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LIST OF ABBREVATIONS

AP	Acidifying Potential
BOM	Bill of Material
CED	Cumulative Energy Demand
EP	Eutrophication Potential
EPD	Environmental Product Declaration
FU	Functional Unit
GRT	Group Rapid Transit
GWP	Global Warming Potential
HVAC	Heating, Ventilation and Air Conditioning
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LIM	Linear motor
LRT	Light Rail Transit
MONM	Modified Organic Natural Materials
Mnt.	Maintenance
ODP	Ozone Depletion Potential
PCR	Product Category Rules
POCP	Photochemical Ozone Creation Potential
PRT	Personal Rapid Transit
PKM	Passenger kilometre
SVC	Safety Vehicle Controller
TKM	Tonne kilometre
VC	Vehicle Controller

1. INTRODUCTION

Passenger transportation is a significant part of modern society and different transport technologies have dramatically changed the way people travel. As the world population grows, the need for increased transport capacity grows with it (Stripple & Uppenberg, 2010). The transport sector is however one of the largest sources of greenhouse gas emissions (Röder, 2001) and road transports are one of the largest emission sources of carbon dioxide, nitrogen oxides and particulate matter to urban communities (Johansson & Åhman, 2002). The emission from traffic on congested streets and roads in many larger cities is so substantial that air quality standards, such as the EU Air Quality Directives, are superseded (Johansson, 2009).

With these concerns being raised regarding the global warming and human health impacts from passenger transportation and with growing demand on transportation due to increase in population not only optimization of existing technologies is enough but new concepts and technologies are needed (Röder, 2001).

Vectus Intelligent Transport is an international company with offices in South Korea and the United Kingdom, as well as an office and test track in Uppsala, Sweden. Vectus develops new transportation solutions within the Personal Rapid Transit (PRT) concept. The fundamental principles of PRT are automated personal transportation with short waiting times, non-stop travel, higher average speed, availability around the clock and lower operation cost. The system includes vehicles, stations, tracks and power supplies (EU, 2004). The vehicles are small in size with capacity for typically two to six passengers. The concept seeks to combine the individuality and flexibility of the car and the environmental benefits and safety of rail transport. So far there are only two operating systems in the world and a third one is currently being built by Vectus in Suncheon, South Korea (Figure 1).

Figure 1. *Concept rendering of the PRT track at Suncheon.*

The Suncheon Coastal Wetland is recognized as a Wetland of International Importance because of its unique eco-system; hence, it is very important to preserve the nature as much as possible (Ramsar, 2012).

By constructing the Vectus PRT system Suncheon City is moving the parking lot and other facilities about 5 km towards the inland. This limits transportation with car and bus at the Wetland Park and thus limits direct pollution and damage to the environment. Suncheon City chose PRT as a transport solution because it has no emission at the point-of-use and is evaluated to have negligible impact on the environment compared to conventional transportation modes (Vectus, 2011a).

The PRT technology is considered a sustainable transport solution that addresses the problem with poor air quality (EU, 2004). A comparison between PRT and other means of transportation has been performed with regard to energy consumption (IST, 2009); however, since the technology is new the understanding of the environmental impact is not well known and there has not been any detailed environmental analysis of a complete PRT system. To address this, this thesis will identify the environmental impact of the Vectus PRT system using life cycle assessment (LCA).

This thesis is divided into nine main sections. After this introductory section the purpose of the thesis is defined in Chapter 2. In Chapter 3 a general overview of the Life Cycle Assessment methodology is given and in Chapter 4 the method and LCA choices are described for the thesis. Chapter 5 presents other studies in the field of LCA for passenger transport and describes the PRT concept. In Chapter 6 the studied system is described from a material and energy perspective – the Life Cycle Assessment Inventory. In Chapter 7 the result, i.e. the environmental impact for the system with different layouts, sensitivity analysis and uncertainty analysis, is presented and described. The result, error sources and uncertainty are discussed in Chapter 8 and conclusions and recommendations are given in Chapter 9.

2. PURPOSE

The purpose of this master thesis was to identify the environmental impact of a Vectus PRT system using LCA. The goal was to provide Vectus with a greater understanding of how the environmental impact was distributed throughout the system and its life cycles. It was also of interest to investigate how different system layouts affected the overall environmental impact. Therefor the LCA was developed to be a flexible model/tool-kit that could be used for analysing different known layouts for the system (length of track, number of vehicles and stations and building material for different components). The model/tool-kit was designed to be as user friendly as possible so that people without great knowledge of LCA could apply it.

The model/tool-kit was used to evaluate different system solutions with regards to environmental impact and to identify where in the life cycle these impacts occur. The main objective for this master thesis was to:

- Identify the parts of the system that contribute to the largest environmental impacts and in which phase of the life cycle these impacts occur.

The main objective gave a better understanding of the environmental impacts of the Vectus system and was used to answer the following questions regarding system layout:

- How does the choice of main material for the track affect the overall environmental impact?
- How does the choice of power system for the vehicles affect the overall environmental impact?
- How large impact has different electricity supply mixes to the overall environmental impact?

These system layout options were chosen since the track and electricity for vehicle operation were identified as the most significant factors during the life cycle. The Suncheon system uses concrete track, power collection and South Korean electricity mix and the Uppsala test track uses steel track, battery power system and Swedish electricity mix, so to answer these questions the Suncheon system layout and the Uppsala test track layout were used.

3. METHOD DESCRIPTION OF LIFE CYCLE ASSESSMENT

The method applied to answer the questions raised in Chapter 2 was Life Cycle Assessment. A LCA is an assessment of how a product affects the environment from the cradle to the grave. The cradle is referring to material acquisition and the grave is referring to the handling of the remains at the product disposal. Thus the product is followed from extraction of raw materials until that the product is dismantled and the remains taken care of, and all materials and processes leading up to that. There is also a concept of "cradle to gate" in LCA. "Cradle to gate" accounts for the processes and materials needed to extract, transport and refine raw materials into the desired material, i.e. all process up till exiting at the factory gate (Baumann & Tillman, 2004).

In a review of recent development in LCA methodology two types of LCA can be distinguished: attributional- and consequential LCA (Finnveden et al. 2009). The difference between the two types of LCA is that the attributional LCA only considers direct impact, while consequential LCA includes processes that can be affected by the results of the study (Finnveden et al. 2009). For example an attributional LCA of an electric car would account for the whole life cycle and this is suitable if comparing it to other transport means such as a conventional gasoline car. With the consequential LCA the study will also see to the consequences of the introduction of the new vehicle. If there would be a modal shift from gasoline driven vehicles to electrical driven vehicles gasoline consumption would go down (or at least not increase as much) and the electricity demand increase. In consequential LCAs these indirect impacts are accounted for.

Attributional LCAs are often used when identifying the "hot-spots" through a products life cycle or when comparing products while consequential LCAs are often used as decision basis. One of the differences when conducting the two types of LCA is the use of average or marginal data. Marginal data reflects the effects that small changes in the output of goods and/or services from a system has on the environmental burdens of the system while average data reflects the actual physical flows (Finnveden et al. 2009).

The methodology of LCA is standardized by the International Organization for Standardization (ISO). It is described in their ISO 14040-series, *Environmental management - Life cycle assessment - Principles and framework*, which includes the four main phases described below: goal and scope, life cycle inventory, life cycle assessment and interpretation. (Baumann & Tillman, 2004)

3.1. GOAL AND SCOPE DEFINITION

In the goal and scope phase the purpose of the study and the product or service to be studied are decided. This includes stating the application and reason of the study and for whom the results are intended. A functional unit (FU) is decided on, which is a quantitative description of the purpose of the product or service being studied. The functional unit corresponds to a reference flow to which all other modelled flows of the system are related. It is a unit that corresponds to the function of the product or service being studied (Baumann & Tillman, 2004).

In the case of a transport system, as in this thesis, the functional unit can correspond to transporting one passenger one kilometre. For comparative LCA studies it is important that the same methodology is used for all systems that are compared to ensure comparability (Rydh et al. 2002).

3.2. LIFE CYCLE INVENTORY

During the inventory analysis phase a model of the studied system is built up according to the goal and scope defined in the previous phase. This is the life cycle inventory (LCI). The model is a flow model of a technical system with defined boundaries according to the ISO-standard. The flow model is a mass and energy balance for the system that considers only environmentally relevant flows. The LCI data is collected from resources, waste and emissions from all the processes in the system. This is done until all flows of importance of energy and materials are traced back to nature. (Baumann & Tillman, 2004)

3.3. LIFE CYCLE IMPACT ASSESSMENT

The third phase is the life cycle impact assessment (LCIA). The LCIA describes the results from the LCI in a more environmentally relevant way. The emissions from the LCI are classified and then characterized into different impact categories such as global warming potential (GWP) and eutrophication potential (EP), see Figure 2. For instance, GWP is measured in relation to carbon dioxide where carbon dioxide has the characterization factor of 1 and methane, a more potent greenhouse gas, has the characterization factor of 23. A substance can contribute to more than one impact category as illustrated in Figure 2. It should be mentioned that the impact categories show the potential impact and not the actual impact; this is because geographical factors are not accounted for (Baumann & Tillman, 2004). The impact categories used in this thesis and definitions of these are described in Chapter 4.1.

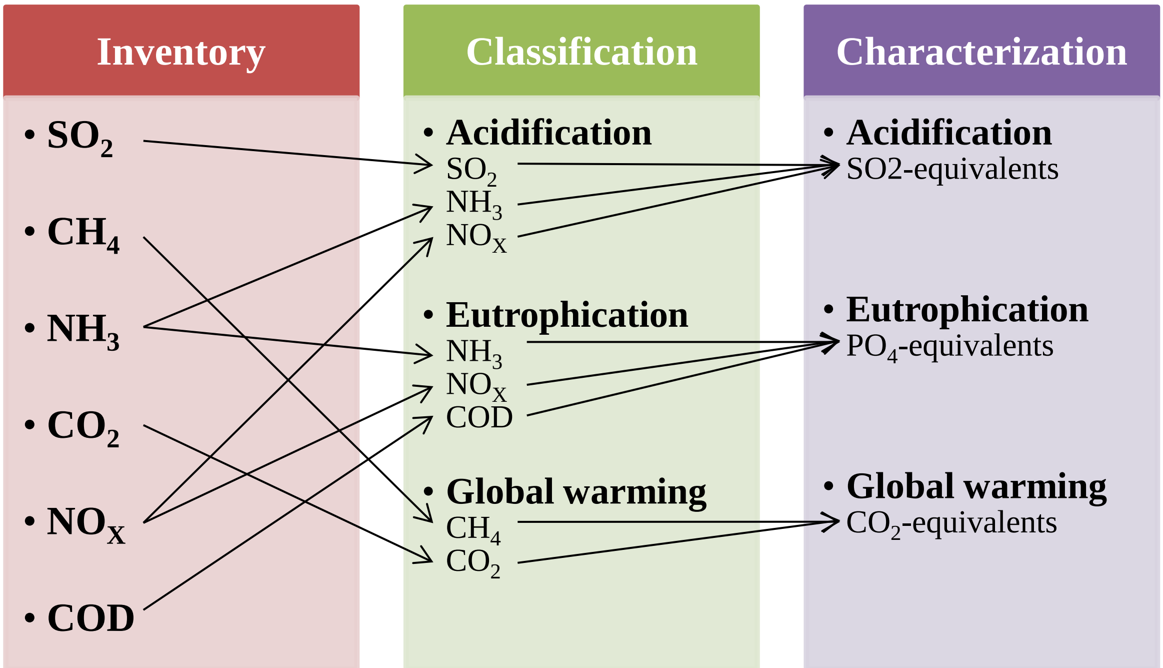

Figure 2. *Schematic illustration of life cycle impact assessment.*

Finally the data quality is examined. This is usually done by means of uncertainty analysis, sensitivity analysis and analysis of variation. Uncertainty analysis shows how the result of the study may vary depending on variations in inventory data. Sensitivity analysis on the other hand is used to judge the impact that selected methods and data have on the result of the study. Variation analysis shows how the result is affected if key assumptions are varied (Rydh et al. 2002).

3.4. INTERPRETATION

The fourth and last phase is the interpretation phase which consists of evaluation and conclusions of the study (Baumann & Tillman, 2004). An independent review of the study according to the ISO-standards is usually carried out. This has not been done for this thesis.

4. SCOPE AND EXTENT OF THE VECTUS LCA

To determine the scope and extent for the Vectus LCA, guidelines developed for environmental product declarations (EPDs) were used. These guidelines, or product category rules (PCR) as they are called, are documents that describe how to perform underlying LCA and other environmental assessments for the development of EPDs according to ISO 14025 and ISO 14040ff standards (IEC, 2009a). These guidelines were used since there has been an interest at Vectus to document the life cycle impacts of the PRT system by means of an EPD.

There are PCR documents for different products and services. However, since PRT is a new technology, there is no single, easily identifiable set of standards to use. There are, however, the following two standards for the rail transport sector:

- Interurban railway transport services of passengers, Railway transport services of freight and Railways (PCR 2009:03)
- Rail vehicles (PCR 2009:05)

The PCR for railway transport services of passengers specifies rules for railway infrastructure and rail transport. The development of this document was carried out by the Swedish National Rail Administration and Linköping University and representatives for different parts of the rail transport sector. These rules are used, in addition to EPDs, to develop data for comparison of different system solutions for railway infrastructure or transports (IEC, 2009a). The rules comprise all the resources and activities that are needed to transport passengers using a railway, i.e. a cradle to grave perspective (IEC, 2009a). The PCR does not apply to tramways, which may better correspond to the Vectus system. However, but since such are not available the PCR for railway transport services for passengers was considered applicable for this thesis.

The PCR for rail vehicles is used for the assessment of the environmental performance of rail vehicles and was developed with initiative from the European rail industry (UNIFE) and the main companies involved was Alstom Transport, AnsaldoBreda, Bombardier Transportation, Siemens Mobility, Knorr-Bremse and Saft Batteries (ICE, 2009b).

In developing the Vectus LCA these two product category rules was used as guidelines when defining system boundaries, choosing a functional unit, impact categories and making other LCA decisions. This chapter describes the layout for the Vectus LCA.

4.1. IMPACT CATEGORIES

An impact category describes a certain environmental impact by summarizing all emissions contributing to that impact. These substances are expressed relative to one substance, an equivalent.

The impact categories that were used in accordance with the PCR for rail vehicles are global warming potential, ozone depletion potential, acidifying potential, eutrophication potential and photochemical ozone creation potential. The cumulative energy demand was also included in the study to give a greater understanding of the energy distribution for the system. The impact categories are described below:

4.1.1. Global warming potential

The GWP is a metric used to compare the potential impact that anthropogenic activities have on the climate, due to emission of long-lived greenhouse gases (Solomon et al. 2007). The GWP is the sum of different greenhouse gases expressed relative to carbon dioxide (CO_2). Due to the fact that different gases have different residence time in the atmosphere GWP can be calculated for different time spans. GWP is expressed in kg CO_2-equivalents per functional unit and according to the PCR for rail vehicles the GWP was calculated for the time span 100 years (IEC, 2009b).

4.1.2. Ozone depletion potential

The ozone depletion potential (ODP) reflects the potential impact on the stratospheric ozone layer that results from anthropogenic emissions. Thinning of the stratospheric ozone layer causes a greater fraction of UV-B radiation to reach the surface of the earth causing harm to humans, animals and terrestrial and aquatic ecosystems (Guinée et al. 2002). The ODP is the sum of ozone-depleting gases expressed relative to trichlorofluoromethane (CCl_3F) as kg CFC 11-equivalents/FU. CFC 11 is the most potent ozone depleting refrigerant. According to the PCR for rail vehicles the ODP was calculated for the time span 20 years (IEC, 2009b).

4.1.3. Acidifying potential

Acidification has a negative impact on the soil, water, biological organisms, ecosystems, materials and buildings. The most common acidifying pollutants are sulphur oxide (SO_2) and nitrogen oxides (NO_x) (Guinée et al. 2002). One of the largest sources to SO_2 pollution is electricity generation from coal plants while NOx often is caused by fuel combustion (Chester & Horvath, 2009). Acidifying potential (AP) is the sum of all acidifying gases expressed as the sum of acidifying potential relative to SO_2 (IEC, 2009b).

4.1.4. Eutrophication potential

Eutrophication is caused by an excess of nutrients in an ecosystem. It affects the balance of ecosystems with increase in primary production and can lead to an undesirable shift in species composition. In aquatic ecosystems increased biomass production can lead to oxygen depletion (Guinée et al. 2002). Eutrophication potential (EP) is the sum of all emissions to water contributing to oxygen depletion/eutrophication relative to phosphate (PO_4^{3-}) (IEC, 2009b).

4.1.5. Photochemical ozone creation potential

Photo-oxidants, also known as summer smog, are formed in the troposphere when volatile organic compounds and carbon monoxide are oxidized under the influence of ultraviolet light. Ozone is the most significant photo-oxidant and can damage human health, ecosystems and crops (Guinée et al. 2002). Photochemical ozone creation potential (POCP) is the sum of all gases that contribute to the creation of ground level ozone relative to ethylene, C_2H_4 (IEC, 2009b).

These impact categories were used for the whole system and according to the PCR for rail vehicles the characterization methods used for weighing the LCIA categories were CML 2001 (IEC, 2009b).

4.1.6. Cumulative energy demand

Cumulative energy demand (CED) is a way to calculate the total primary energy input for the generation of a product or service and is useful to identify the life cycle phases with high energy-resource demand (Röhrlich et al. 2000). The cumulative energy demand is divided into the following categories;

- Non-renewable, fossil
- Non-renewable, nuclear
- Renewable, biomass
- Renewable, wind, solar, geothermal
- Renewable, water

all with a weighing factor of 1 and expressed in MJ-equivalents (Goedkoop et al. 2008). In this thesis these five categories was summed to form the total cumulative energy demand. CED is not an environmental impact but was included to give a greater understanding of the energy demand for the system.

4.2. FUNCTIONAL UNIT

The functional unit used for the Vectus system was defined as one passenger-kilometre (pkm) and included all the processes needed to transport one person a distance of one kilometre.

4.3. LIMITATIONS AND ASSUMPTIONS

The definition of the system boundaries determined which parts of the studied system that was included in the study. This was done to reduce the complexity of the study, as well as to adapt the study to the goal. There can be boundaries towards nature, i.e. the extent of the material and energy flows, boundaries towards other technical systems, i.e. to determine where one system ends and another begins and boundaries in space and time.

The PCR documents describe which system boundaries to use when designing LCAs for the specified products and services; i.e. defines which processes and flows to include or exclude. An advantage with using standardized system boundaries is better comparability between products and services within the same categories.

The Vectus system was divided into eight subsystems: track concrete, track steel, passenger station large, passenger station small, substation and power collection, control and communication system, maintenance facility and vehicle. For the vehicle subsystems the PCR for rail vehicles was used as guideline and for the other seven subsystems the PCR for Interurban railway transport services of passengers was used. The guidelines were adopted to better correspond to the Vectus system. Any differences between the PCR guidelines and those used were accounted for. The general system boundaries are described below. More specific system boundaries and assumptions are described in each model inventory in Chapter 6. Since the LCA is used to compare different system layouts and may be used to compare the Vectus system to other transport means an attributional LCA approach was used.

The Vectus system is not an absolute defined system but can be modified according to preference from the costumer. Vehicle, stations etc. can, in varying degrees, be equipped with various additions. The system described in this LCA is a standard system with only the functions needed to fulfil the purpose of PRT.

It was desired to use the local supply mix of electricity during the different life cycle phases for the different subsystems, but there were no available LCIA-data for the South Korean electricity mix. Instead the Japanese supply mix was used as it is similar to the Korean supply mix (see Appendix F).

4.3.1 System boundaries

According to LCA and PCR guidelines, all processes needed to construct, operate and maintain a PRT was included in the LCA. This included track (soil and rock excavation, construction, building material etc.), power supply system (distribution system, power feed cables, control system etc.), signalling system (vehicle control system, signs etc.), telecom system, stations, workshops, other installations and operation and maintenance of these structures. In addition to infrastructure the production, operation, maintenance and dismantling and recycling of the vehicles were included. No dismantling or recycling of the railway infrastructure were required according to the PCR but instead reinvestments should be included (IEC, 2009a). This is probably because these infrastructures are seen as permanent installation. In this study for the Vectus system dismantling and recycling of infrastructure were accounted for.

The track being built in Suncheon consists of two lanes due to the fact that the track passes back and forth along the same route. The model however is based on a single line track and the material and construction work used for 1 km of Suncheon double track was divided in half to represent a single track in the model.

The PCR for rail vehicles is applicable to all types of rail vehicles and the system boundaries for such vehicles included production of materials, production-, operation-, maintenance- and recycling of vehicle. For these processes energy use, material resources, waste and emissions were accounted for. (IEC, 2009b)

4.3.2. Boundaries in time

The calculated lifetime for the Vectus system was 60 years for the infrastructure and 20 years for the vehicles. When conducting the LCA it was assumed that the vehicles would be replaced with new ones every 20 years.

4.3.3. Boundaries towards nature

According to the PCR for passenger transportation the land use of the studied system should be part of the LCI and emissions of greenhouse gases caused by changes in land use (e.g.

deforestation) should be accounted for (IEC, 2009a). Because PRT systems are often considered to be constructed in urban areas elevated from the ground and no forestation occurs at the Suncheon wetlands land use was assumed to be unchanged for the Vectus LCA.

4.3.4. Boundaries towards other technical systems

Roads and parking spaces at passenger stations were considered belonging to the road system and were not included. Neither was transportation of passengers to and from the stations. Roads needed to be built for constructing the railway was included. Production of manufacturing equipment and personnel activities was not included (IEC, 2009a). Electrical power line from the main line to the system was not included, however power feed cables for the vehicles were included.

Infrastructure needed for material acquisition and manufacturing was included in the model. This was not needed according to the PCR but was automatically included in the datasets used.

4.3.5. Data quality rules

It is important to define the data quality requirements so that the goal and scope of the LCA study defined by the ISO 14040 standard can be fulfilled. According to the LCA and PCR standardization selected data for electricity and energy and material inputs and outputs should represent the conditions of the country where the process is taking place. Generic data should not be older than from 1990. Material utilization data should be confirmed by suppliers and site-specific data should be used for all core processes and auxiliary materials used for rail vehicle assembly. (IEC, 2009b)

EcoInvent is a LCA database that supplies international LCI and LCIA data on different materials, services and products. The EcoInvent database was used to access LCIA data for the various materials and processes that the Vectus system consists of. For a complete list of the datasets used for the LCA, see Appendix D.

5. LITTERATURE REVIEW

5.1. GENERAL DESCRIPTION OF PERSONAL RAPID TRANSIT

Personal Rapid Transit (PRT) as a concept has been discussed for decades, and extensive research and various investigations have been carried out to determine its potential as a future transportation system (Gustafsson & Lennartsson, 2009). However it is only in recent years that PRT has come to realization with a couple of systems in operation.

The Personal Rapid Transit, sometimes called podcar, system is defined from a service perspective by The Advanced Transit Association (Dahlström, 2009) as:

- Direct travel from start to destination without stop at intermediate stations
- Small vehicles available for individual travel or for chosen groups
- Demand-controlled service instead of time table bound traffic
- Fully automated, driverless vehicles, available at all times
- Track exclusive for PRT vehicles
- Light, slim and usually elevated guideways
- Vehicles can make use of the entire guideway network and all stations

PRT is a technically advanced system for fast individual or collective transportation without stops at intermediate stations. The traveller choses his/her destination when embarking and the PRT system automatically choses the fastest and most efficient path to the destination. The podcar is a driverless vehicle on an independent guideway (SIKA, 2008). PRT guideways can be at grade, elevated or in tunnels. Because tunnels are expensive and guideways at grade would create barriers, PRT guideways are in most cases elevated (Vectus, 2011b).

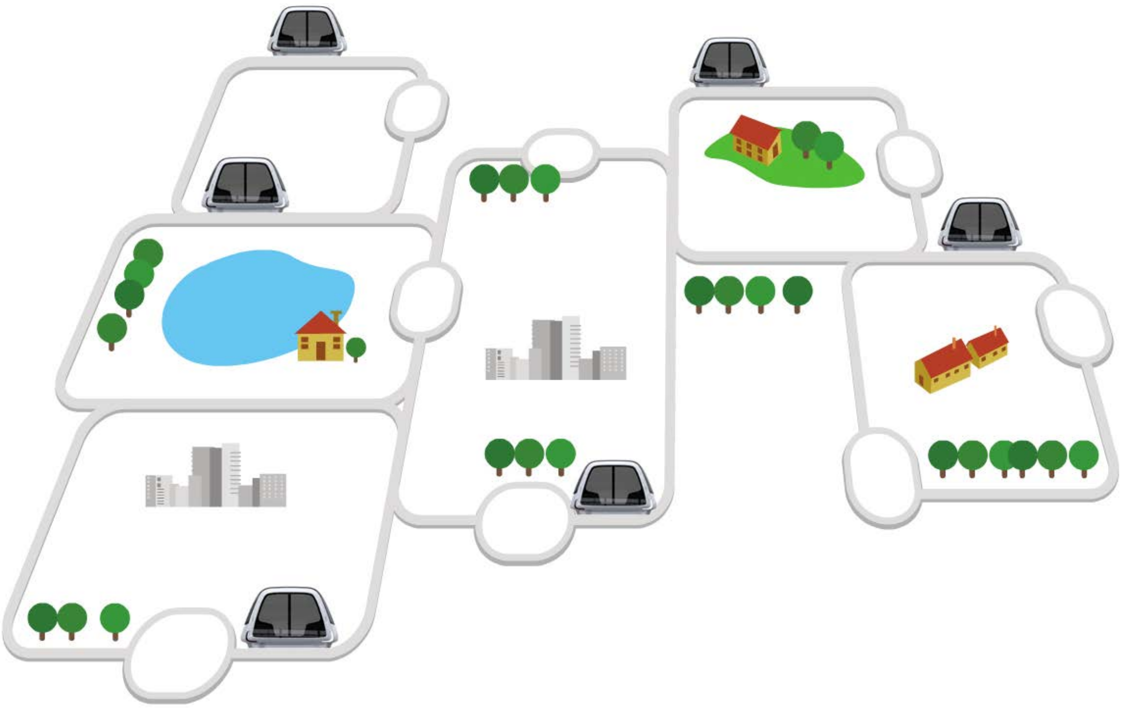

Figure 3. *Illustration of a PRT track network. The vehicles have access to the complete network.*

The PRT system seeks to combine the individuality and flexibility of the car and the environmental benefits and safety of rail transport. By using one-way tracks the risk for accidents is also reduced (SIKA, 2008). A PRT system differs from the public transportation system of today when it comes to network structure (see Figure 3). A single vehicle in a PRT system can access the whole network range while vehicles in public transportation networks are bound to one single line (Dahlström, 2009).

PRT is often described as environmental friendly which stem from the fact that it is powered by electricity with no emissions at the point-of-use and with an energy consumption of about 20 % of that of a private car (SIKA, 2008). PRT guideways are also less energy demanding to construct compared to construction of new roads (Gustavsson & Kåberger, 1994). However, existing underground railway (metro) and commuter trains have even higher capacity and lower energy consumption per person kilometre during operation (IST, 2009). PRT has no direct emissions that cause human health impacts due to the fact that it is electrically powered. However, PRT cannot be considered emission free. Emissions instead occur during the production of electricity. If the electricity used is from renewable sources, the emissions are minimal, while electricity from coal or oil results in higher emissions. A PRT systems impact on the environment during operation should thus depend largely on the choice of electricity mix. Emissions that can occur at the point-of-use are particulate matter from potential friction between the vehicle and the guideway (Dahlström, 2009) and wear from brakes and power collectors (Johansson, 2009).

5.1.1. Existing systems

Advanced Transport Systems Ltd in the UK started to develop the PRT system ULTra in 1995 and has recently opened their first commercial track at Heathrow airport as a shuttle between a large parking facility and the new International Terminal 5. Propulsion is achieved with conventional rotating, battery-powered electric motors and rubber tires on asphalt path with guiding magnetic loops and edge beams (Dahlström, 2009). The vehicles can take four passengers and the system carried 370,000 passengers during 2011, its first year in operation. It uses 70 % less energy per passenger during operation compared to a car and 50 % less than a bus (Ultra Global, 2012).

The Dutch company 2getthere has experience in several small PRT tracks on ground level with the same concept as the ULTra system. In 2009 they inaugurated the first phase of a PRT system in the new city Masdar in the United Arab Emirates. Masdar is planned to be the first carbon dioxide free city and automobiles will be prohibited in favour for PRT (Dahlström, 2009).

5.2. EARLIER STUDIES ON THE SUBJECT

When comparing passenger transport alternatives from an environmental perspective energy consumption and emissions from the vehicle tailpipe has been the conventional method to quantify the impact. Automobiles, busses, trains and aircrafts have been compared to each other with no regard to manufacturing, construction, maintenance etcetera.

Another way to compare means of transportation is through LCA where the direct and indirect processes and services required to operate the vehicle are considered. This includes raw materials extraction, manufacturing, operation, maintenance and end of life disposal. This approach gives a more holistic view, but still the infrastructure needed to operate the vehicles such as roads or railways are often neglected when making LCA for different means of transportation.

When using the LCA approach including infrastructure (end-of-life phase not included) it has been found that energy inputs and greenhouse gas emissions contribute an additional 63 % for onroad and 155 % for rail systems over vehicle tailpipe operation. For rail bound systems the construction and operation of infrastructure results in a total energy demand about twice that of vehicle operation. It was also found that rail modes were the main contributor to SO_2 emissions compared to other transport modes due to its electricity demand during operation. This study used average US data for onroad mode components and rail operational performance was determined from specific systems located in the US with both Diesel and electricity powered trains. The lifetime for infrastructure was 50 years (Chester & Horvath, 2009).

Another factor that affects the result when comparing different means of transportation is the vehicle occupancy. A private car that is fully packed has a lower environmental impact than a bus with few passengers (as during low peaks) when considering passenger kilometres. But when calculated for a full day the bus probably causes less impact (Johansson, 2009).

There is no known LCA for a PRT system, but LCAs have been published for other medium capacity passenger transport systems and railway systems that may be the systems closest to the Vectus PRT system since they are rail-bound. A Japanese study compared six different means of medium capacity transportation (Automated Guideway Transit, GuideWay Bus, High Speed Surface Transports, Light Rail Transit (LRT), Bus Rapid Transit, Monorail and Subway) using LCA. The study concluded that the LRT system had the least environmental impact in all considered impact categories of the six studied systems. However, reductions in system life cycle CO_2 by the modal shifts from passenger car were modelled, meaning that a reduction in people traveling by car was assumed and an increase in people travelling by medium capacity transportation (Osada et al. 2006). This will very likely ease the environmental loads since the reduction of CO_2 from decreased car usage was included in the study and the increased capacity lowered the impact per FU.

A LCA of the Bothnia line railway in Sweden was made by the Swedish Environmental Research Institute as part of an EPD. It includes the life cycle for both infrastructure and vehicles, but with a focus on the infrastructure. A flexible model of the system was constructed from several sub models for the different parts of the system (such as railway track foundation, railway track, passenger station and vehicle). These sub models could then be integrated to form a large model of the complete railway system. The Bothnia line was assumed to have over 12 million passengers per year and an energy consumption of 0.08 kWh per pkm for trains with occupancy of 40 %.

The assessment showed that the traffic (31.5 % passenger and 68.5 % freight) stood for about 57 % of the total primary energy use, for which 53 % was train operation, and thus the infrastructure stood for 43 %. The global warming potential (GWP) derived from greenhouse gas emissions from the system was mainly caused by infrastructure (93 %, mainly construction including deforestation) and thus 7 % from the train traffic. It should be mentioned that the electric power used during operation was a certified electricity mix based almost exclusively of hydropower (Stripple & Uppenberg, 2010).

The main contributions to all environmental impact categories (global warming potential, ozone layer depletion, eutrophication, acidification and photochemical oxidants) except primary energy resources came from raw material acquisition and production of material used for infrastructure like concrete and steel. Steel and cement for example stood for 85 % of the total material use related to CO_2 emissions for the Bothnia Line infrastructure. (Stripple & Uppenberg, 2010)

5.3. THE VECTUS SYSTEM - OVERVIEW OF THE SYSTEM AND SUBSYSTEMS

Vectus has since 2007 a fully operational test track in Uppsala, Sweden and is currently constructing their first commercial track in Suncheon, South Korea (Figure 4). The Suncheon PRT system will consist of 9 km of track, 40 vehicles with a capacity of 6 seated and 3 standing persons per vehicle, 2 stations and 1 maintenance facility. The system is assumed to transport 2 – 3 million passengers per year. In Suncheon the vehicles have conventional rotating electric motors, but at the test track linear motors (LIMs) in track are used for propulsion (Vectus, 2011b).

Figure 4. *Concept rendering of Suncheon station with concrete track and vehicles.*

The Vectus system is a new “on demand” light urban PRT solution. The system includes vehicles, stations, tracks and power supplies which are described below. All stations are normally situated off the main track. Vehicles having business at a station to pick up or drop off passengers go onto a short side-track which keeps the main track free for other vehicles to pass without restriction. This keeps the system free from congestion and hence increases speed. Average speed for the Vectus system is almost the same as operational speed. Vectus can therefor with a comparably low top speed of about 45 km/h still produce shorter travel times than existing mass transit systems; such as buses, trams and metro trains that have an average speed in the range of 15 - 30 km/h. For the PRT system to be able to transport large numbers of passengers, a large number of vehicles are required. These needs to be capable of running quite close to each other, and the Vectus system has a headway (time interval) of about 3 seconds between vehicles. With such a short headway line capacities are comparable to tram lines (Gustafsson, 2009).

5.3.1. Track

The Suncheon PRT system track (see Figure 4) consists of 9 km of elevated concrete guideway with running rail and guide rail made of steel. The track gauge is 1 meter and the average elevation of the Suncheon track is 5 meter. The track has no moving parts and switches are fixed installations with the switching mechanism mounted on the vehicles (Vectus, 2011b). The guideway at the test track in Uppsala is 400 meter long and has a track gauge of 0.75 meter and is made completely out of steel with concrete only as foundation.

5.3.2. Vehicle

The Vectus vehicle (seen in Figure 4) is fully automated (driverless) and has the size of an average car, is electrically powered and can transport up to 6 seated passengers. The vehicle can generally be divided into four parts; cabin, bogie, electrical system and pneumatic system (Vectus, 2012). Vectus has also concept plans on larger vehicles, so called Group Rapid Transit (GRT) vehicles, which can fit a large number of passengers.

Cabin

The cabin is constructed using lightweight carbon phenolic composites assembled on an aluminium chassis. Sliding doors are located at each side of the cabin. The glazing of the cabin and doors are laminated, chemically tempered glass systems in accordance with automotive standards. The interior of the cabin is provided with LED lightning, fully automatic heating, ventilation and air-conditioning. The vehicle is equipped with two passenger information displays, CCTV and emergency alarm (Vectus, 2012).

Bogie

The vehicle is equipped with two bogies. Each bogie has two axles with four running wheels and four guide wheels. The wheel surface is made of polyurethane. The running wheels are used for propulsion and takes up the vertical load while the guide wheels provide lateral guidance along the guide way (Vectus, 2012).

Switch wheels are mounted on each side of the vehicle to guide the vehicle through switches where the guide rail on one side is discontinued for a section. Each bogie has an electrical motor that gives propulsion to two of the running wheels. The vehicle can also be configured to be driven with linear motors (LIM) mounted either on the track or on the bogie. Then a reaction plate is needed on the opposite part (bogie or track). Propulsion system with a combination of electrical motor and LIM can also be a configuration (Vectus, 2012).

Electrical system

The electrical system consists of several subsystems. A propulsion system with one inverter per motor and a battery system powering the controls of the vehicle (24 V) and powering the doors. There is also an auxiliary power system providing 3-phase AC voltage supplying e.g. the HVAC system. There are two control systems for the vehicle functions, Vehicle Controller (VC) and Safety Vehicle Controller (SVC). These control systems communicate with the wayside functions over a radio interface. In Suncheon a high voltage system supplies the vehicle with electricity through a current collector (as on electrical trains). There is also the possibility to have battery driven vehicles; this is the case for the vehicles at the Uppsala test track (Vectus, 2012).

Pneumatic system

The pneumatic system consists of air supply system (compressor and tank) and air control (valves and pressure sensors) for supplying brakes and switch wheels with pressure. The pneumatic system is also regulating the vehicle suspension by adjusting the air pressure in the air bellows.

5.3.3. Station

The stations (seen in Figure 4) can be located off the main line with a separate station track. This, however, is not the case for the Suncheon system. The number of vehicle positions determines capacity, as well as configuration of the station itself. A basic example would be a station where vehicles are queued in a line waiting for passengers. There would be some number of station berths, as well as additional waiting positions for holding empty vehicles for future trips. The stations can also be used to store excess vehicles during lower traffic demands allowing empty vehicles to be available when passengers arrived at the station.

5.3.4. Maintenance facility

The maintenance facility is a large workshop for maintenance of the vehicles. The building in Suncheon is a three story concrete building with an elevator to transport the vehicles between the floors. The maintenance facility holds all tools and equipment for maintaining the vehicles. In Suncheon the control room and offices are also housed in the maintenance facility.

5.3.5. Substations and power collection

The power for Vectus PRT system in Suncheon is supplied by a 22.9 kV medium voltage cable. A cable along the guideway distributes the power to three rectifier substations. Two of these will be located at the station areas in either end of the line, while the third will be located approximately midway out along the guideway. Each substation is equipped with one transformer, two 12-pulse rectifiers, switchgear, surge arrestors, current measurements and control, supervision and protection systems. The power is transferred to the vehicles from a conductor rail using power collectors on each vehicle (Vectus, 2011b).

5.3.6. Control and communication

The vehicles are controlled from a control room, in Suncheon housed in the maintenance facility. Alongside the track there are radio boxes every 90 meters linked with fibre optics which communicate wirelessly with the vehicles.

6. LIFE CYCLE ASSESSMENT INVENTORY

6.1. MODEL DESCRIPTION

The Vectus LCA model was divided into eight sub models:

- Track concrete
- Track steel
- Passenger station large
- Passenger station small
- Substation and power collection
- Control and communication
- Maintenance facility
- Vehicle

Each sub model where based on material and energy flows during the whole life cycle. Data for the different models were based on different sources such as bill of material (BOM) lists, interviews, drawings, manuals and literature. The different sub models were then combined to form a complete LCA of a PRT system. For the complete model different system parameters could be altered so that different system layouts could be considered and analysed. The life cycle was divided into three phases (Figure 5); construction, operation and end of life.

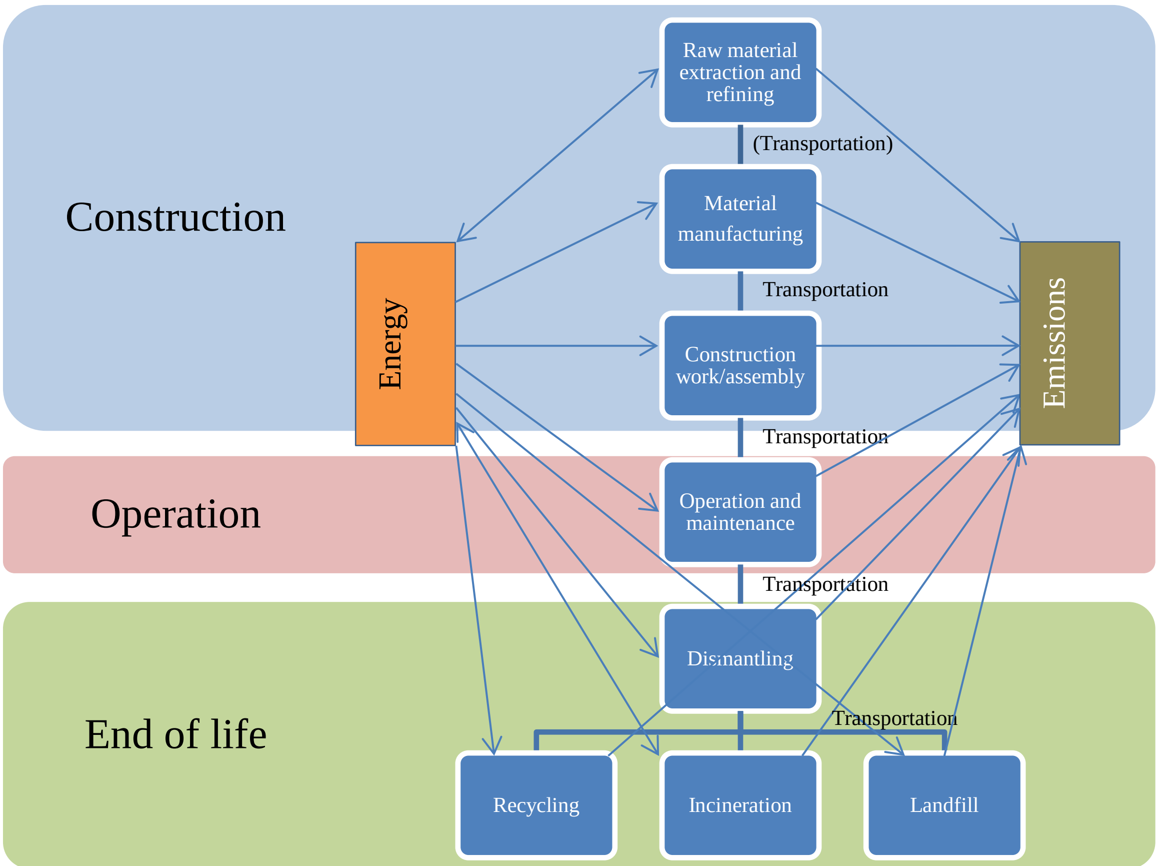

Figure 5. *Flow chart of sub model illustrating the different steps and phases of the life cycle. This example is for the track sub model.*

6.1.1. Construction

When manufacturing complex products such as rail vehicles or electronics the direct control of emissions from production is small. For electronics it is estimated that 60 – 70 % of the total environmental emissions during production originates from part suppliers. The assembly itself often causes little impact (Baumann & Tillman, 2004). The Vectus system is a complex product in which only the vehicle itself consists of over 800 unique parts, mostly from different sub suppliers. To acquire specific environmental data for all these parts would not be possible. Partly because it would be too time consuming and require too much resources and mainly because this would aggravate Vectus on-going procurements with sub suppliers. Instead the model uses generic LCIA-data for the material and energy flow of the system.

During the construction phase material acquisition, manufacturing of components (including spare parts), transportation and assembly or construction were accounted for. Each sub model was broken down into smaller parts depending on the level of detail of the input data. For each part (or assembly) of the sub model the three main materials, according to weight, were accounted for. The lifetime of all parts were considered and if the lifetime of the system exceeded the parts lifetime extra, complete, parts was added in the model as spare parts.

The different materials for all parts was summed and LCIA-data with a “cradle to gate”-perspective were used. This, however, did not include the manufacturing of the different parts. To account for this the different materials were divided into the following eight material groups according to PCR standardization:

- Metals
- Polymers
- Elastomers
- Glass
- Fluids
- Modified organic natural materials (MONM)
- Aggregates (building material such as gravel, concrete etc.)
- Others (including components for which the material contents cannot be established e.g. compounds, electronics)

These eight material groups were used when calculating manufacturing impact and the material group was representative for all different materials included in the group. General LCIA-data for these material groups were used. Here raw material and energy was seen as inputs and manufactured components and emissions as outputs. This approach with quantifying material data for components and adding of manufacturing factors are used by e.g. Bombardier when performing LCAs for their vehicles (Paulsson, 2012).

During assembly/construction energy consumption were accounted for based on machinery used at site and construction/assembly duration. Use of auxiliary materials was also accounted for. Electricity used during the assembly/construction was modelled with the local supply mix. The manufacturing of equipment was not part of the model.

6.1.2. Operation

This phase included the resources that were needed to keep the system operational. This mainly consisted of energy in form of electricity but some maintenance materials were accounted for. Electricity consumed for operation used LCIA-emission data for the local supply mix.

6.1.3. End of life

The end of life phase handled dismantling, recycling, incineration and landfill. The subsystems were broken down into its material elements according to the material categories defined in 6.1.1.

Generic data was used for the dismantling of the subsystems. Metals, Polymers, Elastomers, Glass and Modified organic natural materials were assumed to be manually dismantled and shredded. Aggregates were assumed to be dismantled in the same way as reinforced concrete and Others were assumed to be manually dismantled in the same way as industrial devices. Each material category was then treated separately and divided into three fractions; recycling, incineration and landfill.

For the recycling fraction the infrastructure, energy and auxiliary materials needed for recycling and the dismantled waste were seen as inputs and emission and generation of second grade raw material were seen as outputs. The raw materials were seen as inputs to another system and were therefore considered as an environmental benefit. The impact that the raw material would have done if considered an input was therefore subtracted from the sub models.

For the incineration fraction the infrastructure, energy and auxiliary materials needed for incineration and the dismantled waste were seen as inputs and emission and generation of electricity and thermal energy were seen as outputs. The electricity and thermal heat were seen as an input to another system and were therefore considered as an environmental benefit. The impact that the electricity and thermal energy would have done if considered an input was therefore subtracted from the subsystem.

For the landfill fraction the infrastructure, energy and auxiliary materials needed for landfill and the dismantled waste were seen as inputs and leachate was seen as output.

Material impact trough the life cycle can be expressed as equation 1 - 3:

$$GWP = X\,(E_{fe,GWP} + M_{m,\,GWP} + D_{m,\,GWP} + r\,R_{m,\,GWP} + i\,I_{m,\,GWP} + l\,L_{m,\,GWP}) \qquad \textit{(Eq. 1)}$$

where E is the impact from extraction of material, M the impact from manufacturing of part, D the impact from dismantling, R the impact from recycling of material, I the impact from incineration, L the impact from landfill, m = metal, r = recycling rate, i = incineration rate, l = landfill rate. The sum of r, i and l is one. In this case GWP is calculated for X kg of iron.

R_m in equation 1 can be expressed as:

$$R_{m,\,GWP} = Rp_{m,\,GWP} - E_{m2,\,GWP} \qquad \textit{(Eq. 2)}$$

and $I_{m, GWP}$ as:

$$I_{m, GWP} = Ip_{m, GWP} - EG_{GWP} - HG_{GWP} \quad \text{(Eq. 3)}$$

where Rp is impact from the recycling process, m2 is secondary metal, Ip the incineration process impact, EG the impact from generated electricity and HG the impact from generated heat.

The transportation of components and material that occurs during the life cycle was based on LCIA-dataset for lorry transportation and the average goods transportation distance in Sweden. The transportation is expressed in tonne kilometre (tkm). One tkm corresponds to transporting one tonne a distance of one kilometre. Distances and means of transportation used in the model can be found in Appendix E.

6.2. THE OVERALL SYSTEM

The eight sub models were combined to form a flexible PRT LCA model. Different LCA configurations, system layouts, capacity, vehicle and infrastructure operating parameters and operating time and end of life configurations could be altered to study different systems environmental impacts (see Appendix A).

The Suncheon system used the system layout seen in Table 1. Six scenarios (described in Chapter 7.2) with different track material, electricity mix and vehicle power system were analysed.

Table 1. *Suncheon system layout.*

System part	Quantity
Length of track [km]	9
Number of large passenger station	2
Number of small passenger station	0
Number of maintenance facilities	1
Number of vehicles	40
Number of substations	3

A scenario with battery powered vehicles was included in the model. In this scenario no power collection was used but instead 200 kg of rechargeable prismatic lithium ion batteries per vehicle with an assumed lifetime of two years. The substations with inventory were assumed to function as charging stations and vehicle power consumption was increased with 10 % due to assumed energy loss during recharging. The vehicle idle/running ratio was constricted to be at least 2:1 to simulate charging intervals. This led to a decrease in vehicle trips per operating day (see Appendix A) and to maintain the same passenger capacity the number of vehicles needed to be increased.

6.3. TRACK CONCRETE

The concrete track sub model was based on the track being built in Suncheon. The track consists of concrete pillars including foundation, concrete girders and guide and running rail in steel (see Figure 6).

6.3.1. Construction

The data used for material composition (Table 2) and construction work (Table 3) was based on interviews with Suncheon PRT project infrastructure manager Chun-Hee Kim in combination with the work of Keoleian et al. (2005) on concrete bridge construction. Material composition for a typical pillar and girder was used to estimate the entire track composition and known equipment and project duration and work hours were used to estimate construction impact.

Figure 6. *Concrete track consisting of concrete pillars and concrete girders being built at site in Suncheon.*

Table 2. *Material composition for 1 km of concrete track.*

Material	Metals	Polymers	Elastomers	Glass	Fluids	MONM	Aggregates	Others
Weight [kg]	507,000	3,670	0	0	0	79,700	4,150,000	0

Table 3. *Machinery used and energy consumed for construction of 1 km concrete track.*

Machinery	Energy consumption
2 boring machines (data for hydraulic hammer)	99,000 kWh
2 cranes, 50 t	174,000 kWh
10 dump trucks	112,000 kWh
2 concrete mixers*	7,920 kWh
1 concrete truck*	148,000 kWh
1 crawler-mounted hydraulic excavator*	211,000 kWh

Energy data based on Keoleian et al. (2005). Machinery with * was included in addition to the site description.

The concrete track consists mainly of aggregates and steel as seen in Table 2. The steel is for reinforcements of the concrete and the rail and the aggregates consist of concrete and gravel. The MONM are timber and plywood used during the concrete casting process. In addition to the site procedures for construction described by Chun-Hee Kim the operation of one concrete truck, two concrete mixers and one crawler-mounted hydraulic excavator was added to the model. This seemed necessary for the construction of the track pillars and track girders and for the groundwork made before the track erection.

6.3.2. Operation

There were no identified operation factors for the concrete track.

6.4. TRACK STEEL

To be able to study different system solutions for the Vectus system a sub model for the steel track used at the test track in Uppsala was created.

6.4.1. Construction

The product manual and drawings were studied and staff at the Vectus Uppsala office interviewed to acquire the material composition (Table 4). Pictures from the construction phase in combination with Keoleian et al. (2005) were used to quantify the construction work (Table 5). The track, which consists almost entirely of steel, is supported by steel beams anchored in concrete foundations (see Figure 7). For the concrete an additional 125 kg of reinforced steel per m^3 concrete was assumed.

Figure 7. *Steel track with concrete foundation at Uppsala test site.*

Table 4. *Material composition for 400 m of steel track.*

Material	Metals	Polymers	Elastomers	Glass	Fluids	MONM	Aggregates	Others
Weight [kg]	151,000	6,950	1,270	0	0	26,200	202,000	0

Table 5. *Machinery used and energy consumed for erection of 400 m steel track.*

Machinery	**Energy consumption**
1 wheeled front end loader	19,600 kWh
1 concrete truck	1,790 kWh
1 crawler-mounted hydraulic excavator	10,200 kWh

The steel components were manufactured in UK and shipped to Sweden. The steel surface was treated with two layers of epoxy and two layers of polyurethane. Application instructions for similar products were used to quantify the amount needed.

6.4.2. Operation

There were no identified operation factors for the concrete track.

6.5. PASSENGER STATION LARGE

The sub model for the large passenger station was based on one of the stations being built in Suncheon.

6.5.1. Construction

The design and construction of the passenger station at Suncheon (Figure 8) was executed by an external architectural firm. Hence no information about the material composition or construction work was obtained. The size of the stations was however described in the project manual and in combination with a LCIA-dataset for a general multi story concrete building according to Mauch et al. (1995), the impact from the station building was estimated. The dataset for the concrete building included the most important materials used (Table 6) and these quantities were added to the model. Also described was the requirement of electricity for construction (Table 7).

Figure 8. L*arge passenger station being built in Suncheon.*

Table 6. *Material composition for large passenger station.*

Material	Metals	Polymers	Elastomers	Glass	Fluids	MONM	Aggregates	Others
Weight [kg]	54,200	1,220	0	4,070	0	40,700	624,000	542

Table 7. *Energy used for constructing multi-storey concrete building.*

Machinery	**Energy consumption**
Building machine	1,830 kWh
Electricity	396 kWh

6.5.2. Operation

During the operation phase energy consumption was accounted for. The power consumption was assumed to be 10 kW for opening hours and 3.4 kW at off hours. This resulted in a total energy demand of 62,800 kWh per year and station for the Suncheon opening hours (see Appendix A). Local electricity mix was used for all station operation.

6.6. PASSENGER STATION SMALL

The Suncheon PRT system consists of two very large passenger stations and these can be seen more as travel centres than traditional stations. To be able to model different system networks with a larger number of stops there was a need of smaller stations. The prototype station built at the Uppsala test track was used for the small passenger station sub model (see Figure 9).

Figure 9. *Small passenger station at Uppsala test track.*

6.6.1. Construction

The product manual and drawings were studied and staff at the Vectus Uppsala office interviewed to acquire the material composition (Table 8). Pictures from the construction phase in combination with Keoleian et al. (2005) was used to quantify the construction work (Table 9).

Table 8. *Material composition for small passenger station.*

Material	Metals	Polymers	Elastomers	Glass	Fluids	MONM	Aggregates	Others
Weight [kg]	5,490	58	68	612	0	1,940	5,460	542

Table 9. *Machinery used and energy consumed for construction of small passenger station.*

Machinery	Energy consumption
1 wheeled front end loader	1,400 kWh
1 concrete truck	1,790 kWh

6.6.2. Operation

As for the large passenger station local electricity mix was used to model the operation impact. The power consumption during operating hours was based on the electrical components used at the prototype station and summed up to 2 kW. At off hours the power consumption was assumed to be a third of the operation hour consumption. This resulted in a total energy demand of 12,600 kWh per year and station for the Suncheon opening hours.

6.7. SUBSTATION AND POWER COLLECTION

6.7.1. Construction

As for the passenger station in Suncheon no data was available for the substation buildings. The same dataset for concrete buildings as for the passenger stations was used and the size of the buildings is 25 m^2. For the power collection the material composition was measured. The total material composition can be seen in Table 10.

Table 10. *Material composition for one substation and 1 km power collection.*

Material	Metals	Polymers	Elastomers	Glass	Fluids	MONM	Aggregates	Others
Weight [kg]	17,800	2,690	0	208	0	1,930	29,600	2,260

Table 11. *Energy used for constructing substation and power collection. Energy data based on Mauch et al. 1995.*

Machinery	Energy consumption
Building machine	87 kWh
Electricity	44 kWh

6.7.2. Operation

Each substation was assumed to have a power consumption of 2 kW. This resulted in a total energy demand of 17,500 kWh per year and substation for the Suncheon opening hours. The local electricity mix was used to model the operation impact.

6.8. CONTROL AND COMMUNICATION

6.8.1. Construction

The control room is Suncheon is located inside the maintenance facility so there was no building included in the model. Instead the control room equipment and power supply was estimated. The communication network along the track was also included which consists of radio boxes every 90 meters connected with fibre optics.

Table 12. *Material composition for control equipment and 1 km of communication network.*

Material	Metals	Polymers	Elastomers	Glass	Fluids	MONM	Aggregates	Others
Weight [kg]	414	417	3	120	0	13	0	428

Table 13. *Energy used for constructing control and communication system.*

Machinery	**Energy consumption**
Building machine	3,170 kWh
Electricity	1 kWh

6.8.2. Operation

The control system was assumed to be operational all day round. Each radio box has the power consumption of 15 W and the control room was assumed to have a power consumption of 1.5 kW. For the Suncheon layout with 9 km of track and one control room the total energy demand was 26,000 kWh per year. Local electricity mix was used to model the operation impact.

6.9. MAINTENANCE FACILITY

6.9.1. Construction

The construction of the maintenance facility (Figure 10) is subcontracted and information about material and construction work was therefore limited. As for the passenger station and the substations the dataset for concrete structures was used in combination with the estimated volume of the maintenance facility. The mass for the maintenance facility building was readjusted with a factor of 0.75 due to its large open spaces. The concrete building dataset was compiled from two residential buildings with smaller rooms and thus more inner walls.

Figure 10. *The maintenance facility under construction in Suncheon.*

The material composition of the maintenance facility and the energy used for construction according to Mauch et al. (1995) are seen in Table 14 and Table 15 respectively.

Table 14. *Material composition for maintenance facility.*

Material	Metals	Polymers	Elastomers	Glass	Fluids	MONM	Aggregates	Others
Weight [kg]	547,000	17,200	0	39,000	0	390,000	5,940,000	0

Table 15. *Energy used for constructing multi-storey concrete building.*

Machinery	**Energy consumption**
Building machine	23,300 kWh
Electricity	5,030 kWh

6.9.2. Operation

Power consumption for the maintenance facility was assumed to be 28 kW. This results in a yearly energy demand of 242,000 kWh. As for the large passenger station local electricity mix was used to model the operation impact.

6.10. VEHICLE

6.10.1. Assembly

The vehicle composition (Figure 11) was based on the pre prototype vehicle, BOM list and measurements of different subcomponents. The overall material composition can be seen in Table 16. To quantify material composition for sub supplier parts the product specifications were used when available, otherwise assumptions were made.

Figure 11. *Concept rendering of Vectus vehicle.*

The assembly occurs in Sweden and thus the electricity use for the assembly was calculated with Swedish supply mix (Table 17). The shipment of the vehicles from Sweden to South Korea was assumed to be with a transoceanic freight ship.

Table 16. *Material composition for vehicle.*

Material	Metals	Polymers	Elastomers	Glass	Fluids	MONM	Aggregates	Others
Weight [kg]	3,930	792	228	360	66	0	0	220

Table 17. *Machinery used for vehicle assembly.*

Machinery	**Energy consumption**
Electricity	72 kWh

6.9.2. Operation

The operation phase included the electricity needed for vehicle operation and the amount was calculated from the vehicle operating parameters. The vehicle drive power consumption was assumed to be 4 kW and the vehicle idle power consumption was 2 kW. The running time was based on number of planned trips and average trip time and the idle time was calculated from daily operating time and running time. For the Suncheon passenger demand the total yearly energy demand per vehicle was 15,800 kWh.

7. ENVIRONMENTAL IMPACT ASSESSMENT

The material and energy inventory described in Chapter 6.2 – 6.10 was translated, as described in Chapter 6.1, into the chosen impact categories described in Chapter 4.1 using LCIA datasets from the EcoInvent database. The result is shown and described in this chapter.

The first section of this chapter, 7.1, shows the impact and material distribution for the Suncheon PRT system being constructed in South Korea. The second section, 7.2, shows the impact result for different system layouts for the Suncheon PRT system. The uncertainty analysis for the model is shown in 7.3. More data are found in Appendix B.

7.1. ENVIRONENTAL IMPACT DISTRIBUTION

The following results are based on the Suncheon PRT system consisting of concrete track, power collection and modelled with South Korean (actually Japanese) electricity mix.

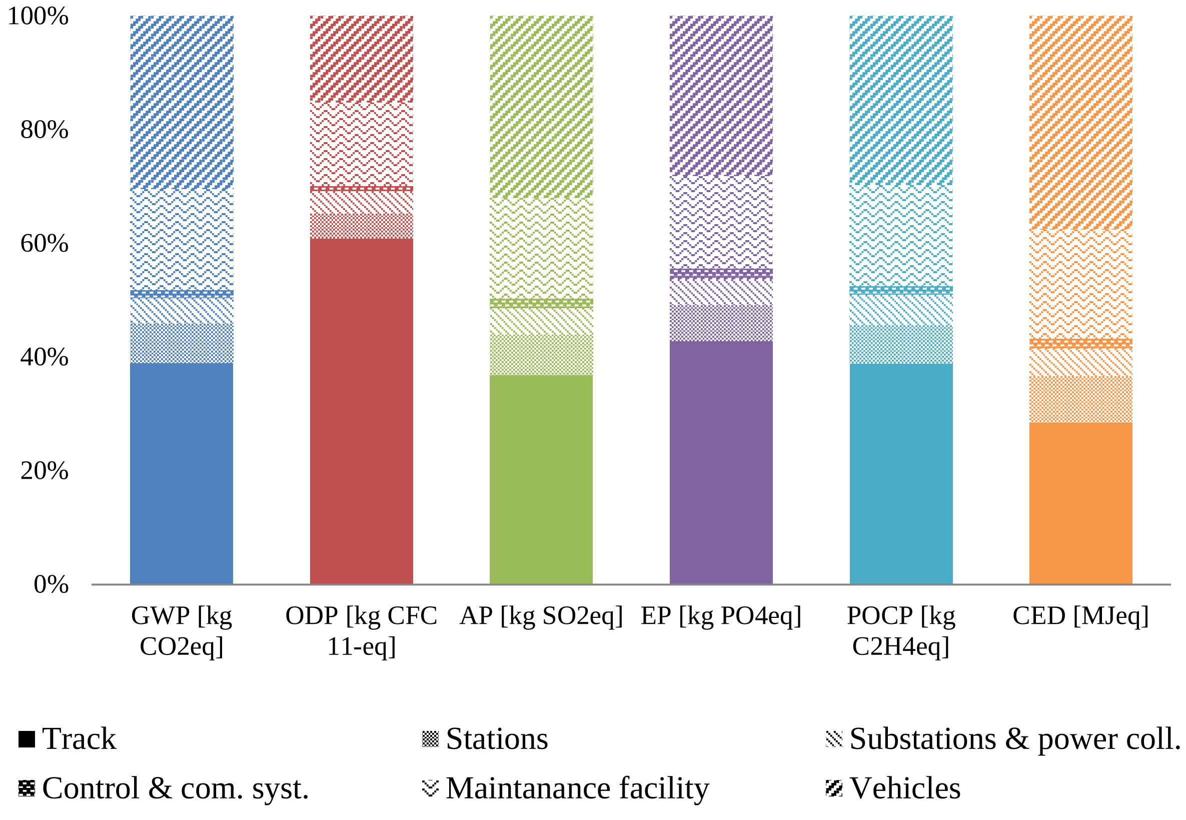

Figure 12. *Impact distribution for the different system parts and impact categories for the Suncheon PRT system.*

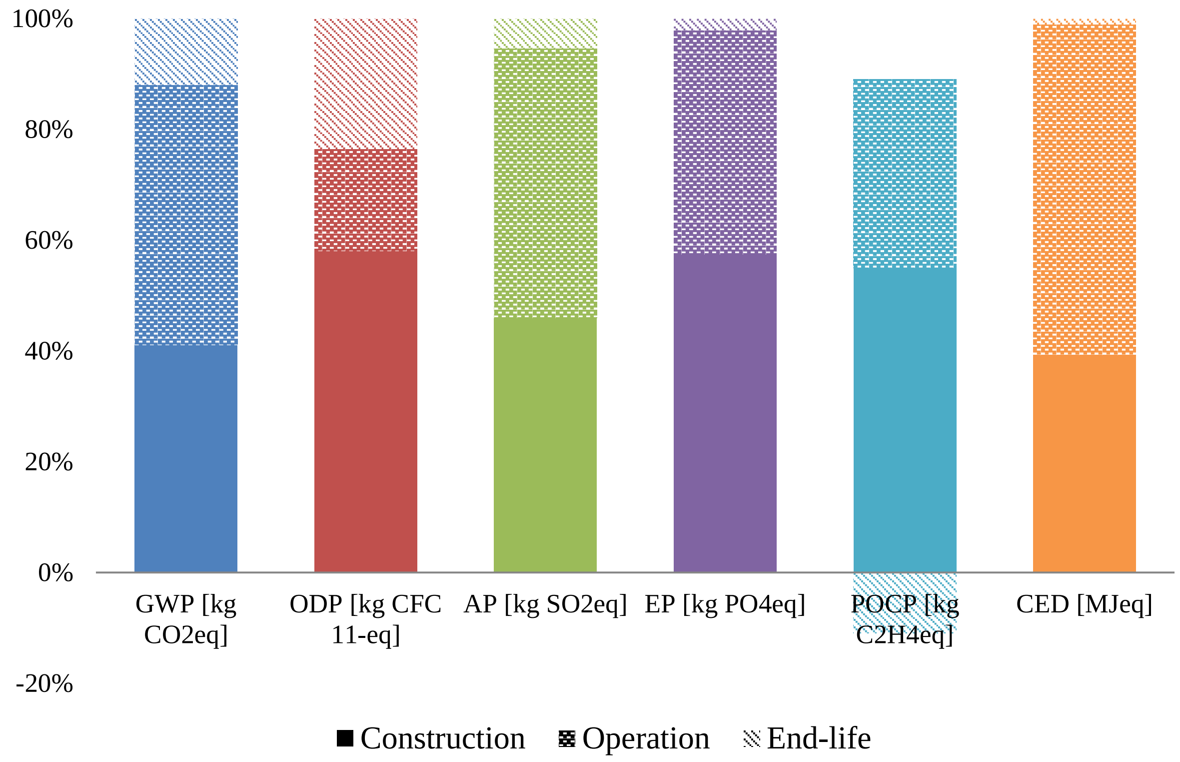

Figure 13. *Impact distribution for the different life cycle phases and the different impact categories for the Suncheon PRT system.*

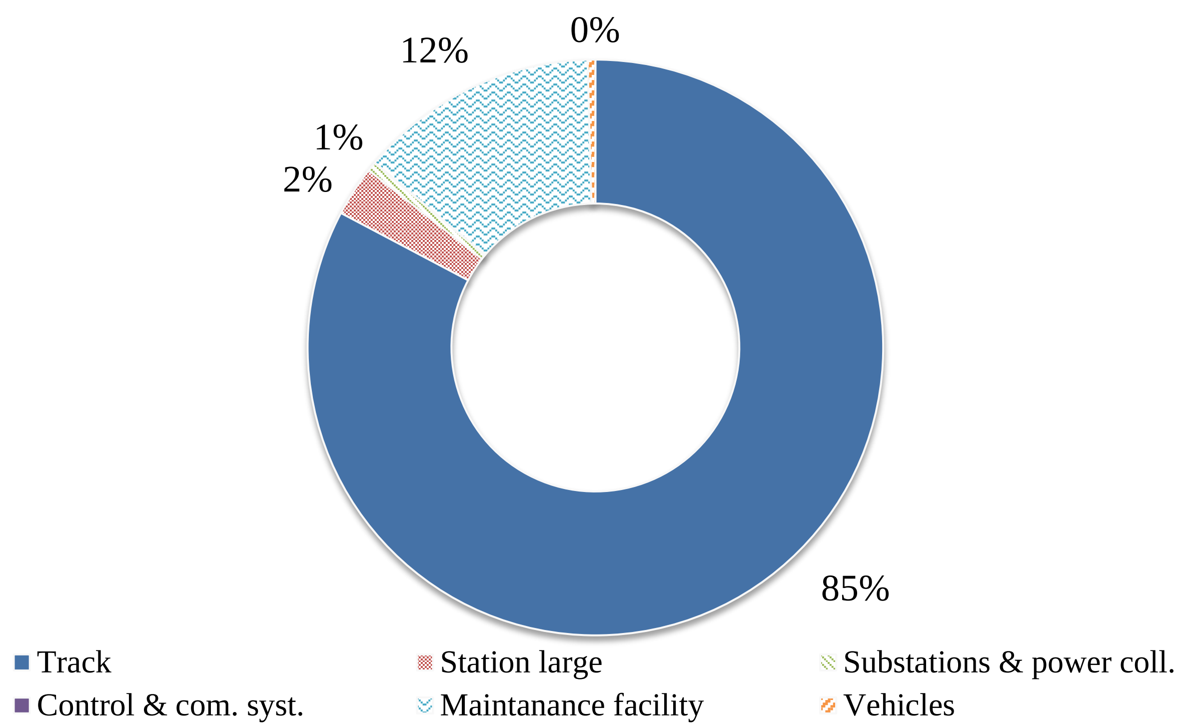

Figure 14. *Mass distribution for the Suncheon PRT system.*

Figures 12 and 13 shows the environmental impact distribution from the Suncheon PRT system and Figure 14 shows how the mass is distributed between system components, i.e. the weight distribution for the system. When comparing the different system parts (Figure 12) it appears that the concrete track is the largest contributor to the overall environmental impact followed by the vehicles. The large impact from the concrete track is due to the fact that the concrete track represents 85 % of the mass of the PRT system and hence the impact originates from raw material extraction and construction work.

The impact from the vehicles, for which the mass is negligible in comparison to the whole system, are due to the electricity that needs to be generated for the operation of the system and the vehicles are therefore also the largest contributor to the overall cumulative energy demand (CED). The concrete track represents over 60 % of the ozone depletion potential (ODP) and this is mainly due to high ODP for metal work and material acquisition.

The maintenance facility is the third largest contributor to the overall environmental impact and this is due to the fact that this part of the PRT system has the next largest mass and a large energy demand during the life phase.

Comparing the traffic impact (vehicle) with the impact from the infrastructure (the other subsystems), as was done in the studies mentioned in Chapter 5.2, one can see that the traffic contribute to around 30 % of the global warming potential (GWP), acidification potential (AP), eutrophication potential (EP) and photochemical ozone creation potential (POCP), 15 % for ODP and almost 40 % for CED.

Figure 13 shows in which phase of the life cycle the impact occurs. The construction phase includes the energy consumed during construction and all materials used (also spare parts), the operation phase includes the energy required to run the system during its lifetime and end-life includes dismantling and recycling, incineration and landfill.

No unequivocal conclusions can be drawn for all impact categories except that the end-life phase contributes the least to the total impact. This is because recycling benefits are included in the model. For POCP even a positive end-life impact is obtained which is the result from the second grade metals produced from recycling and energy gained at incineration. The high ODP and EP for construction are mainly due to metal product manufacturing and partly raw material extraction and POCP for construction is mainly due to raw material extraction and partly metal product manufacturing.

The largest fraction of the overall CED originates from the electricity consumed during the operation phase while GWP and AP are quite evenly distributed between the construction phase and the operation phase.

7.2. IMPACT OF DIFFERENT SYSTEM LAYOUTS

Six different scenarios (see Table 18) for the Suncheon PRT system were compared to see how these affected the environmental impact. The results for four of these scenarios can be seen in Figures 15 – 24.

Table 18. *Description of the different scenarios for Suncheon PRT system.*

Scenario	Description
S. Korea, battery	Japanese electricity mix, battery power source, concrete track
S. Korea, concrete	Japanese electricity mix, power collection, concrete track
S. Korea, steel	Japanese electricity mix, power collection, steel track
Certified, battery	Certified electricity mix, battery power source, concrete track
Certified, concrete	Certified electricity mix, power collection, concrete track
Certified, steel	Certified electricity mix, power collection, steel track

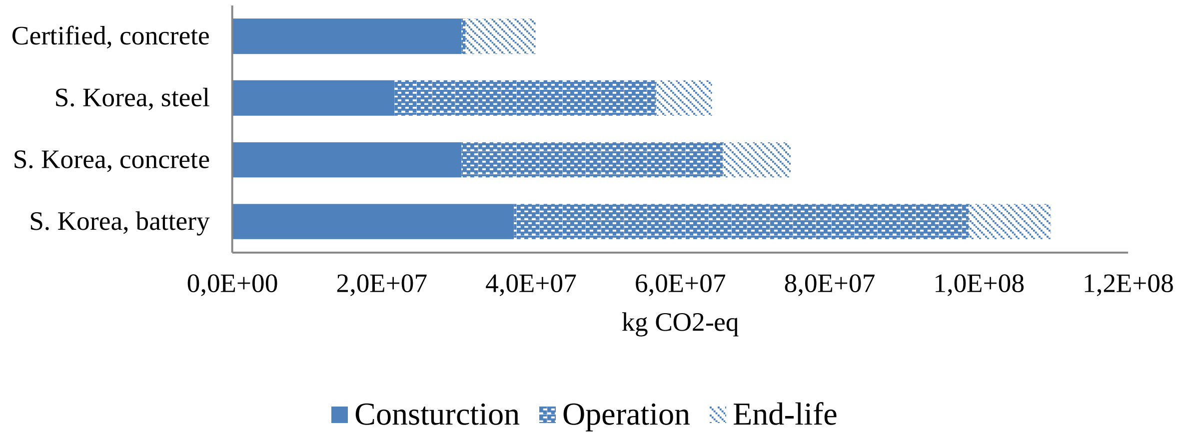

Figure 15. *GWP for different life cycle phases and system layouts for the Suncheon PRT system.*

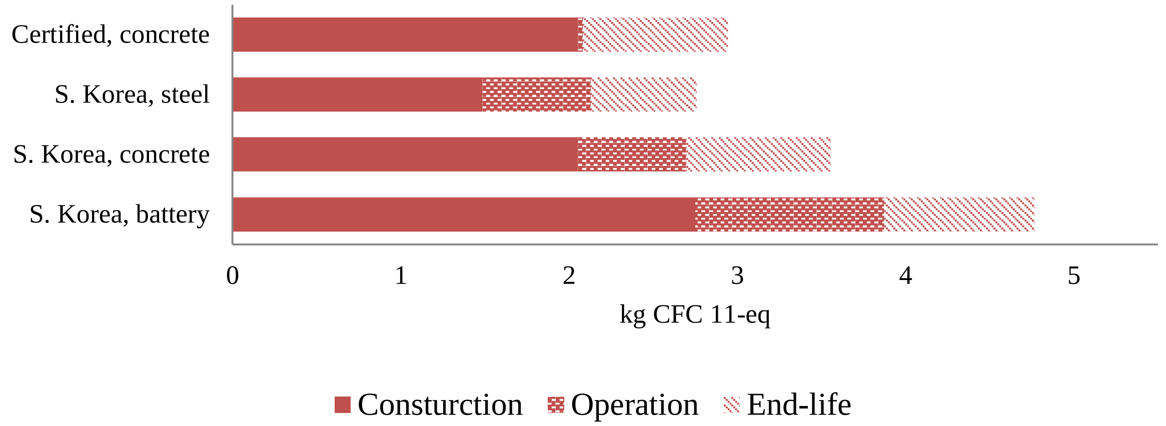

Figure 16. *ODP for different life cycle phases and system layouts for the Suncheon PRT system.*

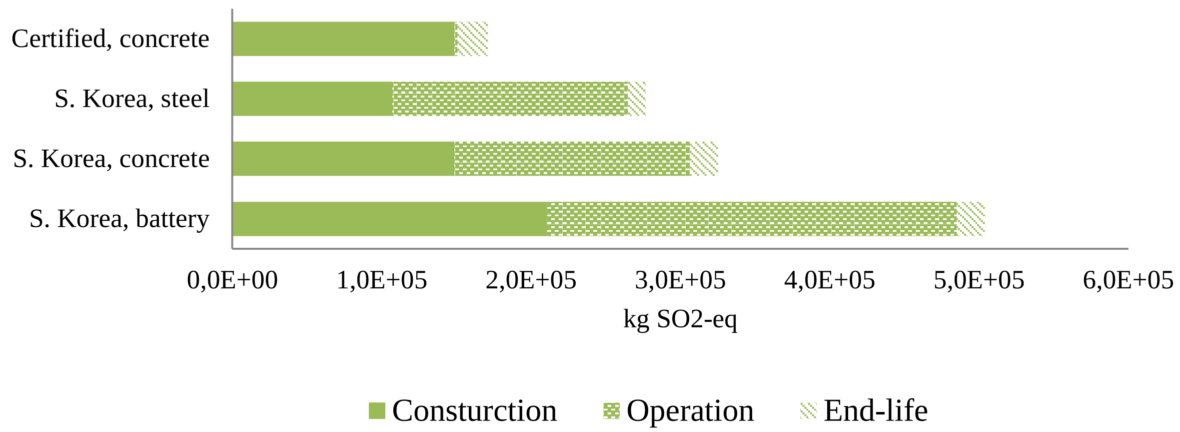

Figure 17. *AP for different life cycle phases and system layouts for the Suncheon PRT system.*

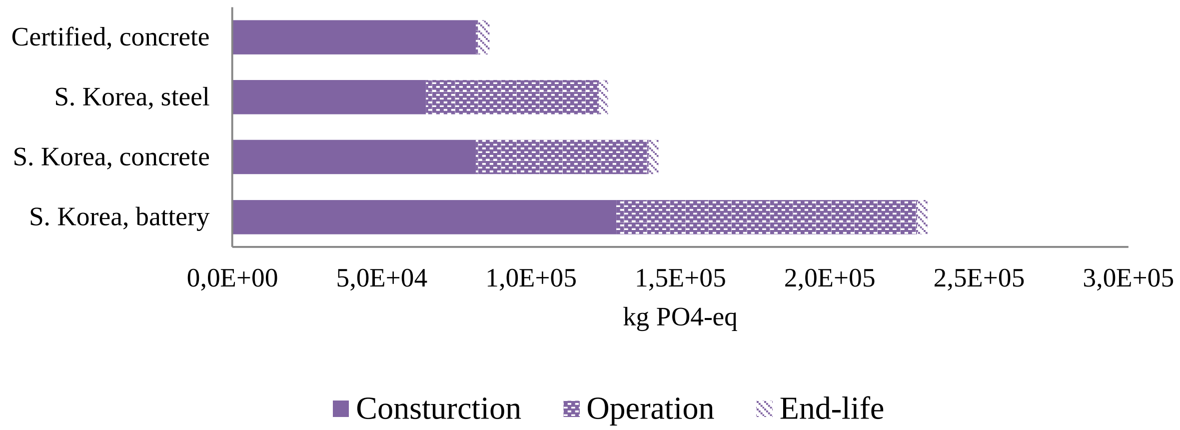

Figure 18. *EP for different life cycle phases and system layouts for the Suncheon PRT system.*

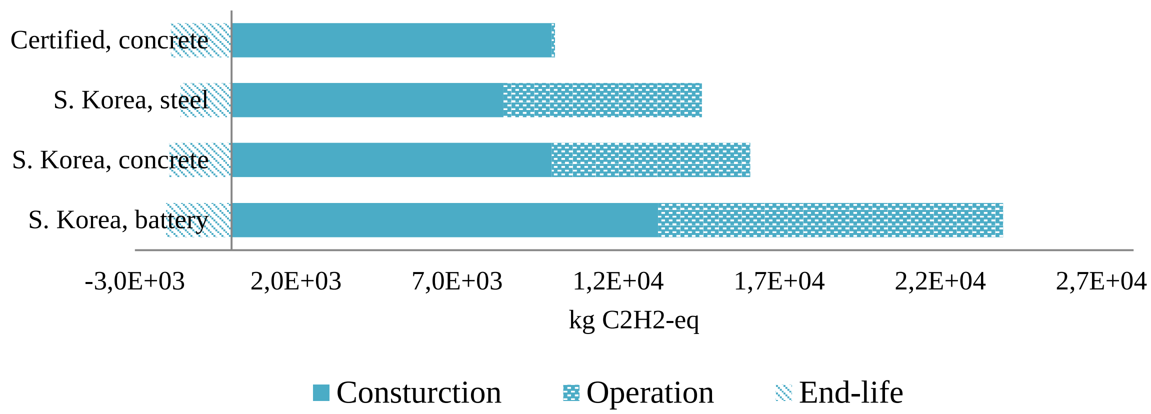

Figure 19. *POCP for different life cycle phases and system layouts for the Suncheon PRT system.*

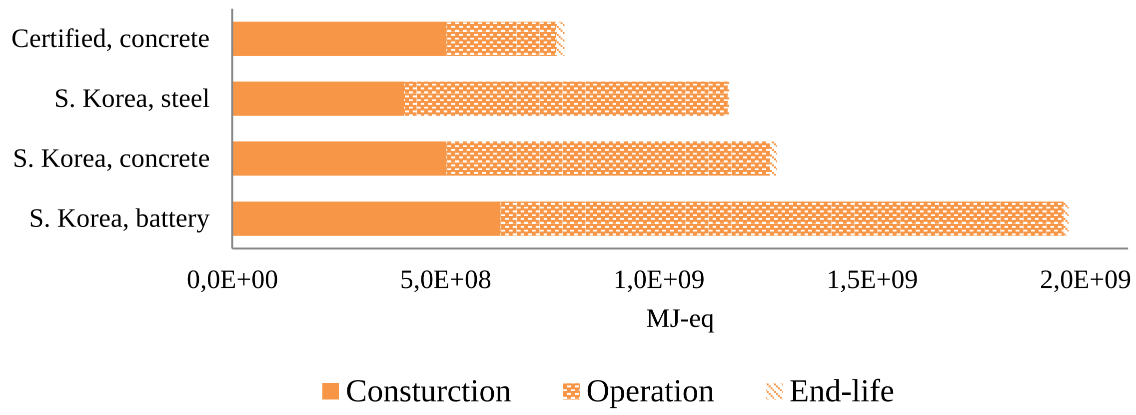

Figure 20. *CED for different life cycle phases and system layouts for the Suncheon PRT system.*

In Figure 15 – 20 the impact distribution for the different life cycle phases is shown for four different layouts. The scenario *S. Korea, concrete* is the scenario described in Chapter 7.1.

7.2.1. Power system

Focusing on the power system for the vehicles it can be shown, when considering the total impact, that the benefits of smaller infrastructure due to the exclusion of the power collection that goes alongside the whole track is overshadowed by the increase in number of vehicles needed to maintain the passenger capacity. This is mainly because of the electricity demand during operation.

The increase in impact during the construction phase for battery powered system compared to power collection can seem strange when it was mentioned above that part of the infrastructure could be excluded. This is explained with the adding of the extra battery needed for powering the vehicles and an increase in number of vehicles. During a lifetime of 60 years the battery mass represent over half of the total mass for a vehicle since the batteries are assumed to be replaced with new ones every second year. This in combination with the large impact from batteries leads to an increased environmental burden during construction. As an example the batteries in scenario *S. Korea, battery* stand for 16 % of the total EP impact but only 1 % of the systems total mass. It should be mentioned that the batteries are not assumed to be recycled; however the small change in the end-life phase indicates that this has an overall small impact.

7.2.2. Building material

For the comparison between the concrete track and the steel track the figures shows that the steel track has an overall lower environmental impact than the concrete track. This is due to the fact that the steel track is lighter than the concrete track. Otherwise, the peer distribution is quite similar for the two systems. The concrete track has however a larger impact during construction, while the steel track has a larger impact during manufacturing. This is because the concrete track is casted at site while the steel track is manufactured and arrives as finished construction parts.

7.2.3. Electricity mix

Comparing South Korean (actually Japanese) electricity mix with certified electricity mix shows the large impact that the choice of electricity generation has for the overall result. The CED for the operation phase (Figure 20) decrease by around 66 % while the environmental impacts for GWP, ODP, AP, EP and POCP during operation (Figure 15 – 19) decrease by over 95 %. An overall decrease of over 40 % could be achieved with just the change of electricity mix for all impact categories except ODP and it differed more than 100 % between the layouts with the largest and the least impact for all impact categories, ODP excluded (see Table 19). The reason for the smaller change in ODP is due to the fact that these impacts mainly occur during the manufacturing and material extraction. ODP is thus not affected by change in the operation phase to the same extent.

Table 19. *Per cent of total impact compared to the Suncheon design, S. Korea, concrete.*

Impact category	S. Korea, concrete	S. Korea, battery	S. Korea, steel	Certified, battery	Certified, concrete	Certified, steel
GWP [%]	100	147	86	67	54	40
ODP [%]	100	134	78	104	83	60
AP [%]	100	155	85	73	53	37
EP [%]	100	163	88	94	60	48
POCP [%]	100	155	92	81	58	49
CED [%]	100	154	91	86	61	52

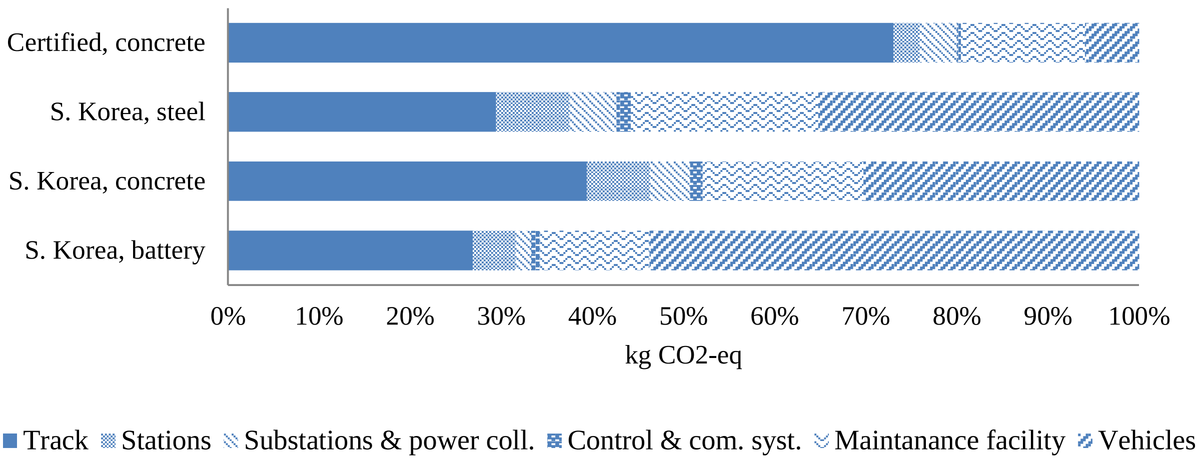

Figure 21. *GWP for different system parts and system layouts for the Suncheon PRT system.*

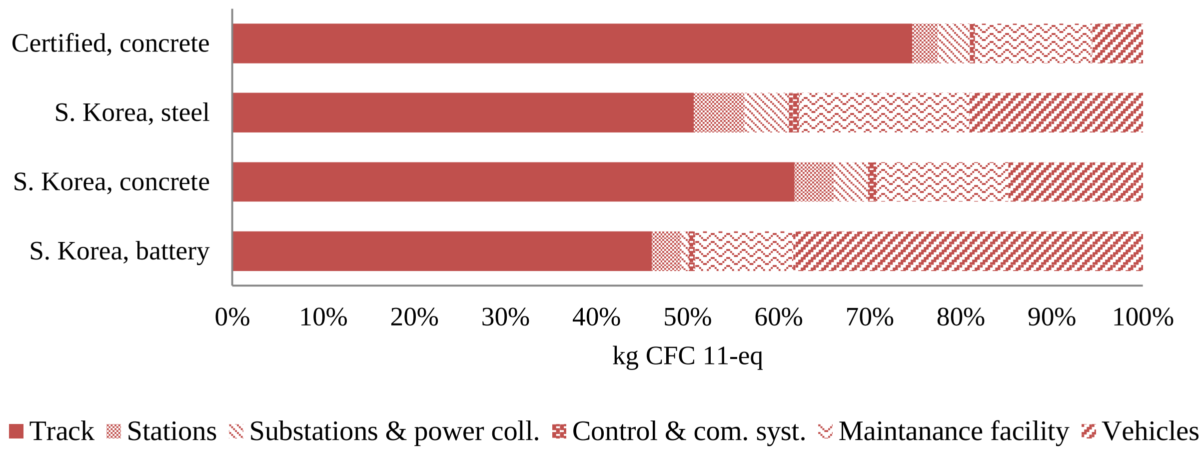

Figure 22. *ODP for different system parts and system layouts for the Suncheon PRT system.*

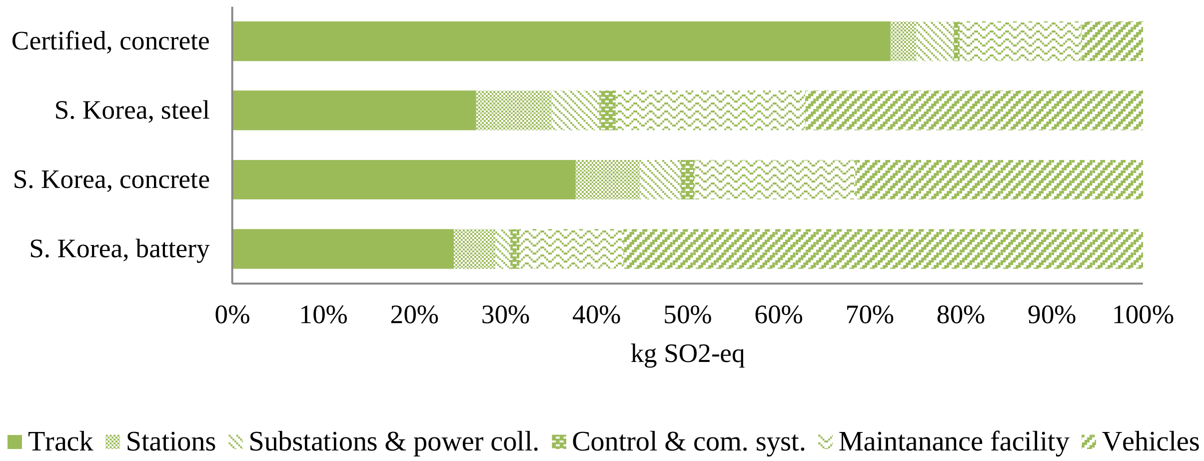

Figure 23. *AP for different system parts and system layouts for the Suncheon PRT system.*

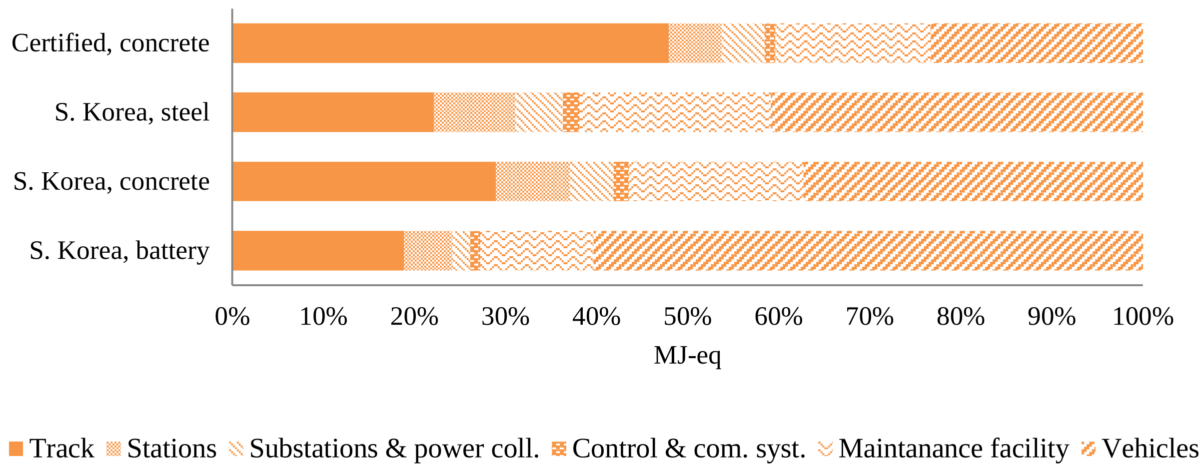

Figure 24. *CED for different system parts and system layouts for the Suncheon PRT system.*

Figures 21 – 24 shows the distribution of the impact for the different parts of the system for four different scenarios. For the scenario with certified electricity the traffics contribution to the impact is under 10 % of the total impact. Comparing the power system for the vehicles, it is shown that for the battery configuration a shift from infrastructure towards traffic dominance occurs for the battery system. This is due to the fact that more vehicles are needed to obtain the same capacity (due to battery recharging) and that part of the infrastructure can be excluded. In this case the number of vehicles had to be significantly increased since the Suncheon system already runs on full capacity (see Appendix A).

7.3. UNCERTANTY ANALYSIS

The robustness of the results for the Suncheon PRT system layout (concrete, power collection and Japanese electricity mix) was examined with both sensitivity and variability analysis which are reported in the following sections.

7.3.1. Sensitivity analysis

A sensitivity analysis was performed to obtain the parameters that contribute the most to the assessment. The analysis was performed for the EcoInvent LCIA-datasets and the system parameters. A change in end-life assumption was also made to see the effect of a chosen methodology.

For the sensitivity analysis for LCIA-data and system parameters, each parameter was increased by 25 % while all other parameters were left unchanged. The change in total impact as a result from the parameter change can be seen in Figures 25 and 26 and more detailed figures are found in Appendix G.

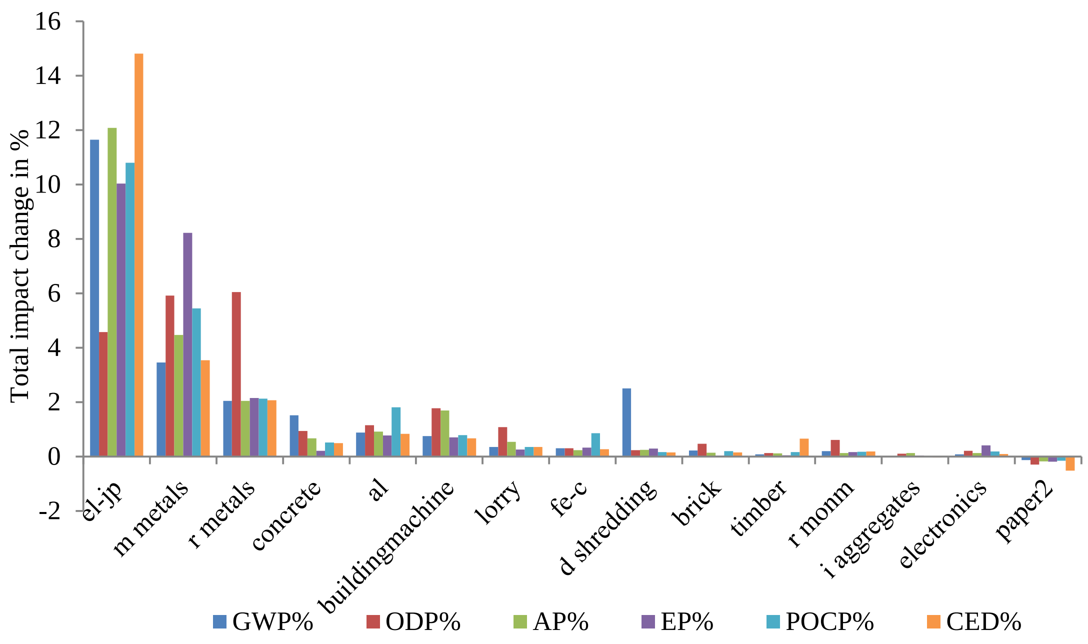

Figure 25. *In-data sensitivity reflected as change of total impact as a result of 25% increase in EcoInvent datasets.*

Figure 25 shows all the top ten contributing datasets for the different impact categories. Abbreviation explanations are found at the end in Appendix B. At top is the *Japanese electricity mix* followed by *manufacturing* and *recycling of metals*. For a dataset to give a large response to the total impact it either needs to occur in large quantities and/or have a relatively large impact per quantity. The electricity mix is used for all electricity consumed during operation and is thus used in large quantities. The same applies to manufacturing and recycling of metals since these are the same for all metals. The dataset *electronics* is an example of a dataset that does not occur in large quantities but instead has a very large impact/kg.

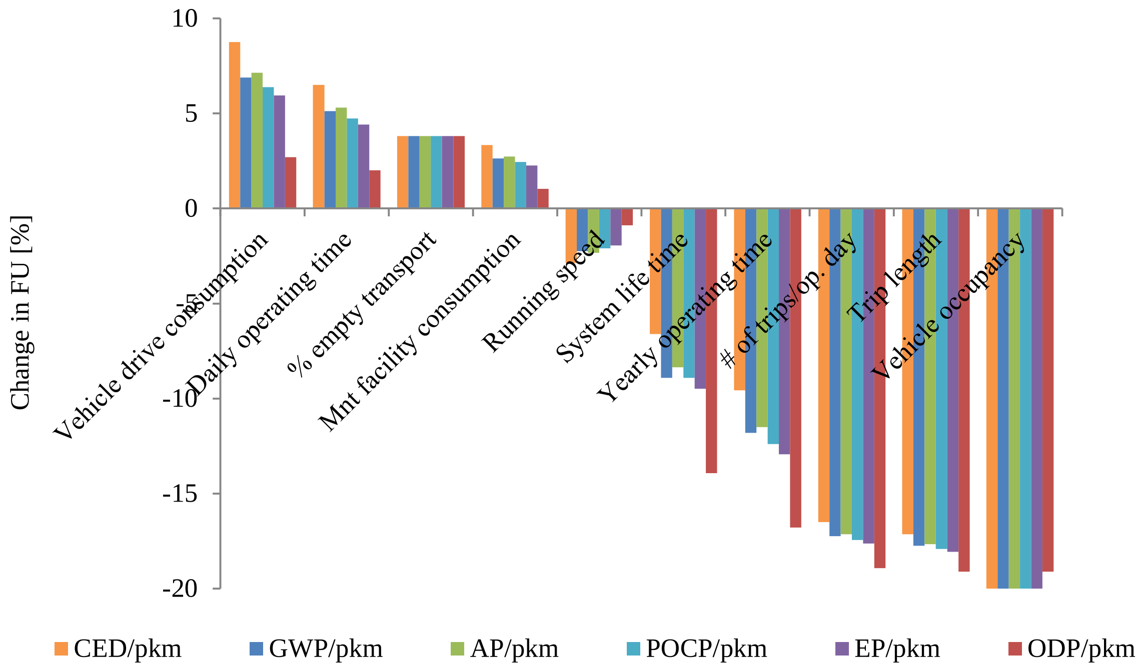

Figure 26. *System parameter sensitivity reflected as change of total impact as a result of 25% increase in system parameters.*

Figure 26 shows the ten LCA system parameters that produce the greatest response to change. The change is expressed for the FU since some of the parameters do not affect the total environmental impact, but instead affects the number of passengers and kilometres travelled. The largest change is obtained for the system parameter *Vehicle occupancy* followed by *Trip length* and *# of trips/op. day*. Increasing these parameters increase the person kilometres travelled and therefor decrease the impact per person kilometre.

With a 25% increase in operating hours, it feels natural that the capacity increases, leading to an increase in the FU and negative impact change. However, this is not the case in the model; instead the number of trips is regulated by *# of trips/op. day*. In this case increased *Daily operating time* only gives increased *Vehicle idle consumption*, the natural thing would be that the *# of trips/op. day* increased as well but this is not the case here. The same applies for *Running speed*; the natural thing would be that an increase in speed would lead to an increase in *Vehicle drive consumption*. This is however not the case in the model since such relationships has not been investigated in this thesis. To understand how the different parameters affect the system, see Appendix A.

For the change in end-life methodology the positive impact (heat and electricity generation at incineration and gain for second grade material at recycling) was set to zero. The result from this change can be seen in Table 20. It shows that the end-life choice of no positive impact for recycling and heat and electricity generation at incineration increased the total impact with about 10 % for all impact categories except for POCP where an increase of 27 % occurred.

Table 20. *Total impact for Suncheon PRT system for two methodological choices, recycling benefits, as used for the results, or not.*

Recycling benefits	GWP [%]	ODP [%]	AP [%]	EP [%]	POCP [%]	MJ [%]
Yes	100	100	100	100	100	100
No	110	111	108	111	127	111

7.3.2. Monte Carlo simulation

To study the models robustness a Monte Carlo simulation was performed. The EcoInvent datasets did not provide any uncertainty information but a variation of ± 25 % was assumed for all datasets. For 2,000 iterations all items in the datasets were randomly and independently varied between 75 % and 125 % and the total impact for each impact category was sampled.

This resulted in a normal distribution (Appendix G, Figures G7 - G12) and the mean value and standard deviation were calculated. From these statistical quantities a 95 % confidence interval was calculated (Appendix G, Table G1). Figure 27 shows, with 95 % confidence, in which interval the total impact can be if all LCIA-datasets were allowed to vary ± 25 %. Observe that the different impact categories are scaled.

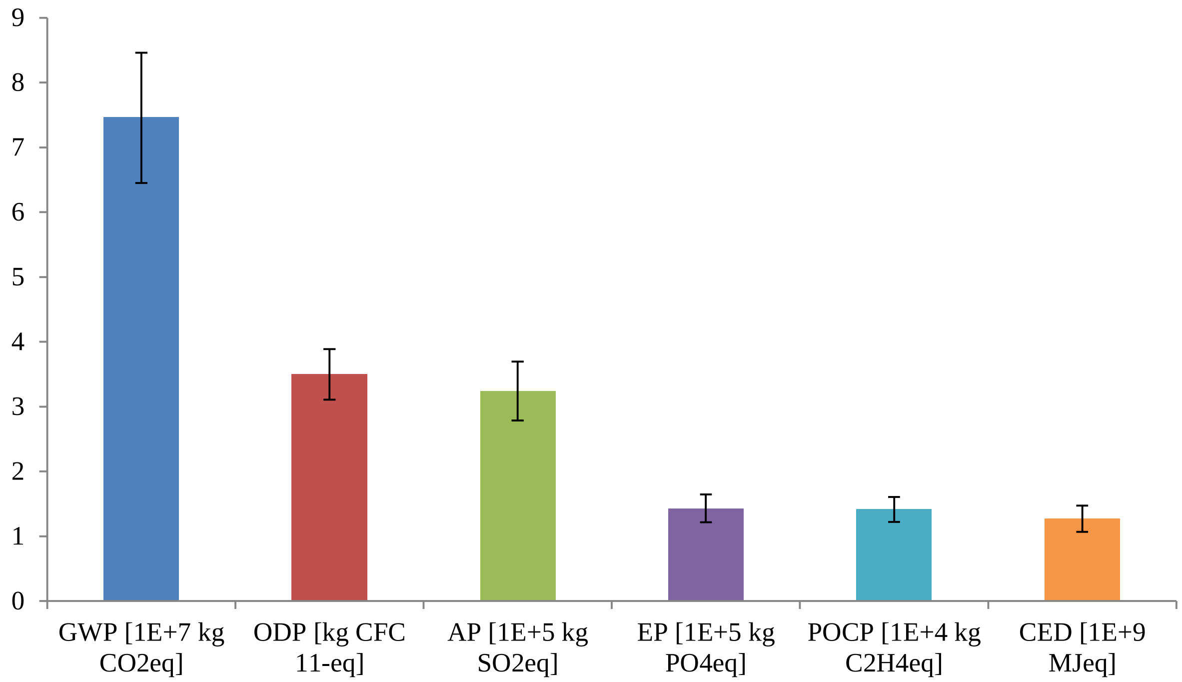

Figure 27. *Total impact for Suncheon PRT system with error bars showing 95 % confidence interval. Note that the different impact categories are scaled.*

8. DISCUSSION

8.1. OVERALL IMPACT

For the Suncheon PRT system the results show that the track stands for the single largest environmental impact among the different subsystems followed by the vehicles. However the phase in which the impact occurs differs between the two. The impact of the track comes almost exclusively from the construction phase while the vehicles, with negligible mass compared to the complete system, causes impact during the operation phase.

This leads to a quite even impact distribution between the construction phase and the operation phase for the total system. The end life phase has a small contribution in comparison and this is due to recycling benefits and heat and electricity generation during incineration. It was shown that if the recycling benefits would not have been included the overall impact would increase with around 10 %.

8.2. IMPACT OF DIFFERENT TRACK MATERIALS

Choosing a track that is made of steel lowers the overall mass of the construction and also the overall environmental impact compared to a track made out of concrete. A decrease of 8 % - 22 % was achieved depending on impact category. The largest reduction was for ODP due to less material acquisition and manufacturing. The peer distribution for the impact was shown to be quite similar for the two constructions but the steel track had larger impact fraction of manufacturing and less impact during construction. It would not be too far-fetched to assume that less construction work at site would lead to fewer impacts in form of noise, traffic obstacles and other disturbances which are usually unaccounted for and would favour the steel track further if accounted.

The concrete track model was based on the Suncheon track which is constructed as a double track. The assumption was made that a single track would have half the mass of a double track which may underestimate the impact. This does however not affect the Suncheon scenario. The steel track model is based on the test track which has a lower elevation height. However the steel pillars are quite small in relation to the rest of the track so the difference is negligible. For example twice the elevation would lead to an increase of under one per cent of total track weight.

8.3. IMPACT OF DIFFERENT POWER SYSTEMS FOR THE VEHICLES

The model shows that the power collection is the preferred choice of power system from an environmental viewpoint. This is due to the large number of vehicles that is needed to obtain the passenger capacity for the battery layout and the short lifetime of the extra batteries. The exclusion of recycling of the batteries has also a small contribution to the large impact. The choice of power collection as power system in Suncheon was done to reduce the cost and it is enjoyable to see that economic and environmental reasons correlate.

The comparison between the power systems for the Suncheon PRT system may be seen as an extreme scenario since the vehicle trip capacity already was maximized. Other system configurations may occur where the difference in power system impacts are not as large.

8.4. IMPACT OF DIFFERENT ELECTRICITY MIXES

The choice of electricity mix has a large effect on the impacts caused during the operation phase; in which the major part of the electricity for the life cycle was consumed. The different impacts originate from the sources of electricity generation (see Appendix F for examples). The impact from the operation phase is thus very dependent on geography, i.e. in which country the system is located. A way to circumvent the geography dependence is to use certified electricity mix. By using certified electricity mix at the Suncheon PRT system a reduction of over 95 % is possible for GWP, ODP, AP, EP and POCP for the operation phase and an overall decrease of over 40 % (ODP excluded) can be achieved.

8.5. PRT COMPARED TO OTHER SYSTEMS

To see how the Vectus PRT system compares to other transportation means the total impact shown in Chapter 7 was divided with the total pkm performed during the lifetime. This gives the functional unit (FU) and can be used when comparing the results with results from the studies mentioned in Chapter 5.2. This can be seen in Figure 28 – 30. The staple named *Vectus (peak)* is to show the systems impact if running on full capacity.

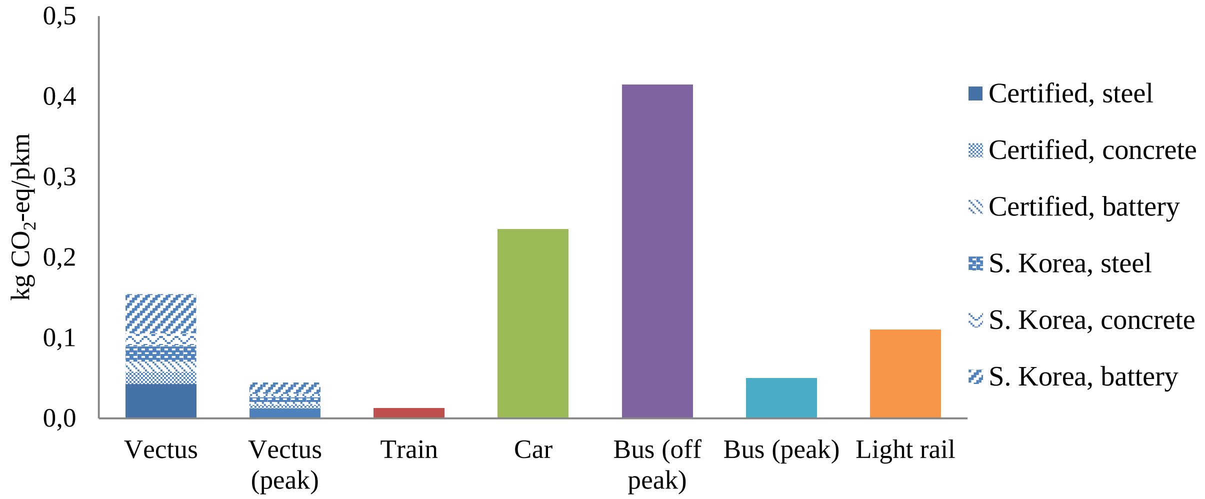

Figure 28. *Total Suncheon system GWP per pkm for different system layouts compared to other means of transportation.*

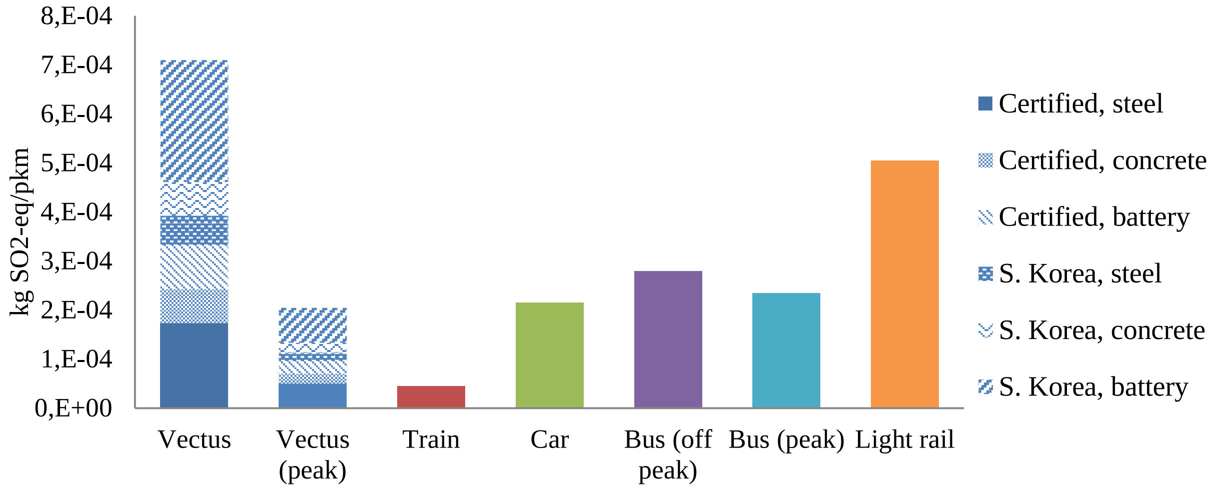

Figure 29. *Total Suncheon system AP per pkm for different system layouts compared to other means of transportation.*

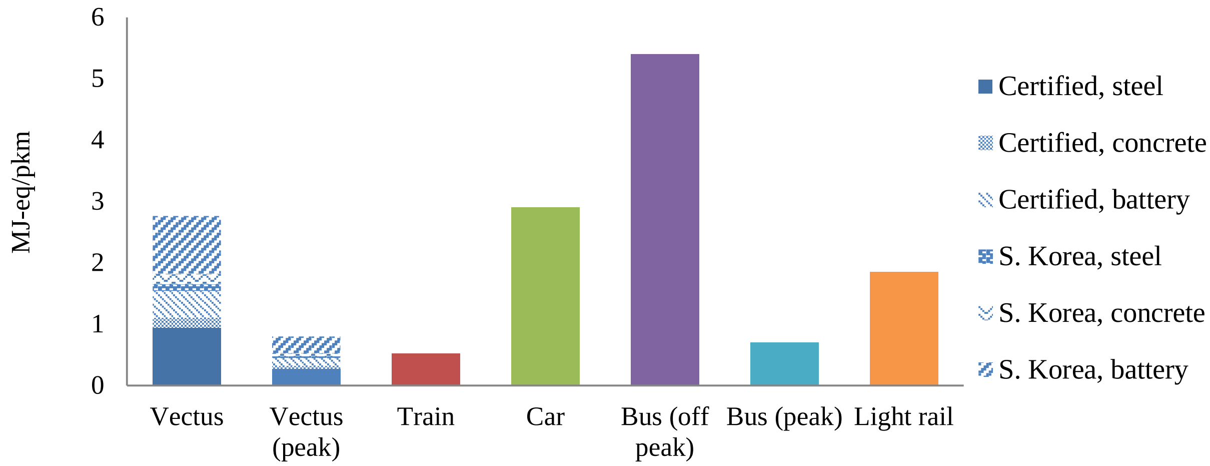

Figure 30. *Total Suncheon system CED per pkm for different system layouts compared to other means of transportation.*

The impact from the Suncheon PRT system (S. Korea, concrete) corresponds very well with the impact from Light rail (Figure 28 – 30), which also is the most similar means of transportation in terms of infrastructure. Light rail systems are however constructed at ground and this indicates that it is possible to construct elevated PRT systems with the same overall impact as other transport systems at ground. The low GWP (Figure 28) and high AP (Figure 29) are due to the fact that the vehicles are electrically powered.

It should be mentioned that the comparing studies have made some other assumptions and used different system boundaries than this thesis. The impact for train, which is based on the study of the Bothnia line by Stripple and Uppenberg (2010), are based on a certified electricity mix based almost exclusively on hydropower. This is reflected in the low impact for this means of transport. The study also uses reinvestment instead of dismantling for the infrastructure. How this difference in end-life assumption would affect the comparison is hard to tell. The study for car, bus and light rail, Chester and Horvath (2009), does not include the end-life phase. Since the end-life impact for the Suncheon system stood for about 12 % of total impact for GWP, 5 % for AP and 1 % for CED (Figure 13) a slight increase in the impact of these means of transportation could be assumed. This is however not shown in the figures above.

By constructing the Suncheon PRT system a modal shift from bus and car to PRT occurs at the wetlands. If assuming that the bus loads arriving to the Suncheon wetlands are crowded, i.e. buses at peak capacity, the impact should roughly estimated lay between *Car* and *Bus (peak)*. By studying Figure 28 and 29 we can see that the GWP would be on the same, or even a bit lower, level while the AP would increase after the construction of the PRT system. However, the overall impacts would not occur at the wetlands so the environmental purpose of the PRT is fulfilled. Furthermore, there is great potential to reduce impacts during operation by choosing renewable power sources. This would not be possible to the same degree for gasoline powered vehicles.

When comparing Suncheon PRT infrastructure to PRT traffic the infrastructure stood for the largest part of the system impact; 70 % of GWP and 62 % of cumulative energy demand. Chester & Horvath (2009) showed that infrastructure stood for about 39 % of greenhouse gas emissions and energy inputs for onroad traffic and 61 % for rail bound systems. The high impact from infrastructure for the Suncheon system is probably due to the fact that these structures are exclusive for the PRT system. Roads are available for all type of vehicles and services; cars, busses, lorries etc. and railways are used by different companies and for both passenger and goods transportation. When calculating impact for these means of transportation using LCA the infrastructure impact is allocated among these different users. This is not the case for the Vectus infrastructure since it is exclusive to passenger transportation. To lower the impact it is important to maximize the capacity of the system, either by increasing the passenger transportation (as illustrated by *Vectus (peak)* in Figure 28 – 30) or by using the infrastructure for other suitable applications.

PRT is a very complex system to analyse and thus a structured methodology, such as LCA, was needed. By using the LCA methodology the infrastructure could be identified as the largest contributor, a conclusion that would not have been possible for conventional tail-pipe emission comparison. Still there is a difficulty in comparing different LCA studies which is derived from the various assumptions and limitations made in each analysis. A way to improve the comparability is by using the PCR guide lines. This however, requires that the different means of transportation compared to each other are in the same product category which is not always the case. But LCA still gives a more just and holistic view of the impact compared to only consider vehicle operation.

8.6. OPPORTUNITIES FOR IMPROVEMENT

It has been shown above that by choosing right materials and system solutions and by using a clean electricity mix the environmental impact can be significantly reduced. By increasing the vehicle occupancy (Chapter 7.3.1) an even more efficient transport system is obtained and this is something that should be encouraged.

The number of vehicle trips per day per vehicle had a significant influence on the total impact per FU. This is due to the fact that the vehicles consume power when idling. It is therefore important to streamline the system by reducing the number of vehicles so that the remaining vehicles run at full capacity. This is however hard to accomplish since the transport demand varies over the day and year. A way to overcome this problem would be to have larger vehicles (GRT vehicles) available at peak hours. Another way to reduce the impact would be to try to decrease the vehicle idle consumption.

As mentioned above, the impact from infrastructure is quite large due to its exclusiveness to PRT. By using the infrastructure for other purposes than passenger transport, e.g. allowing goods transport during off peaks or building in other infrastructure, such as power lines or water pipes in the track, the impact from the infrastructure may be lowered.

The passenger stations described in the model are independent stations which are quite large in size. For systems in dense urban areas scenarios where the small stations are not larger than a bus stop or built in to existing buildings and large stations are shared with other means of transportation may occur which leads to a lower impact from infrastructure.

The importance of recycling and proper waste handling was shown in Table 20. A decrease of around 10 % of total impact for all impact categories was a result of recycling benefits and heat and waste generation. Hence it is very important to consider materials that can be recycled during the design phase and to always have this in thought. A dismantling and recycling guide for the different system parts would be a good way to increase the recycling ratio at the end-life. This is something that Vectus should establish.

Some other interesting observations that emerged from the analysis was that the steel track actually consist of more concrete than steel since the weight of foundations are larger than the actual track and that, when using the dataset *multi-storey concrete building* for the maintenance facility, the 4.5 km double concrete track in Suncheon is equivalent in weight to five and a half 5-storey apartment buildings of size 20 m x 45 m each.

8.7. ERROR SOURCES

As with all models the Vectus LCA cannot fully describe the reality. Many assumptions have been made and generic data have been used to describe the environmental impact that various materials and processes used during a PRT systems lifetime causes. Different levels of detail have been available for the subsystems; from the steel track where every screw nut could be counted to the concrete track where only total concrete and steel weights were available. However, the inventory phase can be extremely detailed and the end result may still be quite uncertain. This is because generic LCIA data are used. As an example the EcoInvent dataset *fleece, polyethylene, at plant* which is used as second grade material for all polymers in the model uses data from one Swiss company which are represented as the European average.

But the models generality was also an aim with the thesis. How the infrastructure is built is very site specific, and a too great level of detail would pull the model away from that goal.

The vehicles however are the same regardless of location and the level of detail was also greater for this sub model.

A large error source could be the use of Japanese electricity mix instead of South Korean since the electricity use is such a large part of the systems life cycle. In the next version of EcoInvent such dataset is available and is something that should be corrected then. Key datasets for material and processes (as shown if Figure 25) should also be validated when main sub suppliers are decided on.

All data in the model are based on current conditions and technologies and no consideration has been taken to future conditions. The overall impact would probably be smaller if the trends of today with environmental thinking and increase in renewable resources continue. However, to interpolate these for the 60 year life span of the system is associated with very substantial uncertainties and not preferred.

Some of the model assumptions and methodologies used for the LCA can also reflect the overall result. The choice of including recycling benefits lead to a lower impact for the end-life phase and the choice of including spare parts for the system under construction lead to larger impact for this phase and a lower impact of the operation phase. Another way to divide the different phases could have been to make an *operation & maintenance* phase. There was however no time to investigate that.

8.8. UNCERTANTY ANALYSIS

The sensitivity analysis for the model shows the datasets and parameters that are most sensitive to change. This means that the datasets and system parameters shown in Figure 25 and 26 are the items that need the highest accuracy to produce a good result for the LCA. When the Suncheon PRT system is operational these items should be evaluated and the datasets corrected if necessary. The same applies for other system that uses the model to identify environmental impacts, but then a new sensitivity analysis has to be made for that specific system configuration.

On the other hand one can see it the other way around. Since changes for these items produce the largest change in environmental impact these parameters or processes are the once to focus on in order to reduce the environmental impact.

The Monte Carlo simulation gives the mathematical/statistical uncertainties and does not reflect uncertainties from assumptions in the model. From Figure 27 it is shown that the confidence interval falls in the range of around ± 10 % of the original result. For the simulation the uncertainties added to the datasets was assumed to be ± 25 %. Are these uncertainties high or low, i.e. are the uncertainties shown in Figure 27 the maximal uncertainties or is it possible that they can be larger? If consulting Figure 25 where the datasets most sensitive to change are listed we can see that the electricity mix is in the top. The uncertainty of this dataset is very low. The metal manufacturing dataset is based on several local to global sized companies and the concrete dataset is based on six Swiss and 11

German plants. For metals, however, it can be a big difference between different metal mixes in terms of their environmental impact. Therefore the recycling of metals probably comes with a great uncertainty. Overall this indicates that the uncertainties chosen should be well sufficient, with reservations for the metals. This means that the variation in system layouts presented in Chapter 7.2 is statistically significant with the chance of exceptions for some environmental impact in the steel track compared to concrete track scenario. It also shows that the difference in environmental impact between PRT and other means of transportation (Figure 28 – 30) are statistically significant, assumed that the other studies results are "exact".

9. CONCLUSIONS AND FURTHER RECOMMENDATIONS

For the Suncheon PRT system the track was identified as the largest contributor to the environmental impact followed by the vehicles. These impacts occur at different phases of the life cycle, the tracks during construction due to its substantial mass and vehicles during operation due to the energy demand.

The steel track and the concrete track consist mainly of the same materials but the steel track has a lower overall mass due to its light structure and hence a lower environmental impact compared to the concrete track. The steel track has less impact at the construction site since it is manufactured in factory.

By using a certified electricity mix the operation phase impact could be reduced by over 95 % for most of the impact categories studied. Changing the electricity mix during operation is the single most efficient way to affect the overall environmental impact of the system.

Using power collection instead of batteries for the vehicle power system is the best alternative from an environmental viewpoint. This because the batteries has to be replaced with new ones every second year and charging time leads to an increase in number of vehicles to maintain the passenger capacity.

By combining these configurations for the Suncheon PRT system the total environmental impact can be lowered by about 50 % for most of the impact categories studied.

The Suncheon PRT system has roughly the same impact as light rail systems and this indicates that it is possible to construct elevated PRT system with the same overall impact as for corresponding systems at ground. PRT has a high proportion of infrastructure relative to traffic and by integrating other infrastructure into the track or by sharing stations with other means of transportation the environmental impact can be reduced further.

By constructing the PRT system at Suncheon a modal shift from busses and cars in favour for PRT takes place. This will lead to a slight decrease in emissions of greenhouse gases but an increase of acidifying substances. However, during operation minimal emissions will occur at the Suncheon wetlands thus fulfilling the purpose of the PRT. There is also a large potential to substantially lower the impacts by choosing a renewable energy source, an alternative that is not available for gasoline driven vehicles to the same extent. Today it is easier to convert the electrical system than the transport system to renewable resources.

In a broader context, it is important to consider how the PRT system is applied. How passenger patterns and mode changes affects the environmental impact. As mentioned before PRT seeks to combine the individuality and flexibility of the car and the environmental benefits and safety of rail transport. If it is introduced to reduce car traffic or to replace existing public transport affect the impact in a consequential life cycle perspective. How the introductions of PRT affect the travel pattern and logistics for passengers and how track network structures affect the traveling patterns is something that should be investigated in future studies.

When the Suncheon PRT system has been in operation for some time the LCA model should be evaluated and corrected. The introduction of GRT vehicles into the PRT system would make the vehicle capacity more efficient and lower the overall impact per FU. This is something that should be investigated in future studies.

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10.2. PERSONAL COMMUNICATION

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APPENDIX A. SYSTEM CONFIGURATION

Following PRT system configurations was used for the different scenarios used in the LCA.

Table A1. *PRT system layouts.*

Parameter	**Parameter abbreviation**	Suncheon, power collection **Input**	Suncheon, battery **Input**
PRT location		S. Korea	S. Korea
Track material		Concrete/Steel	Concrete/Steel
Vehicle power system		Power collection	Battery
Track length [km]		9	9
L. passengers station		2	2
S. passengers station		0	0
Maintenance facility		1	1
Vehicles [# of]	NV	40	124
Sub/charging stations		3	3
Vehicle capacity [# people]	VC	9	9
Average vehicle occupancy [# people]	AVO	2.6	2.6
Empty transports [%]	ET	12.8	12.8
Average running speed [km/h]	ARS	40	40
Average trip distance [km]	ATD	4.5	4.5
Length of each station stop [s]	SST	45	45
Average stops/trip [# of]	NSS	2	2
Planned trips/op. day [# of]	NT	80	26
Mnt. during op. hours. [hours]	MNT	3	3
Daily op. time [hours]	OH	14	14
Yearly op. time [days]	OD	360	360
System lifetime [years]		60	60
Vehicle drive consumption [kW]	VDC	4	4
Vehicle idle consumption [kW]	VIC	2	2
Average substation consumption [kW]	SC	2	2
Average mnt.facility consumption [kW]	MNTC	28	28
Average L. station consumption [kW]	LSC	10	10
Average S. station consumption [kW]	SSC	2	2
Parameter		**Output**	**Output**
Max transportation per year [passenger/year]		9,040,896	9,108,703
Average capacity [passenger/hour]		518	522
Peak hour capacity [passenger/hour]		1,794	1,807
Vehicle trips/year [# of]		1,152,000	1,160,640
# passenger trips/year		2,611,814	2,631,403
# passenger km/year		11,753,165	11,841,314
Max passenger km/year		40,684,032	40,989,162
Effective average speed [km/h]		33	33
Average trip time (incl. stop) [hours]		0.14	0.14
Max # vehicle trips/op. day [trips/day/vehicle]		80	26
Vehicle running hours [hours/day]		11.0	3.6
Vehicle idle hours [hours/day]		0.0	7.4
Vehicle off hours [hours/day]		13	13
Yearly vehicle energy demand [kWh/year]		15,840	11,543
Yearly substation consumption [kWh]		17,520	17,520
Yearly mnt. facility energy demand [kWh]		2,41,920	241,920
Yearly L. station energy demand [kWh]		62,800	62,800
Yearly S. station energy demand [kWh]		12,560	12,560

Table A2. *End of life handling.*

Material group	Recycling [%]	Incineration [%]	Landfill [%]
Metals	80	0	20
Polymers	50	25	25
Elastomers	50	25	25
Glass	50	0	50
Fluids	0	100	0
MONM	50	25	25
Aggregates	0	20	80
Others	0	50	50

The output parameters shown in Table A1 are calculated from the following equations. Parameter abbreviations are also available in Table A1.

System capacity parameters:

$$Max\ transportation\ per\ year = Max\ vehicle\ trips\ per\ op.day * OD * VC * NV * (1 - \frac{ET}{100})$$

$$Average\ capacity = NT * \frac{AVO}{OH} * NV * (1 - \frac{ET}{100})$$

$$Peak\ hour\ capacity = Max\ vehicle\ trips\ per\ op.day * \frac{VC}{OH} * NV * (1 - \frac{ET}{100})$$

$$Vehicle\ trips\ per\ year = NT * NV * OD$$

$$Passengers\ per\ year = Vehicle\ trips\ per\ year * AVO * (1 - \frac{ET}{100})$$

$$Passenger\ km\ per\ year = Passengers\ per\ year * ATL$$

Vehicle operation parameters:

$$Average\ trip\ time = \frac{ATD}{ARS} + NSS * \frac{SST}{3600}$$

$$Effective\ avarage\ speed = \frac{ATL}{Average\ trip\ time}$$

$$Max\ vehicle\ trips\ per\ op.day\ (power\ collection) = \frac{OH - MNT}{Average\ trip\ time}$$

$$Max\ vehcile\ trips\ per\ op.day\ (battery) = \frac{OH - MNT}{3 * Average\ trip\ time}$$

$$Running\ hours = NT * Average\ trip\ time$$

$$Idle\ hour = OH - MNT - Running\ hours$$

$$Vehicle\ off\ hours = 24 - OH + MNT$$

Energy demand parameters:

$$Vehicle\ energy\ demand\ per\ year = (VDC * Running\ hours + VIC * Idle\ hours) * OD$$

$$Substation\ energy\ demand\ per\ year = SC * 24 * 365$$

$$Maintenance\ facility\ energy\ denabd\ per\ year = MNTC * 24 * OD$$

$$Large\ station\ energy\ demand\ per\ year = LSC * (OH * OD + \frac{(24 - OH) * OD}{3} + \frac{(365 - OD) * 24}{3})$$

$$Small\ station\ energy\ demand\ per\ year = SSC * (OH * OD + \frac{(24 - OH) * OD}{3} + \frac{(365 - OD) * 24}{3})$$

APPENDIX B. LCIA RESULTS

The following figures show the LCIA results for the remaining impact categories described in Chapter 7.2.

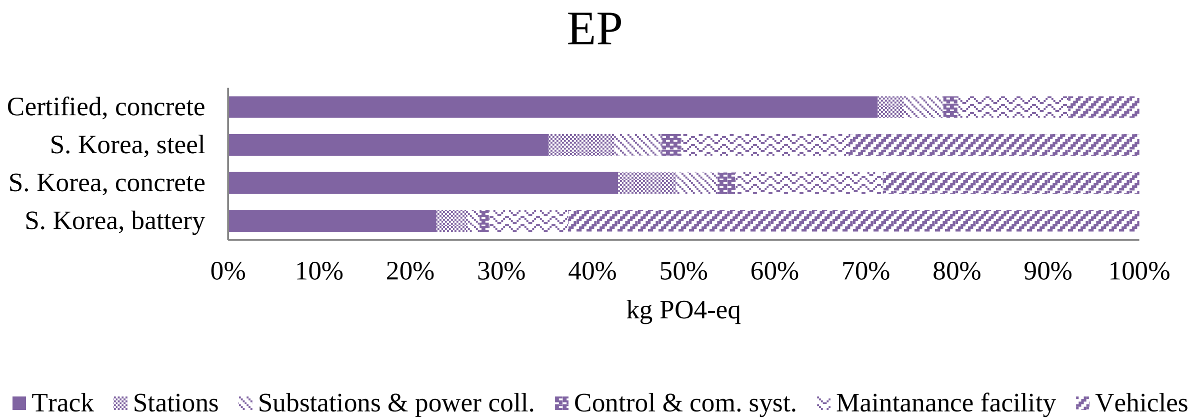

Figure B1. *EP for different system parts and system layouts for the Suncheon PRT system.*

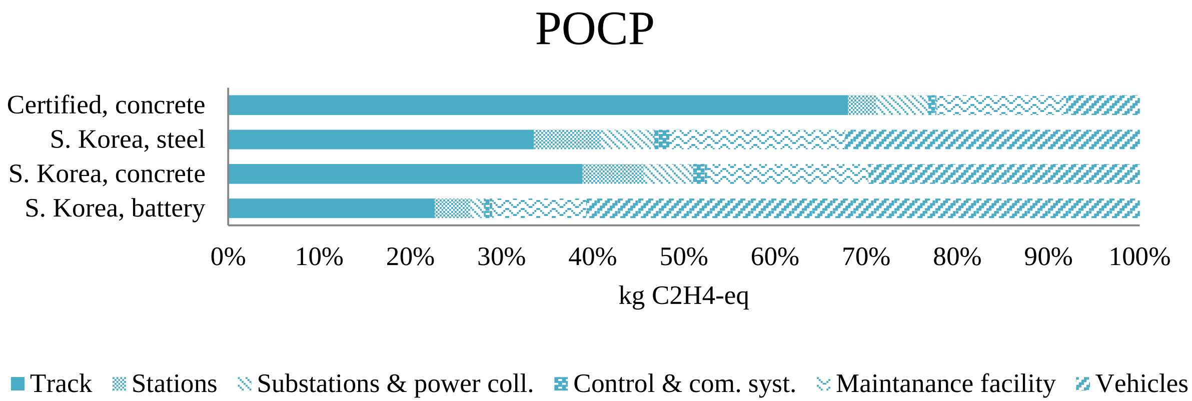

Figure B2. *POCP for different system parts and system layouts for the Suncheon PRT system.*

The following tables show the material composition, tonne-km and LCIA-results for the different subsystems. In the end is a list of abbreviations used for the different data-sets used.

Table B1. *Track Concrete subsystem overview [based on 1 km Suncheon track]*.

Foundation summary		Material	Total weight [kg]	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	concrete	1,637,440	**GWP**	348,069	211,190	18,250	5,77,509
lorry	133,030	fe-c	112,960	**ODP**	1E-02	2E-02	3E-03	3E-02
ship	0	N/A	0	**AP**	923	1,186	121	2,230
air	0	N/A	0	**EP**	401	964	25	1,390
		N/A	0	**POCP**	103	63	3	170
		N/A	0	**MJ**	3,620,024	3,688,547	314,293	7,622,864

Guidway summary		Material	Total weight [kg]	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	concrete	2,508,520	**GWP**	898,842	738,009	31,117	1,667,968
lorry	226,818	fe-c	392,597	**ODP**	4E-02	6E-02	5E-03	1E-01
ship	0	hdpe	3,672	**AP**	2,766	4,141	206	7,113
air	0	timber	62,832	**EP**	1,361	3,361	43	4,766
		plywood	16,830	**POCP**	351	220	6	577
		N/A	0	**MJ**	13,987,979	12,924,806	535,873	27,448,658

Construction work summary		Work type	Amount	LCI results	buildingmachine	Transportation	Total
Transport	**Tonne-km**	buildingmachine	751,740	**GWP**	249,109	0	249,109
lorry	0	N/A	0	**ODP**	3E-02	0E+00	0
ship	0	N/A	0	**AP**	2,417	0	2,417
air	0	N/A		**EP**	443	0	443
		N/A		**POCP**	49	0	49
		N/A		**MJ**	3,740,182	0	3,740,182

Table B1. *Track Concrete subsystem overview [based on 1 km Suncheon track] (continued).*

Dismantling and recycling		Material	Total weight	LCI results	Dismantling	Recycling	Incineration	Landfill	Total
Transport	**Tonne-km**	Metals	505,557	**GWP**	712,082	-23,093	-7,702	51,673	732,960
lorry	359,849	Polymers	3,672	**ODP**	0	0	0	0	0
		Elastomers	0	**AP**	817	347	161	185	1,511
		Glass	0	**EP**	250	-126	25	51	201
Distance to [km]:		Fluids	0	**POCP**	22	-217	-1	12	-185
Recycling	76	MONM	79,662	**MJ**	1,844,261	-831,419	-280,407	687,777	1,420,212
Incineration	76	Aggregates	4,145,960						
Landfill	76	Others	0						

Table B2. *Track Steel System overview [1 km of track].*

Foundation summary		Material	Total weight	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	concrete	112,455	**GWP**	69,213	37,427	2,610	109,249
lorry	19,022	fe-c	17,719	**ODP**	0	0	0	0
ship	0	gravel	89,985	**AP**	257	206	17	481
air	0	psfoam	3,938	**EP**	95	164	4	263
		plywood	8,316	**POCP**	47	11	0	58
		timber	17,875	**MJ**	2,013,472	691,293	44,940	2,749,705

Guidway summary		Material	Total weight [kg]	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	fe-c	133,333	**GWP**	217,157	253,958	11,323	482,438
lorry	72,552	epdm	1,272	**ODP**	0	0	0	0
ship	127,434	epoxy	1,317	**AP**	776	1,422	96	2,295
air	0	pur	1,695	**EP**	449	1,152	17	1,618
		N/A	0	**POCP**	114	75	3	192
		N/A	0	**MJ**	3,549,412	4,476,439	193,031	8,218,881

Table B2. *Track Steel System overview [1 km of track] (continued).*

Construction work summary		Work type	Amount	LCI results	buildingmachine	Transportation	Total
Transport	**Tonne-km**	buildingmachine	31,600	**GWP**	10,503	137	10,640
lorry	1,000	Welding	200	**ODP**	0	0	0
ship	0	N/A		**AP**	102	1	103
air	0	N/A		**EP**	19	0	19
		N/A		**POCP**	2	0	2
		N/A		**MJ**	157,645	2,363	160,008

O&M summary		Service	Amount	LCI results	Service	Transportation	Total
Transport	**Tonne-km**	Welding	100	**GWP**	16	0	16
lorry		pur	0	**ODP**	0	0	0
ship		epoxy	0	**AP**	0	0	0
air		N/A		**EP**	0	0	0
		N/A		**POCP**	0	0	0
		N/A		**MJ**	212	0	212

Dismantling and recycling		Material	Total weight	LCI results	Dismantling	Recycling	Incineration	Landfill	Total
Transport	**Tonne-km**	Metals	151,052	**GWP**	206,544	3,189	3,039	10,501	223,274
lorry	29,481	Polymers	6,950	**ODP**	0	0	0	0	0
		Elastomers	1,272	**AP**	121	153	9	12	294
		Glass	0	**EP**	52	11	2	7	72
Distance to [km]:		Fluids	0	**POCP**	3	-64	0	2	-59
Recycling	76	MONM	26,191	**MJ**	289,410	-220,577	-56,497	41,827	54,163
Incineration	76	Aggregates	202,440						
Landfill	76	Others	0						

Table B3. *Large Station System overview [1 station].*

Building summary		Material	Total weight	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	fe-c	31,852	**GWP**	283,913	103,470	1,986	389,369
lorry	14,479	concrete	306,055	**ODP**	0	0	0	0
ship	0	brick	234,511	**AP**	1,376	581	13	1,970
air	0	cement	81,418	**EP**	488	467	3	957
		glasscoated	4,066	**POCP**	96	31	0	128
		timber	40,709	**MJ**	5,674,625	1,820,504	34,206	7,529,336
		al	11,194					
		cu	11,194					
		rockwool	1,716					
		pvc	1,214					

Service utilities summary		Material	Total weight [kg]	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	electronics	542	**GWP**	14,164	5,771	6	19,941
lorry	46	fe-c	60	**ODP**	0	0	0	0
ship	0	ps	6	**AP**	97	50	0	147
air	0	N/A	0	**EP**	135	25	0	161
		N/A	0	**POCP**	6	2	0	8
		N/A	0	**MJ**	252,617	67,614	109	320,341
		N/A	0					

Construction summary		Work type	Amount	LCI results	buildingmachine	Transportation	Total
Transport	**Tonne-km**	buildingmachine	1,833	**GWP**	822	137	959
lorry	1,000	el-jp	396	**ODP**	0	0	0
ship	0	N/A		**AP**	7	1	8
air	0	N/A		**EP**	1	0	2
		N/A		**POCP**	0	0	0
		N/A		**MJ**	13,760	2,363	16,123

Table B3. *Large Station System overview [1 station] (continued).*

O&M summary		Service	Amount	LCI results	Service	Energy use	Transportation	Total
Transport	**Tonne-km**	Welding	0	**GWP**	0	407,419	0	407,419
lorry		pur	0	**ODP**	0	0	0	0
ship		epoxy	0	**AP**	0	1,834	0	1,834
air		N/A		**EP**	0	673	0	673
		N/A		**POCP**	0	72	0	72
		el-jp	753,600	**MJ**	0	8,827,270	0	8,827,270

Dismantling and recycling		Material	Total weight	LCI results	Dismantling	Recycling	Incineration	Landfill	Total
Transport	**Tonne-km**	Metals	54,299	**GWP**	119,995	7,929	-765	17,877	145,035
lorry	54,291	Polymers	1,220	**ODP**	0	0	0	0	0
		Elastomers	0	**AP**	128	36	31	30	226
		Glass	4,066	**EP**	40	-4	6	14	56
Distance to [km]:		Fluids	0	**POCP**	3	-23	0	4	-15
Recycling	76	MONM	40,709	**MJ**	290,797	-480,698	-73,089	106,765	-156,225
Incineration	76	Aggregates	623,700						
Landfill	76	Others	542						

Table B4. *Small Station System overview [1 station].*

Building summary	
Transport	**Tonne-km**
lorry	1,031
ship	0
air	0

Material	Total weight
fe-c	3,931
concrete	2,657
plywood	1,799
rockwool	258
psfoam	30
osb	74
gravel	2,543
glassdouble	612
fe-cr	1,498
epdm	68
ps	22
timberlami	69

LCI results	Material	Manufacturing	Transportation	Total
GWP	16,791	10,393	141	27,325
ODP	0	0	0	0
AP	79	58	1	139
EP	32	47	0	79
POCP	7	3	0	10
MJ	361,472	182,920	2,435	546,827

Service utilities summary	
Transport	**Tonne-km**
lorry	46
ship	0
air	0

Material	Total weight [kg]
electronics	542
fe-c	60
ps	6
N/A	0
N/A	0
N/A	0
N/A	0

LCI results	Material	Manufacturing	Transportation	Total
GWP	14,164	5,771	6	19,941
ODP	0	0	0	0
AP	97	50	0	147
EP	135	25	0	161
POCP	6	2	0	8
MJ	252,617	67,614	109	320,341

Table B4. *Small Station System overview [1 station] (continued).*

Construction summary		**Work type**	**Amount**	**LCI results**	**Excavation**	**Transportation**	**Total**
Transport	**Tonne-km**	Excavation	200	**GWP**	1,196	0	1,196
lorry	0	Welding	200	**ODP**	0	0	0
ship	0	Buildingmachine	3,192	**AP**	11	0	11
air	0	N/A		**EP**	2	0	2
		N/A		**POCP**	0	0	0
		N/A		**MJ**	17,918	0	17,918

O&M summary		**Service**	**Amount**	**LCI results**	**Service**	**Energy use**	**Transportation**	**Total**
Transport	**Tonne-km**	Welding	0	**GWP**	0	407,419	0	407,419
lorry		pur	0	**ODP**	0	0	0	0
ship		epoxy	0	**AP**	0	1,834	0	1,834
air		N/A		**EP**	0	673	0	673
		N/A		**POCP**	0	72	0	72
		el-jp	753,600	**MJ**	0	8,827,270	0	882,7270

Dismantling and recycling		**Material**	**Total weight [kg]**	**LCI results**	**Dismantling**	**Recycling**	**Incineration**	**Landfill**	**Total**
Transport	**Tonne-km**	Metals	5,489	**GWP**	9,186	646	923	1,000	11,755
lorry	1,040	Polymers	58	**ODP**	0	0	0	0	0
		Elastomers	68	**AP**	5	6	1	1	13
		Glass	612	**EP**	2	0	0	1	3
Distance to [km]:		Fluids	0	**POCP**	0	-2	0	0	-2
Recycling	76	MONM	1,941	**MJ**	12,039	-14,330	-1,430	1,786	-1,935
Incineration	76	Aggregates	5,458						
Landfill	76	Others	542						

Table B5. *Substation & power collection subsystem overview [based on Suncheon substation & power collection].*

Substation building summary		Material	Total weight	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	fe-c	1,508	**GWP**	13,448	4,899	94	18,441
lorry	686	concrete	14,491	**ODP**	0	0	0	0
ship	0	brick	11,125	**AP**	65	28	1	93
air	0	cement	3,855	**EP**	23	22	0	45
		glasscoated	193	**POCP**	5	1	0	6
		timber	1,928	**MJ**	268,745	86,198	1,621	356,564
		al	530					
		cu	530					
		rockwool	81					
		pvc	58					

Power collection [km of track / # sub stations]		Material	Total weight [kg]	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	ps	7,740	**GWP**	328,039	93,213	553	421,805
lorry	4,034	al	33,660	**ODP**	0	0	0	0
ship	0	fe-c	11,676	**AP**	1,423	516	4	1,943
air	0	N/A	0	**EP**	520	412	1	934
		N/A	0	**POCP**	126	27	0	153
		N/A	0	**MJ**	5,536,650	1,701,942	9,530	7,248,123

Power supply summary		Material	Total weight	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	electronics	200	**GWP**	16,568	23,265	25	39,858
lorry	184	cu	150	**ODP**	0	0	0	0
ship	0	pur	36	**AP**	109	202	0	312
air	0	ps	15	**EP**	85	101	0	187
		glasscoated	15	**POCP**	5	7	0	12
		transformer	2,000	**MJ**	310,403	272,014	434	582,851

Table B5. *Substation & power collection subsystem overview [based on Suncheon substation & power collection] (continued).*

Control cabinet summary		**Material**	**Total weight [kg]**	**LCI results**	**Material**	**Manufacturing**	**Transportation**	**Total**
Transport	**Tonne-km**	electronics	60	**GWP**	1,555	625	1	2,180
lorry	5	N/A	0	**ODP**	0	0	0	0
ship	0	N/A	0	**AP**	11	5	0	16
air	0	N/A	0	**EP**	15	3	0	18
		N/A	0	**POCP**	1	0	0	1
		N/A	0	**MJ**	27,733	7,244	11	34,987

Construction summary		**Work type**	**Amount**	**LCI results**	**buildingmachine**	**Transportation**	**Total**
Transport	**Tonne-km**	buildingmachine	87	**GWP**	39	0	39
lorry	0	el-jp	19	**ODP**	0	0	0
ship	0	N/A		**AP**	0	0	0
air	0	N/A		**EP**	0	0	0
		N/A		**POCP**	0	0	0
		N/A		**MJ**	652	0	652

O&M summary		**Service**	**Amount**	**LCI results**	**Service**	**Energy use**	**Transportation**	**Total**
Transport	**Tonne-km**	N/A		**GWP**	0	568,310	0	568,310
Lorry		N/A		**ODP**	0	0	0	0
Ship		N/A		**AP**	0	2,558	0	2,558
Air		N/A		**EP**	0	939	0	939
		N/A		**POCP**	0	100	0	100
		el-jp	1,051,200	**MJ**	0	12,313,198	0	12,313,198

Table B5. *Substation & power collection subsystem overview [based on Suncheon substation & power collection](continued).*

Dismantling and recycling		Material	Total weight	LCI results	Dismantling	Recycling	Incineration	Landfill	Total
Transport	**Tonne-km**	Metals	48,054	**GWP**	64,710	7,289	5,929	2,293	80,221
lorry	6,792	Polymers	7,849	**ODP**	0	0	0	0	0
		Elastomers	0	**AP**	34	90	-6	3	121
		Glass	208	**EP**	16	41	-3	1	55
Distance to [km]:		Fluids	0	**POCP**	1	-20	0	0	-19
Recycling	76	MONM	1,928	**MJ**	82,773	70,442	-39,210	9,190	123,194
Incineration	76	Aggregates	29,553						
Landfill	76	Others	2,260						

Table B6. *Control & communication system [/km track].*

Control room / km track network		Material	Total weight	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	electronics	15	**GWP**	467	211	1	678
lorry	5	fe-c	24	**ODP**	0	0	0	0
ship	0	osb	13	**AP**	3	2	0	5
air	0	abs	6	**EP**	4	1	0	5
		polyols	3	**POCP**	0	0	0	0
		N/A	0	**MJ**	8,800	2,844	11	11,655

Track network communication [/km]		Material	Total weight [kg]	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	pur	375	**GWP**	5,793	2,326	9	8,128
lorry	68	cu	270	**ODP**	0	0	0	0
ship	0	glassfiber	60	**AP**	42	17	0	59
air	0	glasscoated	60	**EP**	42	10	0	52
		electronics	133	**POCP**	3	1	0	3
		N/A	0	**MJ**	127,147	36,081	161	163,389

Table B6. *Control & communication system [/km track] (continued).*

Power supply summary		**Material**	**Total weight**	**LCI results**	**Material**	**Manufacturing**	**Transportation**	**Total**
Transport	**Tonne-km**	electronics	160	**GWP**	4,533	1,931	3	6,467
lorry	24	Cu	120	**ODP**	0	0	0	0
ship	0	Pur	36	**AP**	34	16	0	50
air	0	N/A	0	**EP**	42	8	0	51
		N/A	0	**POCP**	2	1	0	3
		N/A	0	**MJ**	88,041	2,4265	57	112,363

Control cabinet summary		**Material**	**Total weight [kg]**	**LCI results**	**Material**	**Manufacturing**	**Transportation**	**Total**
Transport	**Tonne-km**	electronics	120	**GWP**	3,109	1,251	1	4,361
lorry	9	N/A	0	**ODP**	0	0	0	0
ship	0	N/A	0	**AP**	21	11	0	32
air	0	N/A	0	**EP**	30	5	0	35
		N/A	0	**POCP**	1	0	0	2
		N/A	0	**MJ**	55,465	14,487	22	69,974

Construction summary		**Work type**	**Amount**	**LCI results**	**work**	**Transport**	**Total**
Transport	**Tonne-km**	buildingmachine	3,168	**GWP**	1,050	0	1,050
lorry	0	Welding	2	**ODP**	0	0	0
ship	0	el-jp	1	**AP**	10	0	10
air	0	N/A		**EP**	2	0	2
		N/A		**POCP**	0	0	0
		N/A		**MJ**	15,773	0	15,773

Table B6. *Control & communication system [/km track] (continued).*

O&M summary		Service	Amount	LCI results	Service	Energy use	Transportation	Total
Transport	**Tonne-km**	Welding	0	**GWP**	0	94,718	0	94,718
lorry		pur	0	**ODP**	0	0	0	0
ship		epoxy	0	**AP**	0	426	0	426
air		N/A		**EP**	0	156	0	156
		N/A		**POCP**	0	17	0	17
		el-jp	175,200	**MJ**	0	2,052,200	0	2,052,200

Dismantling and recycling		Material	Total weight	LCI results	Dismantling	Recycling	Incineration	Landfill	Total
Transport	**Tonne-km**	Metals	414	**GWP**	1,178	658	668	246	2,750
lorry	106	Polymers	417	**ODP**	0	0	0	0	0
		Elastomers	3	**AP**	1	4	-1	0	4
		Glass	120	**EP**	0	3	0	0	3
Distance to [km]:		Fluids	0	**POCP**	0	0	0	0	0
Recycling	76	MONM	13	**MJ**	1,461	5,541	-3,816	386	3,572
Incineration	76	Aggregates	0						
Landfill	76	Others	428						

Table B7. *Maintenance facility system overview [1 facility].*

Building summary		Material	Total weight	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	fe-c	303,355	**GWP**	2,705,009	985,449	18,929	3,709,388
lorry	137,979	concrete	2,914,873	**ODP**	2E-01	8E-02	3E-03	3E-01
ship	0	brick	2,237,762	**AP**	13,112	5,532	126	18,769
air	0	cement	775,422	**EP**	4,643	4,450	26	9,119
		glasscoated	38,721	**POCP**	919	293	4	1,215
		timber	387,711	**MJ**	54,057,323	17,338,503	325,985	71,721,811
		al	106,608					
		cu	106,608					
		rockwool	16,343					
		pvc	11,566					

Service utilities summary		Material	Total weight [kg]	LCI results	Material	Manufacturing	Transportation	Total
Transport	**Tonne-km**	fe-cr	30,000	**GWP**	156,446	62,231	391	219,068
lorry	2,850	ps	5,625	**ODP**	9E-03	5E-03	6E-05	1E-02
ship	0	timberlami	1,875	**AP**	776	344	3	1,123
air	0	N/A	0	**EP**	257	275	1	5,32
		N/A	0	**POCP**	47	18	0	65
		N/A	0	**MJ**	2,850,615	1,140,625	6,733	3,997,973

Construction summary		Work type	Amount	LCI results	buildingmachine	Transportation	Total
Transport	**Tonne-km**	buildingmachine	23,281	**GWP**	10,433	0	10,433
lorry	0	el-jp	5,029	**ODP**	0	0	0
ship	0	N/A		**AP**	87	0	87
air	0	N/A		**EP**	18	0	18
		N/A		**POCP**	2	0	2
		N/A		**MJ**	174,734	0	174,734

Table B7. *Maintenance facility system overview [1 facility] (continued).*

O&M summary		Service	Amount	LCI results	Service	Energy use	Transportation	Total
Transport	**Tonne-km**	Welding	0	**GWP**	0	7,847,353	0	7,847,353
lorry		pur	0	**ODP**	0	0	0	0
ship		epoxy	0	**AP**	0	35,321	0	35,321
air		N/A		**EP**	0	12,963	0	12,963
		N/A		**POCP**	0	1,379	0	1,379
		el-jp	14,515,200	**MJ**	0	170,023,343	0	170,023,343

Dismantling and recycling		Material	Total weight	LCI results	Dismantling	Recycling	Incineration	Landfill	Total
Transport	**Tonne-km**	Metals	546,571	**GWP**	1,181,883	81,003	-10,641	168,299	1,420,545
lorry	519,770	Polymers	17,191	**ODP**	0	0	0	0	0
		Elastomers	0	**AP**	1,242	407	299	283	2,230
		Glass	38,721	**EP**	395	-10	61	129	575
Distance to [km]:		Fluids	0	**POCP**	33	-226	-4	40	-158
Recycling	76	MONM	389,586	**MJ**	2,814,711	-4,540,307	-681,682	1,015,483	-1,391,796
Incineration	76	Aggregates	5,944,400						
Landfill	76	Others	0						

Table B8. *Vehicle System overview [1 vehicle].*

Bogie summary

Transport	Tonne-km
lorry	52
ship	0
air	0

Material	Total weight
fe-c	937
pur	29
fe-cr	199
epdm	6
al	120
cu	1
ps	11
glycolether	15
dimethylbutan	51

LCI results	Material	Manufacturing	Transportation	Total
GWP	3,590	2,400	7	5,997
ODP	0	0	0	0
AP	15	13	0	29
EP	7	11	0	18
POCP	2	1	0	2
MJ	62,621	42,350	123	105,094

Cabin summary

Transport	Tonne-km
lorry	245
ship	0
air	0

Material	Total weight [kg]
al	1,650
pc	600
glasscoated	360
epdm	45
silicone	120
pvc	30
polyols	45
pe2	15
fe-c	300
hdpe	30
abs	15
nylon	15

LCI results	Material	Manufacturing	Transportation	Total
GWP	20,225	4,710	34	24,969
ODP	0	0	0	0
AP	86	26	0	112
EP	27	20	0	47
POCP	7	1	0	8
MJ	326,413	91,164	579	418,156

Table B8. *Vehicle System overview [1 vehicle] (continued).*

Electrical syst summary	
Transport	**Tonne-km**
lorry	69
ship	0
air	0

Material	Total weight
al	203
fe-cr	348
battery	120
cu	99
ps	32
electronics	90
pvc	6
circutboard	9
N/A	0

LCI results	Material	Manufacturing	Transportation	Total
GWP	9,096	3,538	9	12,644
ODP	0	0	0	0
AP	60	27	0	87
EP	64	16	0	80
POCP	4	1	0	5
MJ	162,743	48,729	163	211,634

Pneumatic syst summary	
Transport	**Tonne-km**
lorry	7
ship	0
air	0

Material	Total weight [kg]
pur	4
brass	2
al	7
ps	6
fe-c	2
fe-cr	54
cu	3
electronics	1
epdm	12

LCI results	Material	Manufacturing	Transportation	Total
GWP	407	158	1	566
ODP	0	0	0	0
AP	2	1	0	3
EP	1	1	0	2
POCP	0	0	0	0
MJ	7,866	2,941	16	10,823

Table B8. *Vehicle System overview [1 vehicle] (continued).*

Assembly summary		Work type	Amount	LCI results	Assembly	Transportation	Total
Transport	**Tonne-km**	Excavation	0	**GWP**	15	2,013	2,028
lorry	5,591	Welding	10	**ODP**	0	0	0
ship	11,5852	el-se	160	**AP**	0	33	33
air		N/A		**EP**	0	4	4
		N/A		**POCP**	0	1	1
		N/A		**MJ**	1,527	32,866	34,392

O&M summary		Service	Amount	LCI results	Service	Propulsion	Transportation	Total
Transport	**Tonne-km**	Welding	100	**GWP**	16	642,268	0	642,284
lorry		pur	0	**ODP**	0	0	0	0
ship		epoxy	0	**AP**	0	2,891	0	2,891
air		N/A		**EP**	0	1,061	0	1,061
		N/A		**POCP**	0	113	0	113
		el-jp	1,188,000	**MJ**	212	13,915,601	0	13,915,813

Dismantling and recycling		Material	Total weight	LCI results	Dismantling	Recycling	Incineration	Landfill	Total
Transport	**Tonne-km**	Metals	3,925	**GWP**	5,876	1,424	685	148	8,134
lorry	425	Polymers	792	**ODP**	0	0	0	0	0
		Elastomers	228	**AP**	3	11	-2	0	12
		Glass	360	**EP**	1	7	-1	0	7
Distance to [km]:		Fluids	66	**POCP**	0	-2	0	0	-2
Recycling	76	MONM	0	**MJ**	6,879	16,581	-9,575	441	14,326
Incineration	76	Aggregates	0						
Landfill	76	Others	220						

Abbrevations

Material

abs	Acrylonitrile-butadiene-styrene	**fe-c**	Steel, carbon	**ps**	Polystyrene
al	Aluminum	**fe-cr**	Steel, stainless	**psfoam**	Polystyrene foam
al2	Aluminum, secondary	**glasscoated**	Glass, coated	**pur**	Polyurethane
battery	48V battery	**glassdouble**	Glass, double	**purfoam**	Polyurethane, foam
brass	Brass	**glycolether**	Glycol ether	**pvc**	Polyvinyl chloride
brick	Bricks	**gravel**	Gravel	**rockwool**	Rock wool
cement	Cement	**hdpe**	Polyethylene	**silicone**	Silicone
circutboard	Circut board	**inverter**	Inverter	**timber**	Sawn timber
concrete	Concrete	**nylon**	Nylon, 6	**timberlami**	Laminated timber
concreteex	Concrete exacting	**osb**	Oriented strand board	**transformer**	Transformer
cu	Copper	**paper2**	Paper, second grade	**N/A**	Not available
dimethylbutan	Dimethylbutan	**pc**	Polycarbonate		
electronics	Electronics	**pe2**	Fleece, polyethylene		
epdm	EPDM-rubber	**plywood**	Plywood		
epoxy	Epoxy	**polyols**	Polyols		

Energy

diesel	Diesel, burned
el-jp	Electricity, JP
el-se	Electricity, SE
el-us	Electricity, US
el-re	Electricity, renewable
heat	Heat from bio waste

Transport

air	Aircraft, freight
lorry	Lorry > 28t
ship	Ship, freight

APPENDIX C. BASIC DATA

Basic data used when calculating material quantities for sub models.

Table C1. *Density for materials.*

Material	Density [kg/m^3]	Reference
Plywood	550	See see Plywood, 2009
Glued laminated timber	527	Hiramatsu et al. 2010
Rock wool	60	Building materials Direct Ltd, 2012
Oriented strand board	600	EPF, 2006
Gravel	1,682	SI metric, 2012a
Rubber	1,522	SI metric, 2012a
Polystyrene	1,050	Nordling & Österman, 2007
Polystyrene foam	30	EcoInvent 2010a
Sawn timber	530	SI metric, 2012c
Steel	7,800	SI metric, 2012b
Concrete, normal	2,380	EcoInvent, 2010b
Concrete, exacting	2,440	EcoInvent, 2010c

Table C2. *Component masses.*

Component	Mass	Reference
HEA-180 steel beams	35.5 kg/m	Montanstahl, 2009
Plastic tubing, HDPE	0.6 kg/m	Onninen, 2006
Laminated safety glass	26 kg/m^2	EcoInvent, 2010d

Table C3. *Energy consumption for equipment during construction from Keoleian et al. 2005.*

Equipment	Energy demand [kW]
Crawler mounted hydraulic excavator	319
Air compressor	261
Concrete mixer	6
Concrete paving machine	186
Concrete truck	224
Crane, 50 t	132
Dumper	17
Hydraulic hammer	75
Motor grader	123
Signal boards	4
Vacuum truck	132
Water truck	336
Wheeled front end loader	175

References to Appendix C

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APPENDIX D. ECOINVENT DATASETS

In Table D1 – D6 the LCIA datasets used from the EcoInvent v.2.2 database are accounted for.

Table D1. *Material datasets.*

Data	EcoInvent ID	Infrastructure included?	Data validity period	Region
copper, from combined metal production, at refinery	10100	Yes	2004 – 2006	SE
aluminium, production mix, at plant	1056	Yes	2002	RER
polyurethane, rigid foam, at plant	1839	Yes	1997	RER
chromium steel 18/8, at plant	1072	Yes	2000 – 2002	RER
reinforcing steel, at plant	1141	Yes	2000 – 2002	RER
epoxy resin, liquid, at plant	1802	Yes	1994 – 1995	RER
concrete, exacting, at plant	502	Yes	1997 – 2001	CH
flat glass, coated, at plant	805	Yes	2000 – 2001	RER
polystyrene, general purpose, GPPS, at plant	1836	Yes	2001 – 2002	RER
synthetic rubber, at plant	1847	Yes	1995 – 2003	RER
gravel, crushed, at mine	463	Yes	1997 – 2001	CH
fleece, polyethylene, at plant	1820	Yes	1993 – 1995	RER
corrugated board base paper, kraftliner, at plant	1683	Yes	1995 - 2005	RER
glazing, double (2-IV), U<1.1 W/m2K, laminated safety glass, at plant	7141	Yes	1996 – 2004	RER
rock wool, at plant	1000	Yes	2000 – 2007	CH
polystyrene foam slab, at plant	998	Yes	2003	RER
plywood, outdoor use, at plant	2486	Yes	1996	RER
glued laminated timber, indoor use, at plant	2447	Yes	1986 – 2002	RER
oriented strand board, at plant	2480	Yes	2000	RER
silicone product, at plant	324	Yes	1997 – 2001	RER
polycarbonate, at plant	1826	Yes	1996 – 2001	RER
polyethylene, HDPE, granulate, at plant	1829	Yes	1999 – 2001	RER
acrylonitrile-butadiene-styrene copolymer, ABS, at plant	1817	Yes	1996 – 2001	RER
nylon 6, at plant	1821	Yes	1993 – 2001	RER
polyurethane, flexible foam, at plant	1838	Yes	1997	RER
acrylonitrile-butadiene-styrene copolymer, ABS, at plant	1817	Yes	1996 – 2001	RER
polyols, at plant	1808	Yes	1995 – 2001	RER
brass, at plant	1066	Yes	2000	CH
cement mortar, at plant	537	Yes	1994 – 2001	CH
brick, at plant	495	Yes	1992 – 2002	RER
sawn timber, hardwood, planed, kiln dried, u=10%, at plant	2500	Yes	1986 – 2002	RER
concrete, normal, at plant	504	Yes	1997 – 2001	CH
dipropylene glycol monomethyl ether, at plant	7211	Yes	2000 – 2006	RER
2,3-dimethylbutan, from naphtha, at plant	6230	Yes	1998 – 2004	RER
glass fibre, at plant	808	Yes	2000	RER
polyvinylchloride, at regional storage	1840	Yes	1998	RER

Table D2. *Manufacturing datasets. MONM and aggregates does not include manufacturing factor, instead impacts from construction is included in the model.*

Material group	Data	EcoInvent ID	Infrastructure included?	Data validity period	Region
Metals	metal product manufacturing, average metal working	8215	Yes	2006 – 2007	RER
Polymers	blow moulding	1848	Yes	1993 – 1997	RER
Elastomers	blow moulding	1848	Yes	1993 – 1997	RER
Glass	tempering, flat glass	813	Yes	2000	RER

Fluids	-	-	-	-	-
MONM	-	-	-	-	-
Aggregates	-	-	-	-	-
Others	assembly, LCD screen	10169	Yes	2001	GLO

Table D3. *Energy datasets.*

Data	EcoInvent ID	Infrastructure included?	Data validity period	Region
electricity, high voltage, at grid	739	Yes	1992 – 2004	SE
electricity, high voltage, at grid	6685	Yes	1992 – 2004	JP
electricity, high voltage, at grid	6682	Yes	2004	US
electricity, high voltage, certified electricity. at grid	11365	Yes	2004 – 2007	CH
diesel, burned in building machine	559	Yes	1996 – 2001	GLO
heat, biowaste, at waste incineration plant, future, allocation price	6724	Yes	2010 – 2020	CH

Table D4. *Component datasets.*

Data	EcoInvent ID	Infrastructure included?	Data validity period	Region
electronics for control units	550	Yes	1995 – 2005	RER
building, hall, steel construction	547	Yes	2000 – 2001	CH
building, multi-storey	549	Yes	1995 – 2001	RER
electronic component, unspecified, at plant	7065	Yes	1994 – 2007	GLO
battery, LiIo, rechargeable, prismatic, at plant	7065	Yes	2009 – 2010	GLO
cable, connector for computer, without plugs, at plant	7017	Yes	2000 – 2006	GLO
inverter, 500kW, at plant	6852	Yes	2004 – 2006	RER
transformer, high voltage use, at plant	7073	Yes	1994 – 2007	GLO

Table D5. *Transportation datasets.*

Data	EcoInvent ID	Infrastructure included?	Data validity period	Region
transport, lorry >28t, fleet average	1994	Yes	2005	CH
transport, transoceanic freight ship	1968	Yes	1992 – 2000	OCE
transport, aircraft, freight, intercontinental	1894	Yes	2000	RER

Table D6. *End of life datasets.*

Data	EcoInvent ID	Infrastructure included?	Data validity period	Region
disposal, building, reinforced concrete, to recycling	2153	Yes	1994 – 2002	CH
dismantling, industrial devices, manually, at plant	10939	Yes	2005	CH
dismantling, shredder fraction from manual dismantling, mechanically, at plant	10915	Yes	2005	GLO
disposal, electronics for control units	2053	Yes	1990 – 2005	RER
disposal, plastics, mixture, 15.3% water, to municipal incineration	2112	Yes	1994 – 2000	CH
disposal, rubber, unspecified, 0% water, to municipal incineration	2121	Yes	1994 – 2000	CH
disposal, steel, 0% water, to municipal incineration	2123	Yes	1994 – 2000	CH
disposal, textiles, soiled, 25% water, to municipal incineration	2124	Yes	1994 – 2000	CH
disposal, residues, shredder fraction from manual dismantling, in MSWI	10922	Yes	1994 – 2000	CH
disposal, glass, 0% water, to municipal incineration	2099	Yes	1994 – 2000	CH
disposal, cement-fibre slab, 0% water, to municipal incineration	2094	Yes	1994 – 2000	CH

disposal, used mineral oil, 10% water, to hazardous waste incineration	2064	Yes	1997 - 2000	CH
disposal, concrete, 5% water, to inert material landfill	2069	Yes	1995	CH
disposal, glass, 0% water, to inert material landfill	2071	Yes	1995	CH
disposal, steel, 0% water, to inert material landfill	2082	Yes	1995	CH
disposal, plastics, mixture, 15.3% water, to sanitary landfill	2230	Yes	1994 – 2000	CH
disposal, packaging cardboard, 19.6% water, to sanitary landfill	2225	Yes	1994 – 2000	CH
aluminium, secondary, from old scrap, at plant	1060	Yes	1995 – 2002	RER
fleece production, polyethylene terephthalate	10845	Yes	1997	RER
glass fibre, at plant	808	Yes	2000	RER
corrugated board, recycling fibre, single wall, at plant	1693	Yes	1995 - 2005	RER
crushing, rock	558	Yes	1999 – 2001	RER

SE stands for Sweden, RER for Europe, CH for Switzerland, JP for Japan, US for United States, GLO for Global and OCE for Oceanic (Frischknecht et al. 2004).

References to Appendix D

The EcoInvent database is available at http://ecoinvent.ch/

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APPENDIX E. TRANSPORTATION

The vehicles are manufactured in Sweden and shipped to South Korea by sea. It is assumed that the transportation is by transoceanic freight ship from Göteborg, Sweden to Yeosu, South Korea. The steel track was manufactured in Dorcaster, UK and shipped from Hull to Göteborg, Sweden by sea and to Uppsala by lorry. Distances can be found in Table E1. For transportation where information of transportation routes where missing a general distance of 76 km was used. This is the average distance for transportation of goods in Sweden (Trafikanalys, 2012).

Table E1. *Transportation and distances.*

Route	Means of transportation	Distance	Source
Hull – Göteborg	Transoceanic freight ship	926 km	Searates, 2012
Göteborg – Yeosu	Transoceanic freight ship	20,722 km	Searates, 2012
Doncaster – Hull	Lorry, 16 t	74.2 km	Google, 2012
Göteborg – Uppsala	Lorry, 16 t	453 km	Google, 2012
Unknown	Lorry, 16 t	76 km	Trafikanalys, 2012

References to Appendix E

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APPENDIX F. ELECTRICITY MIX

Since no LCIA-data for the Korean electricity mix could be found Japanese electricity mix was used instead. To see the influence of the local electricity mix the Japanese mix was compared with Swedish electricity mix. The difference in generation source can be seen in Table F1.

Table F1. *Share of total electricity production 2009 (IEA, 2012) for Japan, Korea and Sweden and 2005 (Frischknecht et al. 2007) for Schweiz.*

Country	Nuclear	Coal/peat	Oil	Gas	Hydro	Biofuels & waste	Geo/solar/wind
Japan	26.7 %	26.7 %	8.7 %	27.2 %	7.8 %	2.0 %	0.8 %
Korea	32.5 %	46.0 %	4.4 %	15.5 %	1.2 %	0.2 %	0.3 %
Sweden	38.2 %	1.2 %	0.5 %	1.1 %	48.3 %	8.9 %	1.8 %
Schweiz, certified mix	2.6 %	0 %	0 %	0 %	96.9 %	0.1 %	0.3 %
US	19.8 %	45.2 %	1.2 %	22.7 %	7.1 %	1.7 %	2.2 %

Table F1 shows the share of total electricity production for year 2009 and does not include electricity trade.

References to Appendix F

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APPENDIX G. SENSETIVITY & UNCERTAINTY ANALYSIS.

To study the LCAs sensitivity to uncertainty in LCIA-input data each dataset was increased with 25% at a time and compared to the change in per cent of the total impact for Suncheon system configuration. The ten data-sets that gave largest change for each impact category can be seen in Figure G1 - G6.

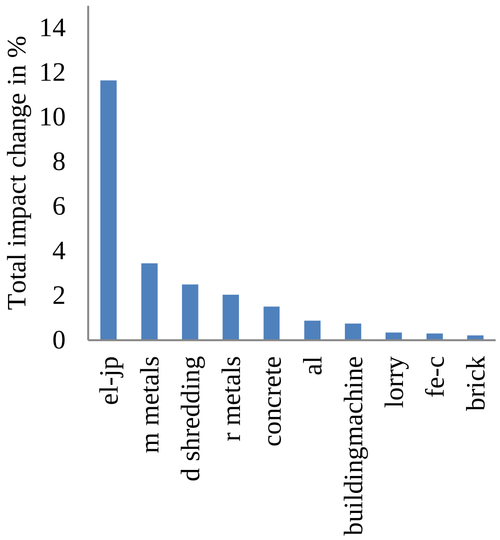

Figure G1. *Response of total GWP impact in per cent for 25 % change in LCIA input, respectively.*

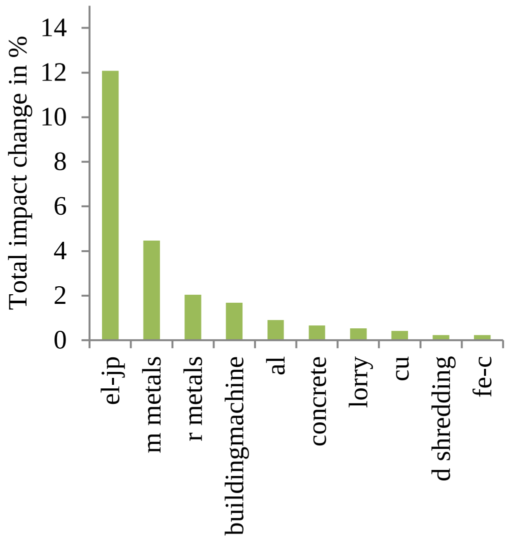

Figure G3. *Response of total AP impact in per cent for 25 % change in LCIA input, respectively.*

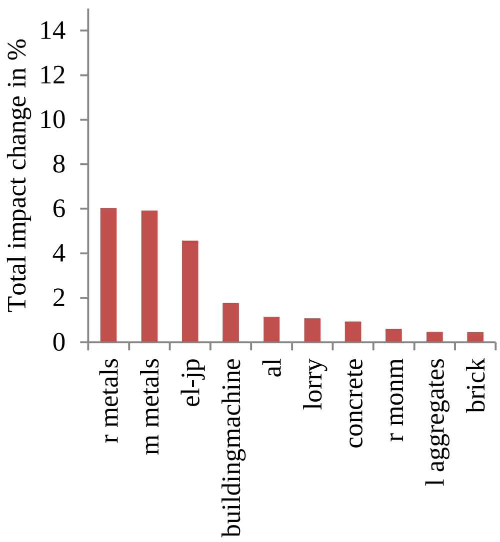

Figure G2. *Response of total ODP impact in per cent for 25 % change in LCIA input, respectively.*

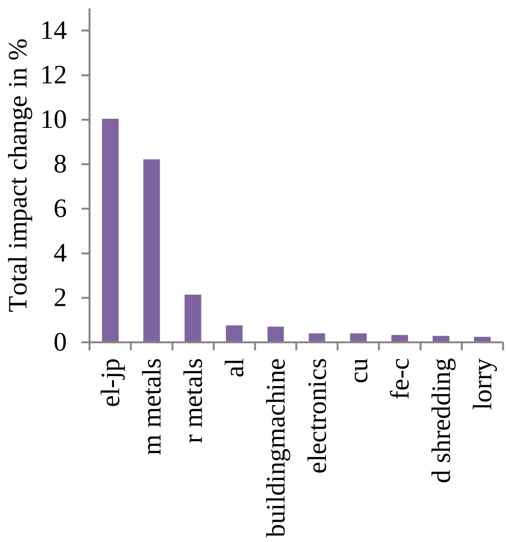

Figure G4. *Response of total EP impact in per cent for 25 % change in LCIA input, respectively.*

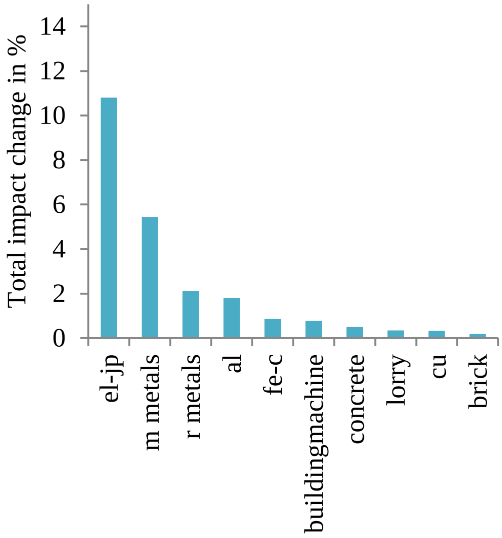

Figure G5. *Response of total POCP impact in per cent for 25 % change in LCIA input, respectively.*

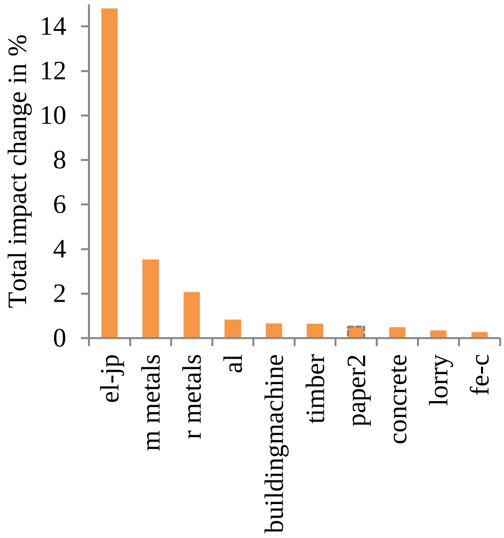

Figure G6. *Response of total MJ impact in per cent for 25 % change in LCIA input, respectively.*

The result from the Monte-Carlo simulation can be seen in Figure G7 – G12 and the calculated confidence interval can be seen in Table G1.

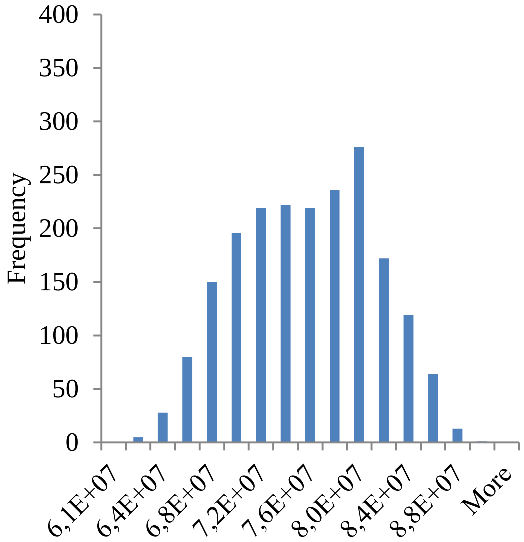

Figure G7. *Distribution of GWP from 2000 iteration of randomly varied input data.*

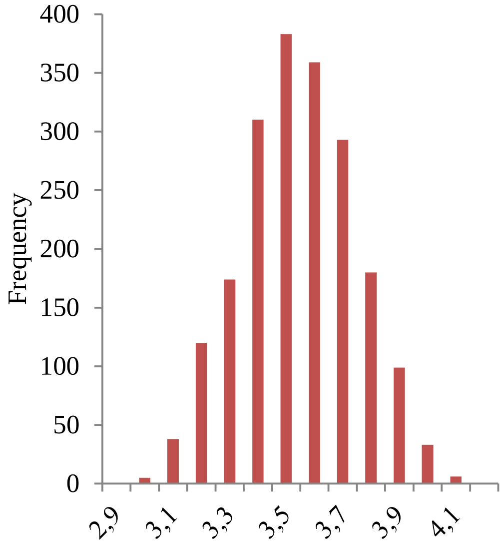

Figure G8. *Distribution of ODP from 2000 iteration of randomly varied input data.*

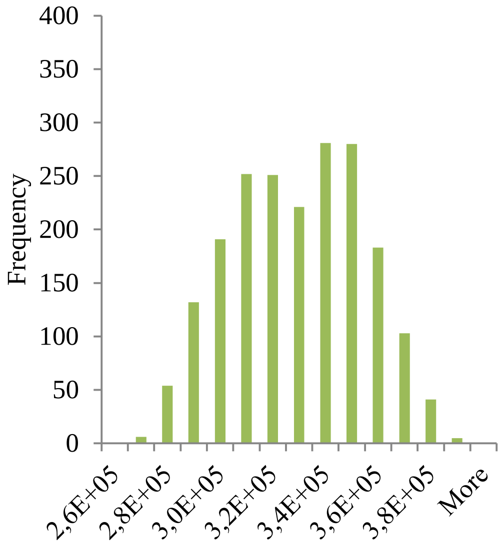

Figure G9. *Distribution of AP from 2000 iteration of randomly varied input data.*

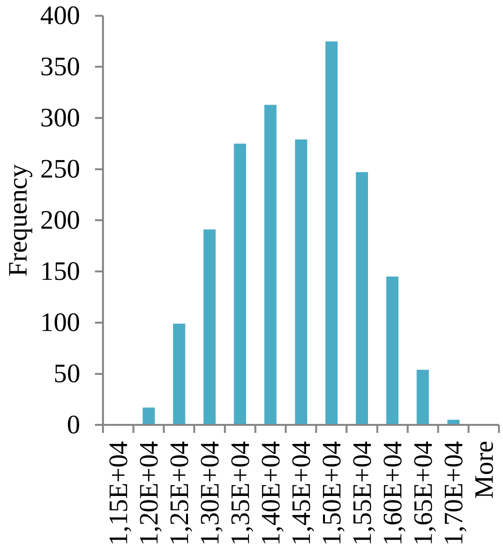

Figure G11. *Distribution of POCP from 2000 iteration of randomly varied input data.*

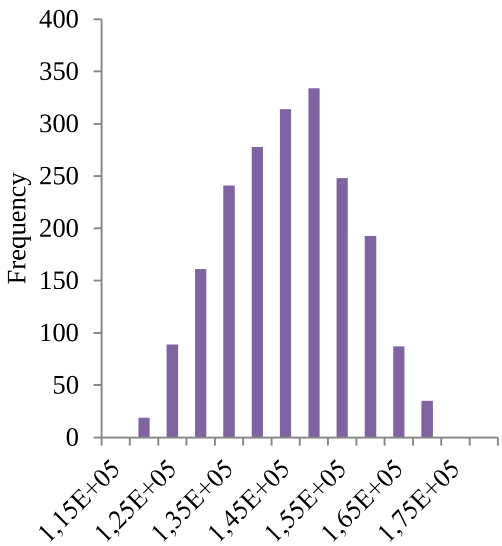

Figure G10. *Distribution of EP from 2000 iteration of randomly varied input data.*

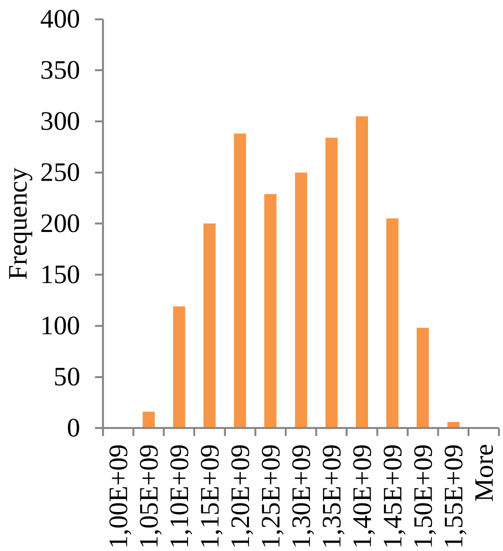

Figure G12. *Distribution of MJ from 2000 iteration of randomly varied input data.*

Table G1. *95 % confidence interval calculated from Monte Carlo-simulation with assumed variance of ±25 % for LCIA-data.*

Interval	**GWP** [kg CO_2eq]	**ODP** [kg CFC 11eq]	**AP** [kg SO_2eq]	**EP** [kg PO_4^{3}eq]	**POCP** [kg C_2H_4eq]	**MJ**
CI95 high	84,600,000	3.90	369,000	164,000	16,100	1,470,000,000
Original value	74,600,000	3.50	324,000	143,000	14,100	1,270,000,000
CI95 low	64,500,000	3.11	279,000	122,000	12,200	1,070,000,000