Energy Efficiency and Conservation Authority

Life Cycle Assessment of Electric Vehicles

Final Report

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Arup
Arup Pty Ltd ABN 18 000 966 165

Arup
Level 17
1 Nicholson Street
Melbourne VIC 3000
Australia
www.arup.com

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Abbreviations

Abbreviation	Description
AC	Alternating current, regarding the type of electrical current
AER	All-electric range
ADF	Abiotic Depletion Factor, determined as the amount of extracted materials compared to the concentration of reserves and rate of de-accumulation from these reserves
ADR	Australian Design Rules, which are national standards for vehicle safety, anti-theft and emissions
BEV	Battery electric vehicle
C_2H_2	Acetylene, as the equivalent unit of measure for photochemical oxidant formation in this study
CML	Institute of Environmental Sciences, an institute of the Faculty of Science of Leiden University
CO	Carbon monoxide
CO_2e	Carbon dioxide equivalent
CTU_e	Comparative toxic units, a unit of measure for ecotoxicity impacts used in this study, which estimates the potentially affected fraction of species
CTU_h	Comparative toxic units, a unit of measure for human toxicity impacts used in this study, which estimates the increase in morbidity in the total human population
DC	Direct current, regarding the type of electrical current
EECA	Energy Efficiency and Conservation Authority of New Zealand
EURO 5	A designation for a European emission standard, defining the acceptable limits for exhaust emissions of new vehicles sold in Europe
EV	Electric vehicle
GWP	Global warming potential, a relative measure of how much heat is trapped by a type of gas, compared to carbon dioxide
ICE	Internal combustion engine
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LFP	Battery type: Lithium iron phosphate
LMO	Battery type: Lithium manganese oxide
LTO	Battery type: Lithium titanate
MJ LHV	Energy measured in megajoules, particularly the lower heating value (LHV) which assumes water is vaporised at the end of combustion, as the equivalent unit of measure for cumulative energy demand in this study
NiMH	Battery type: Nickel metal hydride
NO_x	Nitrogen oxides

Abbreviation	Description
NMC	Battery type: Lithium nickel manganese cobalt oxide
NMVOCs	Non-methane volatile organic compounds
NZ	New Zealand
OECD	Organisation for Economic Co-operation and Development
PEV	Plug-in electric vehicle
PHEV	Plug-in hybrid electric vehicle
$PM_{2.5}$	Particulate matter less than 2.5µm in diameter by size, as the equivalent unit of measure for particulate matter in this study
PM_{10}	Particulate matter less than 10µm in diameter by size
POFP	Photochemical ozone formation potential
RUCs	Road user charges
Sb	Antimony, as the equivalent unit of measure for mineral depletion in this study
SO_2	Sulfur dioxide, as the equivalent unit of measure for air acidification in this study
UDDS	Urban Dynamometer Driving Schedule
UNECE	United Nations Economic Commission for Europe
US	United States of America
VOC	Volatile organic compounds

1 Introduction

1.1 Overview

Electric vehicles (or plug-in electric vehicles as referred to in this study) have generated significant interest in New Zealand, especially among motoring enthusiasts, sustainable transport advocates and energy providers.

Generally regarded as a low-emission vehicle technology, plug-in electric vehicles (PEVs) are well-known for their reduced on-road emissions relative to conventional vehicles, as they use electricity stored in an on-board battery for propulsion. Much of New Zealand’s electricity is generated from renewable sources (such as hydro power) and the carbon intensity of the grid is low. As a result, PEVs seem especially appealing in the New Zealand context as they promise to reduce emissions from the road transport sector.

Yet it is not just the operation of a motor vehicle that needs to be considered when its overall impact upon the environment and upon human health is to be assessed. “Life cycle assessments”, which consider the entire journey from raw material extraction, through manufacture, shipping and operation to eventual disposal, have become commonplace overseas, and many of these have shown that PEVs can stack up favourably when compared to their conventional counterparts. However, no such study has yet been undertaken in New Zealand. To give an accurate reflection of the impact of these vehicles applied to the local context, factors such as the list below must be considered:

- where do they come from (and how are they made)?
- how they will be driven?
- what will happen to them at end of their usable life?
- what will be their ecological impact during use (whilst being driven)?

To address a potential information gap, New Zealand’s Energy Efficiency and Conservation Authority (EECA) has asked expert consultants Arup and Verdant Vision to prepare this life cycle assessment (LCA) comparing the environmental impacts of PEVs to conventional vehicles.

1.2 LCA approach

A life cycle assessment (or LCA) is a technique for assessing potential impacts, including upon the environment and human health and well-being, associated with a product, system or service. Commonly referred to as a “cradle-to-grave” study, an LCA reviews the full range of impacts from the beginning to the end of a product’s life by:

- compiling an inventory of relevant inputs and outputs of a product system;
- evaluating the potential environmental and human health impacts associated with those inputs and outputs; and

- interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

An LCA approach to the measurement of environmental impacts differs from other environmental management approaches in that its focus is upon the measurement and calculation of impacts normalised per unit of output.

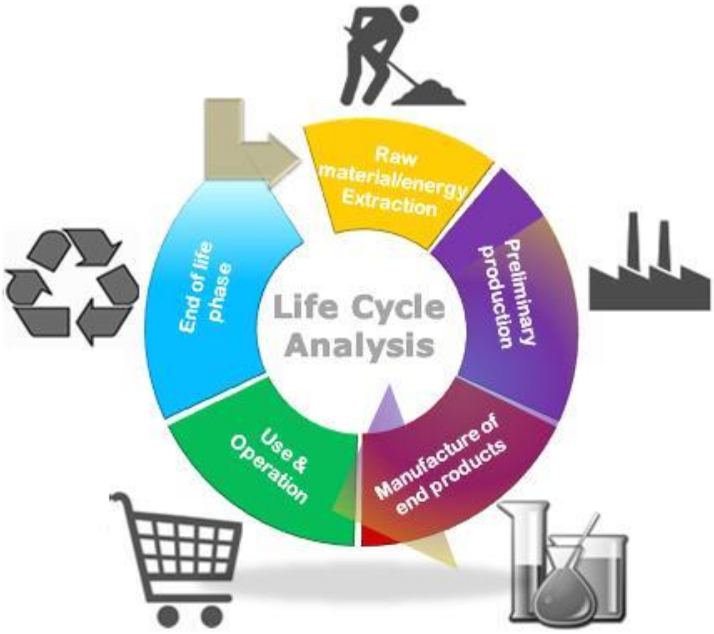

Figure 1 Typical life cycle assessment (LCA) of a product's life[1]

The scope of the LCA is to compare the life cycle impacts of the vehicle technology types below and outlined in Section 2.3:

- conventional petrol engine vehicle;
- conventional diesel engine vehicle;
- battery electric vehicle (BEV); and
- plug-in hybrid electric vehicle (PHEV).

Based on information collected in the New Zealand vehicle market, a representative vehicle is used to provide a like-for-like comparison of each of the four technologies considered (without naming a specific product or brand). While there is ample data available in the public domain to characterise conventional petrol and diesel engine vehicles, there is limited data available for BEVs and PHEVs, given how new these are to the marketplace. For this reason, some aspects of the data used to characterise BEVs and PHEVs in this LCA rely upon industry-based assumptions – these are described in detail in Sections 0 and 4.

The LCA and technical report have been undertaken to comply with International Standards concerning the various phases of an LCA.

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[1] European Technology Platform on Advanced Engineering Materials and Technologies (EuMaT) (2015) *Work Group 5: Life cycle, Impacts, Risks,* accessible at http://www.eumat.eu/home.aspx?lan=230&tab=1036&pag=1053

- *ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework* (ISO14040); and
- *ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and Guidelines* (ISO14044).

Extracts from the standard are included in grey shaded boxes throughout this document for reference.

1.3 Report structure

This report comprises the following components:

- **Section 2 – Goal and scope of study**

  This section describes the purpose of the study and the boundaries of the assessment: i.e. what components and related processes are included as part of this study or excluded.

- **Section 3 – Vehicles in the New Zealand context**

  This section describes the vehicle market in the New Zealand context, particularly regarding environmental aspects of PEVs, incorporating a review of prior work in this area.

- **Section 4 – Data and assumptions**

  This section describes the data and assumptions applied to this study. This section justifies the assumptions and the suitability of the data used.

- **Section 5 – Results**

  This section provides an assessment of the results of the LCA, with particular regard to the impact categories defined in the goal and scope.

- **Section 6 – Sensitivity and Uncertainty Analysis**

  This section discusses the sensitivity and uncertainty analysis of the study. A number of key variables were tested for sensitivity, to understand the impact upon the key findings if assumptions were changed. A summary of the uncertainty analysis on data quality is also provided.

- **Section 7 – Conclusion**

  This last section of the study interprets the outcomes of the LCA and offers commentary regarding the comparison of conventional vehicles against PEVs from an environmental and human health impact perspective.

1.4 Review of industry LCAs

Many LCAs have been conducted in other markets and geographies to assess the environmental impacts of alternative vehicle technologies, of which PEVs are one. To inform this LCA, as well as to identify best practice and potential shortcomings in approach, Arup and Verdant Vision reviewed a number of industry publications regarding LCAs of conventional vehicles and PEVs.

Sources for this review include the following, and are described further in Appendix A:

- Schweimer GW, Levin M (2000) *Life Cycle Inventory of the Golf A4*.
- Hischier R., Classen M., Lehmann M. and Scharnhorst W. (2007) *Life Cycle Inventories of Electric and Electronic Equipment: Production, Use and Disposal*.
- Arup, UK Department for Business Enterprise and Regulatory Reform (2008) *Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plug-in Hybrid Vehicles*
- Patterson J, Alexander M, Gurr A (2011) *Preparing for a Life Cycle CO_2 Measure – A report to inform the debate by identifying and establishing the viability of assessing a vehicle's life cycle CO_2e footprint*
- Hawkins T, Singh B, Majeau-Bettez M, Stromman A (2012) *Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles*
- Del Duce, Gauch, Althaus (2013) *Electric passenger car transport and passenger car life cycle inventories in ecoinvent version 3*.
- United States Environmental Protection Agency (2013) *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles*

The LCAs above have informed this study regarding the formation of the goal and scope, system boundaries, as well as the procedures used for the allocations of certain components. The results from these LCAs also provide a useful basis for comparison for the outcomes from this report.

In particular, the study utilises life cycle inventory data that is already available and recognised by the industry. The passenger vehicle life cycle inventory data for conventional vehicles and PEVs from ecoinvent v3.1 was modified and applied to this study. Relevant references for assumptions and use of data from these studies have been included throughout this report. The data assumptions are further discussed in Section 4.

1.5 Study limitations

This LCA seeks to provide a robust and well-researched representation of how PEVs compare to conventional vehicles in terms of environmental and human health impact when applied to the New Zealand context. However, as with all studies, our findings are tempered by limitations.

The following is a list of the limitations that we believe have most directly affected the outcome of this LCA:

- **PEV market maturity**

On sale globally only since 2008, modern-day PEVs are still very new to the automotive sector. The impact of this market's youth has specific effects pertaining to this LCA, in particular:

  - A far less diverse range of products to choose from relative to the conventional vehicle market.
  - The New Zealand market for PEVs is particularly immature, with only a few hundred sold since their introduction and at time of writing.
  - Some level of uncertainty as to what really happens at the end of a PEV's life, including uncertainty about the number of times a battery will need to be replaced over the life of the vehicle, a lack of firm plans within industry for treatment of end-of-life batteries, and an accurate understanding of how long PEV owners will keep their vehicles.

- **Predicting the future**

The PEV sector, as well as the automotive transportation sector generally, is undergoing rapid evolution due to technological advances and socio-economic and geopolitical trends. Given the high rate of change, it is almost impossible to say with confidence what the world will look like in only 10-20 years from now (i.e. within the lifetime of a single vehicle).

This study does not attempt to predict future scenarios, but rather conducts the LCA comparison based on present circumstances and is therefore best regarded as a snapshot in time. The only forecasts included are those required to make educated assumptions about the PEV sector in New Zealand at a meaningful scale (notably that it will be greater than at present). Otherwise forecasts about potential change in transport behaviours, evolution of conventional and PEV technologies, decarbonisation of the energy sector, or other relevant factors, have not been attempted in this study.

- **Access to complete data**

Given the limited number of products available in the marketplace and the commercial sensitivities surrounding PEV technologies within the industry, the availability of vehicle-specific data is limited. In cases where specific data could not be obtained from reliable industry sources, well-informed inferences were used to fill gaps.

These gaps occurred in certain aspects of both the operation of the vehicle and the component manufacturing and disposal. For example, Section 4.1 discusses some of the limitations in the life cycle inventory data and Section 4.3 discusses the assumptions made concerning the operational phase of "typical" PEVs.

- **LCA impact categories – modelling methodologies**

To paint a full picture of the environmental and human health impacts of a vehicle over its life, this study uses computer modelling to collate data concerning a range of processes, components, products and materials. This study considers eight categories of impacts divided into two broad categories (environmental and human health) and each of these categories have been assigned characterisation models and factors to determine their relative impact. This required specific studies and weightings to be undertaken by researchers in order to identify the magnitude of the impacts within each category.

All of the impact categories are the fruit of the research from various sources, and they have been described in further detail in Section 2.7 and Appendix B1. As there are many different weighting and conversion factors feeding into the models underlying each impact category (e.g. to produce the extent to which copper contributes to an overall toxicity score — hardly an exact science) there are inherent residual uncertainties in the results reported in this study. Therefore, an uncertainty analysis has been undertaken (Section 6.5) to understand and attempt to quantify the uncertainties surrounding the various impact categories.

Interpretation of the results from this study should therefore take the uncertainties and the particular manner in which impacts are calculated into account.

The results for the life cycle assessment have been expressed in relative terms. Furthermore, the life cycle assessment results do not predict impacts on category endpoints, nor do they provide a basis for measuring any exceedances of thresholds or safety margins.

1.6 Peer review

In accordance with International Standards, EECA commissioned a third-party, independent review as part of the study. The third party critical review was carried out by Life Cycle Strategies.

2 Goal and scope

2.1 Goal of the study

> The goal of an LCA study shall unambiguously state the intended application, the reasons for carrying out the study, the intended audience (i.e. to whom the results of the study are intended to be communicated) and whether the results are intended to be used in comparative assertions intended to be disclosed to the public.
>
> ***ISO 14044:2006 Section 4.2.2***

In order to pre-empt a potential information gap, EECA intends to provide authoritative information to New Zealanders about the impact — positive and negative — of adopting PEV technology compared to conventional vehicles.

Therefore, the goal of this LCA study is to undertake a quantitative comparison between four vehicle technologies to determine, from a life cycle perspective, the most favourable option. The four technologies considered in this LCA are:

1. conventional petrol engine vehicle;
2. conventional diesel engine vehicle;
3. battery electric vehicle (BEV); and
4. plug-in hybrid electric vehicle (PHEV).

The goal of the study also took into consideration the following:

- **The intended application of the study results** – the results are intended to inform the general public, and are therefore presented in a format appropriate for a general readership.
- **The target audience** – the results are intended to inform the New Zealand public, particularly the subset who may be especially interested. These people may include motoring enthusiasts, sustainable transport advocates, and energy providers.
- **Regarding comparative assertions** – it should be noted that this study provides comparative assertions which are disclosed to the public.

2.2 Functional unit

> The scope of an LCA shall clearly specify the functions (performance characteristics) of the system being studied. The functional unit shall be consistent with the goal and scope of the study.
>
> One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalised (in a mathematical sense). Therefore the functional unit shall be clearly defined and measurable.
>
> Having chosen the functional unit, the reference flow shall be defined. Comparisons between systems shall be made on the basis of the same function(s), quantified by the same functional unit(s) in the form of their reference flows.
>
> If additional functions of any of the systems are not taken into account in the comparison of functional units, then these omissions shall be explained and documented. As an alternative, systems associated with the delivery of this function may be added to the boundary of the other system to make the systems more comparable. In these cases, the processes selected shall be explained and documented.
>
> ***ISO 14044:2006 Section 4.2.3.2***

In this study, the "functional unit" is the metric against which the vehicle technologies are compared. The project team have defined this functional unit in two ways:

- the life cycle impact of a vehicle travelling for one kilometre; and
- the life cycle impact of a vehicle over its estimated lifetime.

The function, functional unit and reference flows are defined below:

Function:	The transportation of a passenger/s using a vehicle, for general use
Functional Unit:	1 kilometre travelled
Reference flows:	Life cycle impacts of the equipment, energy input required, and waste disposed
Reference period	One year of operation, and lifetime of vehicle

2.3 Technologies considered

Broadly speaking, the study is performing comparative life cycle assessments on two types of vehicles — "conventional vehicles" and "electric vehicles"[2] — with two main variants within each type. The study makes a number of assumptions in order to compare these two types of vehicles, particularly in determining what the general use of a vehicle is. These assumptions are spelled out in Section 4.3.

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[2] *Hybrid vehicles*, such as the Toyota Prius or Camry Hybrid are neither strictly conventional vehicles nor PEVs, even though they operate with both a petrol (or diesel) engine and an electric motor and battery. Hybrid vehicles are sometimes confused with PEVs because of their on-board battery, but are a separate vehicle technology altogether, as they do not charge their batteries from an external source. They are not considered as part of this study or discussed further in this report.

In today's marketplace, any vehicle that runs on electricity originating from an external source (e.g. the electricity grid, standalone generators, etc.) is called an "electric vehicle" (EV). However, there is considerable variation within the broad definition of electric vehicles, which can create confusion for the reader.

Best practice globally refers to all types of electric vehicles as *plug-in electric vehicles* or PEVs because it is their distinguishing feature that they can be "plugged in" to use off-board electricity as a form of fuel.

Conventional vehicles

Conventional vehicles are the vehicles we most commonly see on the roads today – everyday passenger cars that run on liquid fuel such as petrol or diesel. These serve as our base case for comparison. Typically, these vehicles have an engine, a fuel tank, an exhaust system, and various other components associated with their operation (including a battery and electric motors), but they do not use an electric motor or battery for propulsion.

Plug-in electric vehicles (PEV)

The plug-in electric vehicle (PEV) category includes two generic types of vehicle technologies:

a) plug-in hybrid electric vehicles (PHEVs), and

b) battery electric vehicles (BEVs).

BEVs are the purest form of a PEV as they only run on one type of fuel – electricity. A BEV has fewer mechanical parts than a conventional vehicle. It has no combustion engine or fuel tank. Simply, a BEV is propelled by a motor that runs off the energy stored in an on-board battery. To charge this battery, you must plug the car into an electrical socket connected to an off-board power source (e.g. the grid or a generator of some description). Once the battery is flat, the car cannot go until it has been charged again by plugging it in.

PHEVs are another type of PEV. Like a BEV, they have an electric motor for propulsion that is supplied from an on-board battery that can be plugged into an external source to be recharged. What sets PHEVs apart from BEVs is that they also have an on-board fuel tank and internal combustion engine (ICE) to supplement the operation of the electric motor, either when more power is required or (more typically) to extend the vehicle's range when the energy stored in the battery is depleted.

A PHEV typically runs for a certain number of kilometres using the electricity stored in its on-board battery and, once that energy is depleted, it then begins to use its internal combustion engine. To achieve more electrified travel, the battery will need to be recharged by plugging in. However, if you plug-in a PHEV before use of the ICE is required, then you can avoid the use of this "range extender" function (the fuel tank/engine etc.), thus operating on battery power alone.

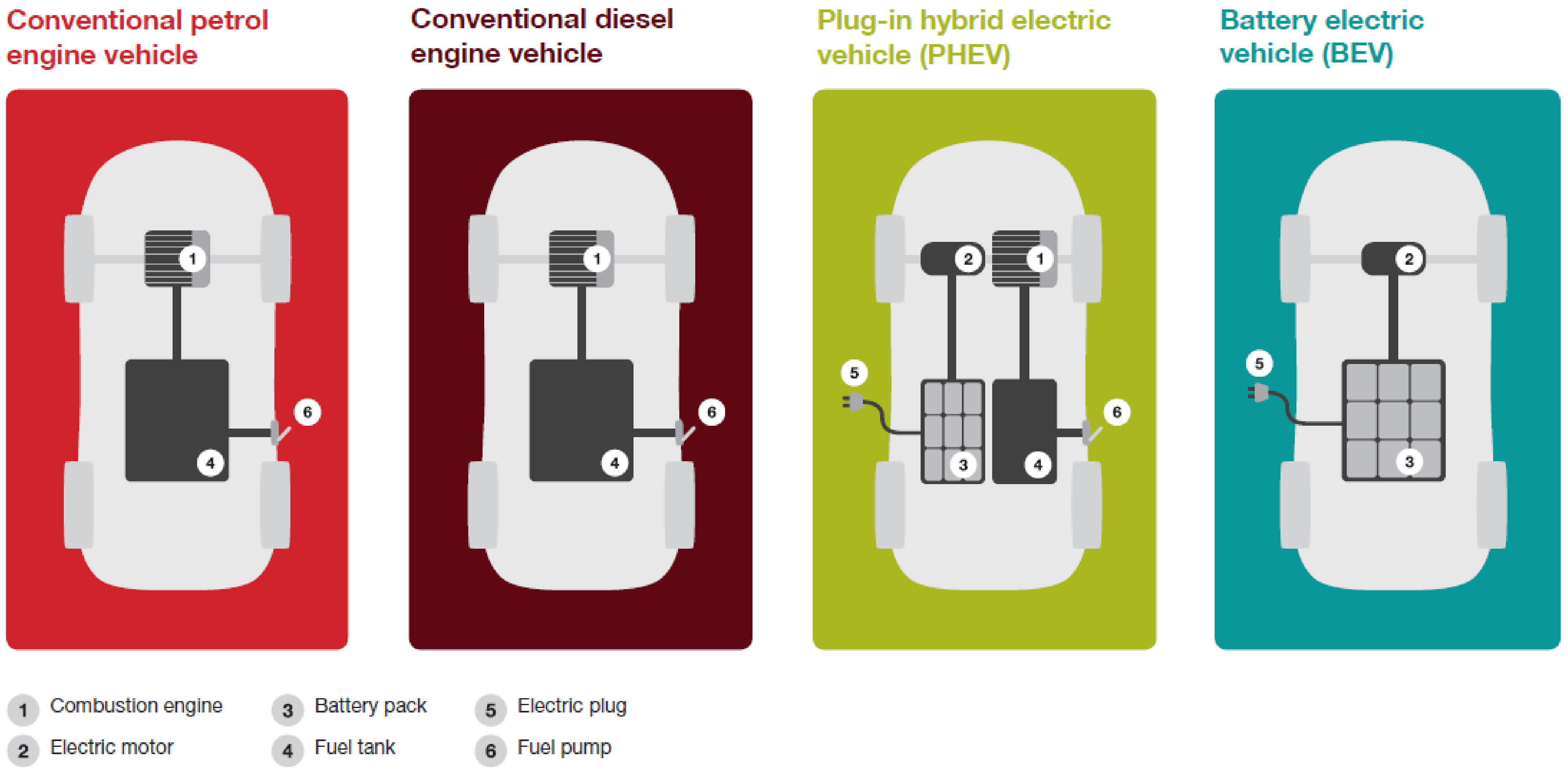

Figure 2 Key components of differing vehicle technologies

2.4 System scope

> The system boundary determines which unit processes shall be included within the LCA. The selection of the system boundary shall be consistent with the goal of the study. The criteria used in establishing the system boundary shall be identified and explained.
>
> ***ISO 14044:2006 Section 4.2.3.3.1***

The way in which New Zealanders use vehicles is central to this study's scope and thus forms the focal point around which the LCA system boundaries are defined.

New Zealand's unique portfolio of energy sources — especially, of course, electrical power and fossil fuels —are another key consideration of the system scope; understanding them is essential to understanding the relative environmental impact of each vehicle technology. Implications for this study are further discussed in 4.3.

However, this LCA does not consider the various components of fuel infrastructure and supply, whether it be the decommissioning and dismantling of the existing fossil fuel refining, transport and supply infrastructure, or the construction of an equivalent network for the supply of electrical power for PEV.

The raw materials aspects and manufacturing/disposal of vehicles and core technology components are included and are central to this study's scope. However, the materials and construction/decommissioning aspects of industrial facilities for the materials processing, manufacturing, recycling and disposal are not included. A diagram outlining these system boundaries is shown in Figure 3 and a summary of the system scope is outlined in Table 1.

Table 1 System scope summary

What we have considered	System Scope
Inputs and outputs in the main processing sequence	All unit processes for the production of any additional parts and operation of a PEV (e.g. battery) when compared to a conventional vehicle. This includes production and operational energy.
Production and use of fuels, electricity and heat	This includes all production and use of fuels, electricity and heat within the main processing sequence which contribute to the production and maintenance of any additional parts for a vehicle. This also includes any upstream and waste treatment processes.
Manufacturing, maintenance and decommissioning of capital equipment	This is applied to any parts of a vehicle. Of particular note are those components in a PEV that are additional to the base-case (such as the battery and motor type). These are only included where the cut-off criteria are met.
Recovery of used products (including reuse, recycling and energy recovery)	Recovery of energy is included to the extent that it reduces the need to source energy for operation. No additional credit is given to these processes.
Distribution/transportation	All distribution and transportation of materials, energy and wastes to and from manufacturing sites.

What we have considered	System Scope
Direct emissions and waste	Refrigerant leakage does not meet cut-off criteria. No other wastes identified.

The diagram on the following page presents a simple flow chart of the components to be assessed in this LCA. The grey boxes indicate parts assumed to be common between both the PEVs and conventional vehicles.

The analysis excludes any charging or refuelling infrastructure: i.e. the manufacturing, construction or operation of electrical charging infrastructure or refuelling stations. The reason for exclusion is that there is still significant uncertainty as to what the infrastructure for PEVs — supposing any were built at all — would look like. This arises because it is not clear:

- What the prevailing infrastructure solution will be (i.e. home-based slow charging versus public fast charge).
- What the population of vehicles versus charging points (required to amortise infrastructure on a per-vehicle-kilometre basis) is likely to be.

Note that because electrical charging infrastructure has not been considered, conventional vehicle fuel supply infrastructure has also been excluded from this study.

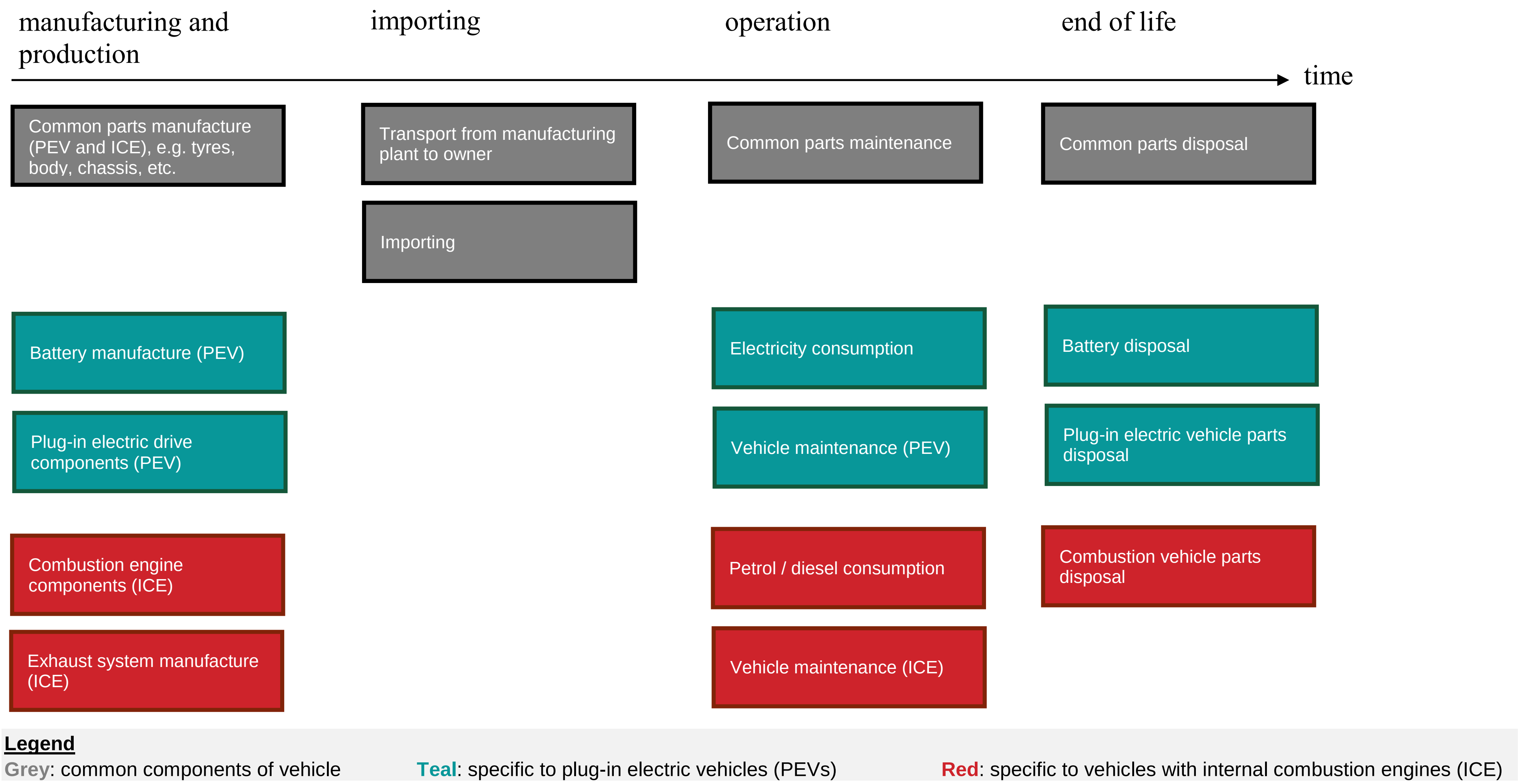

Figure 3 LCA system boundary

2.5 Cut-off criteria

> The cut-off criteria for initial inclusion of inputs and outputs and the assumptions on which the cut-off criteria are established shall be clearly described. The effect on the outcome of the study of the cut-off criteria selected shall also be assessed and described in the final report.
>
> Several cut-off criteria are used in LCA practice to decide which inputs are to be included in the assessment, such as mass, energy and environmental significance.
>
> ***ISO 14044:2006 Section 4.2.3.3.3***

A number of cut-off criteria were used to provide a series of filters with which to make a decision about whether to include a process (or material) in the study. The three main considerations, in order of importance are:

1. Mass
2. Energy
3. Environmental/human health relevance

Making the initial identification of inputs based on mass contribution alone may result in important inputs being omitted from the study. Therefore the project team evaluated each input according to the cut-off criteria listed below. Inputs meeting the cut-off criteria were included and those that failed to meet the cut-off criteria were excluded.

Mass: Inputs that cumulatively contribute more than 1% to the mass input of any one product system being modelled.

Energy: Inputs that cumulatively contribute more than 1% of any one product system’s energy inputs.

Environmental/human health relevance: Inputs that contribute more than an additional 1% to the estimated quantity of each individual data category of any one product’s system.

Mass, energy and environmental/human health relevance cut-offs were determined during the data and life cycle inventory collection process.

2.6 Calculation procedure

In LCA terms, this study has been undertaken using an “attributional approach” to modelling. As described in the ISO 14040 standard, an attributional life cycle assessment “assigns elementary flows and potential environmental impacts to a specific product system typically as an account of the history of the product”. This method of assessment was chosen as the PEV market is one that is only emerging globally and there was limited information as to what the electric vehicle market would look like in New Zealand, even in the near future.

As part of this attributional approach, this study details the assumptions behind any processes used (Section 4), using the best current and publicly available data.

LCA modelling software

Life cycle assessments are conducted using computer-based software which analyses a series of inputs based on the system boundaries (as discussed above) and produces a quantitative result that is reviewed and interpreted.

The LCA was modelled in SimaPro 8.0.5 LCA software. SimaPro stands for “System for Integrated Environmental Assessment of Products”. SimaPro offers its users a generic setup, making it possible to analyse both processes and services. SimaPro 8.0.5 provides a tool to collect, analyse and monitor the environmental performance of products and services. Complex life cycles can be modelled in a systematic and transparent way, following the ISO 14040 series recommendations and is therefore regarded as an eminently suitable tool for this study.

2.7 Impact categories

> The selection of impact categories, category indicators and characterization models shall be both justified and consistent with the goal and scope of the LCA.
>
> The selection of impact categories shall reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration.
>
> ***ISO 14044:2006 Section 4.4.2.2.1***

Two broad categories of impact were considered in this study: (1) impacts upon the environment (notably including contribution to climate change), and (2) impacts upon human health and well-being.

To address these areas of interest, eight specific “impact categories” have been devised. These are summarised in Table 2 along with their relevance and the justification for their inclusion in the study. Detailed descriptions of the eight impact categories are provided in Table 3, with further information also provided in Appendix B.

Table 2 LCA output for areas of interest

Areas of interest	Impact categories	Relevance and justification of inclusion
Environmental related	Climate change (CO_2e) Cumulative energy demand (MJ LHV) Resource (abiotic) depletion (Sb)* Air acidification (SO_2)* Ecotoxicity (CTU_e)*	Of particular interest to New Zealand is the role of carbon emissions and its contribution to climate change impacts. The assessment will provide further context for the transportation sector, particularly from the emerging market of electric vehicles. Another environmental area of concern is with resource depletion and energy requirements to produce vehicles - both impact categories provide an indication of the amount of energy and limited resources is required to produce, operate and dispose of vehicles. The categories of air acidification and ecotoxicity look at potentially negative impacts to natural environments and habitats.
Human health related	Particulate matter ($PM_{2.5}$) Photochemical oxidant formation (C_2H_2) Human health toxicity (CTU_h)*	These impact categories particularly relate to air emissions and their impact to the environment and health. Air emissions are commonly an area of concern particularly for conventional vehicles and tailpipe emissions. Inclusion of these impact categories will provide a life cycle perspective of air emissions from vehicles. Toxicity is a point of interest from the public when considering new technologies in the transportation sector, particularly with electric vehicles, for example the potential impacts on communities affected by mining or the effect on communities from the disposal or recycling of batteries.

* These impact categories have high levels of uncertainty, which the interpretation of results has taken into account. A full discussion on uncertainty analysis is in Section 6.5.

Table 3 Impact category definitions

Areas of interest	Impact Category	Description
Environmental related	Climate change	Total global warming potential (GWP) of the greenhouse gases emitted.
	Cumulative energy demand	The total amount of energy required across the life cycle of the functional unit, measured in MJ Lower Heating Value (LHV).
	Resource depletion*	Abiotic depletion is related to the economically and technically reserves available for, due to inputs in the system. The Abiotic Depletion Factor (ADF) is determined for each extraction of resources (kg antimony equivalents/kg extraction) based on reserves and rate of de-accumulation.
	Air acidification*	Total emissions of acidifying substances (such as sulphur dioxides, nitrogen oxides and other nitrogen compounds) into the air per functional unit. These emissions have the potential to result in acidification of water bodies and vegetation.
	Ecotoxicity*	Potentially affected or disappeared species from toxic stress – particularly on aquatic ecotoxicity impacts as the ecotoxicity potential, measured as comparative toxic units (CTU_e).

Areas of interest	Impact Category	Description
Human health related	Particulate matter	Quantification of the impact of premature death or disability that particulates/respiratory inorganics have on the population, in comparison to $PM_{2.5}$. It includes the assessment of primary (PM_{10} and $PM_{2.5}$) and secondary PM (including the creation of secondary PM due to SO_x, NO_x and NH_3emissions) and CO.
	Photochemical oxidant formation	Total emissions of air polluting substances (such VOC, CO and NO_x) into the air per functional unit which may result in the formation of reactive chemical compounds such as ozone.
	Human health toxicity*	Number of disease cases due to ill-health from non-carcinogenic and carcinogenic impacts, measured as comparative toxic units (CTU_h), which estimates the increase in morbidity in the total human population.

* These impact categories have high levels of uncertainty, which the interpretation of results has taken into account. A full discussion on uncertainty analysis is in Section 6.5.

2.8 Impact category limitations

While it is considered that the eight impact categories chosen form a sound basis for the comparative impact of each vehicle technology, certain limitations and blind spots can be identified. For example, a major proportion of the particulate matter that the conventional technologies produce arises in their operational phase (that is, when they are being driven). The PEVs, by contrast, produce comparatively less (and in the case of the BEV, practically none) while they are being operated. But there is potential for the processes involved in the extraction of materials and in the manufacture of PEVs to produce significant quantities of particulates. An accurate assessment of the impact of these upon human health would require a detailed knowledge of site specifics (e.g., the wind-shed of a mine or factory, its proximity to centres of population etc.). It is not feasible to gather information to this level of detail, and there are other modelling techniques that are better suited for these assessments, such as air quality dispersion modelling. This imposes a limitation upon the comparison of PEV and conventional technologies with regards to particulates, however the impact category selected is useful in outlining the extent of particulates (by mass) emitted from vehicles across its lifecycle.

Similarly, it should be noted that a high level of uncertainty afflicting certain of the impact categories was revealed, mostly due to the absence of scientific consensus as to how these impacts are to be measured. This somewhat compromises the results in the resource depletion, human toxicity, ecotoxicity and air acidification categories. But it is submitted that even given the uncertainties, a meaningful comparison across the technologies was possible (and in many cases, the impact in these categories of each technology was insignificant). At any rate, the uncertainties and their implications are discussed in more detail in Section 6.5.

3 Vehicles in the New Zealand context

This section provides a brief overview of the New Zealand context — the vehicle market and the way in which New Zealanders use their cars. Where relevant, implications for the life cycle assessment study are signalled, and these are included and referred to in the data and assumptions set out in Section 4.

3.1 Global market development of PEVs

Modern-day, commercially-produced PEVs have been available in the marketplace globally, albeit in limited numbers, since 2008. The global fleet of PEVs is still small (less than 1% of the light vehicle fleet), but sales worldwide have been steadily increasing. The International Energy Agency forecasts sales to the order of 110 million PEVs by 2050 (Figure 4) and of that figure, a significant portion are anticipated to be within the Asia/Oceania vehicle market, which includes New Zealand.

At the end of 2014, more than 650,000 PEVs had been sold globally.

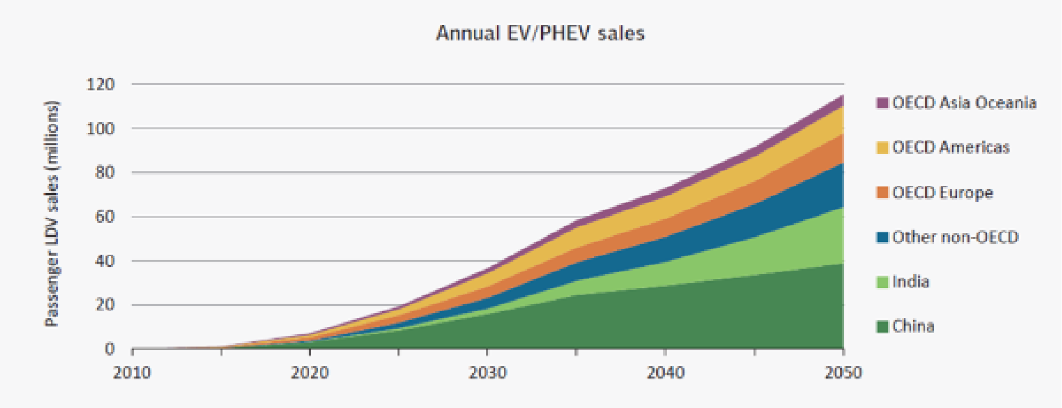

Figure 4 Forecast for annual PEV sales globally[3]

A number of individual countries have shown tremendous growth in their PEV markets. China, the United States and Japan remain the largest markets for PEVs but on a per capita basis, Norway has by far the greatest market share of any other PEV market, with more than 1% of its fleet electrified[4].

3.2 PEVs in New Zealand

Although sales volumes have been low in New Zealand to date, it is poised to be a promising market for PEVs. Some recent strides in policy development and on-the-ground activity locally indicate likely growth in the sector in the coming years — hence the need for full assessment of the environmental implications of the growth of the nascent PEV market.

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[3] International Energy Agency (IEA) *Global EV Outlook 2013*

[4] International Energy Agency (IEA) *Global EV Outlook 2015*

Motorist interest in PEVs has been steadily growing in the last couple of years, though only 660 PEVs[5] were registered in New Zealand as of 31 May 2015.

Given that any new or imported PEV that meets New Zealand road-worthiness criteria may be driven locally, additional PEVs have probably entered the New Zealand fleet through the imported used market over time, though in limited numbers. While it is possible that earlier models of commercially-produced PEVs could have been or yet will be imported into New Zealand, we assumed that the base case for a New Zealand PEV is a brand-new, locally sold model. The earliest model year PEV sold commercially in New Zealand was the Mitsubishi iMiEV, which was released for sale in 2011.

The table below provides a list of all commercially produced PEV products that have been sold in New Zealand or are currently for sale.

Table 4 PEVs available in New Zealand

Make and model	Technology Type	First year available
Audi e-Tron	PHEV	2014
BMW i3 Rex	PHEV	2014
BMW i8	PHEV	2015
Holden Volt	PHEV	2012
Mitsubishi i-MiEV	BEV	2010
Mitsubishi Outlander PHEV	PHEV	2014
Nissan Leaf	BEV	2012
Tesla products (one-off imports only)	BEV	2012

In coming years, with an increase of product diversity and availability globally, it is likely that the PEV product composition in New Zealand will expand over time. It is also fair to assume that increased support for PEVs from governments, councils, utilities and community organisations such as *DriveElectric*[6] will also promote market expansion.

The Government of New Zealand has shown some leadership in adoption of PEVs, starting with a public guide to deploying EVs published by EECA in anticipation of the first market release of EVs in 2012, and a reprieve of road user charges (RUCs) for electric vehicles until 2020[7].

LCA study implications: ***The LCA considers PEVs that are currently available to the New Zealand market (via importing of used or newly purchased vehicles).***

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[5] Ministry of Transport New Zealand (2015)

[6] Drive Electric. http://driveelectric.org.nz/ Accessed 25 June 2015

[7] EECA Energy Wise. *Regulations for electric vehicles* http://www.energywise.govt.nz/your-vehicle/electric-vehicles/regulations Accessed 25 June 2015

3.3 Vehicle fleet of New Zealand

New Zealand has the highest rate of per capita vehicle ownership in the developed world[8]. Vehicle ownership has been gradually increasing since 2000, with passenger vehicle ownership at its highest mark reported in 2013[9] (Figure 5).

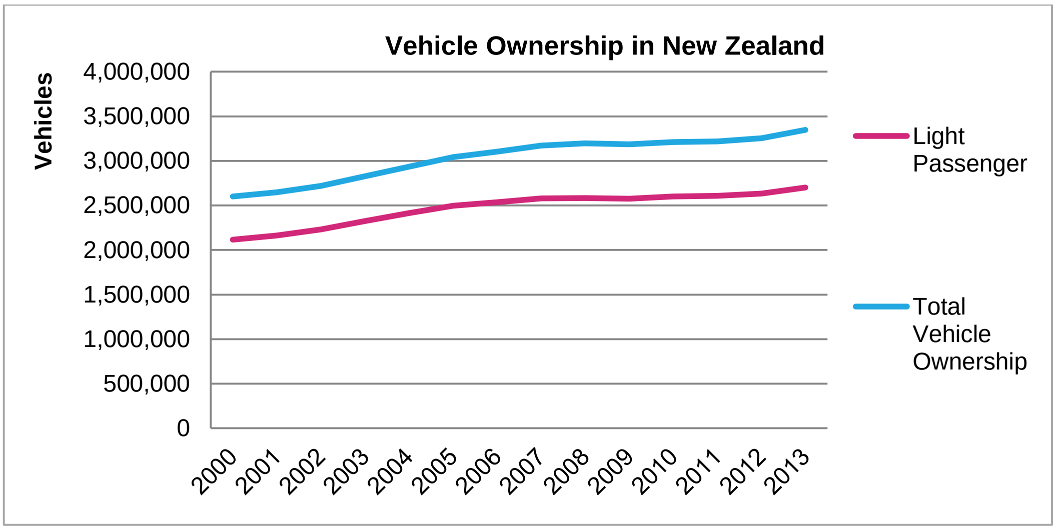

Figure 5 Vehicle ownership over time[9]

The entire New Zealand light vehicle fleet (not including motorcycles) is composed of more than three million vehicles of the following types:

- Passenger cars and commercial vehicles with gross vehicle mass of less than 3,500kg;
- A relatively even split between vehicles sold new in New Zealand (NZ new) as against used imports (the proportion of used imports is high relative to most OECD markets);
- An average vehicle age of approximately 13 years (higher relative to OECD peers such as the USA or Australia) and trending rapidly toward 14 years (per Figure 5 above); and
- Approximately five times as many petrol vehicles as diesel vehicles.

Within the light vehicle fleet, the category of "passenger cars" is most relevant to this life-cycle assessment of PEVs, since passenger cars account for almost 90% of the light vehicle fleet, and the PEV products currently being sold into New Zealand are predominantly passenger cars as well. New Zealand cars cover more than 31 billion kilometres[10] each year producing more than 7 million tonnes of CO_2-equivalent emissions[11] based on their consumption of more than 3 billion litres of fuel[12]. Therefore passenger cars are a logical place to consider PEVs and their potential to improve the environmental credentials of the vehicle fleet.

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[8] OECD Indicators, *Environment at a Glance 2013*. http://www.keepeek.com/Digital-Asset-Management/oecd/environment/environment-at-a-glance-2013_9789264185715-en#page70
[9] Ministry of Transport New Zealand (2013). *TV004 Vehicle fleet numbers*
[10] Ministry of Transport, *The New Zealand 2013 Vehicle Fleet: Data Spreadsheet*, Tab 1.4 to 1.7
[11] Ministry of Transport, *The New Zealand 2013 Vehicle Fleet: Data Spreadsheet*, Tab 1.10
[12] Ministry of Transport, *The New Zealand 2013 Vehicle Fleet: Data Spreadsheet*, Tab 1.9

3.3.1 Vehicles entering the New Zealand fleet

New Zealand logged 187,311 additional car registrations in 2013, of which 55% were used imports[13]. Registrations confirm that the majority of cars were petrol followed by diesel (in a ratio of approximately 10 to 1).

Within the petrol car registrations, the majority (60%) were used imports with an average age and odometer reading of approximately eight years and 75,000km respectively. The most popular engine size for a petrol used import was 1.25-1.5L, whereas for NZ-new petrol vehicles it was slightly larger at 1.75-2.0L (with the most popular new petrol car sold being the Toyota Corolla). Despite the engine size trends, the average test cycle fuel consumptions across all NZ-new and used-import petrol vehicles were quite similar at 7.7L/100km (or 177g/km CO_2e from petrol). Emissions standards of petrol vehicles are improving, with Euro 5 now being the most common level sold for NZ-new petrol vehicles and with the Japanese 05 level being the most common for petrol used imports.

In contrast, the diesel car registrations were dominated by NZ-new vehicles (90%) with engine size of 2.5-3.0L the most popular, whereas there were hardly any used-import diesel cars at all. Given the prevalence of larger engines, the average test cycle fuel consumption and emissions for NZ-new diesel vehicles was also higher at approximately 8.0L/100km (or 208g/km CO_2e from diesel fuel). The Euro 4 emissions standard is the most common level sold for NZ-new diesel vehicles.

PEVs only accounted for 37 registrations in 2013 of which just over half were used imports. Data for 2014 showed a strong shift to NZ-new PEVs (80%) as new products became available; however, the PEV market is still too immature to assess the trajectory of this trend. In 2014 there was a noticeable shift to PHEVs (65% of PEVs) as these became more readily available. The average odometer of used-import PEVs was quite low at only 10,000km approximately, so these could be considered as “almost NZ-new” cars.

Most cars entering New Zealand, whether new or used, originate from Japan. A breakdown of the proportion of vehicles entering the New Zealand market by country is shown in Table 5. It is clear that Japan is the predominant source of vehicle imports to New Zealand, accounting for 95% of second-hand imports in 2013[14]. The exception is for NZ-new diesel vehicles, which are predominantly sourced from Thailand with South Korea and Japan tied for a distant second place.

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[13] New Zealand Transport Agency. NZ Motor Vehicles Registration Statistics 2013.
[14] New Zealand Transport Agency. NZ Motor Vehicles Registration Statistics 2013.

Table 5 Proportion of vehicles entering New Zealand Market, by country

Country	Petrol			Diesel			Electric		
	New	Used	Total	New	Used	Total	New	Used	Total
Japan	46.0%	86.1%	70.1%	12.2%	39.7%	14.1%	87.5%	88.8%	87.8%
Germany	8.0%	8.6%	8.4%	9.8%	33.3%	11.4%	2.8%	0.0%	2.1%
South Korean	14.0%	0.4%	6.0%	14.6%	1.3%	13.7%	0.3%	0.0%	0.2%
Thailand	5.0%	0.1%	2.1%	43.9%	2.7%	41.1%	0.0%	0.0%	0.0%
United Kingdom	3.0%	1.4%	2.2%	2.6%	13.8%	3.3%	0.0%	3.1%	0.7%
United States of America	2.0%	1.8%	2.0%	2.4%	1.5%	2.3%	6.5%	5.1%	6.2%
Rest of world	18.0%	1.4%	9.3%	14.7%	7.5%	14.3%	2.8%	3.0%	2.8%

LCA study implications: ***This study nominates a Japanese mid-sized car as the baseline petrol vehicle as this is representative of a typical New Zealand petrol car. PEVs are also predominantly Japanese and an appropriate mid-sized diesel car from South Korea was considered in lieu of a recognisable Japanese model. NZ-new cars were assumed for all technologies, despite the popularity of petrol used-import cars, as there is seemingly no practical difference in the country of origin or the operational fuel consumption of new vs used petrol cars and given that the overwhelming majority of diesel cars and PEVs are already sold as NZ-new.***

3.3.2 Vehicles exiting the New Zealand fleet

The retirement age (odometer reading) of a vehicle is a crucial parameter in the amortisation of manufacturing and disposal impacts over a vehicle's operating life.

The retirement of light vehicles from the New Zealand fleet occurs at an average age of 20 years and an average odometer reading of 215,000km. For passenger cars (only) the average retirement is 210,000km compared to light commercial vehicles with a higher 260,000km.

More granular data on the retirement of passenger cars (only) was not available, but in the broader category of light vehicles, there is little difference between the retirement ages of NZ-new and used-import vehicles. NZ-new light vehicles retire at an average age of 21 years with an average odometer reading of 232,000km. whereas used-import light vehicles retire at an average age of 19 years with an average odometer of 205,000km (relative to their entry at 8 years and 75,000km). The implied average annual kilometres for the NZ operational phases are remarkably similar at approximately 11,000km for both types.

In light vehicles, there is a more pronounced difference between the retirements of petrol and diesel vehicles. The average retirement for all petrol light vehicles (NZ-new and used-import) occurs at 20 years and 210,000km. By contrast, the average retirement for diesel light vehicles occurs after fewer years (18) but more kilometres (250,000), implying greater annual kilometres for diesel. However, specific retirement data was not available for diesel passenger cars and it should be noted that light commercial vehicles constitute the majority (60%) of the light diesel fleet and are known to have much higher annual travel.

LCA study implications: ***This study nominates a passenger car operational life of 210,000 km for all vehicles based on the above statistics. There is no evidence in the current data to suggest that retirement assumptions should differ between petrol vs. diesel vs. PEV passenger cars of equivalent size, nor is there any substantive difference between the retirement attributes of NZ-new vs. used-import cars. Note that there is little data on the retirement of PEVs due to their lack of market maturity (Section 3.2), and thus well-informed inferences are required.***

3.4 Travel behaviour in New Zealand

Light vehicle travel is the most common mode of transport in New Zealand, with more than 70% of householders using a car to arrive at a destination. The top three destinations of motorists (in order of frequency) are work, social visits and shops[15]. In New Zealand, the automotive industry regards 14,000 kilometres travelled per year [16] for an "average" motorist as standard. However, as this LCA study is being conducted on a per-vehicle basis, it is important to distinguish between the annual travel distances of people as distinct from cars.

The average annual travel distances of NZ light vehicles are presented in Table 6, with passenger cars (87% of the fleet) travelling less distance on average than light commercials (13% of the fleet). The distances for petrol light vehicles vs. diesel vehicles are relatively matched to the distances for passenger cars vs. light commercials respectively, given the relative popularities of either fuel in either fleet segment. Within the passenger car segment, the difference between petrol and diesel is more subdued, and can be attributed to the fact that the most popular diesel cars have larger engines, implying larger vehicles with more utility that tend to get driven further.

Table 6 Annual average travel distances for NZ light vehicles[17]

Fuel type	All Light Vehicles	Passenger Cars	Light Commercials
All Fuels	12,000km	11,500km	15,100km
Petrol only	11,300km	11,200km	*no data*
Diesel only	15,500km	13,800km	

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[15] Ministry of Transport. *Driver Travel, New Zealand Household Travel Survey 2011 - 2014* March 2015

[16] Scott, RA, GV Currie and KJ Tivendale (2012) *Company cars and fringe benefit tax – understanding the impacts on strategic transport targets*. NZ Transport Agency research report 474, http://www.nzta.govt.nz/resources/research/reports/474/docs/474.pdf

[17] Ministry of Transport, *The New Zealand 2013 Vehicle Fleet: Data Spreadsheet*, Tab 8.2a,b,c

Vehicle travel surveys show that there is little difference between weekday and weekend daily distances for light vehicles in New Zealand. For all days of the week, the median distance is 24km per day, with 75% of days involving less than 48km driven and 95% of days less than 125km (see "*All Light Vehicle Travel*" in Figure 6).

As you would expect, there is a difference in average travel distance between vehicles in urban and rural areas in New Zealand. The median vehicle distance for main urban areas is 22km per day with 75% of days less than 42km, whereas for rural use, the median is 35km per day with 75% of days less than 67km (approximately 60% higher on both metrics – see Figure 6). To put this finding in context, approximately 78% of the population are considered to live in "urban" or "secondary urban" areas (communities or city centres accounting for more than 10,000 people), with the remainder in rural areas[18].

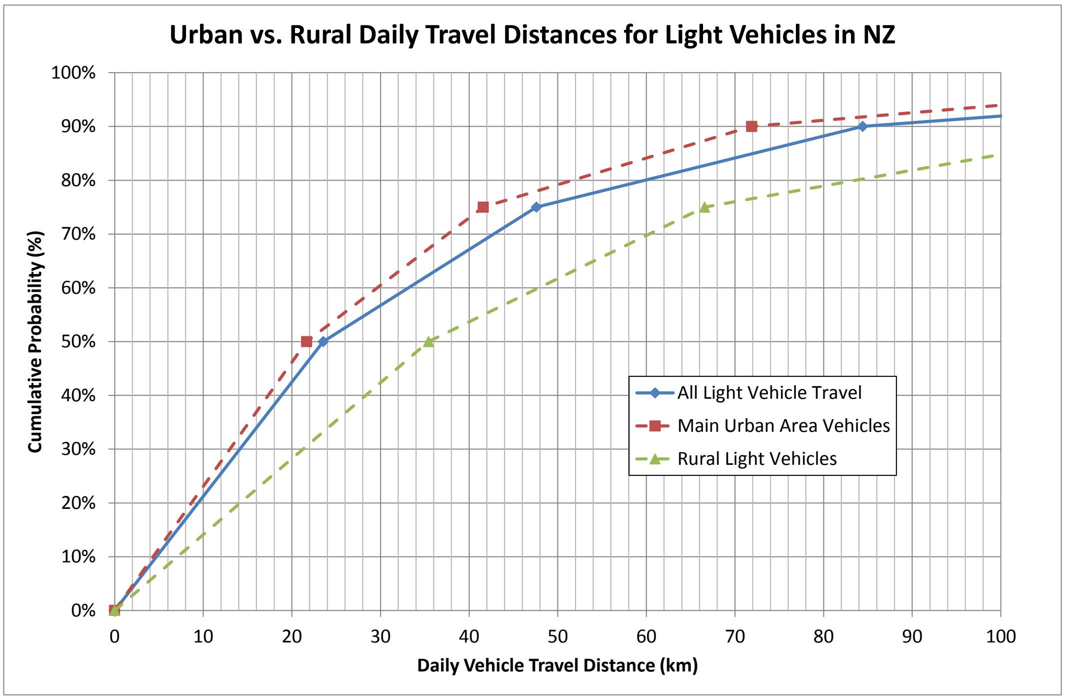

Figure 6 Travel distances for light vehicles in New Zealand[19]

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[18] Statistics New Zealand. Urban/Rural Migration. http://www.stats.govt.nz/browse_for_stats/population/Migration/internal-migration/urban-rural-migration.aspx Accessed 2 May 2015

[19] Ministry of Transport. *Driver Travel, New Zealand Household Travel Survey 2011 - 2014* March 2015

LCA study implications: ***Annual travel distances are not directly relevant to the LCA since the functional unit is on a per-km basis and the manufacturing/disposal footprint is amortised over the full vehicle life (not annually). But for context we overlook the difference in annual travel between petrol vs. diesel vehicles as we attribute this to different vehicle/engine sizes and assume that equivalent petrol vs. diesel vehicles travel similar distances. We also assume that BEVs (as well as PHEVs) support the same annual travel since 95% of days are within the range of current BEV products and these tend to deploy in urban areas where typical trip lengths are shorter and there are more opportunities for recharging.***

For PHEVs the distribution of daily vehicle travel distances govern the assumed proportion of electric- vs. petrol-fuelled kilometres and this is discussed in more detail in Section 4.3 (vehicle operation and use).

3.5 Vehicle energy sources

Liquid fuels – petrol and diesel

Liquid fuels (e.g. petrol) are the predominant form of energy used for road transport. In terms of overall energy consumption, in 2013 New Zealanders used almost twice the amount of petroleum-based fuels (46%) as they did electricity (26%)[20]. In New Zealand, petrol fuel consumption is slightly decreasing, while diesel consumption is on the rise. Petrol is the leading fuel for the light passenger vehicle sector, with 94% of total transport sector petrol consumption attributable to light vehicles. Diesel fuel is more commonly consumed in the commercial segment of the transport sector, with only 16% of its total consumption in light passenger cars[20].

New Zealand has large reserves of oil and produced 35,500 barrels of oil per day on average in 2013. In 2013, Refining New Zealand produced an estimated 64% of domestically consumed petroleum products, although a large-scale growth project due to be completed at the end of 2015 may increase that figure. However, as it stands, New Zealand is a net importer of petroleum, with the largest portion of its imported crude oil coming from the Middle East (59%)[20].

LCA study implications: ***This study, where public data is available, accounts for the particular life cycle impacts associated with petrol and diesel fuel. However, limited data regarding processes and pollution associated with fuel refining in New Zealand is available. However, given that New Zealand is a net importer of petroleum and assuming that the refining occurring in New Zealand is largely equivalent to the process undertaken globally, global data from the ecoinvent v3.1 database for petrol and diesel has been used as an appropriate proxy. This has been accounted for in the operational stages of the conventional petrol and diesel engine vehicles, and the PHEV.***

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[20] Ministry of Business, Innovation and Employment. (2013) E*nergy in New Zealand 2014.Pg 4.*

Electricity

In 2013, New Zealand generated almost 42,000 GWh of electricity and consumed close to the equivalent amount (including losses for transmission and distribution). Consistent with other similar markets, household electricity consumption is in decline, with a 1.7% decrease in residential consumption to approximately 12,000 GWh in 2013[20]. New Zealand is one of few countries in the world whose energy generation is predominately renewable, with around 80% of energy generation in 2014 originating from renewable sources such as geothermal, hydro, biomass and wind. The Government of New Zealand declared that it intended to see 90% of the country's electricity generated from renewable sources by 2025 and to date, it appears to be on track to meet this target[21]. However, as per this study's stated limitations, the forecast future emissions intensity of the NZ grid is not accounted for.

LCA study implications: ***The study has accounted for the current electricity mix in New Zealand (2014), and has applied this across the lifetime of the vehicle. Given that New Zealand has a target to further increase renewable energy generation, this assumption provides a conservative estimate of PEV greenhouse gas emissions benefits over the life of the vehicle.***

Vehicle Emissions

Despite the number of cars in New Zealand, passenger vehicle greenhouse gas emissions are declining, consistent with trends around the world[22]. This is further described in Section 4.3).

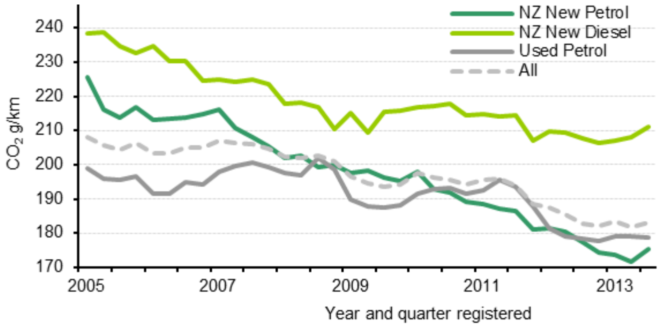

Figure 7 Light vehicle registrations, CO_2 emissions[9]

In New Zealand, the transport sector remains the largest source of greenhouse gas emissions, representing 44% of emissions from the whole energy sector. Specifically, road transport combustion emissions represented 40% or 12,688 kt CO_2e in 2013. However, growth of the NZ PEV market may help reduce these vehicle emissions. The relevant energy source emissions factors are presented in Table 7.

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[21] Ministry of Business, Innovation and Employment. (2014) *Record Renewables in 2014.* *http://www.med.govt.nz/sectors-industries/energy/news/record-renewables-in-2014 Accessed 21 May 2015.*

[22] New Zealand annual vehicle fleet statistics (2013), accessible for http://www.transport.govt.nz/research/newzealandvehiclefleetstatistics/

Table 7 Emissions factors for relevant LCA fuels in New Zealand[23]

Emissions 2013	Unit	Amount
Liquid fuels		
Premium petrol	kt CO_2e/PJ	66.72
Regular petrol	kt CO_2e/PJ	66.51
Diesel	kt CO_2e/PJ	69.57
Electricity		
Generation emission factor	kt CO_2e/GWh	0.14
Consumption emission factor	kt CO_2e/GWh	0.16
Annual generation	GWh	41,867
Annual consumption	GWh	38,696

LCA Study Implications: ***Given the trend of vehicle emissions in NZ is consistent with those from a global market perspective, vehicle emissions assumptions based on global market standards have been used for this study. This is described in detail in Section 4.3.***

3.6 Lithium-ion battery materials

There is currently a general misunderstanding or misconception of the technology, likely due to the immaturity of the PEV market. For example, lithium, which is a common element in modern-day PEV batteries is neither a rare earth mineral nor a precious metal, despite public alarm that increased used of PEVs could result in diminished rare earth mineral/precious metal supply or social mining impacts (for further details refer to Section 5.3.3).

Lithium-ion batteries are considered well suited for vehicle propulsion applications, given their high energy density and cycle life, among other favourable qualities. Within the general category of lithium-ion batteries used for PEV applications, there are many chemistries with markedly different manufacturing processes and raw material inputs. For example, here is a list of lithium-ion battery cells that are used in some well-known PEV products:

- Mitsubishi/GS Yuasa – large format prismatic (30Ah), manganese-oxide cathode (LMO)
- Nissan/AESC – large format pouch (33Ah), nickel/manganese/cobalt-oxide cathode (NMC)
- Holden/LG Chem – large format pouch (15Ah), manganese-oxide cathode (LMO)
- Honda/Toshiba – large format prismatic (20Ah), titanium-oxide cathode (LTO)
- BYD – large format prismatic (10Ah), iron-phosphate cathode (LFP)

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[23] Ministry of Business, Innovation & Employment, *Energy Greenhouse Gas Emissions 2013*

- Tesla/Panasonic – small format cylindrical (3.3Ah), nickel/manganese/cobalt-oxide (NMC)

Other common metals in lithium-ion battery cell constructions include aluminium, steel and copper.

Making apples-with-apples LCA comparisons of conventional and PEVs is somewhat clouded and all the more so in the public understanding due to confusion over definitions and applications of “rare earth” and precious metals, as opposed to industrial materials such as steel, aluminium, copper, nickel, manganese, titanium, and metal salts (of such as lithium, magnesium, etc.) that are plentiful and produced in many locations around the world.

Despite their name, lithium constitutes only a small proportion of lithium-ion batteries (the lithium salts dissolved in the electrolyte comprise approximately 1-2% of the total battery weight) relative to other metals. Neither lithium nor any of the other materials mentioned above are classified as “rare earths” – the so-called rare earth metals are a group of fifteen lanthanides plus scandium and yttrium. Contrary to popular misconception, these are rarely (if ever) used in lithium-ion batteries[24], and then only in minute quantities. By contrast, the nickel metal hydride (NiMH) batteries commonly found in conventional hybrid vehicles contain significant quantities of the rare-earth lanthanum — doubtless the source for much of the confusion.

Conventional vehicles contain similarly minute quantities of rare earth materials, but frequently also contain precious metals (e.g. platinum, palladium, rhodium, etc.) that serve as oxidation catalysts in the catalytic converter (part of a conventional vehicle’s exhaust system).

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[24] Plug-in Electric Vehicle Resource Centre (2015) “About Batteries”, http://driveclean.ca.gov/pev/

4 Data and assumptions

> Data selected for an LCA depend on the goal and scope of the study. Such data may be collected from the production sites associated with the unit processes within the system boundary, or they may be obtained or calculated from other sources. In practice, all data may include a mixture of measured, calculated or estimated data.
>
> ***ISO 14044:2006 Section 4.2.3.5***

The following section provides a description of the kinds data utilised and the assumptions applied by this LCA study[25]. This section is divided into the four life cycle stages of:

1. manufacturing and production;
2. importing;
3. operation and use; and
4. end of life.

Each life cycle stage used specific data and assumptions as appropriate to the New Zealand context. A breakdown of the data inventory applied for this study is included in Appendix C.

4.1 Stage 1: Manufacturing and production

In collecting data for the manufacturing and production phase of vehicles (both conventional and electric), a number of assumptions were applied.

A literature review of any existing high-quality and publicly available life cycle inventory data was conducted (this is discussed in Section 1.4). Based on the literature review, the life cycle inventory datasets in ecoinvent v3.1 for conventional and PEVs were chosen, and modified to suit the New Zealand context. Table 8 provides a description of the components considered in these datasets.

Table 8 Components of vehicles

First-order component	Conventional vehicles	PEVs
Glider	Body and frame, chassis, axle, brakes, wheels and tyres, interior fittings and electronic equipment, etc.	Body and frame, chassis, axle, brakes, wheels and tyres, interior fittings and electronic equipment, etc.
Drivetrain	Internal combustion engine, gearbox, cooling system, fuel system, exhaust system, etc.	Electric motor, gearbox, controller, charger, cables, cooling system, etc. (Note: PHEVs also include the relevant fuel, engine and exhaust components.)

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[25] In line with the ISO 14040 standard, this section describes the Life Cycle Inventory phase of the LCA study.

First-order component	**Conventional vehicles**	**PEVs**
Propulsion Battery	None	Li-ion battery

The following section describes the assumptions and modifications applied to ecoinvent v3.1 data for the purposes of this study.

Conventional vehicle considerations

The original ecoinvent v3.1 dataset was based upon a conventional ICE vehicle, the Volkswagen Golf A4 (2008), and subsequently updated to the Volkswagen Golf VI (2009-2013). Upon review of the data, it was found that this dataset is the most comprehensive for conventional vehicle components and material breakdowns for use in this study. The specific make and model in question is also a good fit with the generic conventional vehicle assumed for this LCA study.

This study has utilised the existing data provided by ecoinvent v3.1. We have adjusted to scale the glider and drivetrain of the conventional vehicle to match our baseline of a small-sized Japanese imported vehicle in the New Zealand market. The scaling has been based on the weight of the vehicle, using the best publicly-available data. Our baseline selection of Japanese conventional and PEVs was described in the contextual discussion in Section 3.

Table 9 Weight comparison of component parts – conventional vehicle

Study	***Ecoinvent v3.1***		***This study***	
First-order component	**Volkswagen Golf VI - Petrol (2009-13)**	**Volkswagen Golf VI - Diesel (2009-13)**	**Japanese mid-sized petrol car (2015)**	**Mid-sized diesel car (2015)**
Glider	913 kg	913 kg	856 kg	872 kg
Conventional vehicle drivetrain	321 kg	401 kg	429 kg	490 kg
Total	**1234 kg**	**1314 kg**	**1285 kg**	**1362 kg**

It should also be noted that whilst ecoinvent v3.1 data is derived from a car manufactured in Europe, similar manufacturing processes and efficiencies exist in Japan. Therefore, the following assumptions have been made regarding use of the dataset:

- Given that manufacturing processes and efficiencies are similar between Europe and Japan, electricity consumption in the direct manufacturing processes of the vehicle was modified to be from Japan only.
- This is also applicable to suppliers of manufacturing parts to the vehicle, as the larger Japanese manufacturers are vertically integrated companies that own most of their supply chains, which are also based in Japan.
- The weights of components (as described in Table 9) have been pro-rated based on available manufacturing data specifications of similar sized vehicles to the Volkswagen Golf VI.

- However, since Japanese manufacturers tend to source raw materials globally the assumptions regarding raw material inputs from ecoinvent v3.1 were left unchanged.

New vs used conventional and PEVs

NZ-new cars were assumed for all technologies, despite the popularity of petrol used-import cars. While there may be some difference in the fuel consumption and tailpipe emissions of new versus used petrol cars, it would not be appropriate to compare new PEVs and diesel cars (the overwhelming majority of PEVs and diesel cars are sold as NZ-new) with significantly older petrol, used-import cars.

For further discussion on this point refer to Section 3.3.

Battery considerations in PEVs

The ecoinvent v3.1 dataset includes a data inventory for batteries for use in PEVs. The battery nominated is a $LiMn_2O_4$ chemistry (referred to commonly as “lithium-ion manganese oxide” or LMO battery), which is consistent with the PEV batteries used by several the manufacturers of several PEVs currently in the New Zealand market. The specific lithium-ion cell underlying the ecoinvent v3.1 dataset is a Kokam 100Ah pouch cell, which is an appropriate cell construction based on current PEV products, and different to the much smaller mAh-size lithium-ion cells more commonly found in consumer electronic devices such as mobiles phones or laptops.

There are two data issues upon review of background reports for the ecoinvent v3.1 battery. Firstly, there is no allowance for a cooling system within the materials comprising this battery pack[26]. However, we assume this cooling system was adequately captured under the “drivetrain” category (see Table 8).

Secondly, regarding the recycled content within new batteries, ecoinvent v3.1 data accounts for the average market recycling rates for certain input materials, namely metals such as copper, aluminium and steel (or iron). However, it remains to be seen whether a New Zealand large-format battery recycling industry will develop and whether it will return recycled battery materials to Asia for the manufacturing of new PEV batteries. It may be the case that further recycling and re-use of used batteries could be greater than standard industry practice for primary metals.

Therefore, as a conservative assumption, this study assumed that only the current commodity market levels of recycled materials (for copper, aluminium and steel) are incorporated in new batteries (whether for the original vehicle, or for replacement batteries). A sensitivity analysis has been conducted regarding further recycling potential from PEV batteries, and is included in Section 6.2.

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[26] Batteries heat up, and require cooling, during recharging. Depending on whether the battery is air-cooled or liquid-cooled, a battery normally contains metallic or plastic components to manage the flow of coolant throughout the pack.

Plug-in electric vehicle considerations

The ecoinvent v3.1 dataset also contains a system process for PEVs. The system process was compiled by the work done by Del Duce et al (2015). The PEV was based on a virtual Volkswagen Golf VI, with the inclusion of electric vehicle components (described in Table 8) from Swiss manufacturer Brusa.

For this study, battery weights were specifically obtained from vehicle manufacturers, and the unit processes attributed to the battery were pro-rated from ecoinvent v3.1 data. Unit process data for the remaining components (glider and drivetrain) were pro-rated based on estimated component weight specifications for an equivalent Japanese PEV.

Table 10 Weight comparison of component parts – electric vehicle

Study	***This study***		
First-order component	**Japanese mid-sized petrol car (2015)**	**Mid-sized BEV car (2015)**	**Mid-sized PHEV car (2015)**
Glider	856 kg	1157 kg	1146 kg
Conventional vehicle drivetrain	429 kg	n/a	263 kg
Electric vehicle drivetrain	n/a	87 kg	114 kg
Battery	n/a	290 kg	198 kg
Total	**1285 kg**	**1534 kg**	**1721 kg**

Recycled content of vehicles

The data used, predominantly from ecoinvent v3.1, accounts for average global market recycling rates for certain metals such as copper, aluminium and steel (or iron). Recycling rates vary depending on the type of material.

Aluminium is known to be an energy- and emissions-intensive material to produce, but depending on the specific grade of aluminium, can also be highly recyclable. The ecoinvent v3.1 dataset contains two types of aluminium that are especially significant in this study’s outcomes:

- Cast aluminium alloy (approximately 85% recycled input) – is used primarily in the manufacturing of ICE drivetrain components (e.g. engine) and therefore is a significant contributor to the total weight of the petrol, diesel and PHEV vehicles. However, this material is relatively benign environmentally due to its high recycled content (since aluminium casting processes are well-suited to the use of recycled material).
- Wrought aluminium alloy (approximately 20% recycled input) – is used primarily in the manufacturing of the PEV components (e.g. battery, motor, inverter, etc.). While it does not contribute as much total weight as the cast alloy above, it is a far more sensitive material due to its low recycled proportion (higher-strength wrought aluminium alloys are less-suited to recycling due to the potential effects of alloy impurities). However, it should

be noted that since the ecoinvent v3.1 PEV dataset is based upon the work of a specific boutique manufacturer (Brusa), the proportion of wrought as opposed to cast aluminium may be overstated. Mass-produced PEV componentry is more likely to use cast aluminium[27].

Copper is a valuable commodity, the mining of which can produce significant toxic impacts, but it is also potentially highly recyclable. Copper is used in the manufacture of both conventional and PEVs, but both types of PEVs (i.e. BEVs and PHEVs) contain up to 5-6 times more copper than conventional vehicles incorporated in their lithium-ion batteries (e.g. in the anode) and various types of copper drivetrain wiring (e.g. power cables and motor windings).

The ecoinvent v3.1 dataset assumes that only 35% of input copper comes from recycled sources, which is consistent with current market practices as cited by the International Copper Association. However, numerous literature sources also suggest that such low recycling rates cannot be sustained into the future given forecast growth in copper demand relative to known primary reserves. A key contributor to growth in copper demand is the growing markets for hybrid vehicles and PEVs, causing manufacturers such as Toyota[28] to pioneer new copper recycling techniques and establish higher recycling standards to ensure the sustainability of their products. This suggests that the ecoinvent v3.1 assumptions for copper may be too pessimistic looking into the future of PEVs. The sensitivity to this is tested in Section 6.2.

The following tables provide a summary of the approximate extent of recycled material in each of the four vehicle types, based on the main materials for all four vehicle technologies which are aluminium, copper and steel (from iron).

Table 11 Recycled material content in vehicles, by metal type

	Aluminium (kg)		**Iron (kg)**		**Copper (kg)**	
Vehicle type	**Recycled**	**Primary**	**Recycled**	**Primary**	**Recycled**	**Primary**
BEV	13.3	49.6	265.7	1,075.6	21.3	40.2
PHEV	141.6	72.8	284.5	1,187.0	19.2	36.1
Conventional petrol engine vehicle	212.6	37.7	214.2	941.5	3.5	6.6
Conventional diesel engine vehicle	242.4	42.8	222.1	982.9	3.7	6.9

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[27] Many of the electric vehicle drivetrain components in the Nissan Leaf, for example, are actually manufactured by casting processes at the Nissan Casting Australia Plant (NCAP).

[28] http://blog.toyota.co.uk/toyota-helps-make-copper-recycling-possible

Table 12 Approximate recycled and primary material content in vehicle, total by percentage

Vehicle type	Recycled	Primary
BEV	21%	79%
PHEV	26%	74%
Conventional petrol engine vehicle	30%	70%
Conventional diesel engine vehicle	31%	69%

Based on Table 12, the LCA model assumes that all vehicles (whether conventional or plug-in electric) have approximately 20-30% overall recycled content, but this proportion varies significantly between aluminium, copper and steel for the four technologies.[29] The model considered the recycled content of these materials in two ways – (1) taking into account the impact associated with reprocessing scrap material into useful product, and (2) avoiding the impacts from the primary material that would have otherwise been used.

4.2 Stage 2: Importing

Japanese importing assumptions

New Zealand no longer manufactures, at mass production scale, any new vehicles, and therefore almost all vehicles entering the market are imports. These imports comprise both new and used vehicles. Current industry market data (2014) shows that 70% of all conventional petrol engine vehicles and 88% of all PEVs entering the New Zealand market (both new and used) are Japanese.

Therefore, this study assumes that the origin of the chosen vehicles was Japan. It is assumed that vehicles are transported via ship. The estimated distance from Japan to New Zealand is assumed to be approximately 9,500km (Tokyo to Wellington terminals).

4.3 Stage 3: Operation and use

The following assumptions were made with regard to the operation of the vehicle. ‘Operation’ includes the fuel and energy used to drive the vehicle, as well as maintenance activities.

NZ electricity mix assumptions

The study utilised a modified version of the New Zealand electricity unit processes[30] from the Australasian System Process Life Cycle Inventory (LCI). This system process is based upon an attributional model and uses Australian default settings for New Zealand power in 2007.

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[29] There may be further recycling content in the form of plastics and other materials, but are much smaller by weight.

[30] AusLCI (2010) *Electricity, New Zealand, low voltage/NZ S*

For the purposes of this study, energy production and emission values were updated to 2013 levels, utilising publicly available data (described below) for electricity generation, greenhouse gas emission and air pollutant data. Where data is unavailable, Australian NPI pollution data was used as a proxy. The following sources of data were used in this study:

- **Electricity mix by fuel type**: the composition of the electricity mix was obtained from government data for 2013 (the most complete emissions and electricity generation dataset available).

  Data reference: New Zealand Ministry of Business, Innovation and Employment (2015) *Quarterly Electricity Graph and Data Tables*, Table 2
- **Energy transformation for electricity**: data for electricity generation using coal and gas was obtained from government data for 2013.

  Data reference: New Zealand Ministry of Business, Innovation and Employment (2015) *Coal Data Tables*, and *Gas Data Tables*
- **Carbon and pollutant emissions from energy generation**: data for carbon and pollutant emissions (CO_2, CH_4, N_2O, CO, NO_x, NMVOCs, and SO_2) were obtained from government data for 2013. These were direct emissions from the electricity generation sector for various fuels, including gas, coal and geothermal sources.

  Data reference: New Zealand Ministry of Business, Innovation and Employment (2015) *Energy Greenhouse Gas Emissions (2013 Calendar Year Edition)*, web tables

Full details of the unit processes and data flows for electricity considerations are included in Appendix E.

Fuel assumptions

New Zealand imports nearly all of its transport fuel. Some of this is as crude oil, which is then refined by The New Zealand Refining Company at the Marsden Point refinery. Refined products include petrol and diesel products, which are used as vehicle fuels. The New Zealand Refining Company is the only oil refinery in the country, and the small remainder is refined internationally with the refined products imported directly to New Zealand.

Although there is data regarding amounts and proportions of imported refined oil, and refined oil in New Zealand, there is very limited publicly available data regarding direct emissions from the refinery processes occurring in New Zealand. Given this limited information, average global petrol and diesel life cycle inventory data from ecoinvent v3.1 has been used.

Vehicle fuel and electricity consumption rates

Vehicle fuel and electricity consumption rates are arguably the most influential parameters in this study, since vehicle LCA comparison results are normally dominated by the operational stage in a vehicle's overall life, and all aspects of the operational stage are proportional to these consumption rates.

The fuel and electricity consumption rates adopted in the model for the four vehicle technology types are shown in Table 13. These figures are derived from official vehicle testing cycle results but are also adjusted upwards to account for various real-world driving effects that tend to increase them in practice.

Table 13 Fuel and electricity consumption rates (assumed real-word driving effects) for the four vehicle technology types

Efficiency/emissions	**Conventional petrol engine vehicle**	**Conventional diesel engine vehicle**	**BEV**	**PHEV**
Petrol (L/100km)	8.40	-	-	6.44
Diesel (L/100km)	-	7.13	-	-
Electricity (kWh/100km)	-	-	22.0	20.0

The petrol, diesel and electric vehicle values are derived from standard Australian Design Rules (ADR) 81/02 test cycle results for specific makes/models that are representative of the Japanese mid-sized car benchmark for this study. ADR 81/02 test cycle results for the PHEV were not suited to this study's modelling methods, so the PHEV data was derived from certified US government testing of equivalent vehicles on a similar test cycle[31]. This allowed the PHEV fuel and electricity rates to be input separately but then weighted based on a factor derived from NZ real-world driving statistics (the PHEV data presented in Table 13 is unweighted, but also subject to the utility factor parameter described below).

For all four technologies, a real-world consumption scaling factor of 1.273 was applied to increase the standard test values[32], and in the case of the PHEV this also adjusted the utility factor, as discussed below. The values in Table 13 include this real-world scaling factor, which was derived from NZ fleet statistics that compared real-world fleet fuel consumption to the average test-cycle consumption rates of the current NZ light vehicle fleet registrations. This real-world scaling factor is also consistent with international observations.[33]

For the petrol, diesel and PHEV, the fuel consumption rate is as measured at the fuel pump / filling station. For the PHEV and BEV, the electricity consumption rates are as measured at the AC charging socket; thus, these are all-inclusive figures that include net battery energy with regenerative braking as well as net recharging losses. The underlying data suggests a net AC to DC electrical recharging efficiency in the range of 85-90% for both types of electric vehicle[34],

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[31] The Urban Dynamometer Driving Schedule (UDDS) has some subtle differences to the ADR 81/02 but was judged similar enough (well within the bounds of uncertainty for this study) to be an appropriate data point for the PHEV figures (which are subsequently adjusted via the NZ-derived utility factor, which is also subject to further uncertainty).

[32] New Zealand fleet statistics (Ministry of Transport, 2013) show an average test-cycle fuel consumption for petrol vehicles of 7.72L per 100km (Tab 7.72), compared to an average real-world fuel consumption for petrol vehicles of 9.83L per 100km. The ratio is 1.273:1.

[33] International Council on Clean Transportation

[34] Rigorous testing and data collection by the US Government's Advanced Vehicle Testing Activity (http://avt.inl.gov) for the makes/models in question showed battery round-trip efficiencies of 98% and on-board charger efficiencies of 87-91%, providing net results of 85-89%.

but this factor is listed here for guidance only, as it is not an input to the LCA model.

Electricity utility factor of PHEVs

PHEVs are powered by two sources of energy (electricity and petrol/diesel) and typically have two distinct modes of operation (electric-only and hybrid). Assuming a PHEV has been fully recharged before use, a typical trip commences in electric-only mode and continues up to the limit of the all-electric range (AER), and then switch to petrol- (or diesel-) fuelled hybrid mode for any further distance travelled. Therefore, a "utility factor" must be calculated to determine the split of electricity and petrol used by a PHEV over its lifetime.

The utility factor is a complex parameter based on the real-world AER of PHEVs, typical vehicle daily travel distances and the frequency of vehicle recharging[35]. Based on rigorous testing of various PHEV models by the US Department of Energy, the real world AER for an equivalent (mid-sized) PHEV car in New Zealand was determined to be 60km (also including the real-world adjustment factor described above). Comparison of this performance against the daily vehicle travel statistics in Section 3.4 derived a real world electric utility factor assumption of 74% for the base case PHEV when averaged over its full operating lifetime.

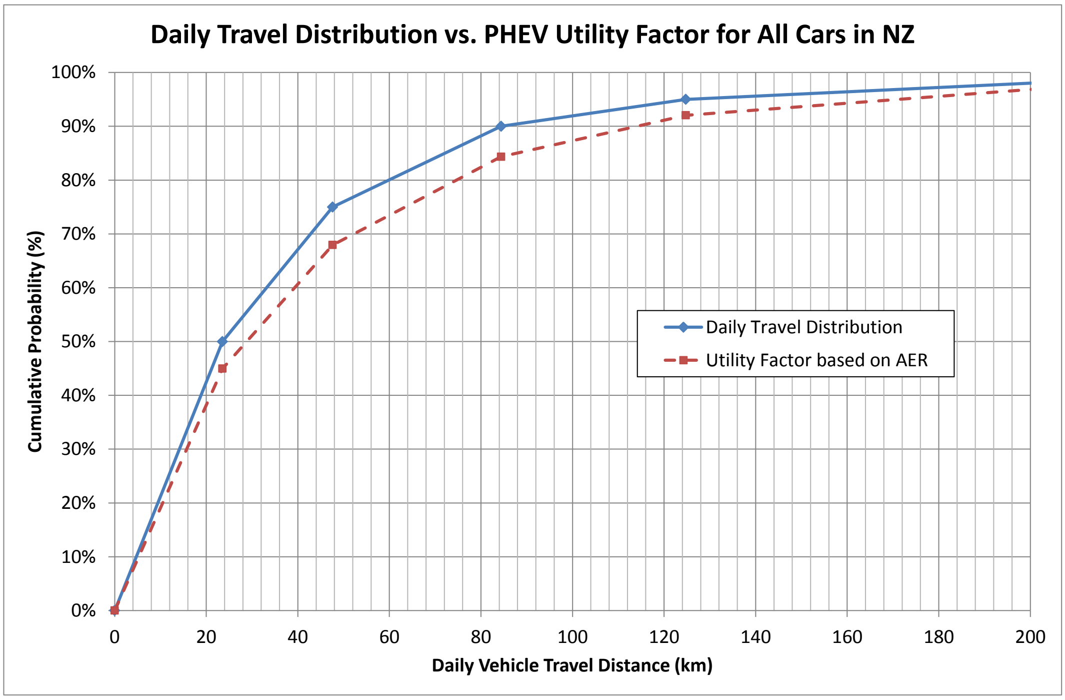

Figure 8 PHEV Utility Factor for cars in New Zealand[36]

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[35] Gonder and Simpson (2007) *Measuring and Reporting Fuel Economy of Plug-In Hybrid-Electric Vehicles*, Proc. World Electric Vehicle Association Journal, volume 1.

[36] Derived in this study from the travel dataset underlying Figure 8.

Emission standards of standard vehicles

New Zealand has rules and regulations regarding the tailpipe emission standards of vehicles entering the country. These regulated tailpipe emissions include toxins such as carbon monoxide and fine particulates in the case of diesel vehicles. The most updated set of regulations is the *Vehicle Exhaust Emissions Amendment 2013*, based on the Land Transport Rule: Vehicle Exhaust Emissions 2007. These regulations state the emission standards required of a vehicle depending on import date, and the manufacture date of the vehicle. Currently, any diesel and petrol vehicle imported with a manufacture date from 2013 onwards needs to meet emissions standards of EURO 5 and Japan 05.

Therefore, given this study primarily assesses relatively new vehicles (whether conventional or plug-in electric), the study assumes that all petrol-based vehicles have EURO 5 levels of tailpipe emissions. Given that EURO 5 levels of tailpipe emissions are of the highest standards in the NZ market, the LCA compares PEVs against the relatively ‘cleanest’ conventional vehicles available on the market. Furthermore, due to a lack of suitable data, no adjustment was made for the real-world tailpipe emissions rates from conventional vehicles (which can be significantly higher than test cycle rates), so the overall net benefits of PEVs in this regard are estimated conservatively in this study.

For the PHEV, tailpipe emissions were pro-rated to those of a petrol conventional vehicle, by the percent of fuel consumed over if its lifetime. This simplifying and conservative assumption was made due to a lack of suitable PHEV-specific data.

Vehicle lifetime

For the purposes of this study, vehicle lifetime is measured in kilometres travelled by the vehicle over its *full* life. This is irrespective of the number of owners of the vehicle over its lifetime, or the vehicle’s country of operation during different stages of its life. NZ fleet data indicates that passenger cars exit the fleet (are disposed of at end of life) with 210,000 km on the odometer. Therefore, a vehicle life of 210,000 km has been assumed for all vehicle technologies (conventional and plug-in electric). Note that there is little data on the retirement of PEVs due to the lack of maturity in their market (refer to Section 3.2), and thus well-informed inferences are required.

Battery replacement

The durability of batteries used in PEVs is continually improving. With 2nd-generation PEV products now entering the global market, it is increasingly suggested that the batteries will last the life of the car. However, in the case of the New Zealand market, the average vehicle life is relatively long (20 years and 210,000km as described above) and many vehicles entering the market are used-imports with an uncertain usage history.

Current BEV products in the US market come with battery warranties of eight years or 160,000km (whichever comes first) and several BEV manufacturers have stated on public record that their batteries have a life expectancy of 10 years (or more) given acceptable rates of degradation. Given that in New Zealand the vehicle life significantly exceeds this battery life expectancy, and that the battery is the sole source of propulsion for the car, this study assumed that at least one BEV battery replacement will occur during the life of the vehicle in New Zealand. A further battery replacement is considered as a sensitivity case.

Current PHEV products in the US market also come with battery warranties of eight years or 160,000km (whichever comes first), but public statements by PHEV manufacturers generally suggest these batteries are expected to last the life of the car given acceptable rates of degradation. This is because in a PHEV the battery is not the sole source of propulsion and the hybrid control system can alleviate the battery load if necessary over time. Therefore for New Zealand this study assumed in the base case that no battery replacement was required during the life of PHEVs (but a single battery replacement is considered as a sensitivity case).

All battery replacements for both BEVs and PHEVs are assumed to occur within the New Zealand phase of a vehicle’s life (not Japan). All replacement batteries are assumed to be manufactured in and imported from Japan, and any used batteries are assumed to be disposed of in New Zealand.

4.4 Stage 4: End of life

Treatment at the end of life of the vehicle has also been considered in this study. This accounts for the disposal and waste treatment processes applied to the entire vehicle, including its key components.

The study assumed that vehicles at their end of life will be scrapped for recycling of materials, with the remaining non-useful waste being disposed of. This applies to vehicle gliders and drivetrains for both conventional and PEVs. This is common practice occurring in New Zealand today.

Treatment of batteries

There is currently no market for recycling PEV batteries in New Zealand due to the currently low number of relatively-new PEVs and the lack of used batteries as a result. Globally, however, there is a growing industry for battery recycling, with a particular focus on the emerging PEV market. There are two methods applied for battery recycling – a hydro-metallurgical and pyro-metallurgical process for separating and extracting useful materials from used batteries. It has been assumed that an equal split of these processes would be applied to used PEV batteries in New Zealand. Recycled material has also been taken into account in battery manufacturing as described in Section 4.1.

Unit processes for these end-of-life battery treatments are available on ecoinvent v3.1. Direct emissions from these treatments were assumed to be the same (per kg of waste treated) in New Zealand as in Europe. However, because of the differing generation profiles of European and New Zealand electricity, the requirements for waste treatment in the European data set were substituted with the New Zealand electricity system processes developed for this study (refer to Section 4.3).

5 Results

> The results and conclusions of the LCA shall be completely and accurately reported without bias to the intended audience. The results, data, methods, assumptions and limitations shall be transparent and presented in sufficient detail to allow the reader to comprehend the complexities and trade-offs inherent in the LCA. The report shall also allow the results and interpretation to be used in a manner consistent with the goals of the study. ***ISO 14044:2006 Section 5.1.1***

The following section presents the results for the life cycle assessment of PEVs compared to conventional vehicles. These results account for impacts across the entire life cycle of the vehicle. The processes that are covered as part of the assessment are described in more detail in Section 2.

This study assesses the impacts of each vehicle technology across their life cycles in the two broad areas of environmental impacts, and impacts upon human health. The first category is further divided into impacts on climate change, resource depletion, cumulative energy demand, the emission of species contributing to air acidification and eco-toxicity. The second category is divided into human toxicity, and also the emission of particulate material and the emission of species contributing to photochemical oxidisation, both of which are known to have harmful effects upon human beings.

5.1 Results summary

The following table provides a summary of all impact categories assessed for this study, against the four vehicle technologies.

Table 14 Life cycle assessment results (per km of vehicle travelled)

Vehicle technology	**Climate Change**	**Particulate matter**	**Photochemical Oxidation**	**Cumulative Energy Demand**	***Resource Depletion***	***Human Toxicity***	***Eco-toxicity***	***Air Acidification***
	kg CO_2e	**kg $PM_{2.5}$**	**kg C_2H_2**	**MJ LHV**	***kg Sb***	***CTU_h***	***CTUe***	***kg SO_2***
Conventional petrol engine vehicle	0.26	11.2 E-05	11.2 E-05	4.36	*4.69 E-05*	*7.76 E-08*	*6.13*	*7.42 E-04*
Conventional diesel engine vehicle	0.22	11.1 E-05	6.81 E-05	4.22	*4.94 E-05*	*8.06 E-08*	*6.65*	*7.15 E-04*
Plug-in hybrid electric vehicle (PHEV)	0.15	9.72 E-05	7.45 E-05	2.79	*5.20 E-05*	*14.7 E-08*	*7.06*	*6.80 E-04*
Battery electric vehicle (BEV)	0.11	8.41 E-05	5.89 E-05	2.56	*4.41 E-05*	*17.3 E-08*	*5.62*	*6.83 E-04*

It should also be noted that each impact category underwent an uncertainty analysis on comparative results from vehicles. This analysis, described in detail in Section 6.5, was undertaken to ascertain the degree of confidence in the following impact category results:

- (Section 5.2) Out of the human health related impacts, the categories with high certainty in results are particulate matter and photochemical oxidation. The result related to human health toxicity, on the other hand, has high uncertainty, and the comparative results should be interpreted with this in mind.
- (Section 5.3) As for the environmental related impacts, the categories with high certainty in results are climate change and cumulative energy demand. The results for the resource depletion, air acidification and ecotoxicity categories have high uncertainties, and the comparative results should be interpreted with this in mind.

In Figure 9 and Table 14, which summarises the study findings, the impact categories highlighted in grey signify those categories with high uncertainties associated with its results.

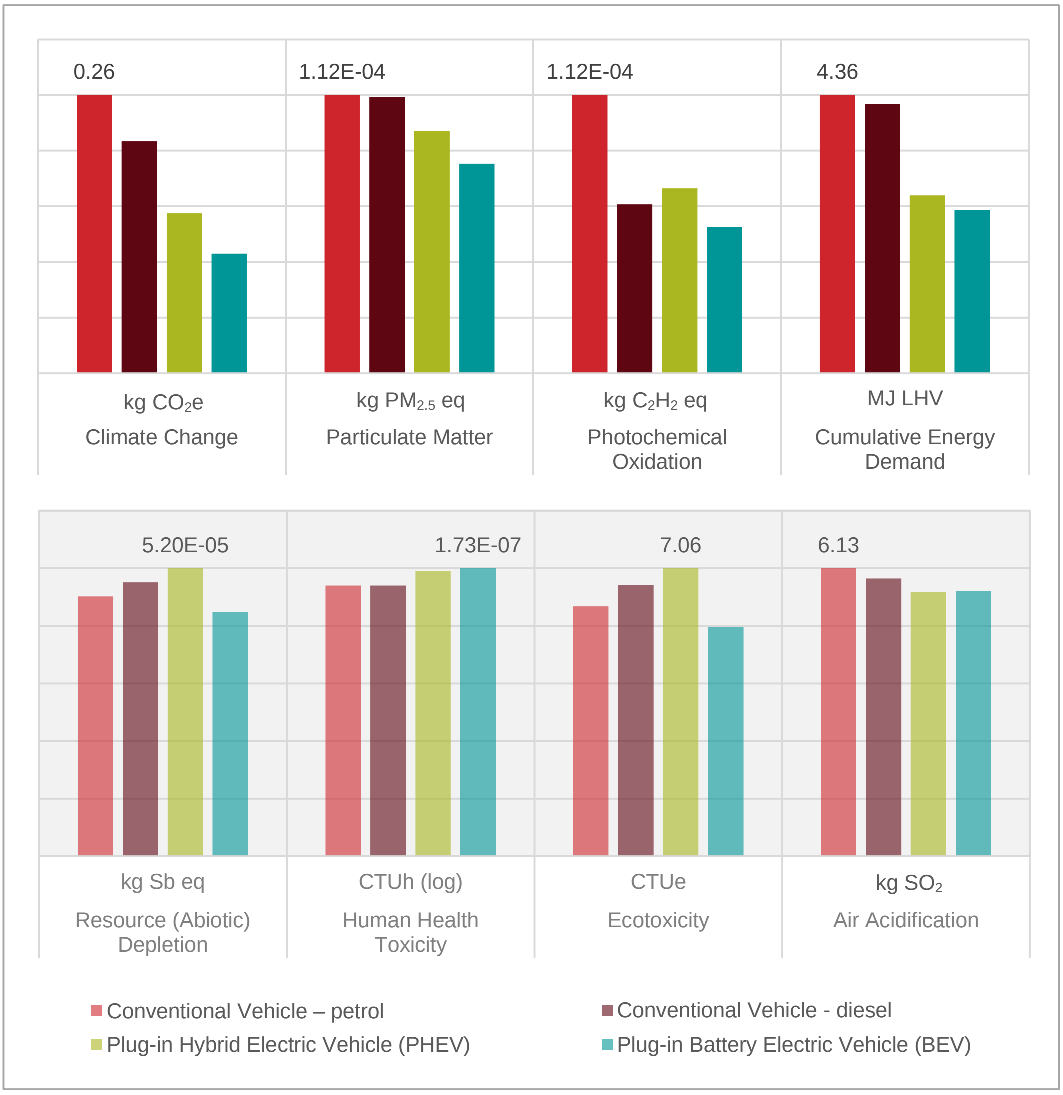

Figure 9 Life cycle assessment results (per km of vehicle travelled)

5.2 Environmental related impacts

The environmental impacts of motor vehicles are not confined to the impact that they have in operation. The processes involved in extracting the raw materials, the manufacture and the disposal of the vehicle at the end of its life all have an impact in terms of the production of greenhouse gases, the depletion of mineral and fossil fuel resources, the total (cumulative) consumption of energy resources, the production of substances that are toxic to species other than human beings and the emission of substances that acidify the air. This study assessed the impact of each of the vehicle technologies with respect to these categories.

5.2.1 Climate change

The first impact category considers climate change or an assessment of the global warming potential (GWP) of the four vehicle technologies. GWP is a measure of the increase in heat that rises in the atmospheric concentration of the so-called ‘greenhouse gases’ will produce. Greenhouse gases — of which carbon dioxide is the most abundant and best-known — are a range of gaseous compounds that absorb and re-emit infrared radiation; an increase in atmospheric concentration of these gases has the effect of retaining heat in the lower atmosphere (much as the glass retains heat in a greenhouse). The GWP of any given gas is described in terms of the equivalent quantity of carbon dioxide (CO_2e), which facilitates the comparison of the relative impacts of various gases released into the atmosphere.

Our findings reveal that the conventional vehicles have the highest overall impact in this category, with 0.26 kg CO_2e per km travelled over the lifetime of a conventional petrol engine vehicle, and 0.22 kg CO_2e per km travelled over the lifetime of a conventional diesel engine vehicle.

As illustrated below, the majority of the contribution to climate change is associated with the operational phase of each vehicle technology. Combustion of petroleum fuels yielded the greatest impact in this category with, 0.21 kg CO_2e per km travelled over the lifetime of a petrol vehicle, and 0.17 kg CO_2e per km travelled over the lifetime of a diesel vehicle.

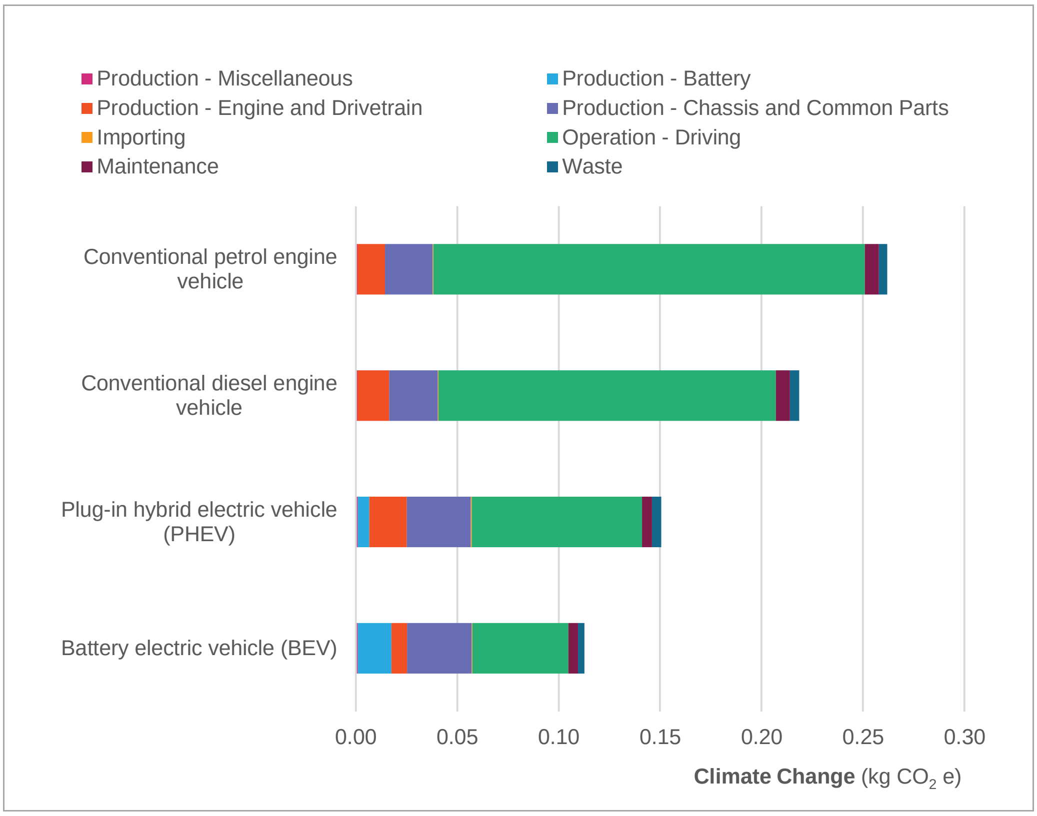

Figure 10 Climate change impact

The climate change impacts of the two PEVs as measured by GWP are more evenly split between the manufacturing and production and operational phases. The BEV makes the lowest contribution to climate change over its life cycle, with the low operational impacts arising from low carbon emissions in the New Zealand electricity mix. It should be noted that any significant change in New Zealand’s electricity generation portfolio (such as the planned closure of the Huntley coal-fired generation plant) could change this assessment.

In relation to the manufacture and production of the BEV, approximately a quarter of the impacts are associated with the manufacture of the lithium batteries (noting that in the base case presented, two batteries are presumed to be required over the 210,000km lifetime), with the other major contributors being emissions associated with the production of reinforced steel and electricity consumed during manufacture. The source of impacts for the PHEV is similar to the BEV, although there is a larger contribution to climate change during operation of the PHEV due to its partial use of a petroleum-based fuel for propulsion.

5.2.2 Resource (abiotic) depletion

Resources, including minerals and fossil fuels, are used at every stage of the production, operation and disposal of motor vehicles. Many — if not most — of these are finite, some in shorter supply than others. There is a widespread public perception that some of the minerals used in the construction of electric vehicles (such as lithium, and the so-called rare-earth metals) are very scarce. The Abiotic Depletion Factor (ADF) is used to measure the extent to which mineral and non-renewable energy resources are consumed. This impact category specifically considers the economic and technical capability of resource extraction at the time of analysis, in this case, for 2002.

Antimony is used as a reference in considering mineral depletion. The extraction of individual minerals is reckoned as kilograms of antimony per kilogram of material extracted (kg Sb/kg extraction), and overall mineral depletion is measured in terms of kilograms of antimony-equivalent (kg Sb). These weightings are based on individual mineral reserves and the rates of de-accumulation for those minerals.

The results for the four vehicle technologies are provided in Figure 11.

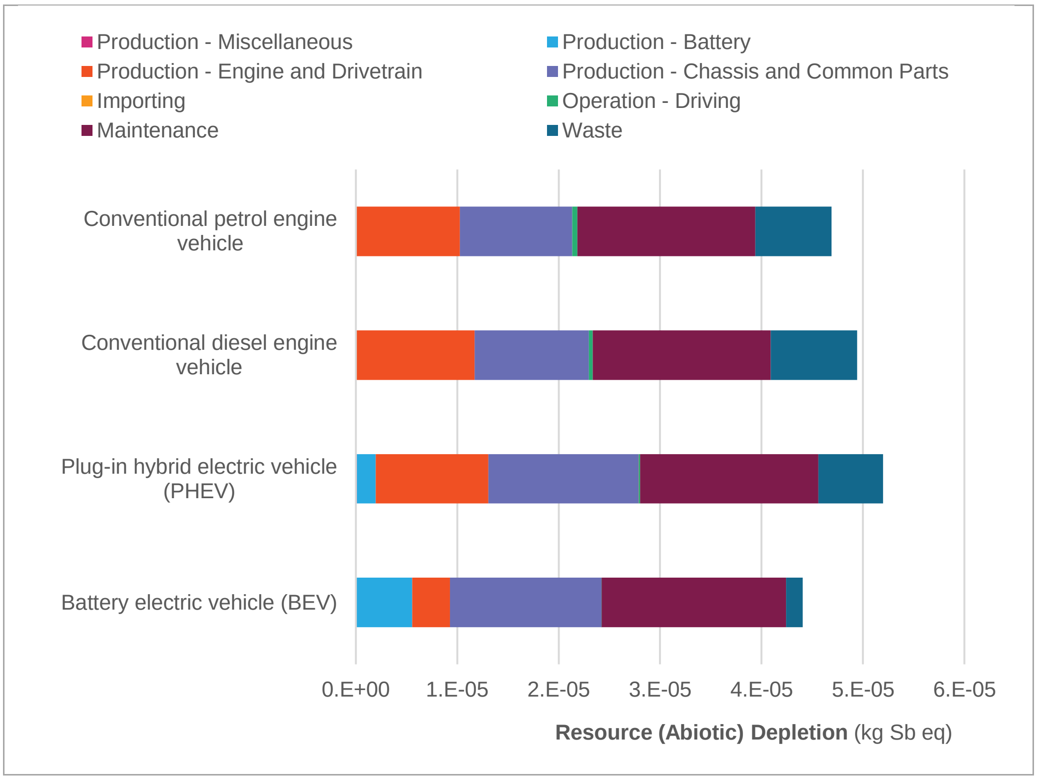

Figure 11 Resource depletion impact

In broad terms, each of the vehicle types consistently contributes to resource depletion across its life cycle stages:

- Approximately 43-50% of impacts are accounted for in the production of the main components (the engine, drivetrain, chassis and common parts). Note that the lithium-ion batteries and drivetrain of the BEV are equivalent (but lower) than the impact of conventional vehicle engines and drivetrains.

- Additionally, all vehicles contribute to resource depletion in maintenance, mainly due to the need for lead-acid battery replacements, which accounts for 34-41% of impacts. It should be noted at this point that BEVs use lead-acid batteries for auxiliary power purposes. It was therefore assumed that all vehicles would experience the same lead-acid battery replacement schedules across the lifetime of the vehicle (i.e. once every four years). Lead-acid batteries can be highly recycled (potentially more than 90% of lead can be recovered). However, in new lead-acid batteries, the recycled content of lead is around 50-60%. The ecoinvent v3.1 dataset used in this study assumes a 50.3% recycled lead content in batteries.

BEV and PHEV demand significant amounts of metal such as aluminium, copper and steel, above the levels commonly used in conventional vehicles. This material demand is required by electronic componentry including motors, charger, batteries, wiring and circuitry etc., as well as the underlying chassis which is typically heavier also.

Our findings in this category demonstrate that the resource depletion impacts are highest for the PHEV, at 5.20E-05 kg Sb per km travelled over the lifetime. A large proportion of this impact (approximately 31%) occurs during production of the PHEV. This is logical, given it requires the manufacture of its battery and not one but two power components — the ICE and electric drivetrains — whereas the BEV and conventional vehicles have only the one or the other.

The BEV has the lowest impacts in terms of resource depletion, 4.41E-05 kg Sb. The production of the battery is a greater contribution to mineral depletion (again noting that two batteries have been assumed to be required over the BEV lifetime in the New Zealand context).

Regarding rare earths

There is a common public belief that electric vehicles use so-called “rare-earth” metals in their manufacture, probably because many conventional hybrid electric vehicles used lanthanum in the chemistry of their lithium-ion batteries. All vehicle technologies do indeed use amounts of rare-earths, especially PEVs, which use neodymium in the electromagnets of their drivetrains. Yet the resource depletion impact associated even with this component was found to be negligible. And contrary to another popular misconception, the lithium used in PEV batteries (in the form of salts) is neither a rare-earth, a precious nor even a particularly scarce metal. Lithium was found to contribute less than 1% of the resource depletion impact for electric vehicles.

Regarding fossil fuels

In overall resource depletion terms, the impact of fossil fuel consumption is minimal, even in conventional engine technologies. The entire “use” phase, which includes fuel consumption and tyre wear, accounts for 1.1% of resource depletion impacts for the petrol conventional vehicle, and 0.77% for diesel. It should be reiterated that this impact category takes into account fossil fuel depletion for crude oil, of which petroleum is a derivative. Crude oil, as consumed in the use phase, contributes 0.052% of total resource depletion impact for a petrol vehicle.

5.2.3 Cumulative energy demand

Cumulative energy demand evaluates the amount of energy consumed during the series of processes undertaken over the course of the life of the vehicle, including material extraction, manufacture, operation of the vehicle, and its end-of-life disposal. This category does not distinguish between differences sources of energy, and therefore accounts for energy from all sources, whether they be fossil or renewable.

Our assessment shows the highest cumulative energy demand per km occurs with the conventional petrol engine vehicle. Both PEV technologies perform well in this metric and better than their conventional counterparts. Across all technology types, the operational phase contributes to the majority of cumulative energy demand. This affirms that the conversion of electricity into kinetic energy to propel a vehicle is more efficient than using energy from combustion.

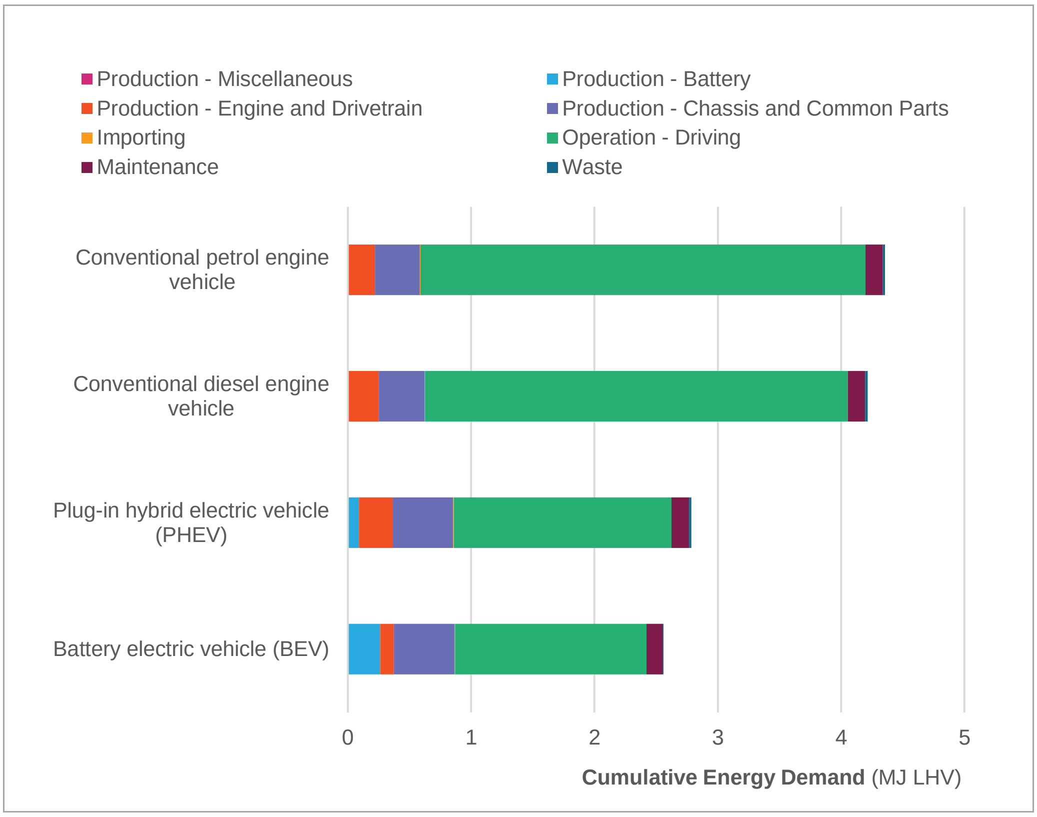

Figure 12 Cumulative energy demand impact

5.2.4 Ecotoxicity

The ecotoxicity impact category considers impacts (particularly due to toxic stress) on species other than human beings for the life cycles of the four technologies.

It should be noted that these results have high uncertainties, as per the results of the uncertainty analysis undertaken on this impact category (discussed in Section 6.5). In context of these high uncertainties, it can be interpreted that there are no significant differences of results between the vehicles.

The assessment indicates that BEVs have lower levels of impact per km travelled compared to the conventional vehicles. PHEVs, by contrast, show the highest impact.

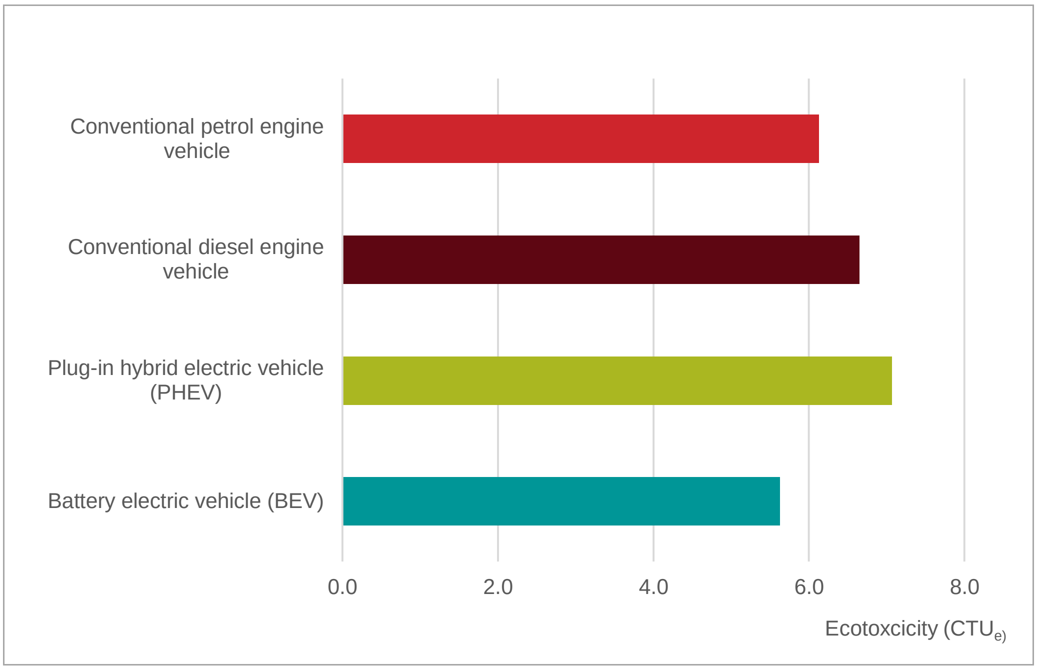

Figure 13 Ecotoxicity, comparison of vehicles

As with human health (see below), the largest contribution to the eco-toxicity result for PEVs arises from the manufacture and production phase, as shown in Figure 14. The production of the lithium battery (noting that two are assumed to be required over the BEV lifetime) represents the largest contribution during this stage, followed by the manufacture of the glider and powertrain for both the PHEV and BEV.

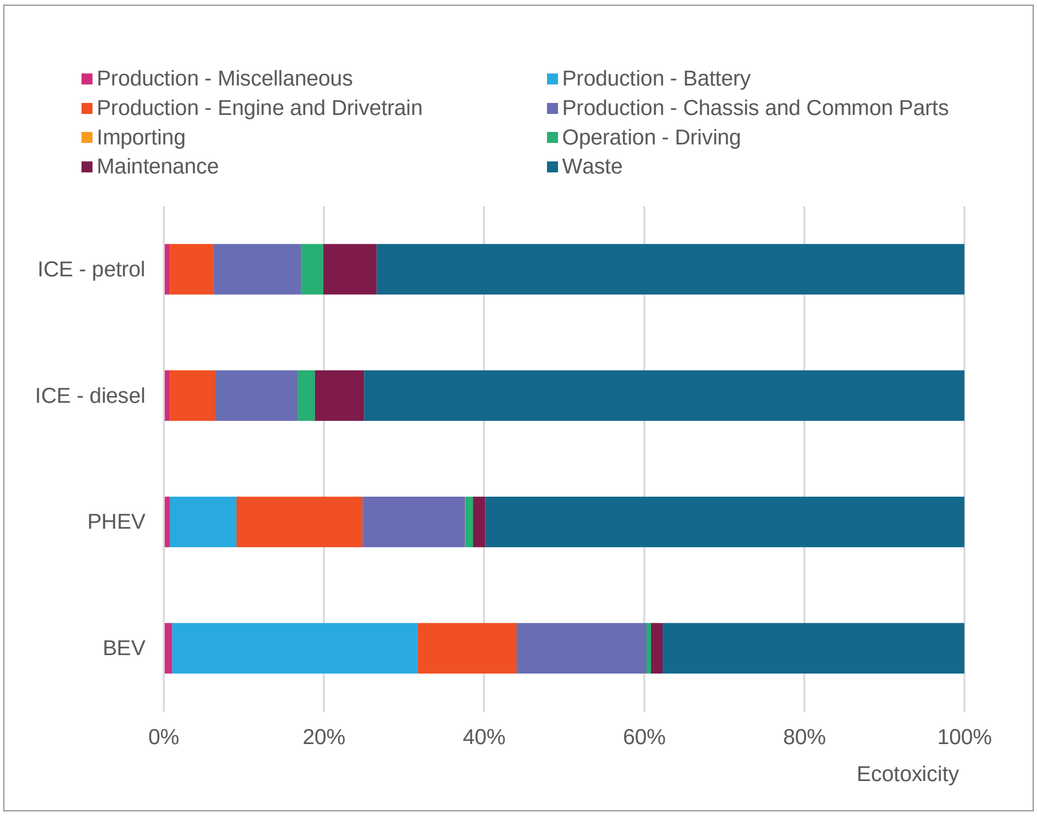

Figure 14 Ecotoxicity impact, breakdown by life cycle stages

Again, as for human health toxicity, a majority of impacts are attributed to the resource extraction processes, particularly those of copper and gold. This is demonstrated in the flow of impacts in Figure 15. The PEV batteries contain a high amount of copper, of which most (65%) comprises primary material. (The sensitivity to recycling rates is tested in Section 6.2).

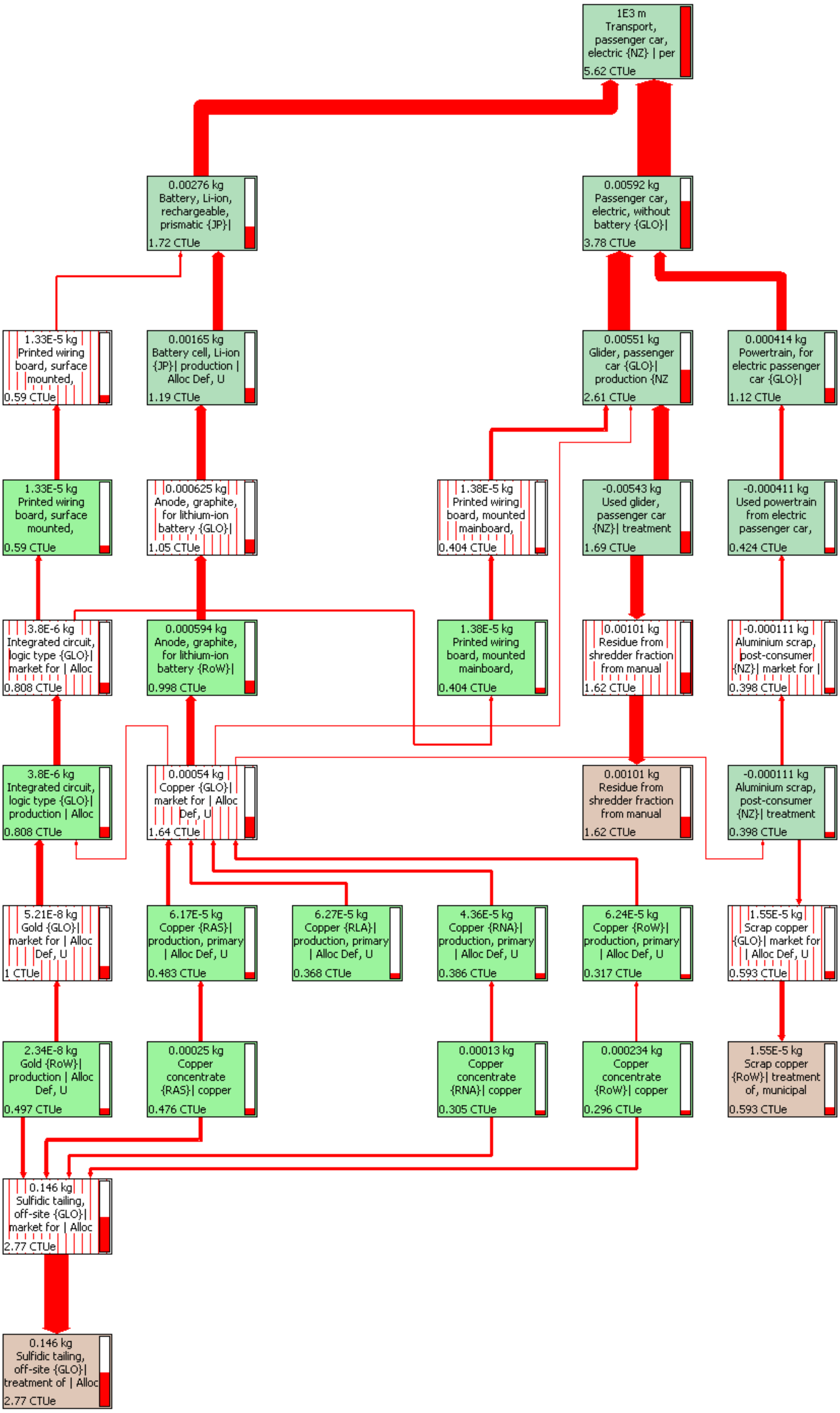

Figure 15 Ecotoxicity flows for BEVs

5.2.5 Air acidification

Air acidification refers to the total emissions of acidifying substances (such as sulphur dioxide) released into the air over the life cycle of a vehicle (and therefore may occur during manufacture, as well as the tailpipe emissions in vehicle operation). These emissions also arise in the generation of electricity from fossil fuels. Emissions that promote air acidification are of concern as this, in turn, can produce a decline in the pH (acidification) of water bodies and of vegetation, with subsequent deleterious effects for ecosystems.

The LCA results for this impact category are presented in Figure 16. It should be noted that these results have high uncertainties, as per the results of the uncertainty analysis undertaken on this impact category (discussed in Section 6.5). In context of these high uncertainties, it can be interpreted that there are no significant differences of results between the vehicles.

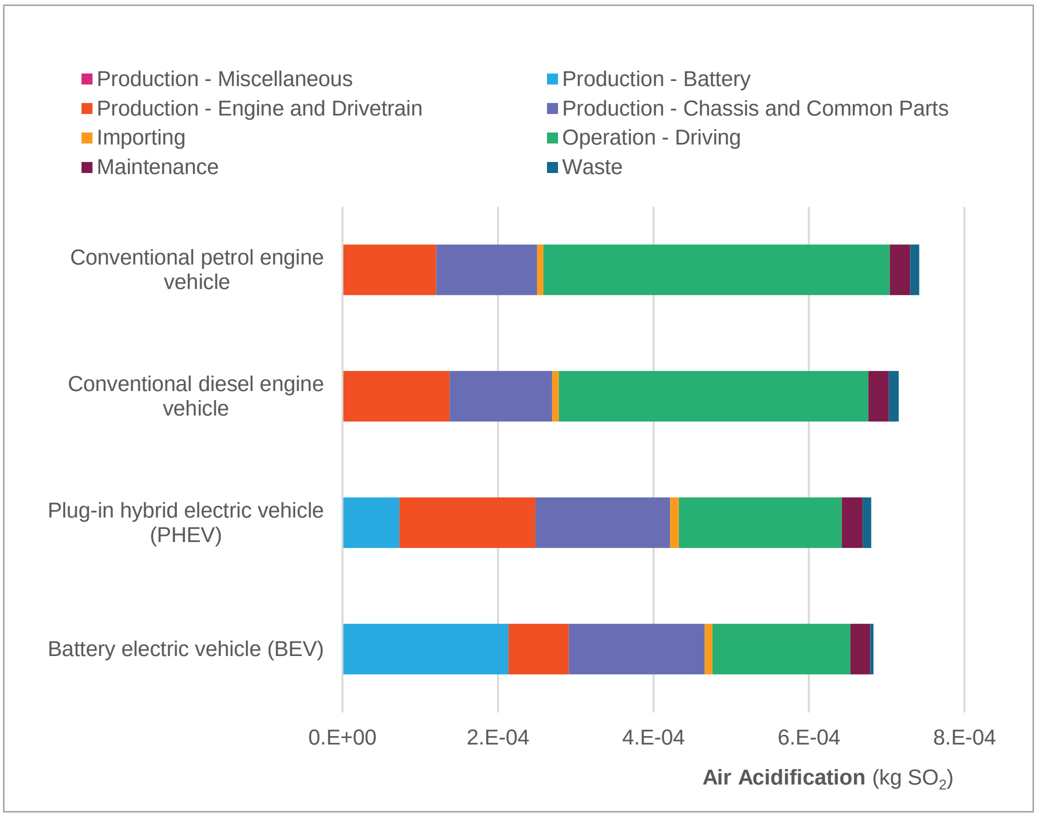

Figure 16 Air acidification impact

Over its life cycle, the petrol vehicle is the highest contributor to air acidification, with 7.42E-04 kg SO_2 per km travelled, followed by the diesel vehicle with 7.15E-04 kg SO_2 per km travelled. The majority of impacts for conventional vehicles are associated with the fuel consumed in the operational phases, with the petrol engine providing a greater contribution to air acidification per km when compared to diesel.

PEVs show lower impacts compared to conventional vehicles. In contrast to conventional vehicles, the manufacturing and production phases contribute significantly to air acidification for both the BEV and PHEV. Within the manufacture and production of the BEV, the production of lithium batteries (noting that two assumed in our model over the BEV lifetime) provide the single greatest impact in this category, followed by the production of reinforced steel for the chassis and common parts. For the PHEV, the manufacture of the chassis and drivetrain (particularly steel and aluminium) is the greatest contributor.

It should also be noted that electricity from coal (a proportion of the electricity used to charge batteries) contributes 17.3% of the air acidification impact of BEVs, with electricity from natural gas contributing 8.69% of the impact. For PHEVs, the contributions are 11.7% and 5.87% respectively. If the imminent closure of coal-based electricity generation in New Zealand occurs (and provided the replacement and additional electricity is generated from renewable sources), air acidification impacts for EVs could potentially reduce.

5.3 Human health related impacts

Besides impacts upon the environment, certain emissions produced in each of the phases of a vehicle's life cycle have the potential to harm human health and well-being. Particulate matter — fine, airborne particles of material — and emissions species that react with sunlight to produce harmful substances in the atmosphere, together with other products that are toxic to human beings, can be produced in the mining of raw materials, the manufacture of vehicles, their operation and their disposal. This study examines the impact of the four technologies in each of these categories.

5.3.1 Particulate matter

Fine particulate material in the atmosphere has been proven to be associated with serious diseases — particularly of the lung — in human beings. For example, in 2008 the Greater London Authority estimated that 4,267 deaths in London could be attributed to long-term exposure to fine particles, many of which arose from the operation of conventional vehicles in the London metropolitan area[37] Particulates can arise as a first-order product of chemical processes such as combustion, or as a second-order effect where chemical emissions react in the atmosphere to produce particulates.

The particulate matter considered in this LCA is both from vehicle tailpipe emissions, as well as from the production of energy, material extractions and other processes involved in the mining of raw materials, manufacture, maintenance and disposal of the vehicle. Therefore, by contrast with others, this study does not limit its consideration of particulate material to that emitted from a vehicle, but considers all those across its life cycle. Figure 17 demonstrates the amount of particulate matter emitted throughout the life cycle of each of the vehicles.

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[37] Miller. B (2011) *Report on estimation of mortality impacts of particulate air pollution in London,* Greater London Authority

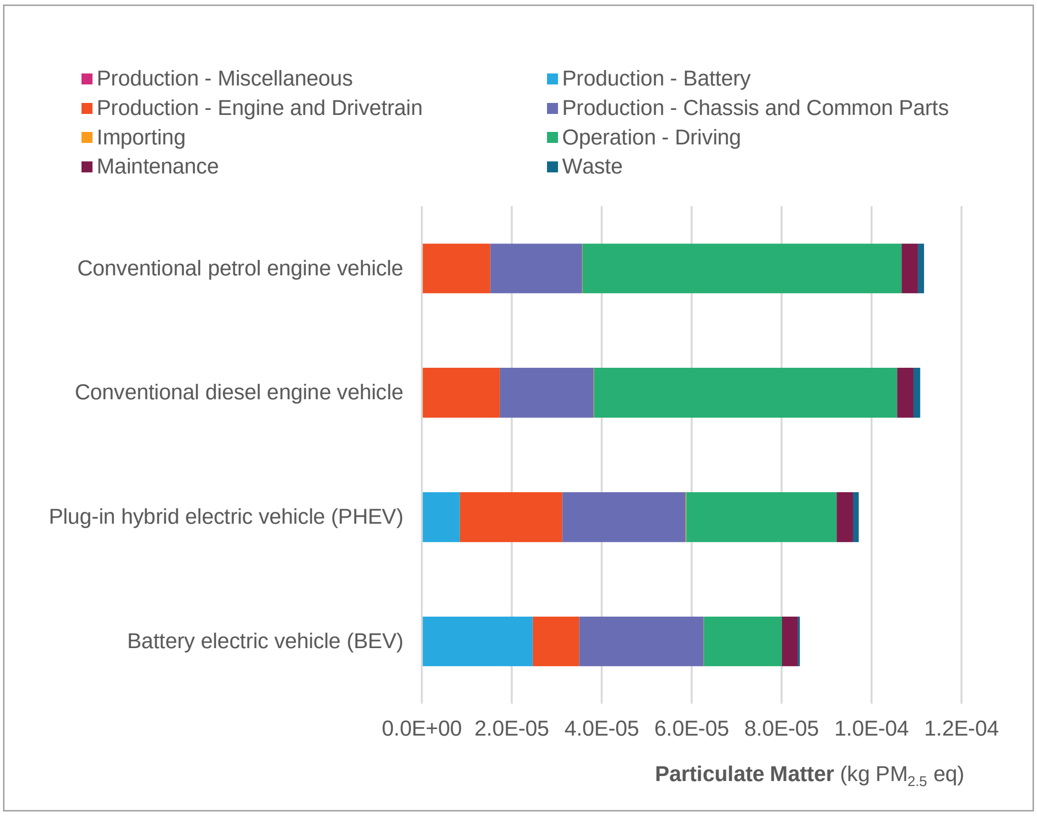

Figure 17 Particulate matter impact

The assessment shows that emission of particulate material is greatest for the conventional vehicles, with petrol vehicles being the most significant emitters. Most of this impact arises from both the tailpipe emissions of the vehicle and from refining and extracting the fuels required (petrol and diesel). As shown in Figure 18, although tailpipe emissions from diesel vehicles are more than 3.7 times higher than petrol vehicles, the life cycle particulate emissions from the production of petrol (compared to diesel) is far greater in magnitude and by comparison.

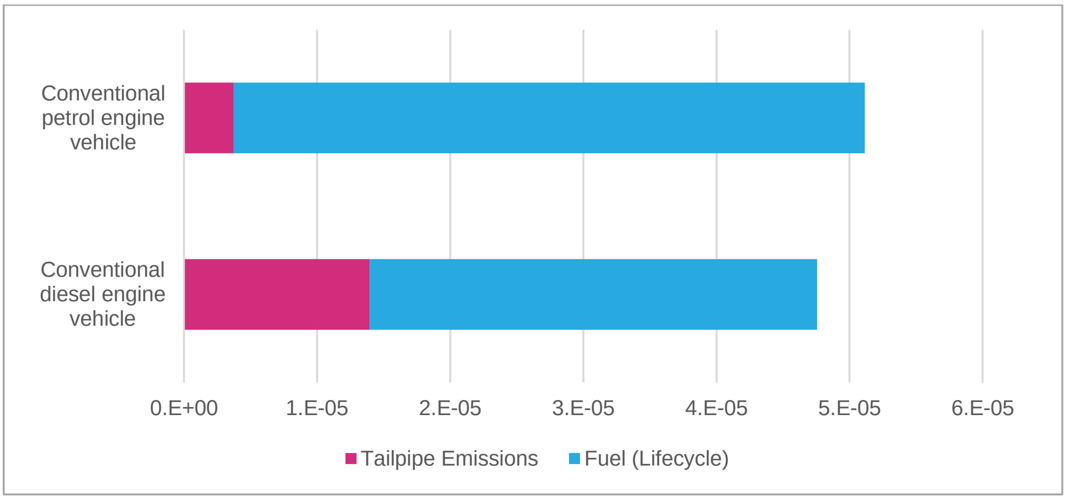

Figure 18 Use phase particulate matter comparison of petrol vs diesel conventional vehicles (per km travelled)

For PEVs, a majority of particulate matter impacts are from the production stages, with significant contributions from the manufacture of chassis and common parts, as well as of the drivetrain and battery (noting that two batteries are presumed to be required over the BEV lifetime). The significant contribution from the PHEV drivetrain is due to the high content of wrought aluminium (80% unrecycled) as per the ecoinvent v3.1 dataset. Similarly, the battery incorporates a high amount of copper (65% unrecycled) and wrought aluminium. The sensitivity to these is tested in Section 6.2.

Significance of air quality issues with respect to vehicles

The introduction of PEVs is commonly advocated on the basis of improved air quality, with an associated benefit to humans being a reduction in respiratory illness. It was desirable to determine whether this model would validate the potential benefit of PEVs with regard to New Zealand air quality. However, a limitation of the US toxicity models is that they do not address emissions associated with such illnesses. The outcome is that substances such as the particulate material and nitrogen oxides that commonly occur in conventional vehicle tail pipe emissions are not being picked up and accounted for in the results. This has implications for the assessment of the impact upon human health. According to the model, the operational phase of both the conventional petrol and diesel engine vehicles have only marginal impact. As a result, the potential benefit of adopting PEVs, particularly in urban area use, could not be properly understood.

To address this shortcoming in the model and to provide a more rounded assessment of the impact of the differing vehicle technologies upon human health, the study included an indicator of particulate emissions.

The particulate matter indicator shows that conventional petrol and diesel engine vehicles both create greater emissions over the life cycle than PEVs, and that these can mostly be attributed to vehicle operation: i.e. tailpipe emissions. The significance of this finding for human health is increased when it is considered that the effect (tailpipe emissions) is at its greatest in and near areas of dense population. While the BEV produces a 25% net overall benefit, it is not without impact with regard to emission of particulates. Yet because most of the particulate matter emitted in the life cycle of a BEV can be attributed to primary extraction and production, it can be argued that it represents a significantly reduced hazard, as most of these emissions are produced remote from population concentrations.

5.3.2 Photochemical oxidation

Emissions of substances such as nitrogen oxides and VOCs occur over a vehicle's life cycle and can react with sunlight to form chemical compounds such as ozone. While ozone is produced naturally in the upper atmosphere and performs a function that is vital to the existence of life on earth, it is a dangerous substance when found at ground levels. This process is known as photochemical oxidant formation, and is measured in this impact category. A comparison of life cycle impacts are provided in Figure 19.

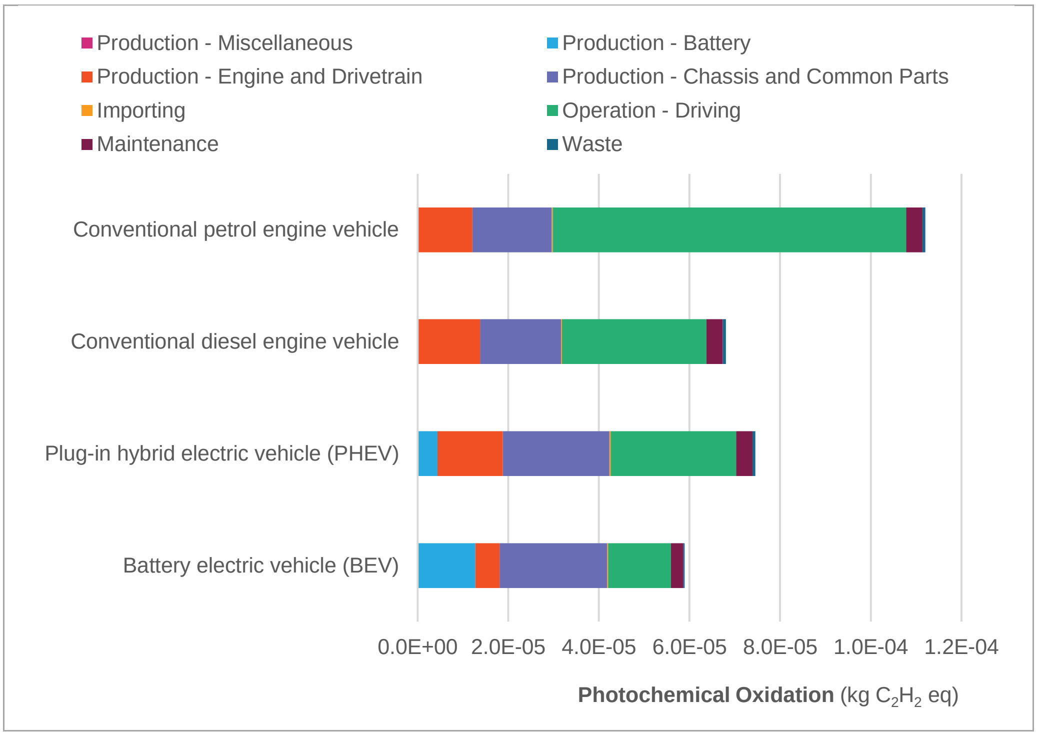

Figure 19 Photochemical oxidation impact

The petrol vehicle provides the largest contribution to photochemical oxidation by an order of magnitude per vehicle km travelled over its life cycle when compared with the other three vehicles. The figure clearly emphasises that this contribution stems from the photochemical oxidation impact of conventional petrol engine vehicles during their operational phase, a logical consequence of the chemistry of combustion of unleaded petrol.

For the same reason, the PHEV, which has a petrol engine, has the next-highest life cycle photochemical oxidation impact per km travelled, although considerably less than that of the conventional petrol engine vehicle. However, in the absence of more precise emissions data for a PHEV, this study used a figure for emissions that was based on pro-rating conventional petrol engine results, which may have overstated PHEV emissions. In practice, PHEVs take advantage of their hybrid architecture and employ combustion techniques and engine control strategies that can achieve photochemical oxidant emissions significantly lower than the pro-rated level.

The PHEV and BEV have the highest and a similar impact per km travelled during production. The chassis and common parts are the greatest source of contribution to photochemical oxidation during the production of these vehicles.

5.3.3 Human health toxicity

Besides particulate material, some of the processes involved in the manufacture, use and disposal of motor vehicles can produce substances that are toxic to human beings. The life cycle human health impacts (excluding particulates) of the four vehicles are illustrated in Figure 20, using a logarithmic scale as the horizontal axis. A logarithmic scale has been used as total impacts for toxicity impact categories should be compared against order of magnitude differences. This is because the total human health toxicity impacts are small, and the results show no significant difference between electric vehicles and conventional vehicles.

It should also be noted that these results have high uncertainties, as per the results of the uncertainty analysis undertaken on this impact category (discussed in Section 6.5).

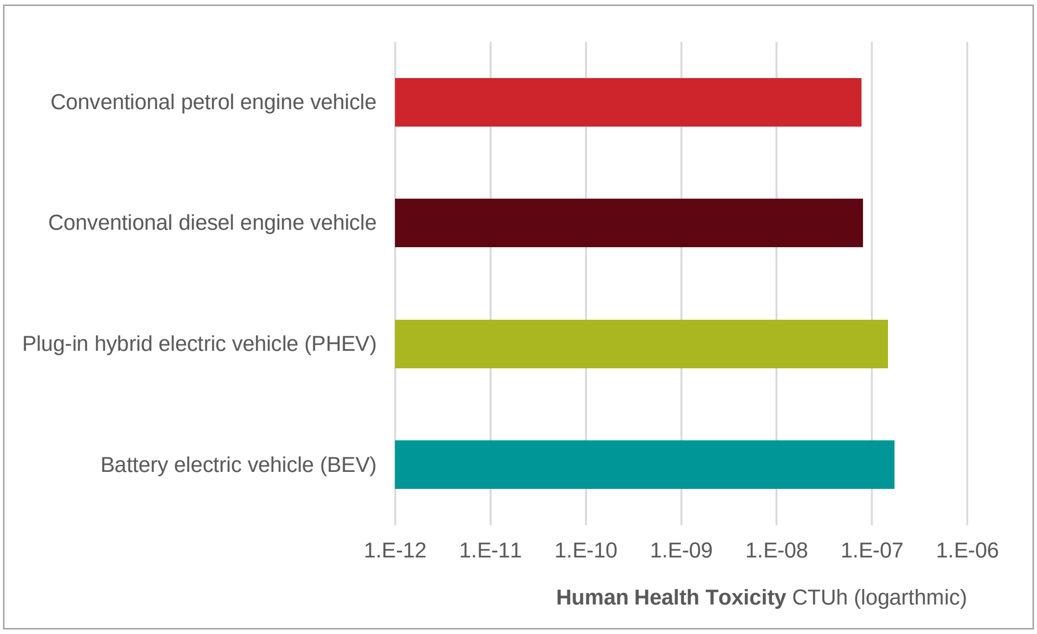

Figure 20 Human health toxicity, comparison of vehicles under logarithmic scale

For the BEV and PHEV these impacts are almost solely associated with manufacture and production (around 85-93% of the human health impacts per km travelled). However, a majority of these products are from material and resource extraction (rather than the manufacturing or production process), particularly the extraction of materials for the battery (noting that two are presumed to be required over the BEV lifetime). A breakdown of life cycle contributions to human health toxicity are shown in Figure 21.

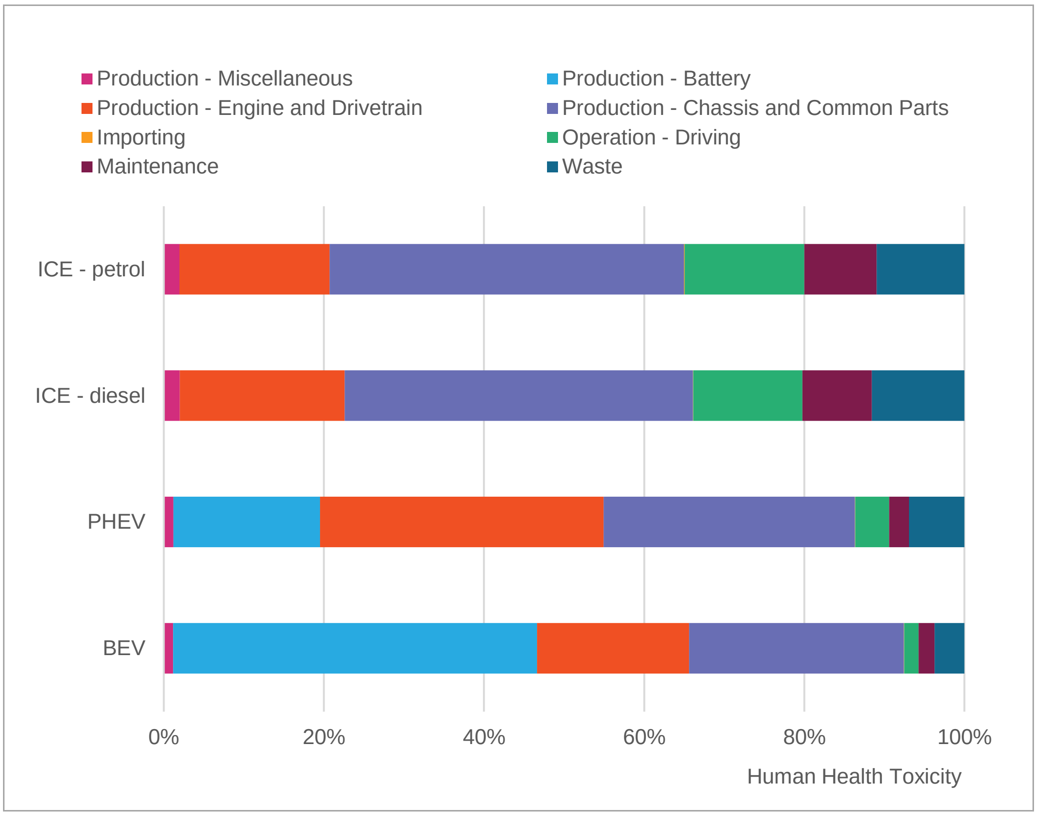

Figure 21 Human toxicity impact, breakdown by life cycle stages

The PEV batteries contain a high amount of copper that is mostly (65%) comprised of primary (that is, not recycled) material. The sensitivity of the study's results to rates of copper recycling is tested in Section 6.2. The figure below demonstrates where the main sources of impacts arise, which is primarily from the extraction and primary production processes for obtaining copper and gold as a raw material. The human health toxicity models are weighted heavily against raw materials such as copper and gold, and the results should be considered in light of this.

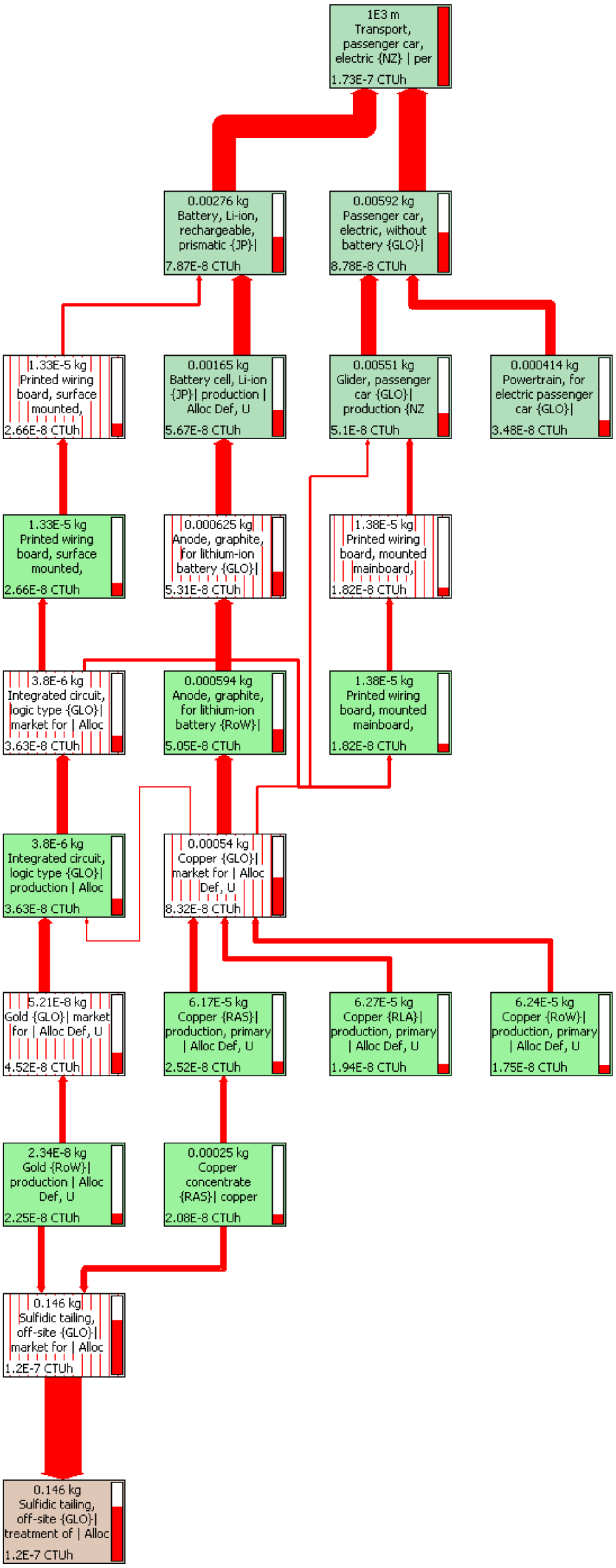

Figure 22 Human health toxicity flows for BEVs

Social impacts of mining

One concern that is occasionally voiced regarding PEVs is that their greater use of metals produces undesirable “upstream” human impacts (that is, in the raw material extraction and manufacturing stages of the PEV life cycle).

While the LCA cannot speak to the allegation that deleterious “social” impacts are suffered by communities where PEVs or the raw materials in their manufacture are produced (the LCA is based on physical flows and emissions), it does generate results that shed light on upstream human health implications. Both the PEV and conventional vehicles LCA models developed for the study account for a complex mix of materials. All these material inventories rely upon data which is representative of world or regional average in their makeup. This means it is not possible to say with any precision where the materials going directly into New Zealand conventional vehicles or PEVs originate. The data applied in this study most strongly indicate North America, Asia and the Pacific as sites of this impact. Rather than speculate, however, some general observations can be made.

The human health toxicity indicator is dominated by metals including steel, aluminium and especially copper in all vehicle types. The PEVs with their greater need for copper, particularly in battery manufacture, carry the greater impact. Sulphide tailings and the many trace compounds (e.g. mercury, cadmium, chromium, etc.) are the main source of impact as they leach into water systems causing human health implications.

It must be stated however that the magnitude of the calculated emissions on this issue are very small. Indeed it has been necessary to represent them on a log scale so as to draw out meaningful interpretation of the data.

The conclusion is that although the PEVs perform worse than conventional vehicles on upstream human health toxicity implications, the size of these impacts overall are determined as very small. Additionally, comparative results related to this impact category have high uncertainties, as discussed in Section 6.5.

6 Sensitivity and uncertainty analysis

> The objective of the sensitivity check is to assess the reliability of the final results and conclusions by determining how they are affected by uncertainties in the data, allocation methods or calculation of category indicator results, etc.
>
> The sensitivity check shall include the results of the sensitivity analysis and uncertainty analysis. The output of the sensitivity check determines the need for more extensive and/or precise sensitivity analysis as well as shows apparent effects on the study results.
>
> ***ISO 14044:2006 Section 4.5.3.3***

A life cycle assessment is built on a range of factors and assumptions each and all of which can have a bearing upon results. The selection of assumptions is particularly important, as certain assumptions chosen as part of this study are necessarily based upon anticipated future events, due to the newness of PEVs to the New Zealand marketplace and the uncertainty surrounding their intended use over time.

The study has proposed and tested various sensitivity analyses on a range of factors designed to ensure the robustness of the findings presented in the base case.

6.1 Sensitivity analysis

> Sensitivity analysis is a procedure to determine how changes in data and methodological choices affect the results of the LCA.
>
> ***ISO 14044:2006 Section 4.4.4.2***

Upon reviewing the assumptions and the context of the study, the following factors of sensitivity have been proposed and tested:

- PEV batteries – percentage of recycled content and attributing of recycling credits.
- Number of PEV battery replacements over a vehicle’s lifetime.

The outcomes of these sensitivity analyses are described in further detail in the sections below.

6.2 Credit for battery material recycling

As described in Section 4.1, the base-case for PEV batteries assumes standard industry rates achieved for the content of recycled materials in the battery components. These are primarily related to metal components.

However, it is largely recognised that a market for recycled batteries is likely to emerge (or grow) internationally, where used PEV batteries may be collected and reprocessed into new batteries. This has not been taken into account in the base-case for PEV batteries.[38]

Two cases of sensitivity were tested, where ***<u>50% or 70%</u>*** of an entire used battery is recycled, reprocessed and used in a subsequent new battery. The results in Figure 23 clearly show that there are benefits associated with recycling, when accounted for in using this method. Reductions are shown across all categories against the base-case, with the greatest benefits in toxicity impact categories.

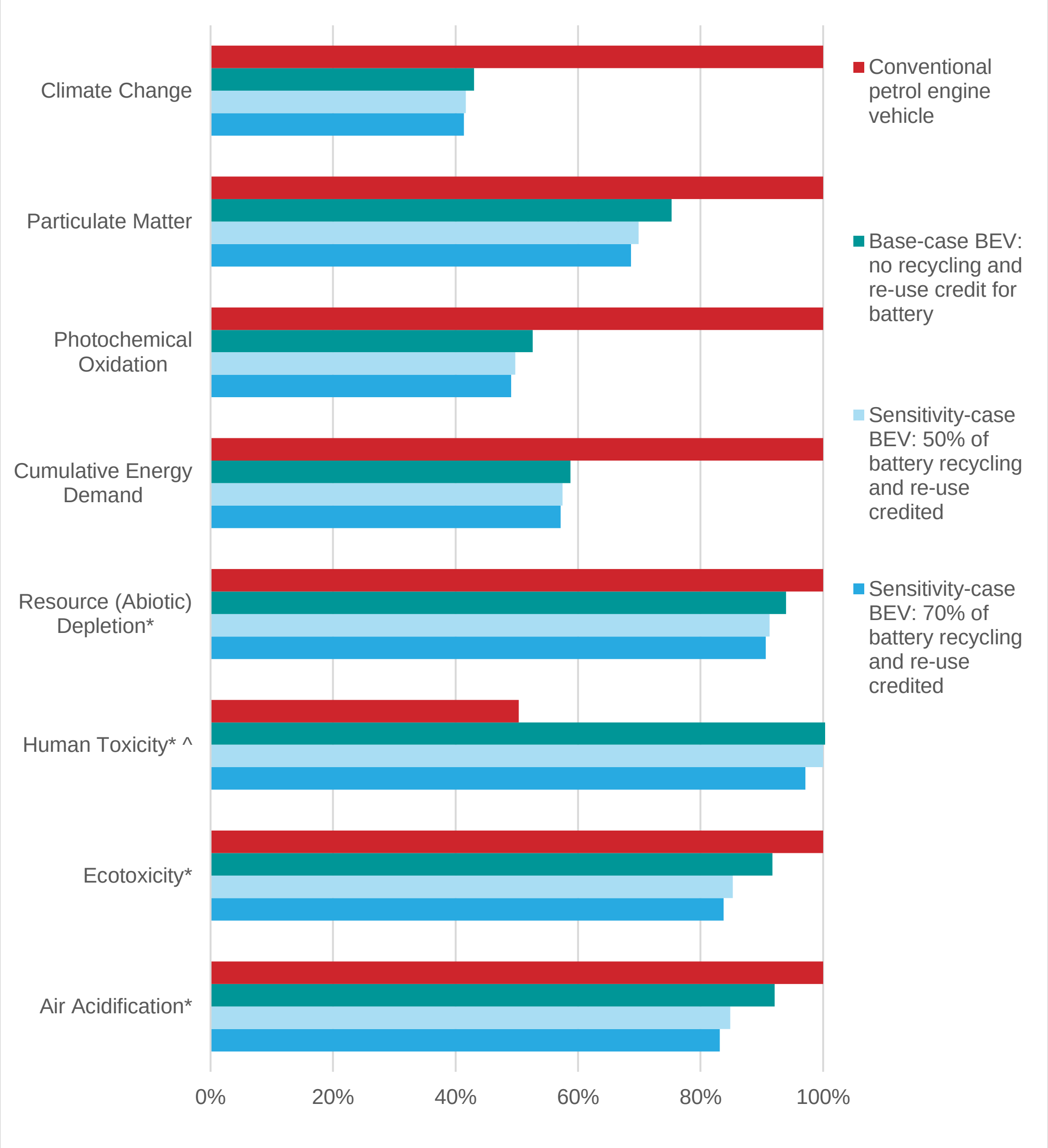

Figure 23 Sensitivity analysis – comparison of impacts by the accounting of credits for battery material recycling and re-input against a conventional petrol engine vehicle measured as the percentage against the maximum impact in the cases

* these impact categories have higher levels of uncertainty

^ for human toxicity, the magnitude of these impact differences are small

---

[38] In LCA terms, a system expansion method has been applied in this case, where the recycling of the original battery produces recycled material products that are subsequently used in replacement batteries. Such a situation is particularly applicable in non-mature markets (but not as applicable to mature markets, such as in new and scrap aluminium markets).

6.3 Number of battery replacements

The base-case assumption for this study for the BEV is that one battery replacement will be required during the life of the vehicle[39]. However, there is current market evidence to show that the original battery is capable of lasting a vehicle's entire lifetime without replacement (albeit with some performance deterioration of the battery over time).

In this sensitivity test, two cases were presented in which (respectively) no battery replacement is required, and an additional battery replacement is required (i.e. two batteries required over the life of the vehicle) for the BEV. The results (Figure 24) clearly show that the battery can influence results, particularly for toxicity impact categories.

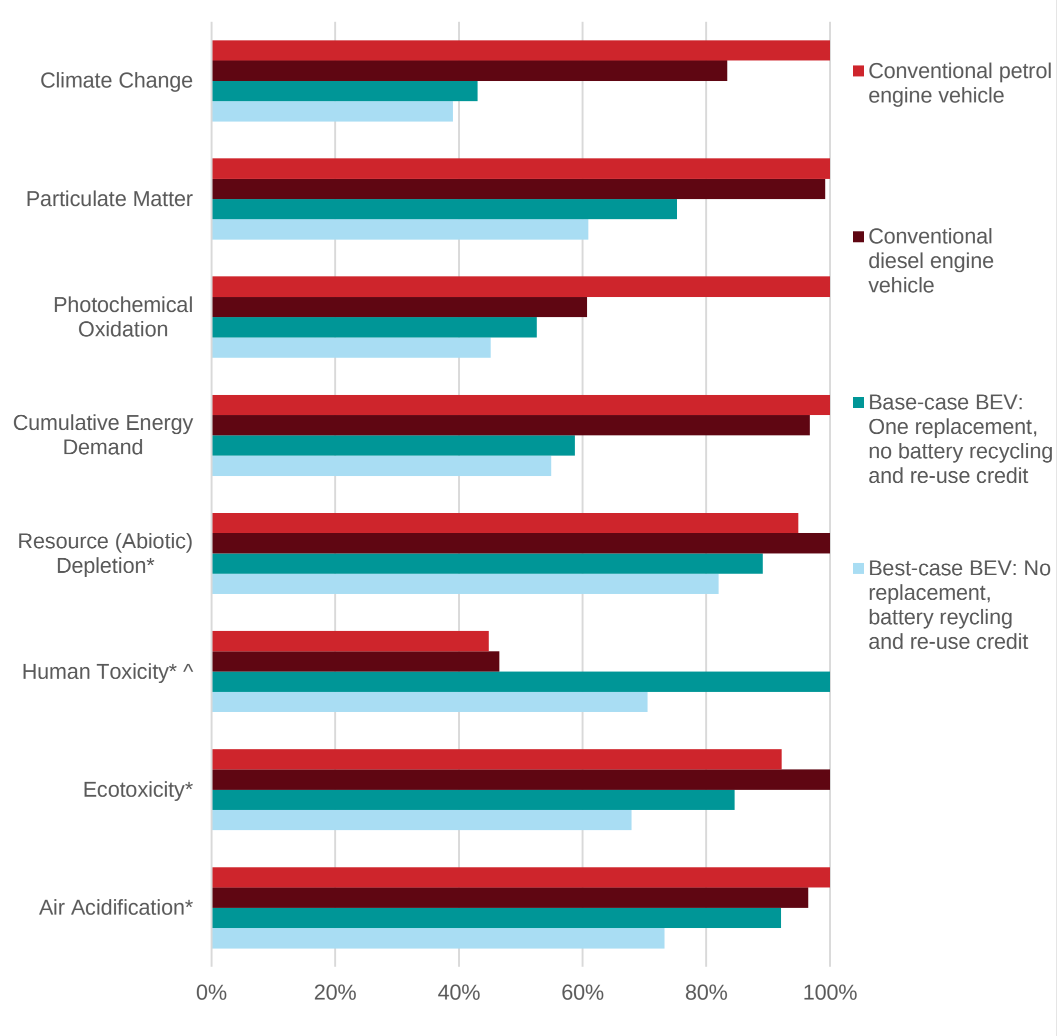

Figure 24 Sensitivity analysis – comparison of impacts by number of battery replacements and against a conventional petrol engine vehicle measured as the percentage against the base-case BEV (one battery replacement)

* these impact categories have higher levels of uncertainty

^ for human toxicity, the magnitude of these impact differences are small

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[39] It should be noted that the base-case assumption for the PHEV assumes no battery replacement is required. A discussion is provided in Section 4.3.

6.4 'Best-case' sensitivity analysis

When applying a combination of these sensitivity factors, a 'best-case' scenario can be found for PEVs. This 'best-case' scenario occurs where no battery replacement is undertaken during the life of the vehicle, and where up to 70% of battery cell material is recycled and used in new batteries (and credited for).

As shown in Figure 25, there are significant reductions in the human health toxicity, ecotoxicity categories and in air acidification. However, impacts in these areas continue to be greater than conventional vehicles, particularly as conventional vehicles contain little or none of the materials required for PEVs that are responsible for the impacts (refer to Sections 5.3.3 and 5.2.4).

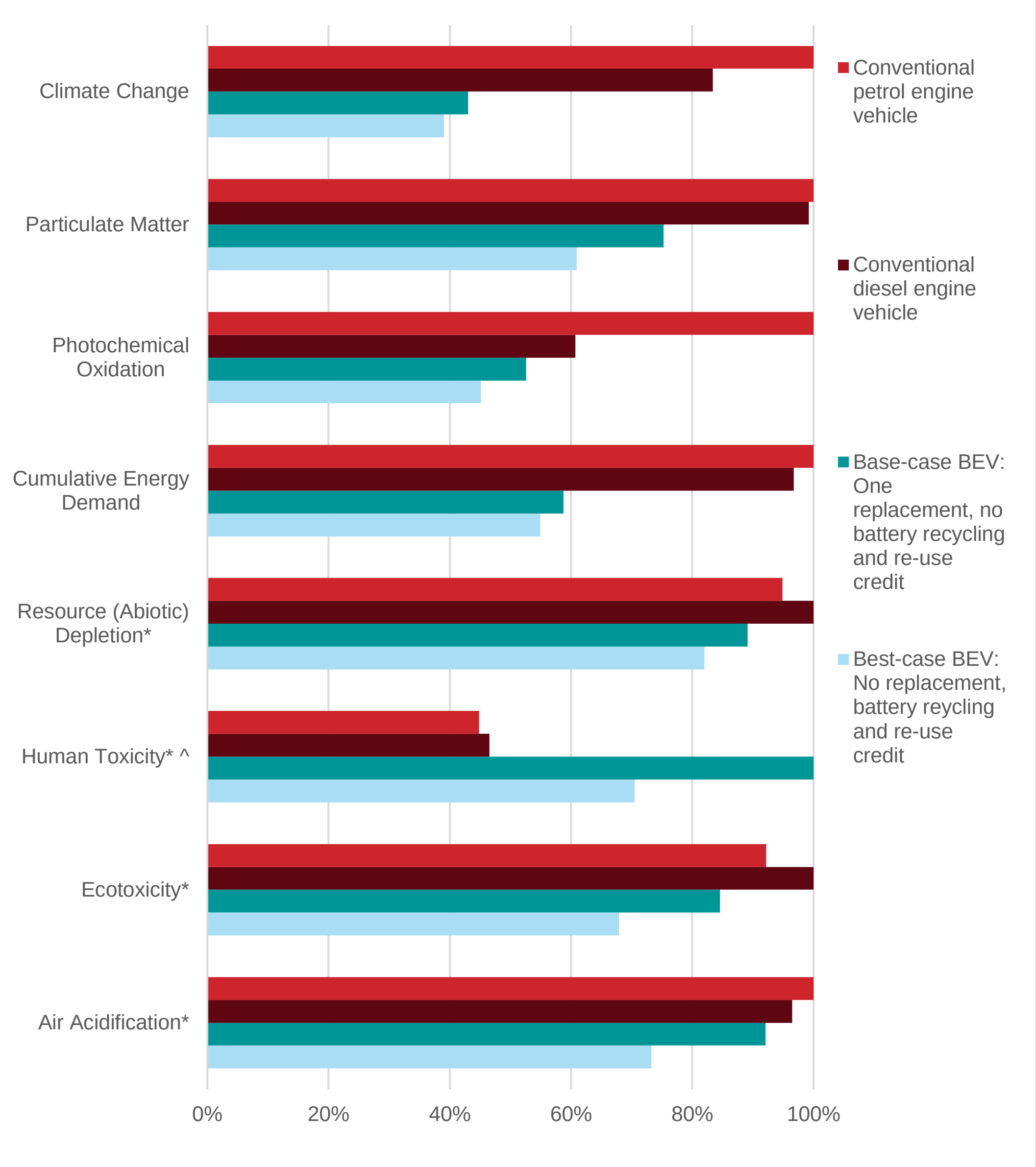

Figure 25 Sensitivity analysis – comparison of best-case BEV sensitivity test against conventional petrol and diesel engine vehicles and a base-case BEV

* these impact categories have higher levels of uncertainty

^ for human toxicity, the magnitude of these impact differences are small

6.5 Uncertainty analysis

> Uncertainty analysis is a procedure to determine how uncertainties in data and assumptions progress in the calculations and how they affect the reliability of the results of the LCA.
>
> ***ISO 14044:2006 Section 4.4.4.2***

6.5.1 Methodology

For the data applied in the model, and for all study-specific assumptions, uncertainty was estimated using the pedigree matrix to define a standard deviation and distribution. The Pedigree matrix, originally developed by Weidema, 1996, assesses each data input against six criteria plus a so-called Basic Uncertainty Factor. These six criteria are data reliability, completeness, temporal correlation, geographical correlation and technological correlation, and are described further in Appendix D1.

For estimations and key data inputs used specifically for this study, specific assessments of uncertainties were applied. These are described in detail in Appendix D2 and based on the assumptions and descriptions of calculations in Sections 0 and 4. For all data and inputs sourced from existing life cycle inventories, such as those used from the ecoinvent v3.1 database, the study adopts the uncertainty values already incorporated in the datasets.

The 95% confidence interval or the squared geometric standard deviation is calculated using the following formula:

$$SD_{g95} = \sigma_g^2$$

$$= \exp\sqrt{(\ln(U_1)^2 + (\ln(U_2)^2 + (\ln(U_3)^2 + (\ln(U_4)^2 + (\ln(U_5)^2 + (\ln(U_6)^2 + (\ln(U_b)^2}$$

The factors U_1 till U_6 referring to the scores for:

- Reliability (U_1)
- Completeness (U_2)
- Temporal Correlation (U_3)
- Geographical Correlation (U_4)
- Further Technological (U_5)
- Sample Size (U_6)

The factor U_b refers to the basic uncertainty factor and is emission-specific.

It should be noted that some processes adopted from ecoinvent v3.1 life cycle inventory databases do not contain values for uncertainty. Additionally, the uncertainty analysis undertaken covers approximately 76-77% of all unit processes within the analysis. Uncertainty analyses were then carried out using a Monte Carlo Analysis over 1,000 runs to determine the uncertainty level in the data.

The uncertainty analysis was undertaken across all impact categories for the four vehicle technologies, on a per kilometre travelled basis.

6.5.2 Results and discussion

The uncertainty analysis results of the Monte Carlo Analysis are described in this section. A full set of results of the analysis are included in Appendix D.

The uncertainty analysis was undertaken across eight impact categories for the four vehicle technologies, on a per kilometre travelled basis. Four of these impact categories – human toxicity, ecotoxicity, resource depletion and air acidification – yielded very high levels of uncertainty. It was nonetheless deemed important that these impact categories be considered in the final report, and it is somewhat reassuring that the impacts in question were found to be relatively slight in any event.

The uncertainty analysis has been undertaken on the comparative results, assessing the percentage of times where a comparative result has occurred: i.e. where BEVs have greater or lesser impacts when compared to conventional vehicles (both petrol and diesel).

The two following figures present the uncertainty analysis results of a diesel and petrol conventional vehicle compared to a battery electric vehicle.

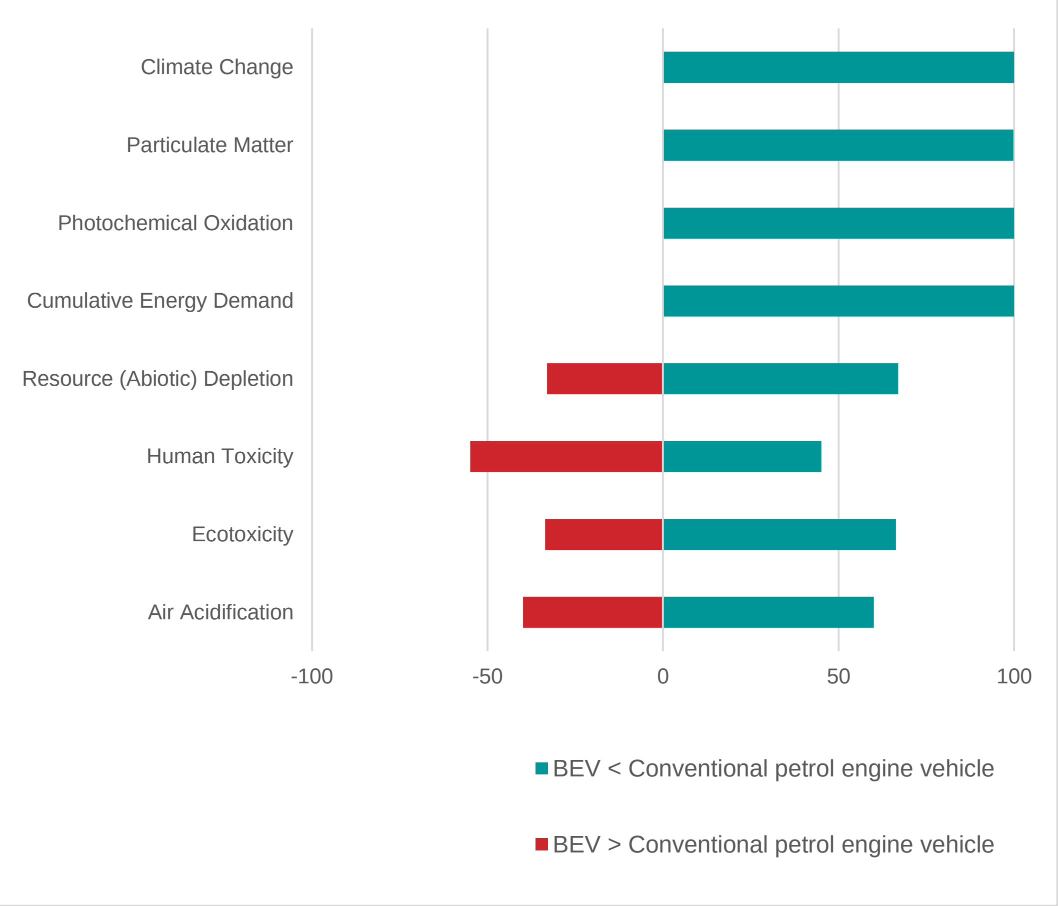

Figure 26 Uncertainty analysis of comparison between BEVs and conventional petrol engine vehicles

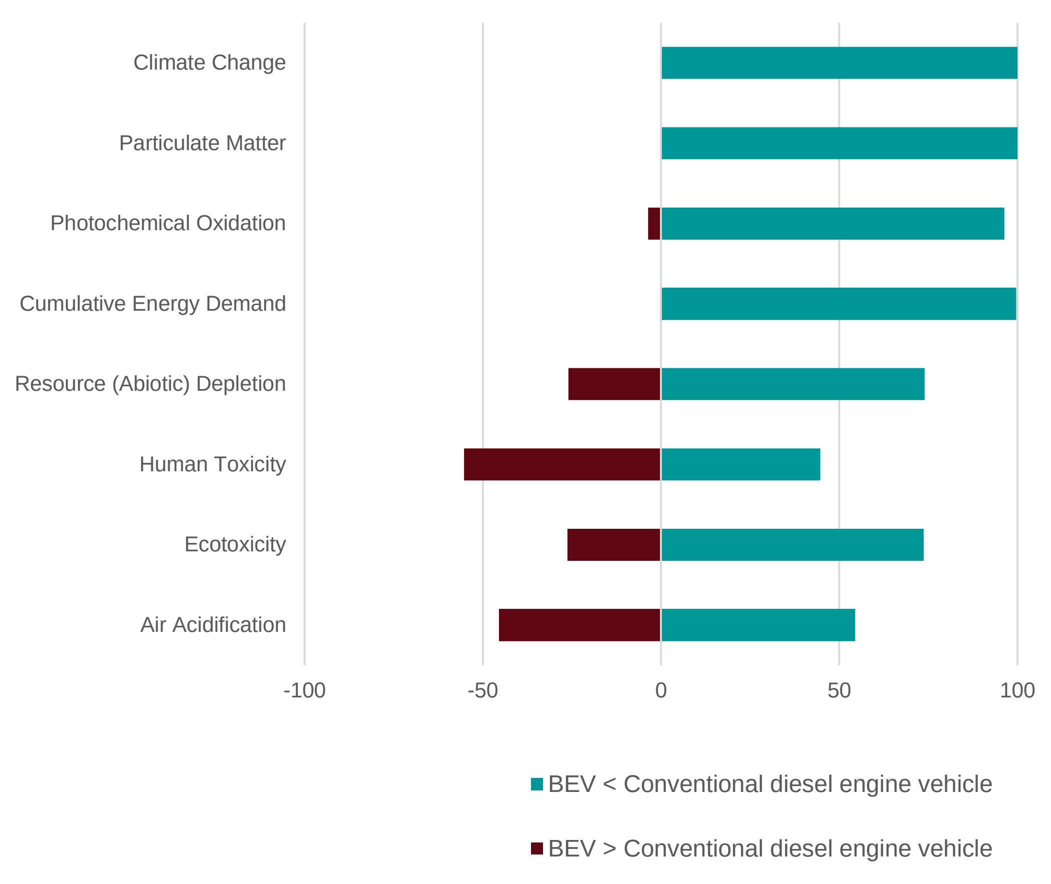

Figure 27 Uncertainty analysis of comparison between BEVs and conventional diesel engine vehicles

For both comparisons of the BEV to conventional petrol and diesel engine vehicles, PEVs have less impact more than 97% of the time in a majority of areas, namely climate change, particulate matter, photochemical oxidation, and cumulative energy demand.

For air acidification, results indicate a higher level of uncertainty, indicating that the BEV has lower impacts than petrol and diesel 54 and 60% of the time respectively.

The toxicity categories also indicate moderate levels of uncertainty, with results showing that BEVs will have lower ecotoxicity impacts compared to petrol and diesel vehicles 66% and 74% of the time respectively. For human health toxicity, uncertainty levels are higher, with BEV showing lower impact levels compared to petrol and diesel vehicles 45% of the time. The high uncertainty associated with toxicity models is due to the inherent uncertainties in the USEtox data utilised here. USEtox contains characterisation factors for impact category modelling that comprised “recommended” and “interim” characterisation factors. Those factors that are “recommended” are those in which there is scientific consensus on their modelling; the “interim” factors are those where not all the minimal requirements (as required by the scientific community) are met for its determination. For toxicity, characterisation factors associated with metals are all deemed as "interim" factors[40]. The analysis shown in the previous figures indicates this level of uncertainty, particularly as results are strongly influenced by the metal content of the vehicles.

In terms of resource (abiotic) depletion, BEV was shown to have less impact than conventional petrol and diesel for 67% and 74% of the time respectively. The higher levels of uncertainty in this impact category were predominantly due to the similarity in manufacturing materials in both conventional and electric vehicles. Also, the consumption of fossil fuels (such as petrol or diesel) was not a dominant factor in this impact category.

The overall conclusion is that there is high confidence in the comparative assertions made between PEVs and conventional vehicles in Section 5, for the included impact categories of climate change, energy consumption, photochemical oxidation and particulate matter. The uncertainties inherent in the data used in the other categories – human toxicity, ecotoxicity, resource depletion and air acidification – mean that it cannot be stated with any confidence that the PEVs had less impact than the conventional vehicles. But it should be noted that in each instance, the impacts were relatively insignificant. That is, in terms of human toxicity, ecotoxicity, resource depletion and air acidification, it can be safely assumed that even if PEVs perform worse than conventional technologies on a life cycle analysis, their impact is nevertheless slight.

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[40] USEtox (2015) *Frequently Asked Questions about USEtox (4),* accessed on 25th August 2015, accessible at http://www.usetox.org/faq#t23n115

7 Conclusion

This life cycle assessment aims to compare four types of similar-sized passenger vehicles in the New Zealand context, namely conventional petrol and diesel engine vehicles, and two types of PEVs (i.e. BEVs and PHEVs). A particular focus of this study is the comparison of PEVs with conventional vehicles.

The LCA utilised publicly available data and, where practical, data and assumptions specifically relevant to the New Zealand context. The study assessed the life cycle impacts of a vehicle travelling 1 km. A summary of results are provided in the following table.

Table 15 Summary of life cycle impacts across vehicles*

Vehicle technology	**Climate Change**	**Particulate matter**	**Photo-chemical Oxidation**	**Cumulative Energy Demand**	***Resource (Abiotic) Depletion***	***Human Toxicity***	***Eco-toxicity***	***Air Acidification***
	kg CO_2e	**kg $PM_{2.5}$**	**kg C_2H_2**	**MJ LHV**	***kg Sb***	***CTU_h***	***CTU_e***	***kg SO_2***
Conventional petrol engine vehicle	0.26	11.2 E-05	11.2 E-05	4.36	*4.69 E-05*	*7.76 E-08*	*6.13*	*7.42 E-04*
Conventional diesel engine vehicle	0.22	11.1 E-05	6.81 E-05	4.22	*4.94 E-05*	*8.06 E-08*	*6.65*	*7.15 E-04*
Plug-in hybrid electric vehicle (PHEV)	0.15	9.72 E-05	7.45 E-05	2.79	*5.20 E-05*	*14.7 E-08*	*7.06*	*6.80 E-04*
Battery electric vehicle (BEV)	0.11	8.41 E-05	5.89 E-05	2.56	*4.41 E-05*	*17.3 E-08*	*5.62*	*6.83 E-04*

* Impact categories highlighted in grey and italicised have high uncertainties associated with results.

In summary, based on these results, the study highlighted the following findings:

- PEVs in New Zealand are forecast to significantly reduce life cycle energy consumption and CO_2-equivalent emissions (consistent with other international studies); however they may cause other, unintended environmental impacts if due attention is not paid to all aspects of their life cycle.
- PEVs perform better than conventional vehicles in the areas of climate change, total energy use, particulate emissions and photochemical oxidation. This is because in practice, the on-road operational impacts of PEVs are improved relative to conventional vehicles.

- The study found that there are no significant differences across the technology types with regard to net resource depletion, considering that levels of uncertainty in these findings was high. However, there is opportunity to reduce resource depletion impact, as sensitivity analysis found that improvements in battery technology (such that battery life is extended) and in the rate of recycling of the materials used in batteries and motors will improve the comparative mineral resource performance of PEVs.
- For toxicity impacts and air acidification, it is difficult to determine whether PEVs perform better compared to conventional vehicles. Results indicate that PEVs are generally better than conventional in air acidification and ecotoxicity, but perform worse for human health toxicity. However, the practical differences in toxicity impacts are minimal, given the overall low absolute toxicity scores either way.

Where PEVs perform worse than conventional vehicles, a majority of the impacts can be attributed to the processes involved in the extraction of raw materials for and the manufacturing of the batteries and electric drivetrains of the vehicles. Consequently, these impacts are particularly sensitive to the materials used for battery and electric drivetrain components. Sensitivity analysis indicates that distinct improvement in the performance of PEVs could be realised with improvements in the rates of recycling of battery components, and in improvements in battery technology that served to prolong their life. Although facilities for recycling battery materials and drivetrain components (notably copper and aluminium) do not exist in New Zealand, recycling and reprocessing facilities are likely to arise as the PEV market increases, with concomitant improvements in the performance of PEVs in those impact categories.

Nonetheless, it is clear from the results of impact categories with high certainty, that PEVs show improved performance in the areas of carbon emissions, particulate matter, photochemical oxidation and lifecycle energy use. Overall, life cycle assessment of the different technologies indicates that there do seem to be significant benefits to the adoption of PEVs.

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Appendix A

Review of industry LCAs

A1 Literature review of relevant life cycle studies

A substantial number of life cycle analyses conducted in the last 10-15 years have considered plug-in electric vehicles at some level. While the defining attributes of each study are unique in their timing, assumptions, data, and considerations of local context, their existence helps us to formulate a basis for our work.

In more recent (and therefore relevant) works, as summarised in the examples reviewed below, we have found a generally favourable outcome for PEVs in considering life cycle impacts relative to their peers in the marketplace. Although a number of considerations have been raised earlier in this document, we believe that we will be able to appropriately assess the four technologies earmarked for study, factoring in some aspects of the approaches taken below.

A1.1 Ricardo / Low Carbon Vehicle Partnership Study

Author: Patterson J, Alexander M, Gurr A

Year: 2011

Title: *Preparing for a Life Cycle CO2 Measure – A report to inform the debate by identifying and establishing the viability of assessing a vehicle's life cycle CO_2e footprint*

Relevance of study: This study was commissioned by the UK Low Carbon Vehicle Partnership to develop an LCA method as a replacement for the tailpipe CO_2 metrics that prevailed in the EU at that time. The study explored some key methodological issues related to the boundary definition of the LCA scope and the potential for a valid assessment based on data availability and accuracy constraints. The study also provided a highly rigorous LCA comparison based on its best-practice industry methods and data at the time.

The study concluded that life cycle CO_2 emissions for hybrid and electric vehicles could be 10-20% reduced compared to a mid-size conventional passenger car in 2015. However it also identified that, for an electric vehicle, nearly half of the life cycle CO_2 could result from the manufacturing stage and that this effect became even more pronounced if low-carbon electricity was supplied for the operational phase. The study also included numerous sensitivities, including the need for battery replacement in electric vehicles which was a highly sensitive factor. Lastly the study identified a series of key methodological gaps in the LCA state of the art as applied to vehicles at that time.

Pros of study: An industry-driven and recognised study (arguably the gold standard) with high-quality, detailed comparisons between electric vehicles and conventional vehicles. Also provides excellent guidance on methodological issues (i.e. what matters and what doesn't).

Cons of study: The study is focused on the UK market and a few years old. The high-quality LCA model and data inputs were proprietary to industry thus not readily available. However the extensive documentation may allow certain data to be extracted and repurposed. Also Arup (UK) is a member of the LCVP which may help obtain more data / models for our use.

A1.2 BERR Electric Vehicles Investigation

Author: Arup, UK Department for Business Enterprise and Regulatory Reform

Year: 2008

Title: *Investigation into the Scope for the Transport Sector to Switch to Electric Vehicles and Plug-in Hybrid Vehicles*

Relevance of study: The study was commissioned in 2008 to investigate the potential impact of switching to electric vehicles until 2030. The study is focussed in the UK market, examining contextual issues that will impact EV and PHEV uptake. A life cycle emissions comparison was undertaken against petrol and diesel vehicles.

Key results from the study are that from a carbon emissions and photochemical oxidant formation perspective, EVs perform better than petrol vehicles. However, air acidification impacts depend largely on the grid-electricity emissions in a given year.

Pros of study: An industry-recognised document, and provides useful summary of the EV in comparison to internal combustion vehicles.

Cons of study: The study is based on the European market, and is now several years' old. There is limited access to the input data for this study. Limited information regarding scope and boundary of the assessment.

A1.3 US EPA Lithium-ion Batteries LCA

Author: United States Environmental Protection Agency

Year: 2013

Title: *Application of Life-Cycle Assessment to Nanoscale Technology: Lithium-ion Batteries for Electric Vehicles*

Relevance of study: The report is a detailed LCA study into the manufacturer, use and disposal of batteries for electric vehicles in the US market. The study utilises existing life cycle inventory data for battery manufacture, and is a potential source of data points for the study.

Of particular note, the study found that the primary driver for recycling of Li-ion batteries is due to the value of the recovered materials (such as cobalt, nickel, and lithium). However, the current demand for Li-ion batteries and the limited availability of recycled lithium requires batteries to be produced using primary lithium sources. Additionally, although recycling of Li-ion batteries is possible (and is currently commercially undertaken in 3 known sites in the US, the production of lithium-ion batteries using significant amounts of recycled lithium material will only occur beyond 2030. The US-industry demand for Li-ion battery recycling will only significantly occur from approximately 2035 onwards.

Pros of study: Provides international context to the LCA treatment of waste disposal (recycling) for Li-ion batteries. Study contains data and bill of materials from battery suppliers, manufacturers and recyclers for Li-ion batteries.

Cons of study: The study is focussed particularly on US manufacture of batteries, and the majority of data is from the US-market.

A1.4 Ecoinvent Methodology Report

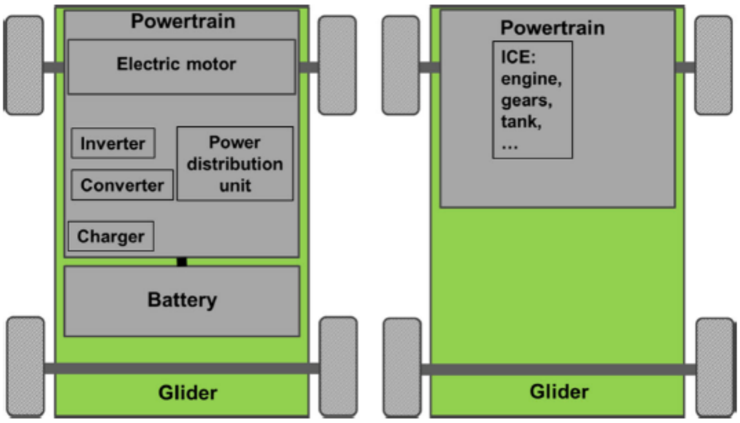
Author: Del Duce A., Gauch M., Althaus H-J

Year: 2014

Title: *Electric passenger car transport and passenger car life cycle inventories in ecoinvent version 3*

Relevance of study: This study was undertake for the development of version 3 of the ecoinvent database. Ecoinvent provides a comprehensive life cycle inventory database for a large number of materials and projects particularly in the European context. Ecoinvent v2 and v3 have life cycle inventory data available for traditional passenger vehicles (petrol and diesel) and an electric vehicle in the European context.

This study provides a comprehensive methodology comparing the ICE and an EV, with the new dataset breaking-down key components of a vehicle, i.e. the glider (common components), EV powertrain, battery for EV, and ICE powertrain (refer to figure below).



The default dataset in ecoinvent v3 is based on literature data, with a specific focus on the Volkswagen Golf, and modifying these factors based on vehicle weights across models (e.g. the Golf VI versus the Golf A4).

Pros of study: Provides a detailed methodology into the components of both a generic ICE and EV, which allows an LCA practitioner to modify key components of a vehicle for a more specific LCA.

Cons of study: As described by the paper itself, the datasets used for ecoinvent v3 are based on all vehicles in 2000. Of particular risk is that the data regarding the ‘glider’ and ICE powertrain may be understating a shift in the car-industry since

2000 to lighter manufacturing materials. However, the study recognises that some of this data has been updated in 2011, and is believed to provide a representation of current vehicle technologies.

A1.5 Hawkins 2012 Study

Author: Hawkins T, Singh B, Majeau-Bettez M, Stromman A

Year: 2012

Title: *Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles*

Relevance of study: The study provides a life cycle inventory of conventional and electric vehicles, for the European context (and particularly accounting for the European electricity mix). The aim of the study is to provide a transparent inventory that can be used for assessing other vehicles and fuels. Vehicle production data was based on an existing model and scaled and adapted for two specific vehicle characteristics – the Mercedes A-Class, and the Nissan Leaf EV.

This study found that the production phase of EVs are substantially more environmentally intensive that for combustion vehicles. However, overall improvements regarding global emissions may be achieved from EVs (dependent on the energy source for electricity).

Pros of study: Includes extensive supporting material content for various parts of the electric and conventional combustion engine.

Cons of study: Based on literature and publicly available data.

A1.6 California Air Resources Board (CARB) / UCLA Study

Author: Aguirre K, Eisenhardt L, Lim C, Nelson B, Norring A, Slowik P, Tu N, Rajagopal D

Year: 2012

Title: *Life cycle Analysis Comparison of a Battery Electric Vehicle and a Conventional Gasoline Vehicle*

Relevance of study: This study calculates the energy inputs and CO_2 equivalents emissions of a conventional gasoline vehicle (CV), a hybrid vehicle, and a battery electric vehicle (BEV) to determine the life cycle environmental costs of each specific to California. Data used were a compilation of the California GREET model, Argonne National Laboratory articles and other relevant peer-reviewed literature. The main purpose of this study was to examine the environmental impact of each vehicle type, taking into account the life cycle energy usage and both CO_2 equivalents and air pollution emitted.

In terms of environmental impacts, the BEV was determined to have the least overall impact, followed by the hybrid, and lastly the CV. The net present cost of all vehicles was also calculated resulting in the hybrid being the least expensive over its lifetime, followed by the CV, and finally the BEV. The hybrid vehicle was found to be the most cost effective for reducing CO_2.

Pros of study: Used the California GREET model, which is publicly available in spreadsheet form via the CARB website. Detailed data may be extracted and repurposed. The study also includes extensive sensitivity testing.

Cons of study: The study and its underlying data are quite specific to California. Study does not appear to have been peer reviewed apart from internally at CARB.

A1.7 Other studies

Author, Year, Title	**Brief description**
Schweimer (2004) *Life Cycle Inventory for the Golf A4*	Original LCA for the Volkswagen Golf A4. A comprehensive LCA study for cradle-to-grave impacts. Utilises data directly from the manufacturer, however, component-level data is not available (only material data for the entire vehicle, making the data impractical to use for other LCAs). The study is very specific to this material type. The life cycle inventory and outputs of this study was included in ecoinvent v2.2 for a standard petrol and diesel passenger vehicle.
Volkswagen (2014) *LCA of e-Golf*	A comprehensive LCA, using the methodology of the Schweimer 2004 study, to compare three versions of the Volkswagen Golf; petrol, diesel and electric. The study presents useful results for comparison. This study is limited in its use for other applications, as access to manufacturer-specific data is unavailable.
Gains, Sullivan, Burnham (2010) *Life-Cycle Analysis for Lithium-Ion Battery Production and Recycling*	A study which was submitted on August 1, 2010 for presentation at and inclusion in the 90th Annual Meeting of the Transportation Research Board, Washington D.C. The study provides a material composition breakdown of various Li-ion battery systems for electric vehicles. Utilises the GREET 2.7 model to compare the impact of batteries on energy use and emissions over the life cycle of a vehicle.
Dominic A. et al. (2010) *Contribution of Li-Ion Batteries to the Environmental Impact of Electric Vehicles*	An LCA study analysing the specific impact of lithium-ion batteries in an electric vehicle. The study looks at cradle-to-grave impacts. The electric vehicle used was a generic vehicle, but comparable to a Volkswagen Golf in size and power (and the LCI was derived from the Schweimer 2004 study). The study was undertaken for the European context (accounting for the average electricity production mix). The study concluded that the operation phase of electric vehicles remains the dominant contributor to environmental burden (so long as the electricity mix is largely renewable).

Appendix B

Description of impact categories

B1 Description of impact categories

The following sections provides further descriptions of the impact categories assessed as part of this study.

B1.1 Climate change

The climate change impact category considers the global warming potential of the greenhouse gas emissions emitted as a result of the project, over a 100 year period. The details of the impact category used in the model are outlined in Table 16 below.

Table 16 Climate Change Impact Category Definition

Impact Category	**Climate Change**
LCI results	Emissions of greenhouse gas per functional unit
Characterisation model	Baseline model of 100 years of the Intergovernmental Panel on Climate Change
Category indicator	Infrared radiative forcing (W/m^2)
Characterization factor	Global warming potential (GWP100) for each greenhouse gas (kg CO_2-equivalents/functional unit)
Category indicator result	Kilograms of CO_2-equivalents per functional unit
Category endpoints	Coral reefs, forests, crops, urban settlements
Environmental relevance	The earth's atmosphere absorbs part of the energy emitted as infrared radiation from earth towards space and thus becomes heated. Infrared radiative forcing is a proxy for potential effects on the climate as a result of that phenomenon
International acceptance of model	The model is based on the factors developed by the Intergovernmental Panel on Climate Change. Factors are internationally accepted for accounting of carbon emissions.

B1.2 Particulate matter

This impact category considers the emissions of particulates into the air, as a result of processes such as combustion of fuels or release of emissions directly. This impact category particularly considers fine particulates (less than 10 µm) that have potential respiratory effects to humans. The impact category also considers other air emissions, such as sulphur and nitrogen oxides, that create secondary particulates.

Table 17 Particulate Matter Impact Category Definition

Impact Category	**Particulate Matter**
LCI results	Amount of particulate matter released from various processes and emissions in order to create a product.
Characterization model	Institute of Environmental Sciences (CML), Universiteit Leiden, CML-IA Characterisation Factors, 2014
Category indicator	Particulate matter
Characterisation factor	Characterisation of a range of air emissions, including $PM_{2.5}$, PM_{10}, sulphur oxides, nitrogen oxides, carbon monoxide and ammonia
Category indicator result	kg $PM_{2.5}$ equivalent
Category endpoints	Air quality
Environmental relevance	Respiratory effects as a result of release of particulates in local air sheds
International acceptance of model	The characterisation models developed by CML are publicly available and updated regularly when new knowledge on substances are available. Models from CML have widely applied in various LCAs and available for use in LCA software.

B1.3 Photochemical oxidant formation

Photochemical oxidant formation is the formation of reactive chemical compounds such as ozone, by the action of sunlight on certain primary air pollutants. The two major primary pollutants, nitrogen oxides and Volatile Organic Compounds (VOCs), combine in sunlight through a series of chemical reactions into what are known as secondary pollutants.

The secondary pollutant that causes the most concern is the ozone that forms at ground level. While ozone is produced naturally in the upper atmosphere, it is a dangerous substance when found at ground level.

The photochemical oxidant formation impact category used in the model is outlined in Table 18 below.

Table 18 Photochemical Oxidant Formation Impact Category Definition

Impact Category	**Photochemical Oxidant Formation**
LCI results	Emissions of substances (VOC, CO and NO_x) into the air per functional unit
Characterization model	UNECE Trajectory model (including fate)
Category indicator	Tropospheric ozone formation
Characterization factor	Photochemical ozone formation potential (POFP) for each emission to the air (in kg ethylene equivalent/kg emissions)
Category indicator result	kg ethylene equivalent/functional unit
Category endpoints	Human health, natural environment

Impact Category	Photochemical Oxidant Formation
Environmental relevance	Production of ozone at ground level is hazardous to human and ecosystem health
International acceptance of model	This characterisation model is developed by the United Nations Economic Commission for Europe (UNECE), which is one of the five regional commissions of the United Nations. This model, in particular for photochemical ozone creation potential, has been applied in various international LCAs and is a widely accepted model.

B1.4 Cumulative energy demand

This impact category considers the total energy resources in the life cycle of a vehicle consumed for the travelling of one kilometre (the functional unit). This includes energy consumed in upstream and downstream processes (such as at power plants during energy generation, during component manufacture and for disposal) in addition to energy consumed by vehicles for travel (such as burning of fuels in an engine, or the consumption of electricity).

Table 19 Cumulative Energy Demand Impact Category Definition

Impact Category	Cumulative energy demand
LCI results	End-use of energy for transport, process heat, fuel extraction and delivery, electricity delivered and electricity lost per functional unit
Characterisation model	Not applied (i.e. no consideration of the relative importance of one energy-end use compared to another or compared to the energy supply available)
Category indicator	Decrease in energy available
Characterisation factor	No characterisation factor
Category indicator result	MJ LHV required per functional unit
Category endpoints	Energy supply networks and the reserves and infrastructure required to meet demand
Environmental relevance	The energy demand decreases the amount of energy available for other useful work. For electricity the energy demand increases the amount of energy to be supplied to the grid from external sources.
International acceptance of model	Energy flows are a common area of interest in LCAs. As this model sums all energy-related flows in a system, it is a non-weighted model. Similar characterisation models are applied by ecoinvent, and used widely in international LCAs.

B1.5 Resource (abiotic) depletion

This impact category considers the extraction of scarce resources, particularly minerals, in order to provide the materials for components into a product. The impact category considers various minerals that have been extracted. An Abiotic Depletion Factor (ADF) is determined for a range of extracted materials, based on concentration accounting for remaining available reserves and the rate by which they are extracted. As this category considers a range of mineral types, the impact category compares results against the mineral Antimony (Sb).

Table 20 Resource Depletion Impact Category Definition

Impact Category	**Mineral depletion**
LCI results	The decrease of availability of reserve base of potential functions of resources for resources used throughout life cycle per functional unit
Characterisation model	van Oers. L, de Koning. A, Guinee J, Huppes. G. *Abiotic resource depletion in LCA*, Road and Hydraulic Engineering Institute, 2002 ILCD 2011 Midpoint+ method
Category indicator	Depletion of base resource, i.e. resources that have a reasonable potential for becoming economically and technically available
Characterisation factor	kg Sb per kg of mineral. Characterisation of various resource types (minerals, fossil fuels, etc.) and its depletion compared to the depletion of the mineral antimony.
Category indicator result	kg Sb per functional unit
Category endpoints	The depletion of resources, direct extracted and required to support material demand
Environmental relevance	The use of raw minerals and resources, recognising that this a depletion of a finite amount of resources. The depletion of various minerals and other abiotic resources can represent further environmental problems.
International acceptance of model	The characterisation models developed by van Oers 2002 were adapted for use in the ILCD Handbook. The ILCD handbook is developed by the European Commission's Joint Research Centre and has been established through a number of stakeholder consultations. More information can be found at http://eplca.jrc.ec.europa.eu/?page_id=86

B1.6 Human health toxicity

The impact category of human health describes the impact or damage on human health. This is described as the number of disease cases from exposure to toxic emissions. Ill-health may be defined as impacts from a range of incidences, from congenital anomalies to cancers. The impact on health is described in CTU_h which accounts for both carcinogenic and non-carcinogenic health impacts.

The USEtox model has been developed under the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry. The characterisation factors within the model is appropriate to be used at a global scale. This impact assessment method has been adopted as a proxy for the New Zealand context. The human health impact category used in the model is outlined in Table 21 below.

Table 21 Human health Impact Category Definition

Impact Category	**Human health toxicity**
LCI results	Number of years lost due to ill-health from non-carcinogenic and carcinogenic impacts per functional unit
Characterization model	USEtox 4 model, Rosenbaum et al (2008), Hauschild et al (2008)
Category indicator	Carcinogenic substances, Non-carcinogenic substances
Characterization factor	The model takes into account toxicity related to ingestion and inhalation exposure, accounting for both carcinogenic as well as non-carcinogenic impacts.
Category indicator result	Comparative Toxic Units (CTU_h), as the number of disease cases per functional unit
Category endpoints	Human health
Environmental relevance	Emissions from air due to industrial activities (mining, energy production, transportation) are detrimental to human health leading to loss of life, disease or health liabilities
International acceptance of model	Developed under the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry, (SETAC) Life Cycle Initiative

B1.7 Ecotoxicity

Ecotoxicity refers to the toxic impact or damage on freshwater, terrestrial and marine environments as a result of toxic emissions to air, water and land. This is described as potentially impacted or disappeared species measured in potentially affected fraction of species per m^3 of an ecosystem per day.

This impact category is characterised by a number of factors. The emissions from the use of pesticides dominate the impacts to freshwater and terrestrial environments. These pesticides include atrazine and metham sodium. Additionally, copper compounds from industrial emissions also significantly impact terrestrial environment. In marine environments, impacts are largely from fluoride air emissions from aluminium smelters, coal-burning electricity plants and water emissions from sewerage treatment plants. The use of grid-electricity, such as coal-burning electricity plants will have an impact on ecotoxicity levels.

This impact assessment method has been adopted as a proxy for the New Zealand context.

Table 22 Ecotoxicity Impact Category Definition

Impact Category	**Ecotoxicity**
LCI results	Potentially affected or disappeared species as a result of toxic stress.
Characterization model	USEtox 4 model, Rosenbaum et al (2008), Hauschild et al (2008)

Impact Category	**Ecotoxicity**
Category indicator	Freshwater aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity
Characterization factor	Impacts from ecotoxicity substances per emission compartment, i.e. emissions in urban air, rural air, freshwater, seawater, agricultural and industrial soil.
Category indicator result	Comparative Toxic Units (CTU_e) as the potentially affected fraction of species (PAF) integrated over time and volume per unit mass of a chemical emitted (PAF m3.day/kg)
Category endpoints	Water bodies, natural environment, ecosystem species
Environmental relevance	Emissions to air, water and land from industrial and agricultural activities will potentially affect species in freshwater ecosystems, which is an indication of ecotoxicity potential.
International acceptance of model	Developed under the United Nations Environment Program (UNEP) and the Society for Environmental Toxicology and Chemistry, (SETAC) Life Cycle Initiative

B1.8 Air acidification

The air acidification impact assessment addresses the emissions which have the potential to result in the decline in the pH (acidification) of water bodies and vegetation as well as associated ecosystem impacts upon deposition. Emissions of sulphur dioxides, nitrogen oxides and other nitrogen are the main contributors to air acidification. Nitrogen oxides are emitted by the main process sequence while sulphur dioxides are emitted in the supply chain providing fossil fuelled energy supply to the life cycle. The air acidification impact category used in the model is outlined in Table 23 below.

Table 23 Air Acidification Impact Category Definition

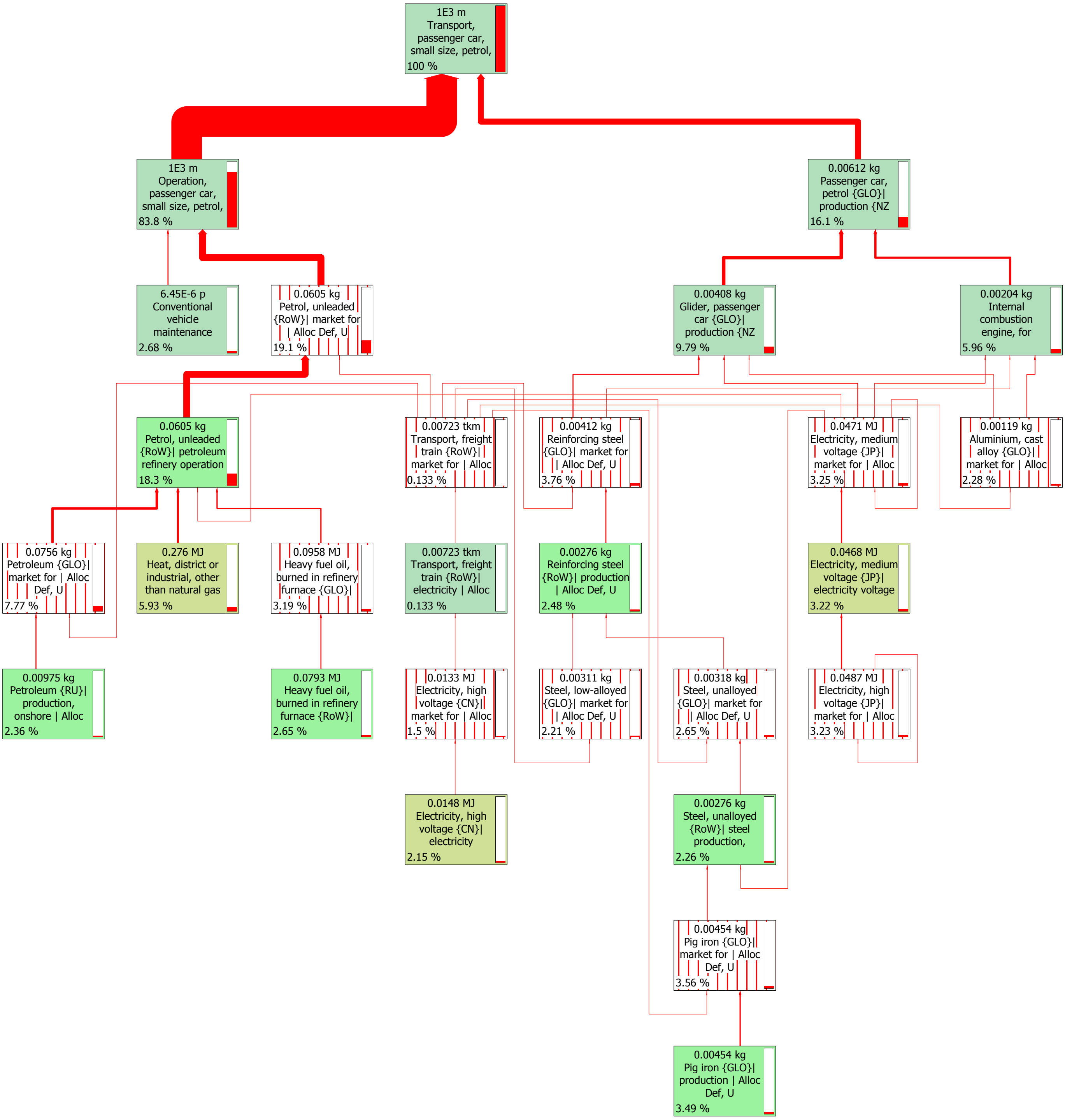
Impact Category	**Air Acidification**
LCI results	Emissions of acidifying substances into the air per functional unit
Characterization model	RAINS10 model developed at IIASA, describing the fate and deposition of acidifying substances, adapted to LCA by CML
Category indicator	Deposition/acidification critical load
Characterization factor	Acidification potential for each acidifying emission to the air gas (kg SO_2-equivalents/functional unit)
Category indicator result	Kilograms of SO_2-equivalents per functional unit
Category endpoints	Lakes, aquatic species, forests, crops
Environmental relevance	Deposition/acidification critical load is a proxy for potential effects of acid rain
International acceptance of model	The characterisation models developed by CML are publicly available and updated regularly when new knowledge on substances are available. Models from CML have widely applied in various LCAs and available for use in LCA software.

Appendix C

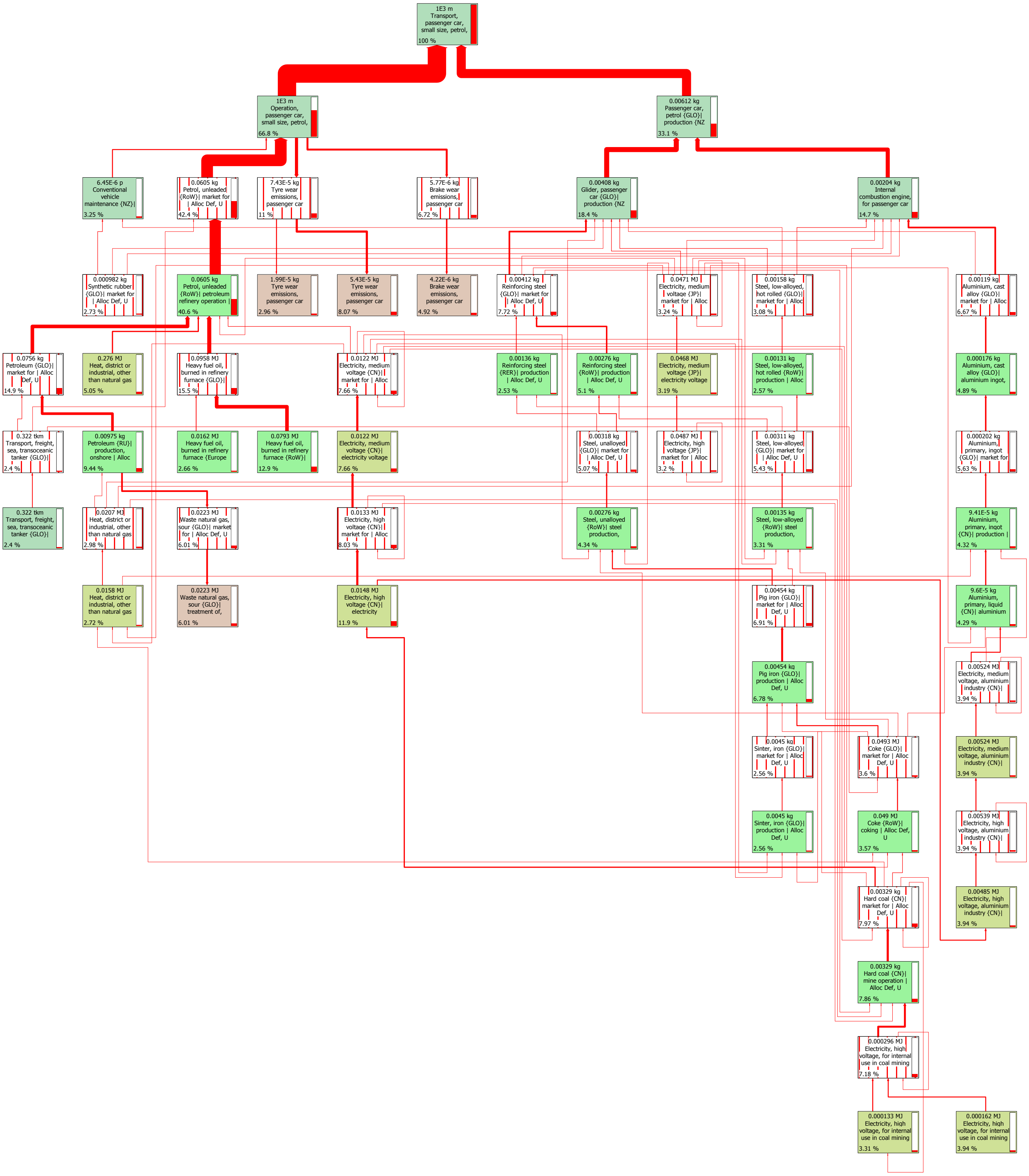
Impact flows

C1 Conventional petrol engine vehicle

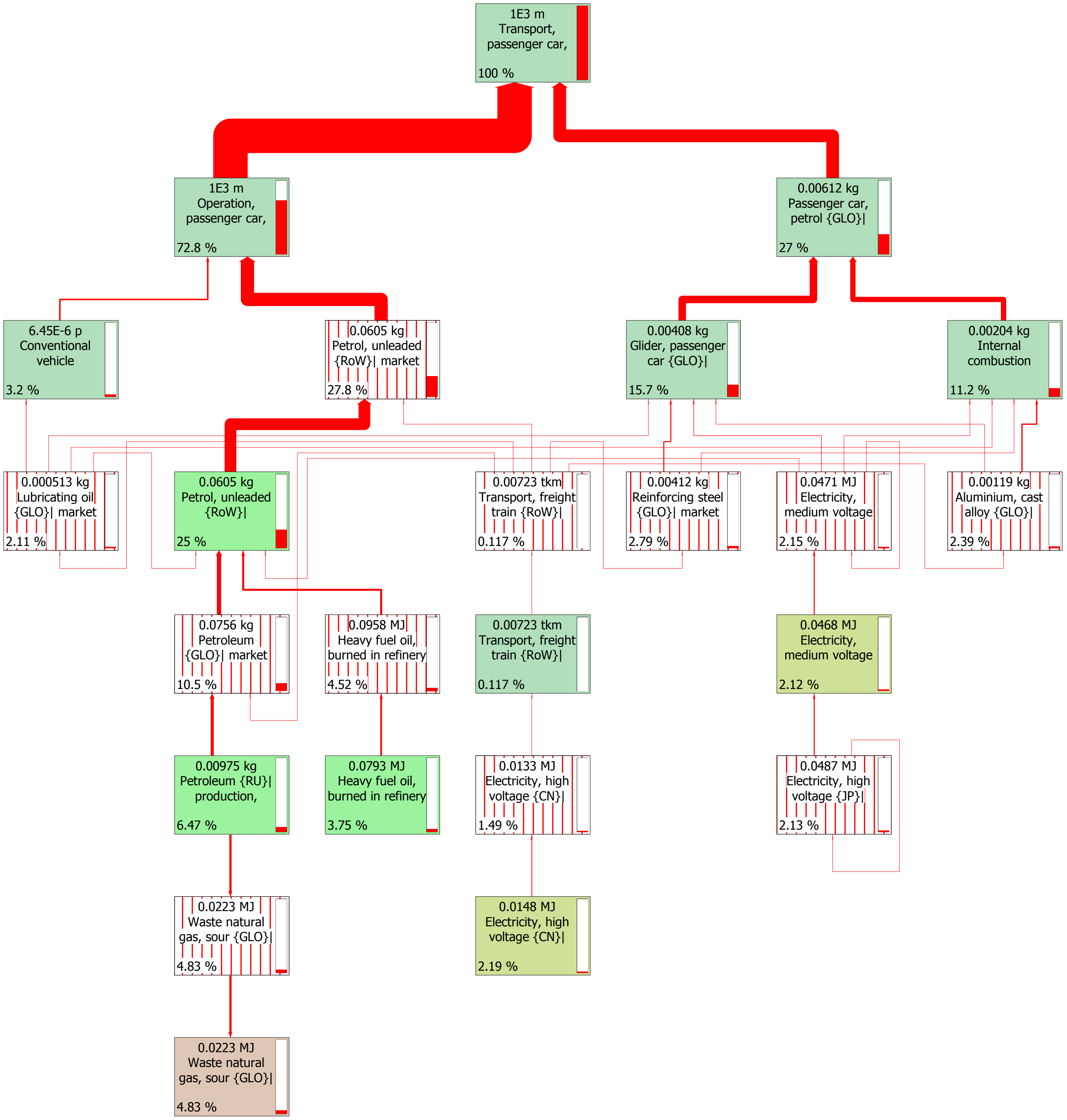
Product:	Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Climate Change (kg CO2 e)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



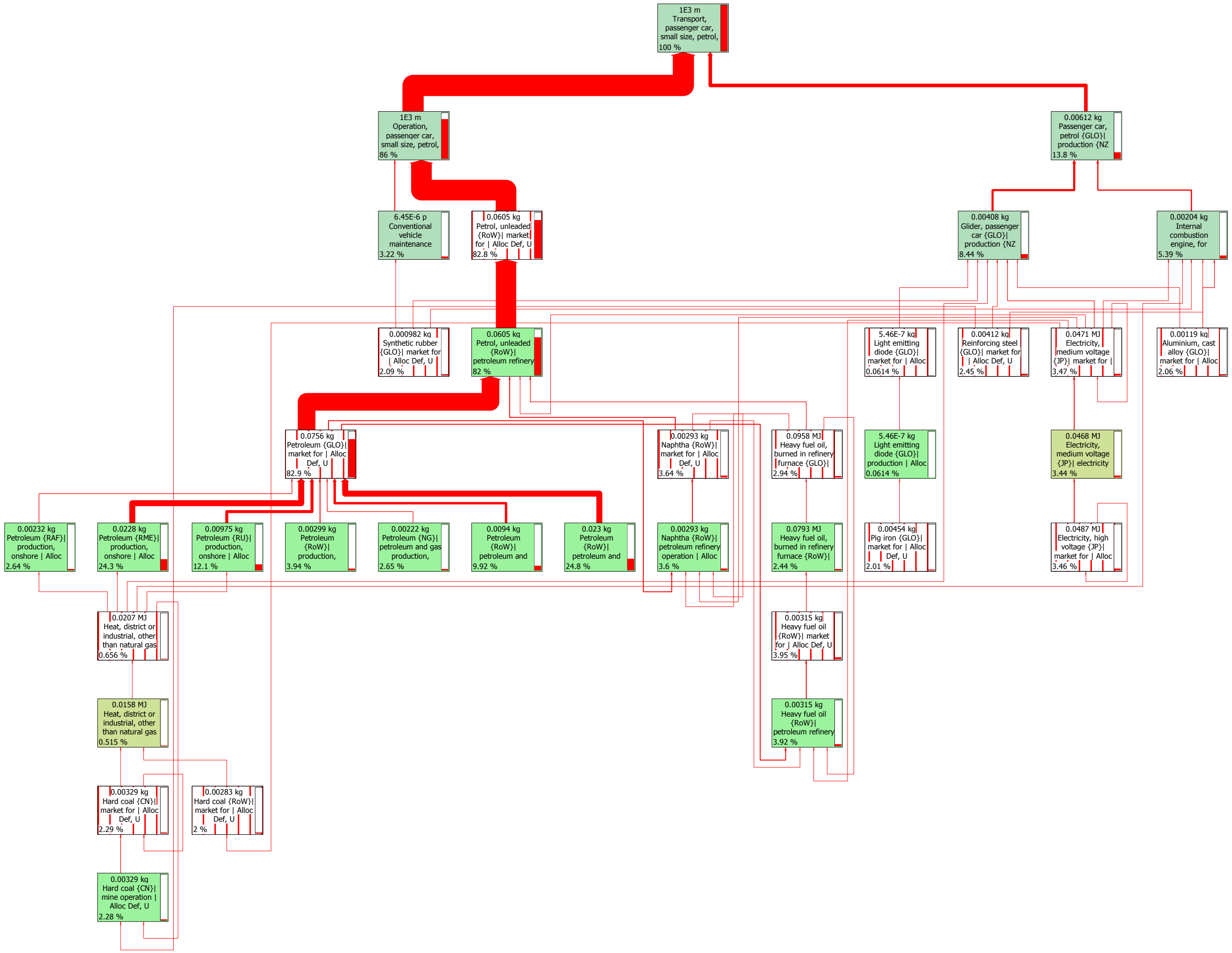
Product:	Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Particulate Matter (kg PM2.5 eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



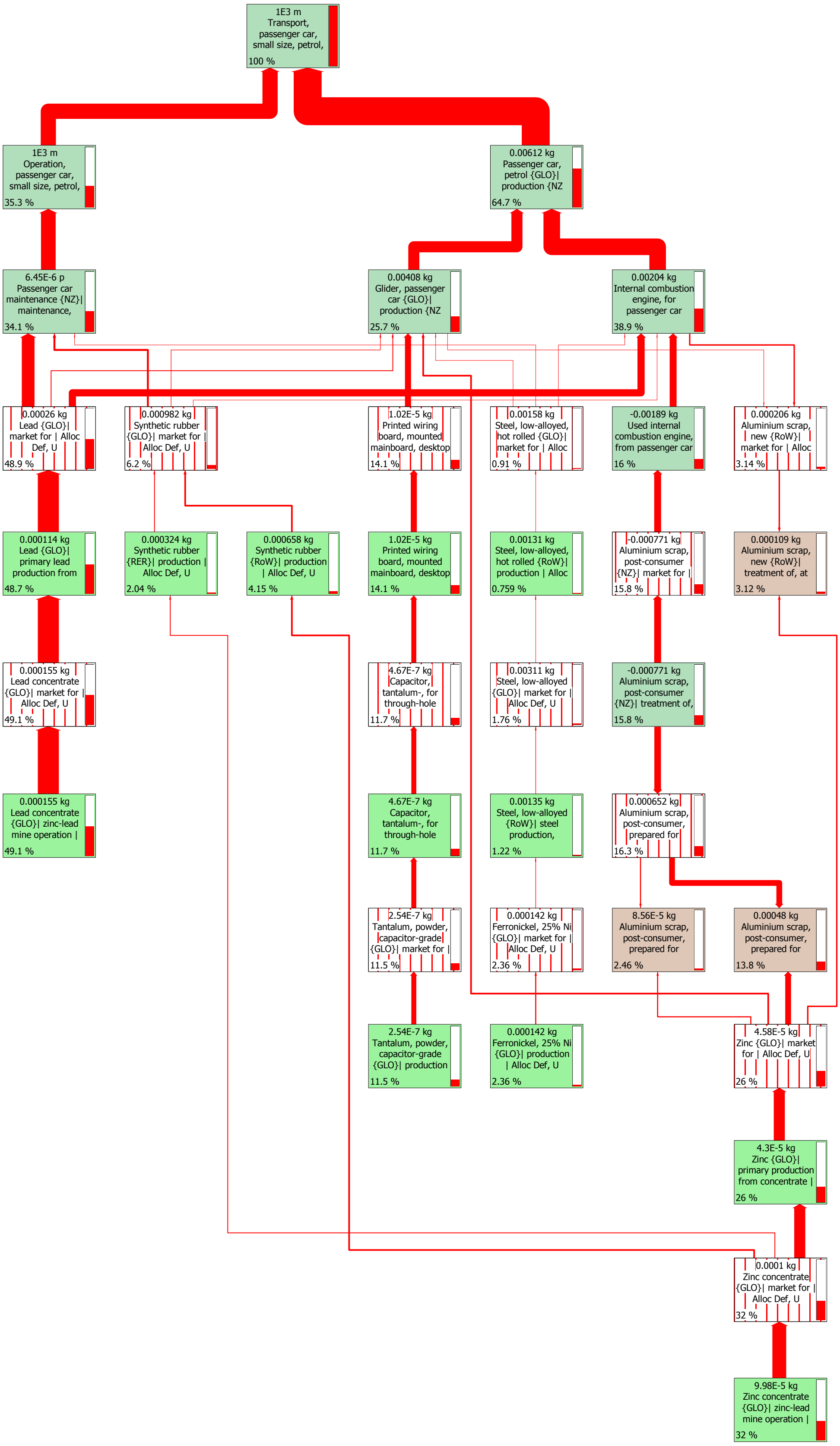
Product:	Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Photochemical Oxidation (kg C2H2 eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



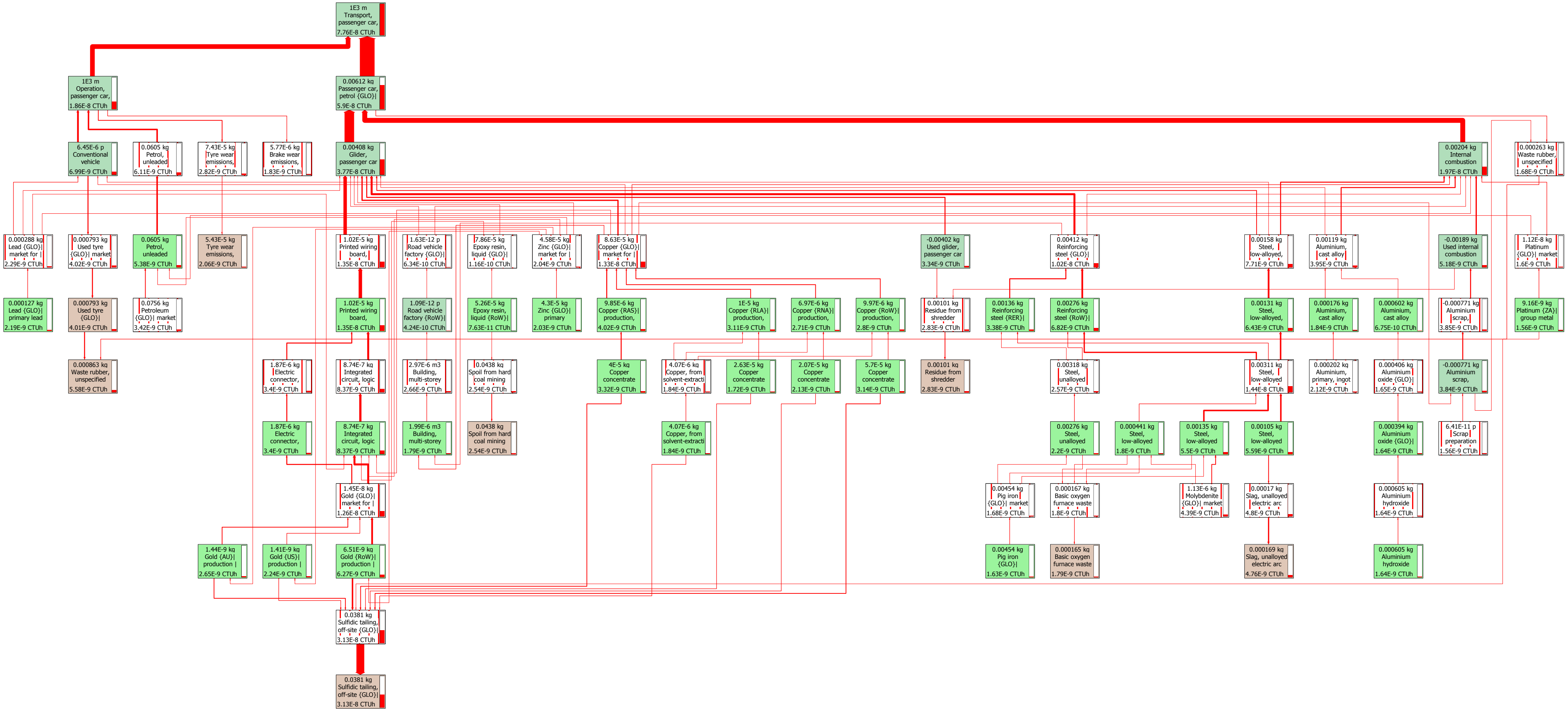
Product:	Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Cumulative Energy Demand (MJ LHV)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



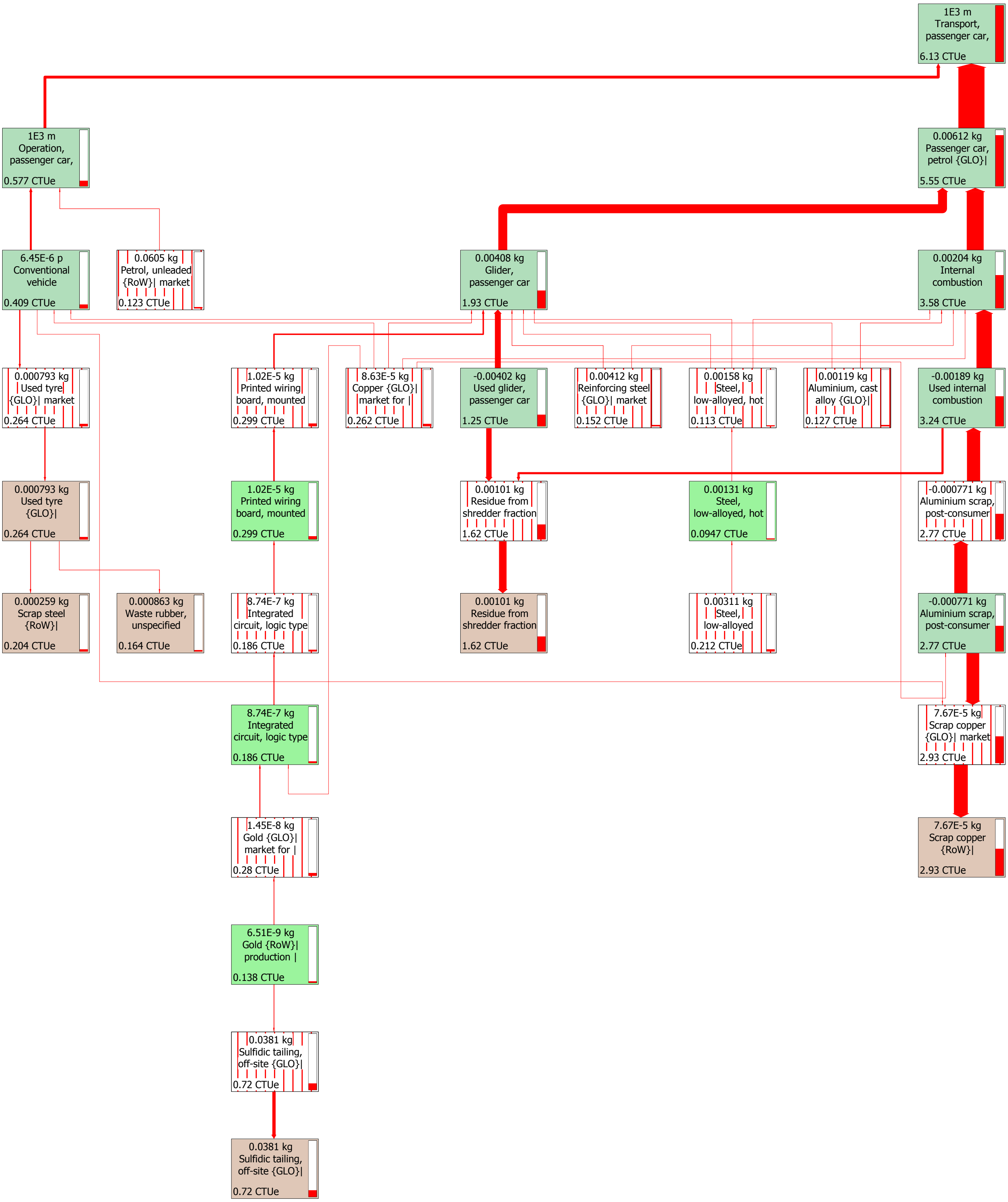
Product:	Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Resource (Abiotic) Depletion (kg Sb eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



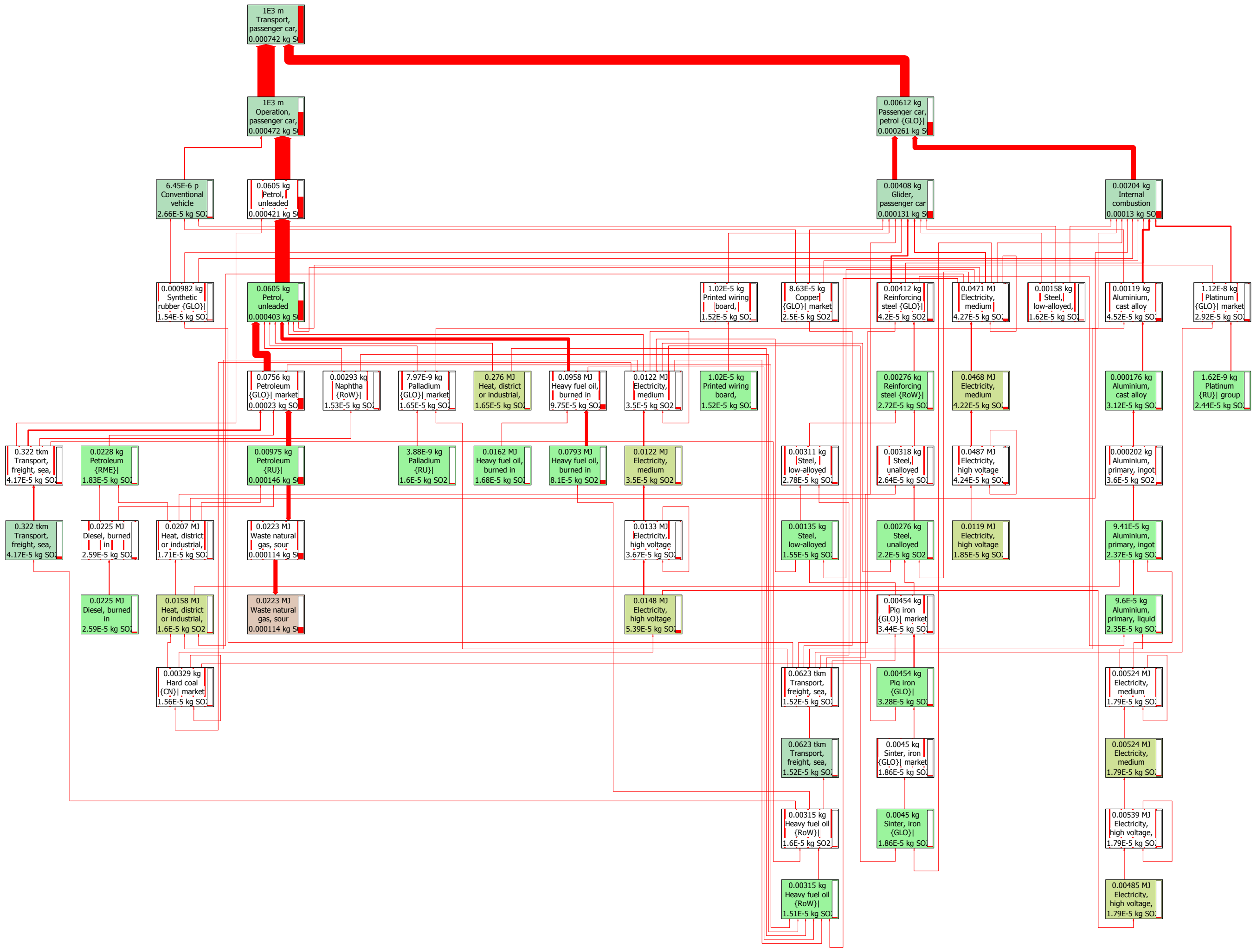
Product:	Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator:	Damage assessment, Human Toxicity (CTUh)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



Product:	Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator:	Damage assessment, Ecotoxicity (CTUe)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %

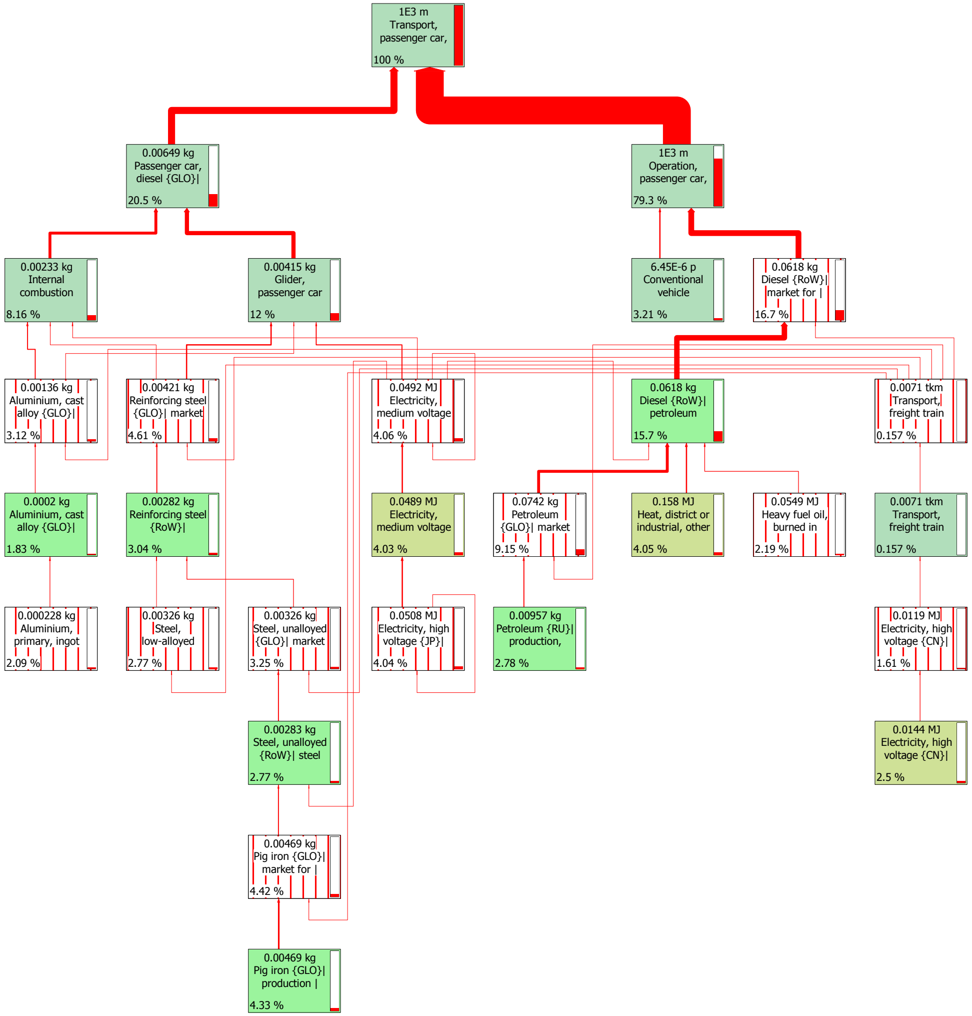


Product: Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project: NZ EECA LCA Study Oct 2015
Category: Transport\! NZ Vehicle Study
Method: NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator: Damage assessment, Air Acidification (kg SO2 eq)
Indicator mode: Cumulated indicator
Exclude long-term emissions: No
Node cut-off: 2 %

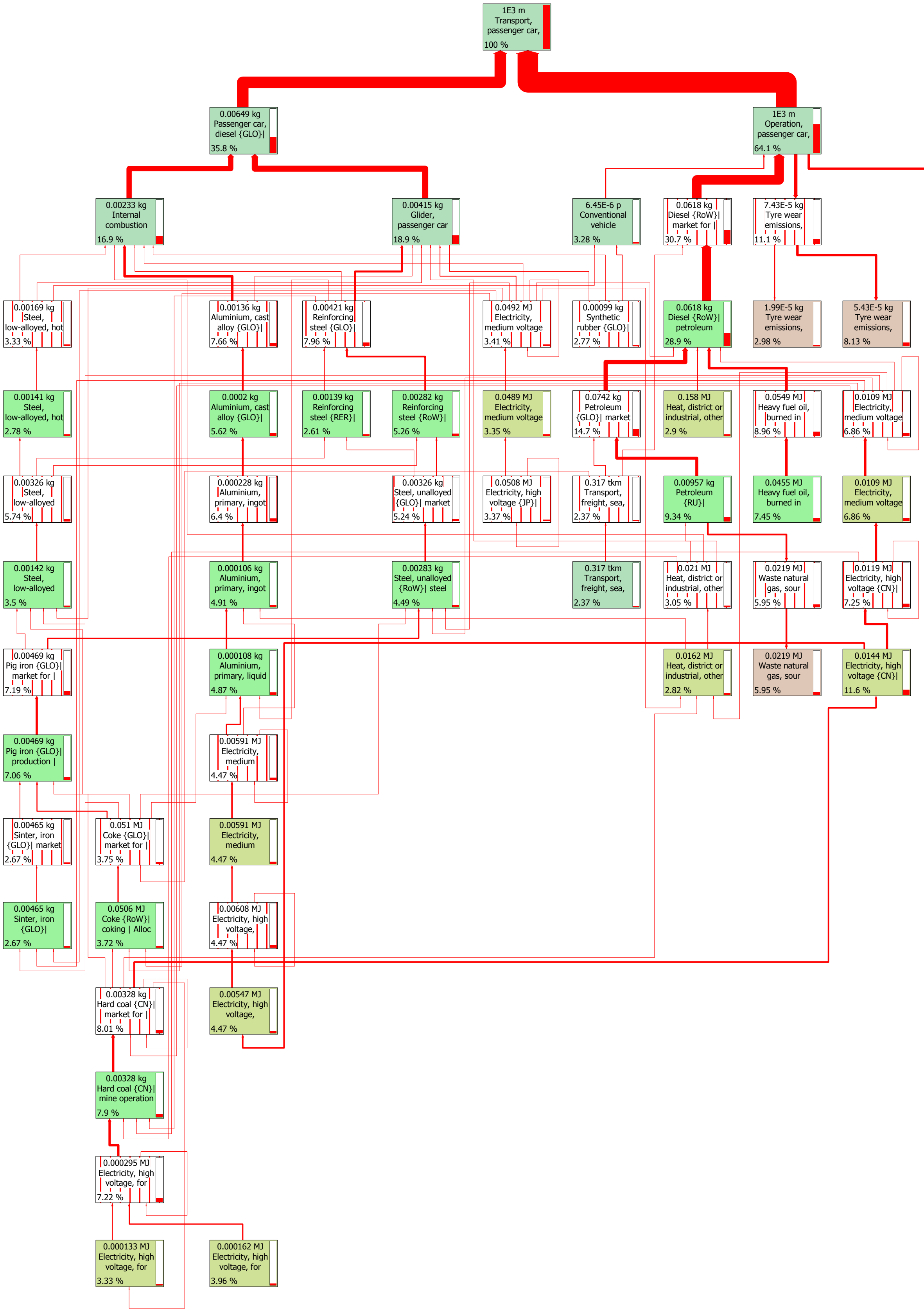


C2 Conventional diesel engine vehicle

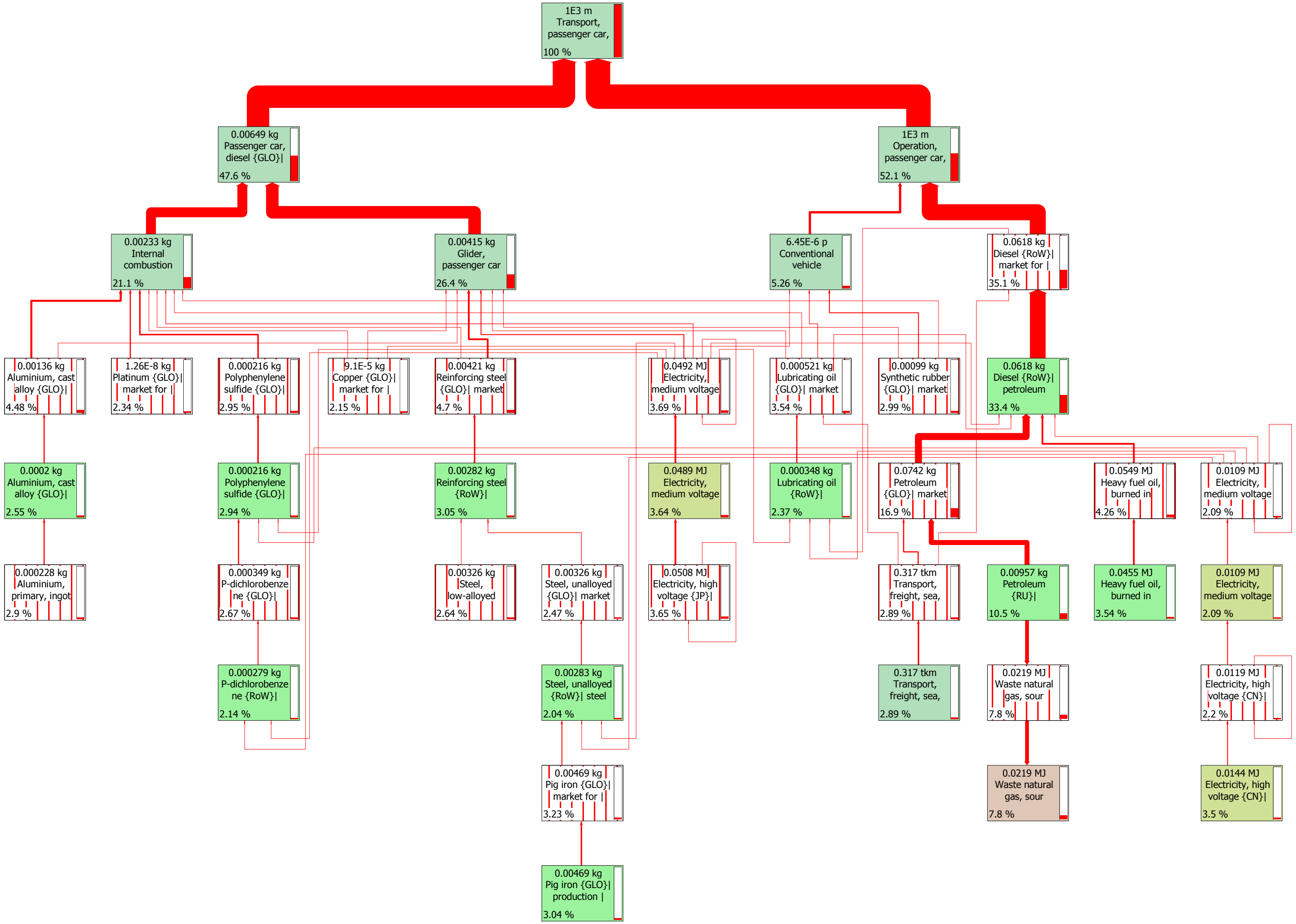
Product: Transport, passenger car, small size, diesel, EURO 5 {NZ}| per km | Alloc Def, U
Project: NZ EECA LCA Study Oct 2015
Category: Transport\! NZ Vehicle Study
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator: Damage assessment, Climate Change (kg CO2 e)
Indicator mode: Cumulated indicator
Exclude long-term emissions: No
Node cut-off: 2 %



Product:	Transport, passenger car, small size, diesel, EURO 5 {NZ}| per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Particulate Matter (kg PM2.5 eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %

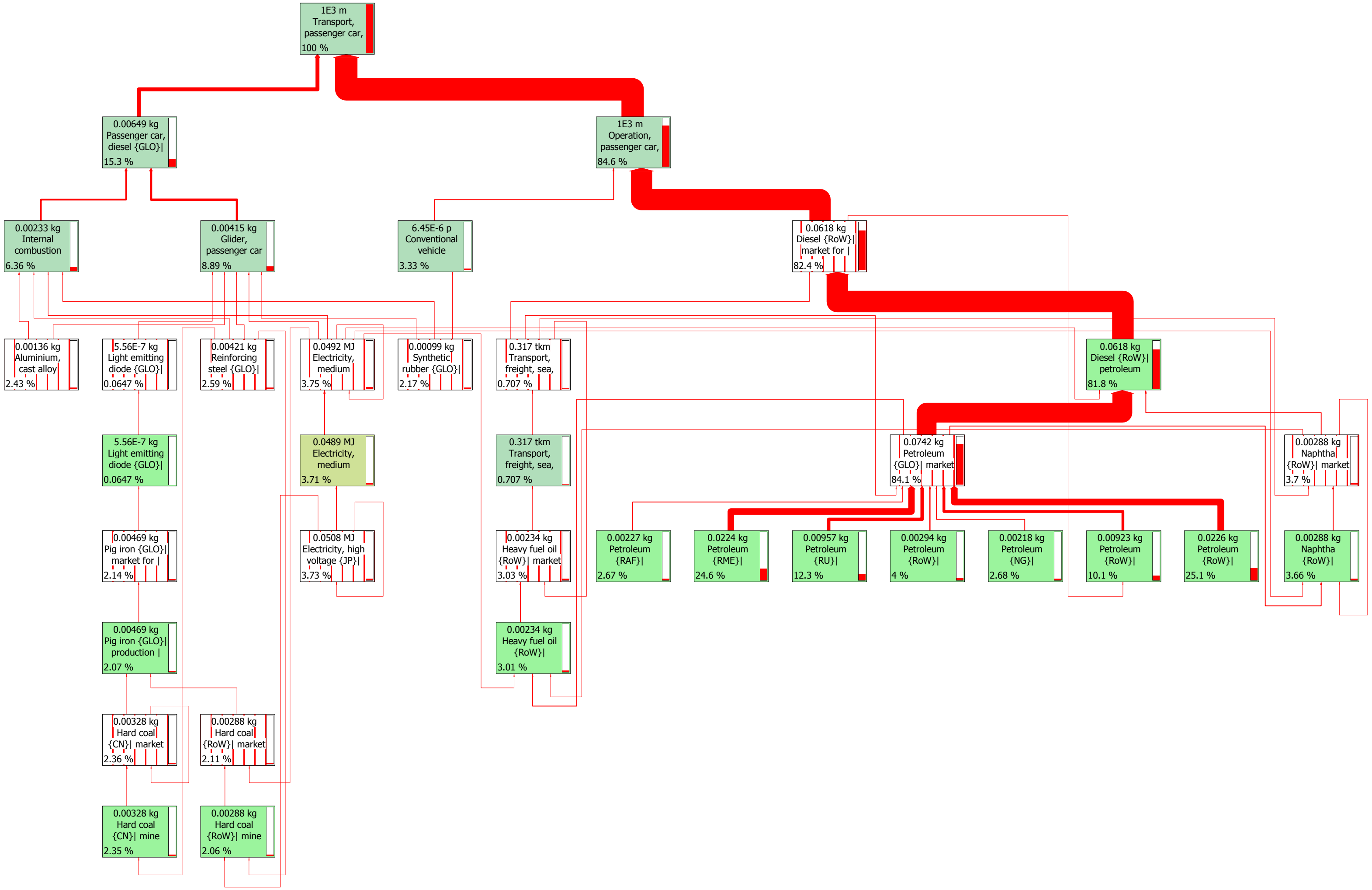


Product: Transport, passenger car, small size, diesel, EURO 5 {NZ}| per km | Alloc Def, U
Project: NZ EECA LCA Study Oct 2015
Category: Transport\! NZ Vehicle Study
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator: Damage assessment, Photochemical Oxidation (kg C2H2 eq)
Indicator mode: Cumulated indicator
Exclude long-term emissions: No
Node cut-off: 2 %



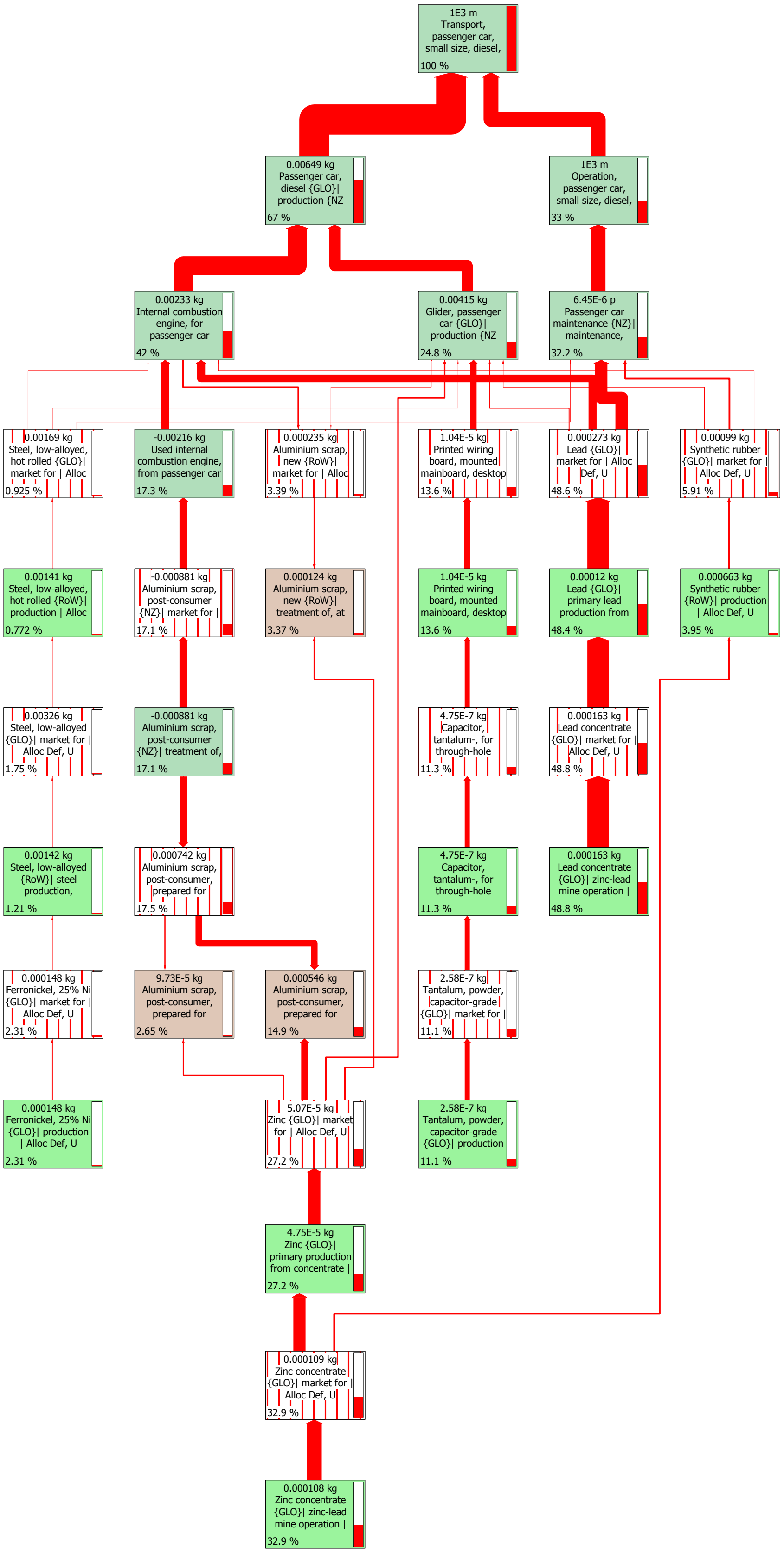
Network

Product:	Transport, passenger car, small size, diesel, EURO 5 {NZ}| per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Cumulative Energy Demand (MJ LHV)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %

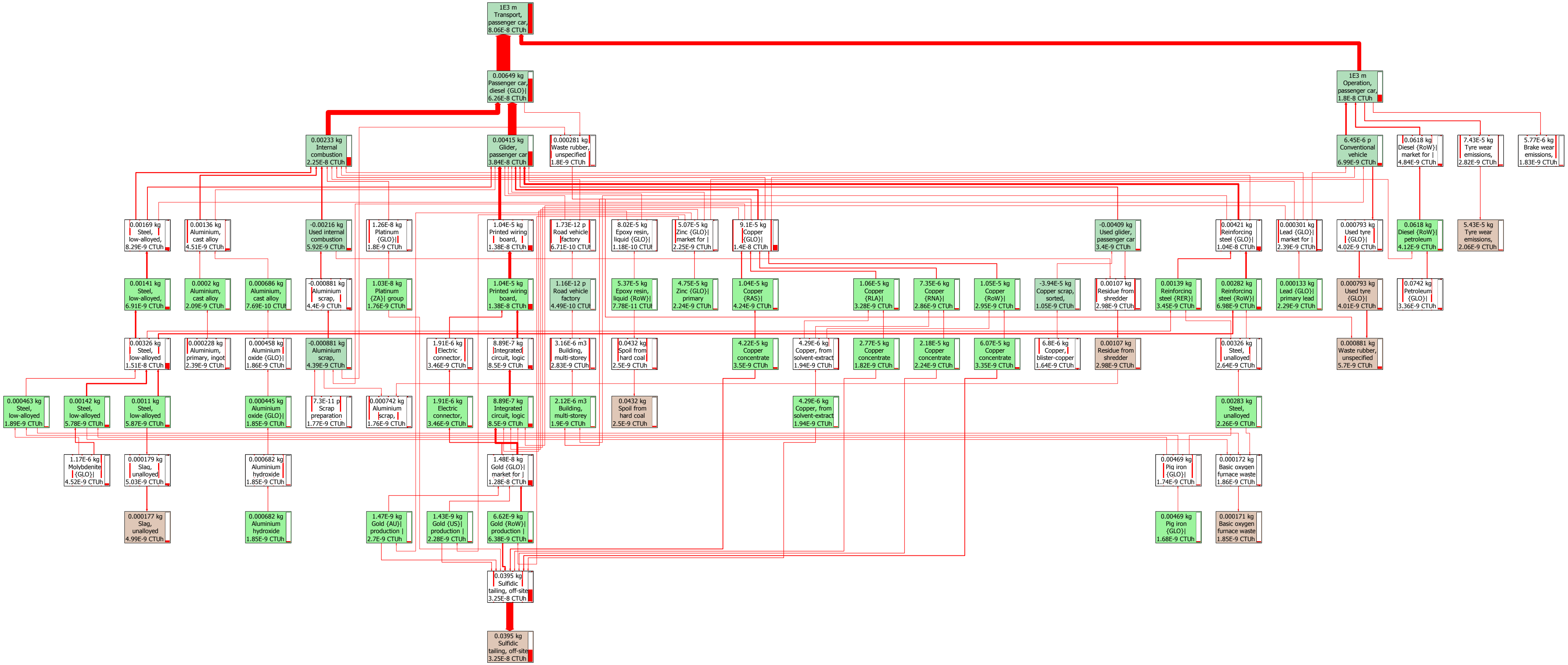


SimaPro 8.0.5.13 Network Date: 26/10/2015 Time: 7:48:55 PM
Project: NZ EECA LCA Study Oct 2015

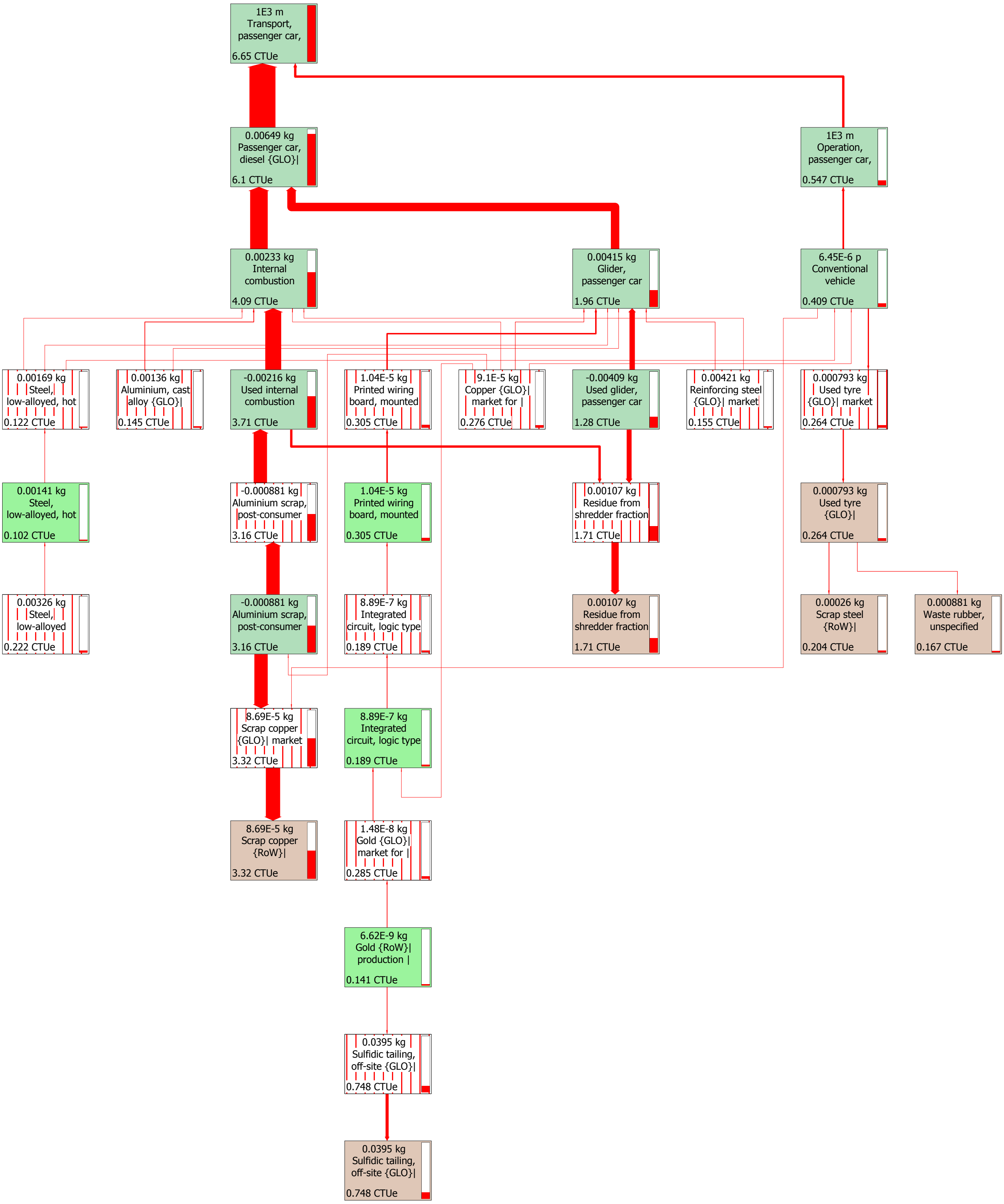
Product:	Transport, passenger car, small size, diesel, EURO 5 {NZ}| per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Resource (Abiotic) Depletion (kg Sb eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



Product: Transport, passenger car, small size, diesel, EURO 5 {NZ}| per km | Alloc Def, U
Project: NZ EECA LCA Study Oct 2015
Category: Transport\! NZ Vehicle Study
Method: NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator: Damage assessment, Human Toxicity (CTUh)
Indicator mode: Cumulated indicator
Exclude long-term emissions: No
Node cut-off: 2 %

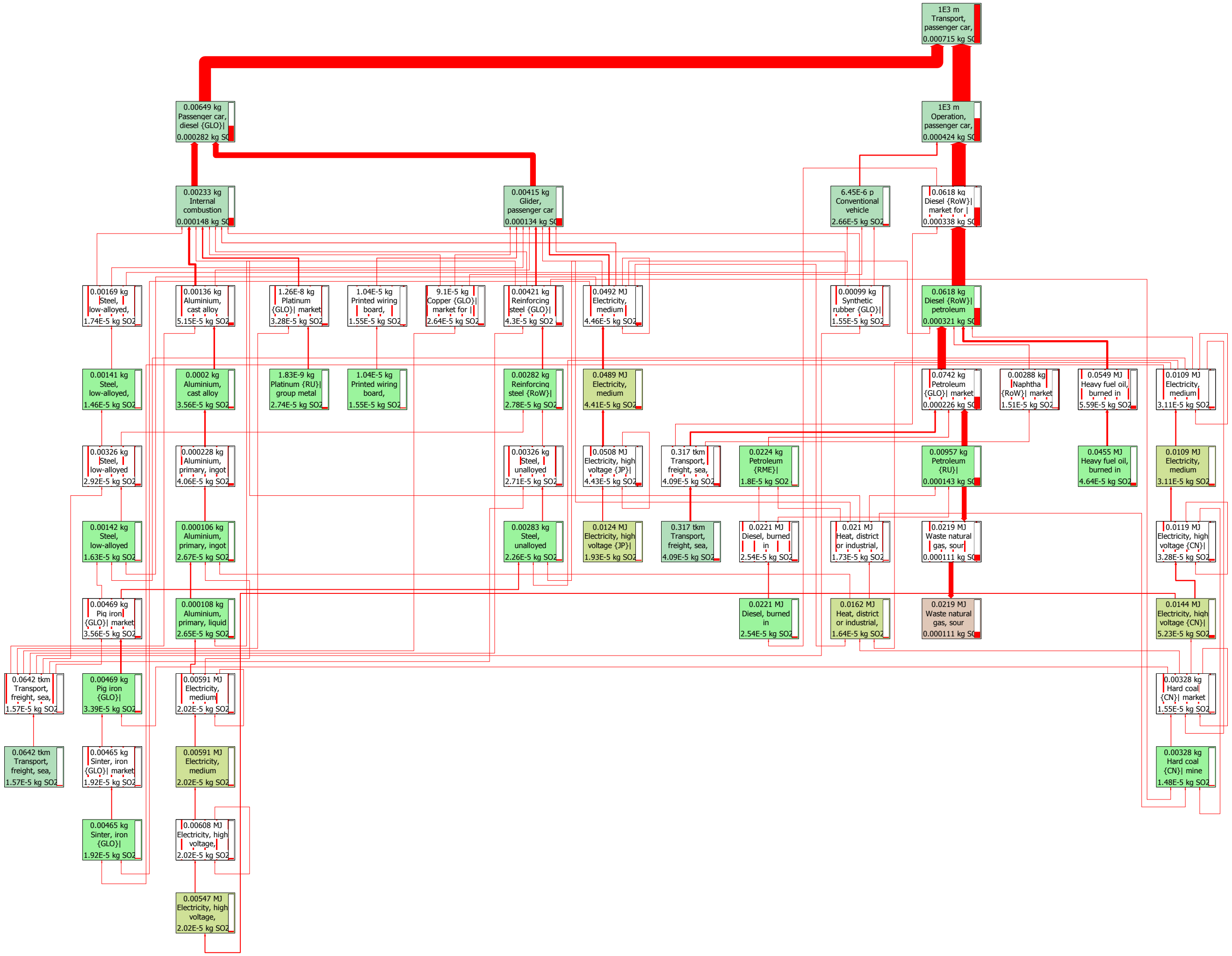


Product:	Transport, passenger car, small size, diesel, EURO 5 {NZ}| per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator:	Damage assessment, Ecotoxicity (CTUe)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



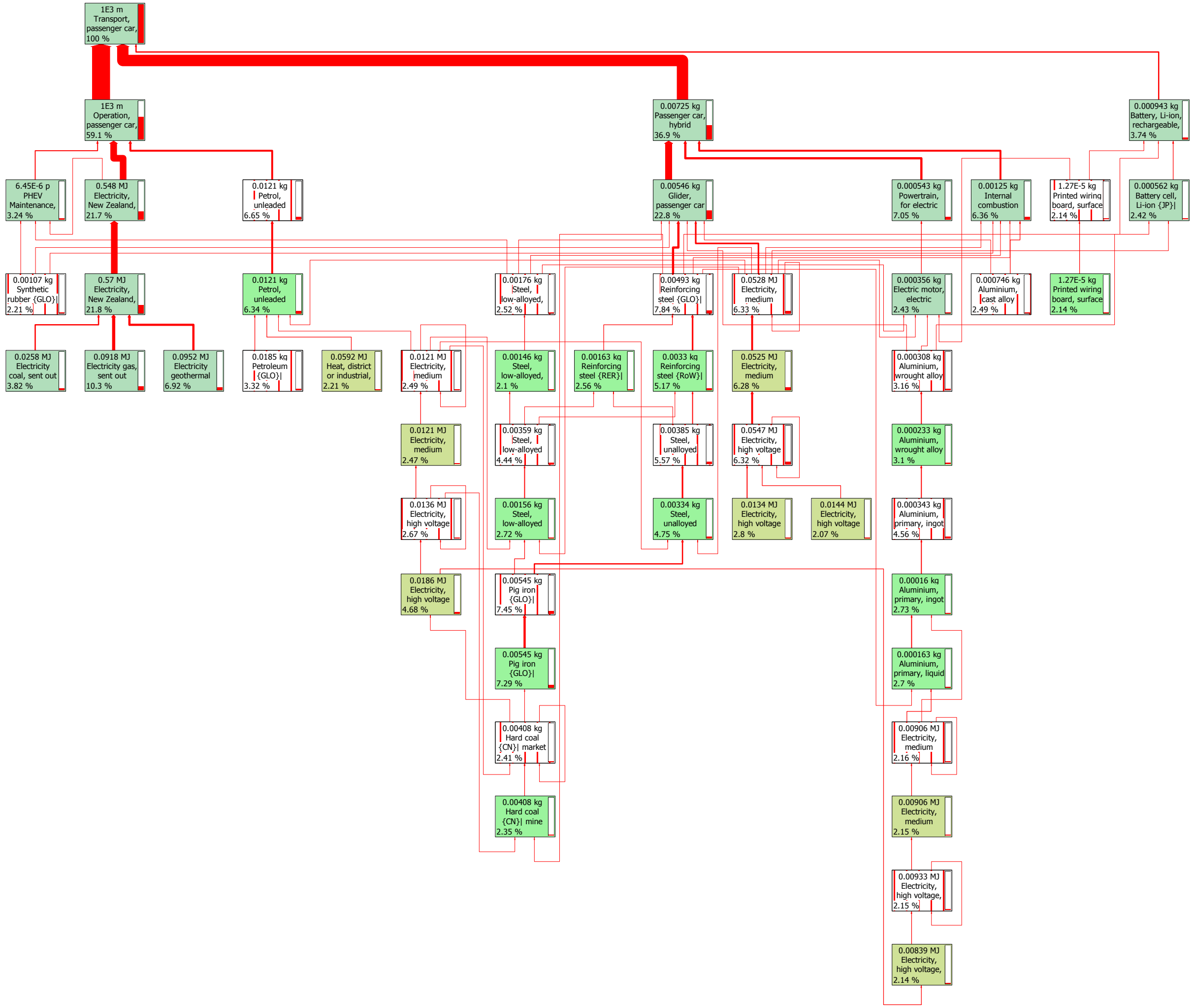
SimaPro 8.0.5.13 Network Date: 10/11/2015 Time: 12:39:38 PM
Project: NZ EECA LCA Study Oct 2015

Product: Transport, passenger car, small size, diesel, EURO 5 {NZ}| per km | Alloc Def, U
Project: NZ EECA LCA Study Oct 2015
Category: Transport\! NZ Vehicle Study
Method: NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator: Damage assessment, Air Acidification (kg SO2 eq)
Indicator mode: Cumulated indicator
Exclude long-term emissions: No
Node cut-off: 2 %



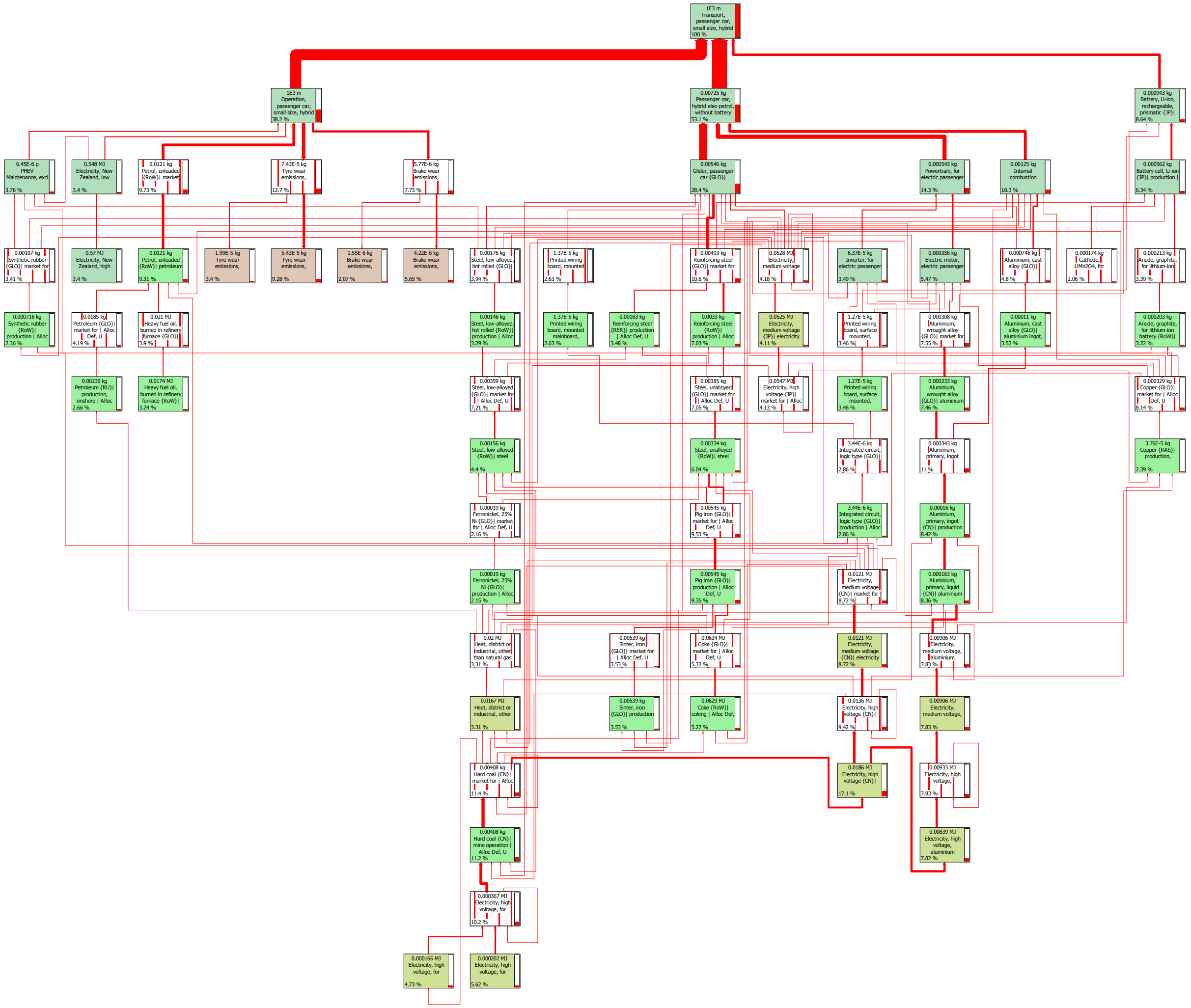
C3 Plug-in hybrid electric vehicle (PHEV)

Product: Transport, passenger car, small size, hybrid elec-petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project: NZ EECA LCA Study Oct 2015
Category: Transport\! NZ Vehicle Study
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator: Damage assessment, Climate Change (kg CO2 e)
Indicator mode: Cumulated indicator
Exclude long-term emissions: No
Node cut-off: 2 %

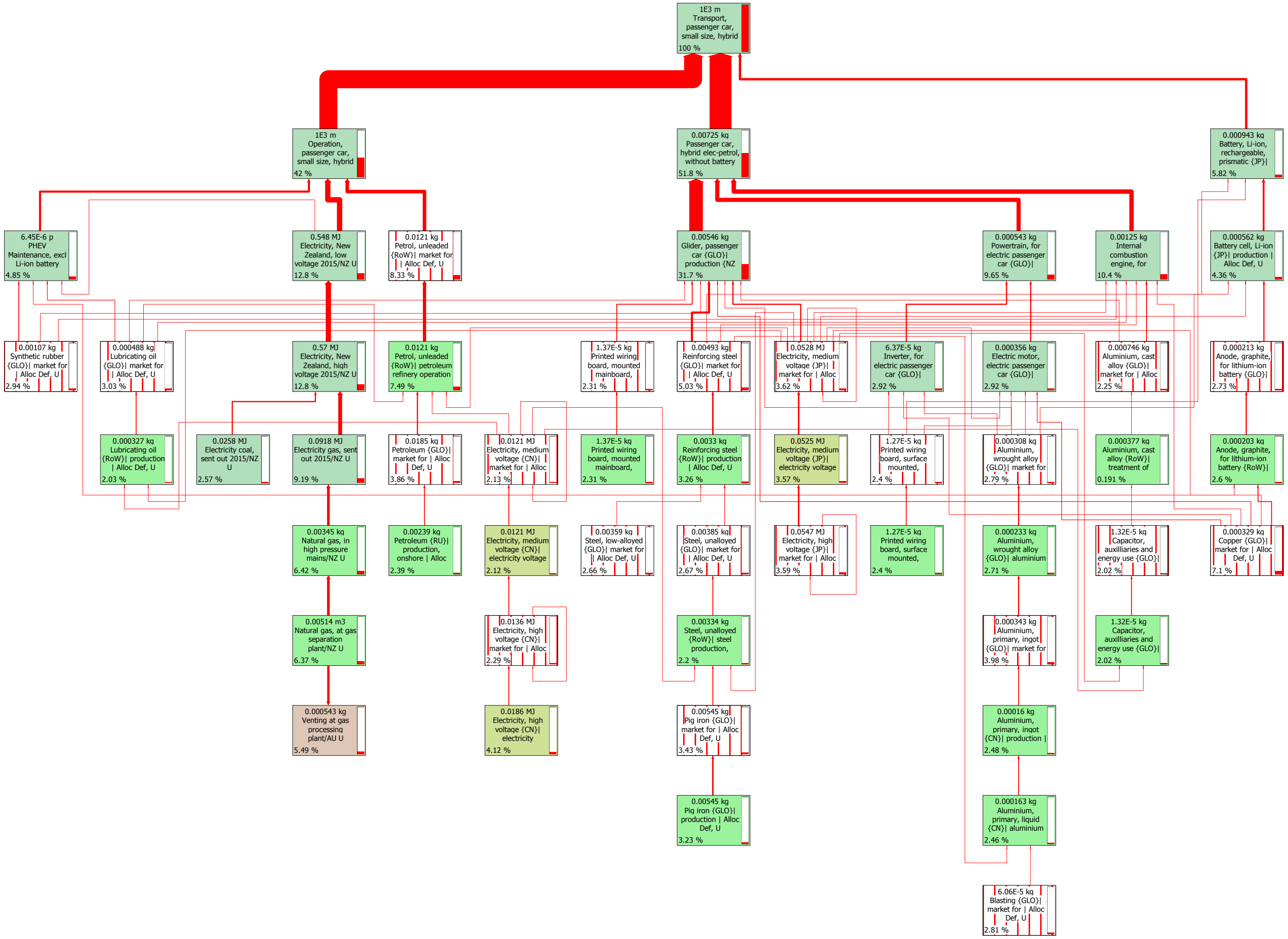


SimaPro 8.0.5.13 Network Date: 27/10/2015 Time: 11:00:52 PM
Project: NZ EECA LCA Study Oct 2015

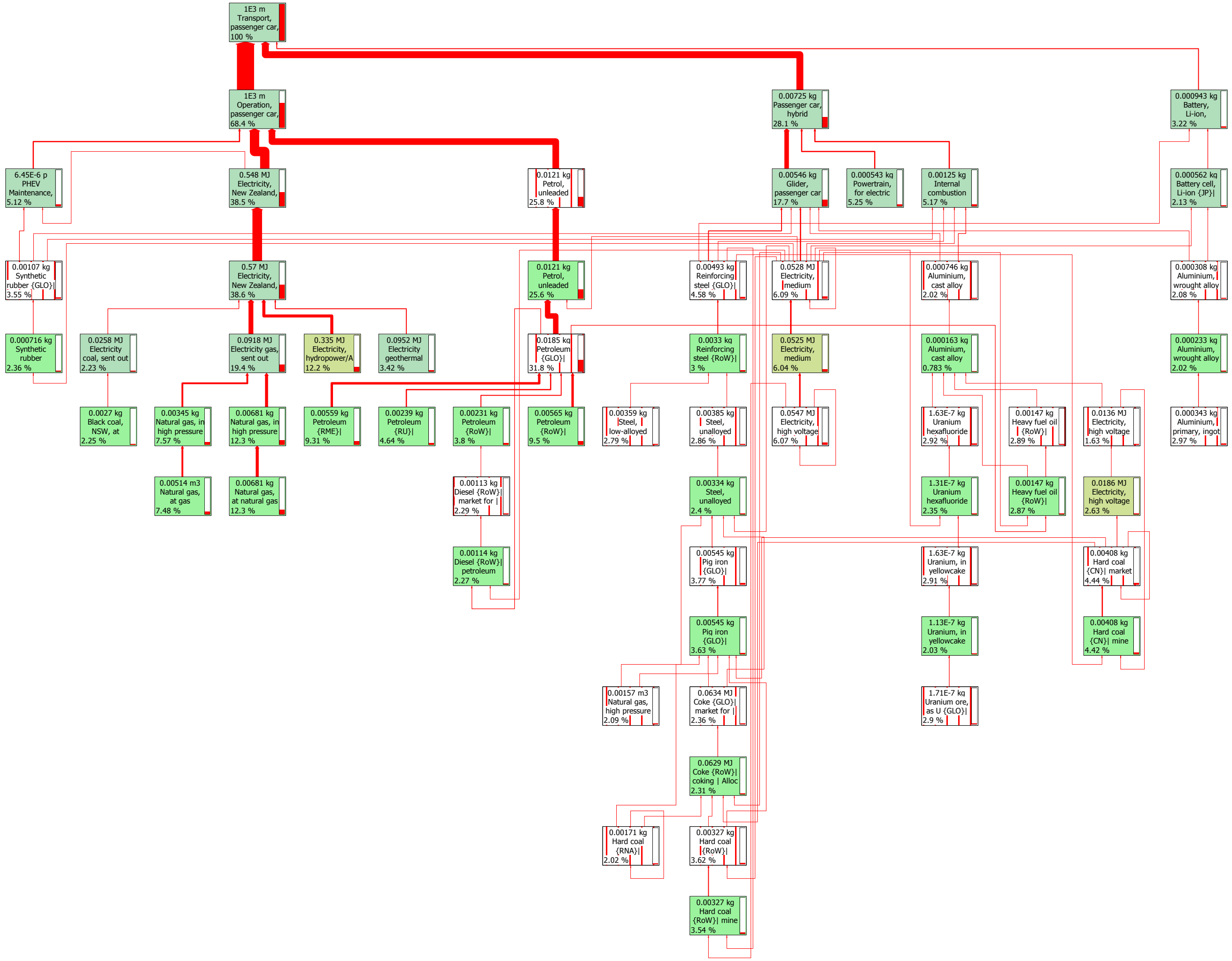
Product:	Transport, passenger car, small size, hybrid elec-petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Particulate Matter (kg PM2.5 eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



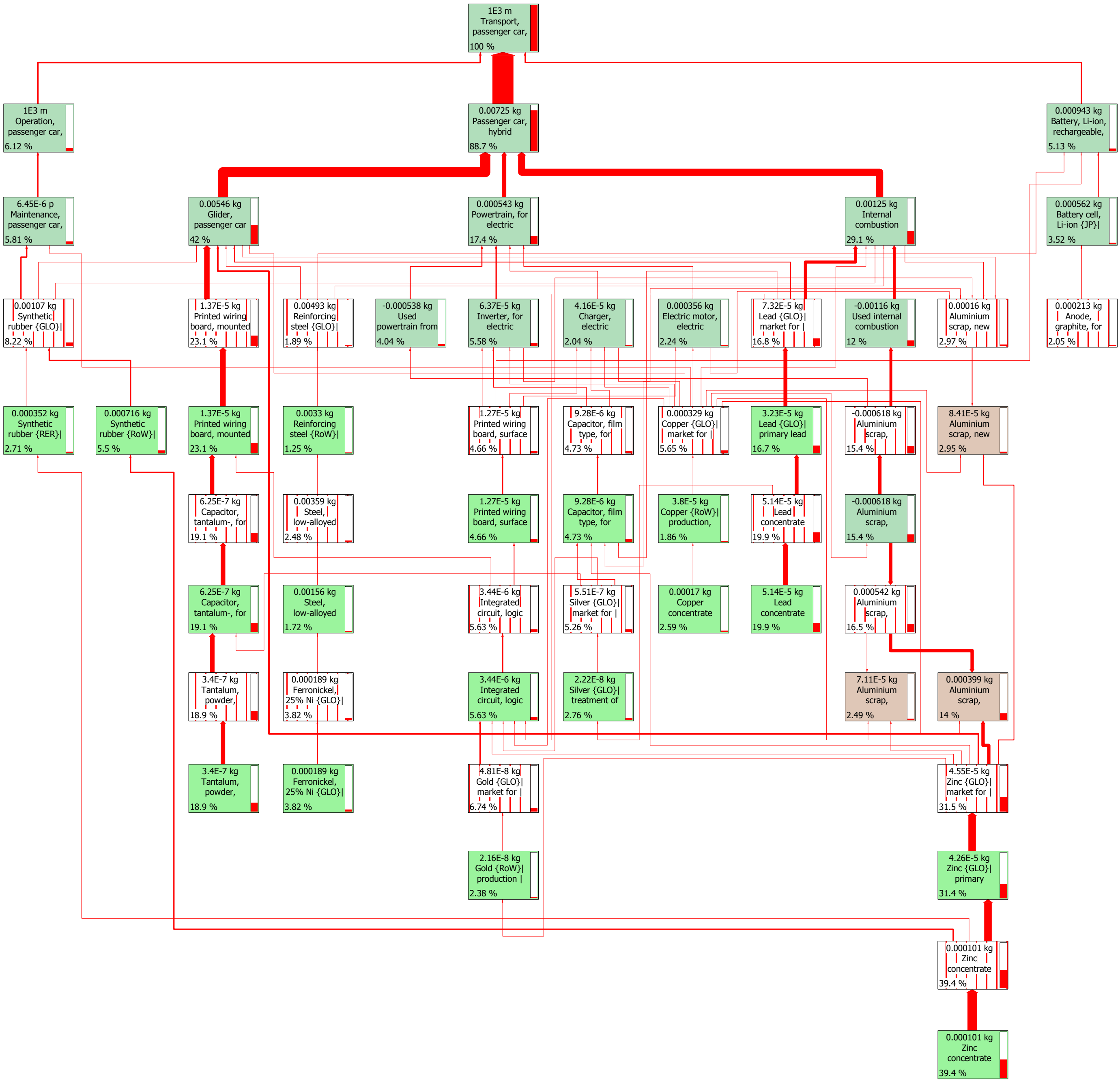
Product:	Transport, passenger car, small size, hybrid elec-petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Photochemical Oxidation (kg C2H2 eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



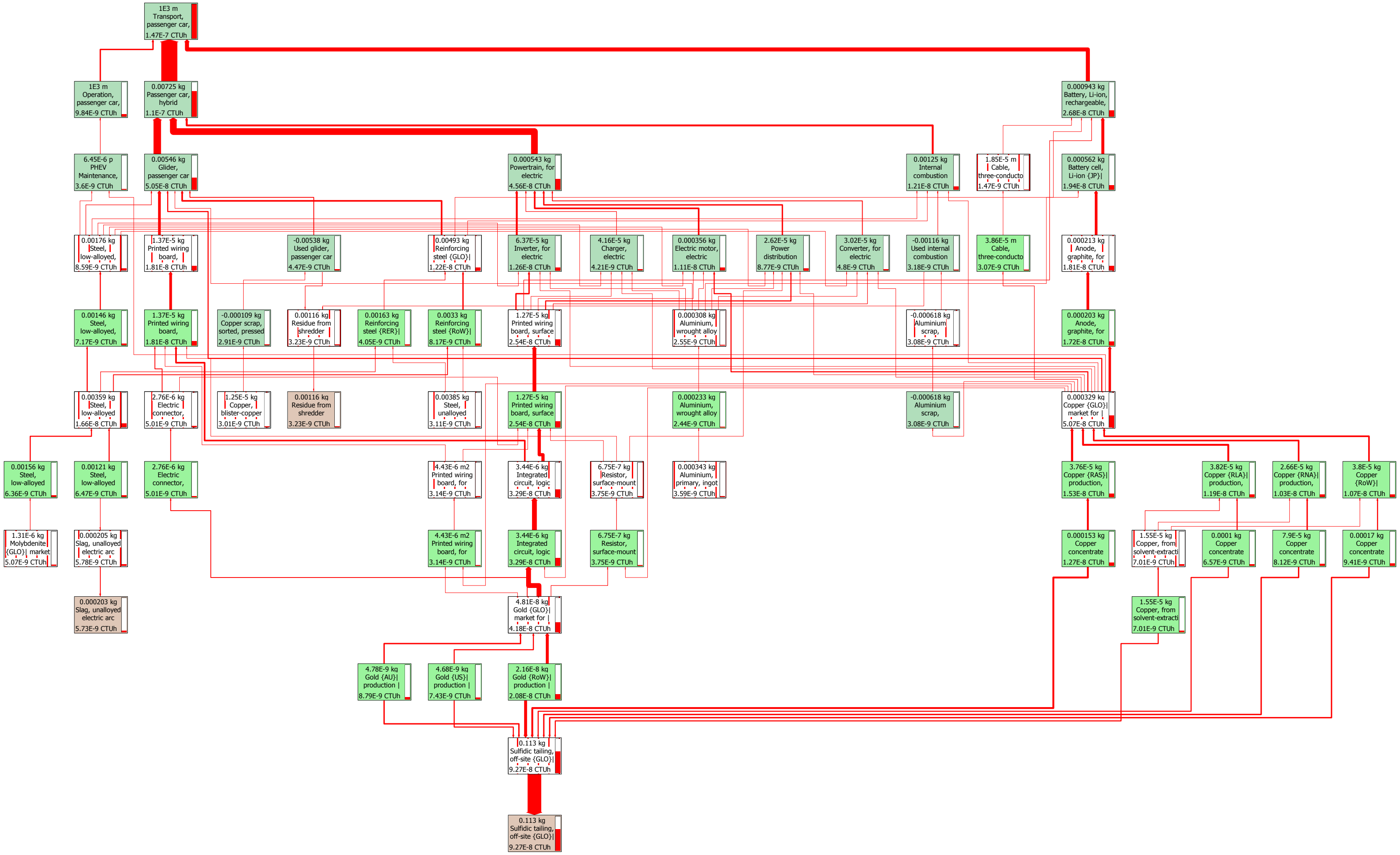
Product: Transport, passenger car, small size, hybrid elec-petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project: NZ EECA LCA Study Oct 2015
Category: Transport\! NZ Vehicle Study
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator: Damage assessment, Cumulative Energy Demand (MJ LHV)
Indicator mode: Cumulated indicator
Exclude long-term emissions: No
Node cut-off: 2 %



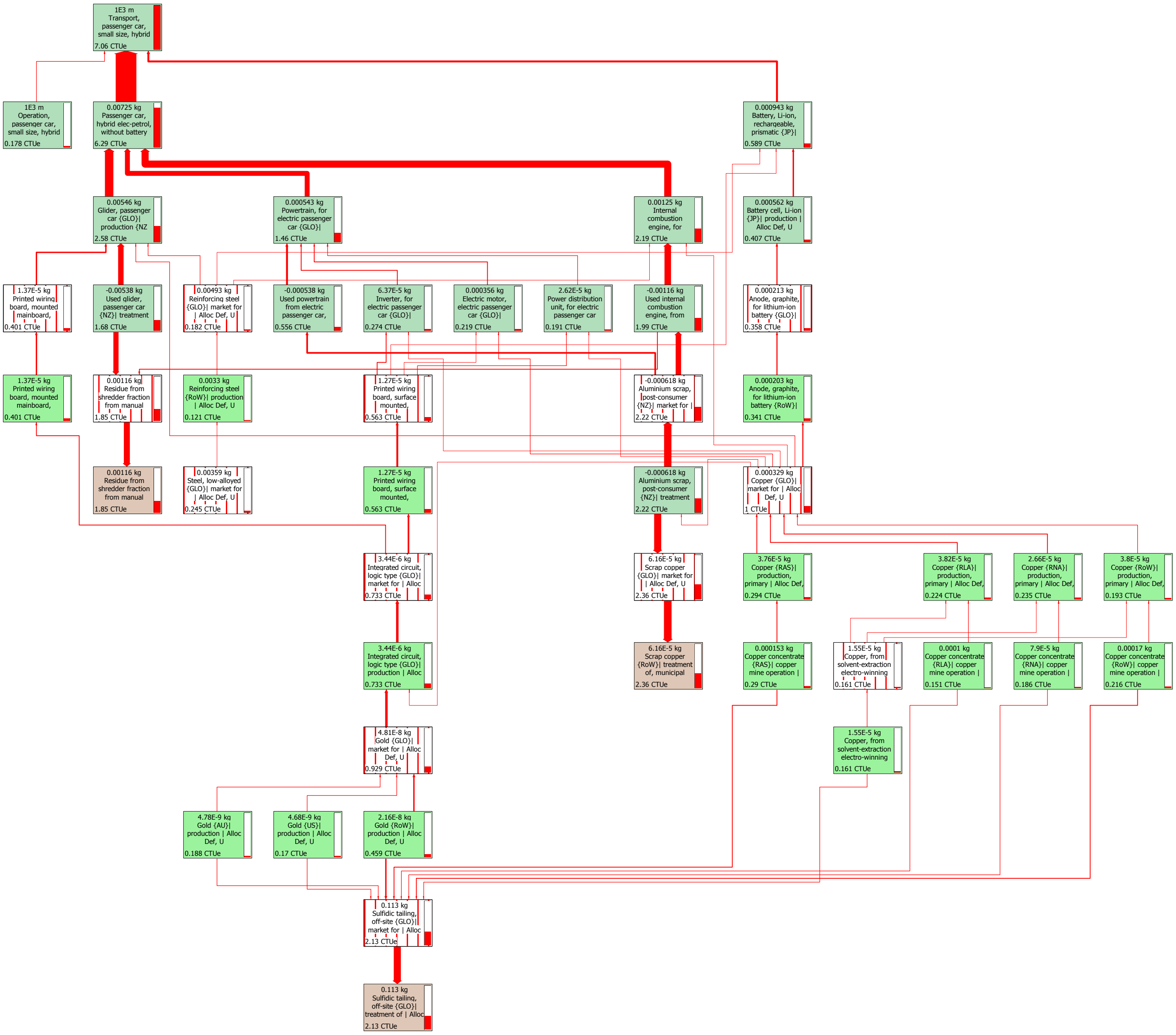
Product:	Transport, passenger car, small size, hybrid elec-petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Resource (Abiotic) Depletion (kg Sb eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



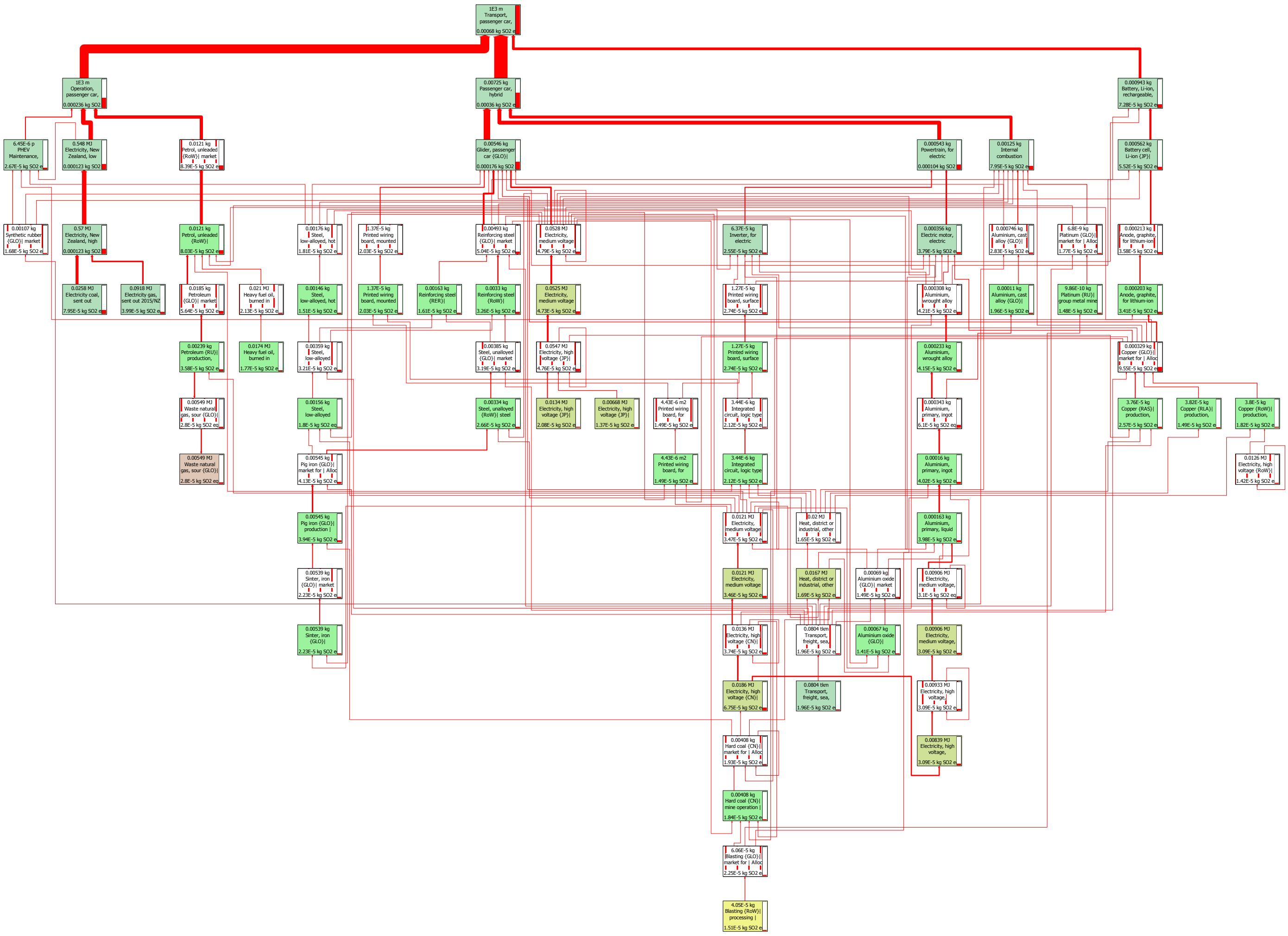
Product: Transport, passenger car, small size, hybrid elec-petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project: NZ EECA LCA Study Oct 2015
Category: Transport\! NZ Vehicle Study
Method: NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator: Damage assessment, Human Toxicity (CTUh)
Indicator mode: Cumulated indicator
Exclude long-term emissions: No
Node cut-off: 2 %



Product:	Transport, passenger car, small size, hybrid elec-petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator:	Damage assessment, Ecotoxicity (CTUe)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %

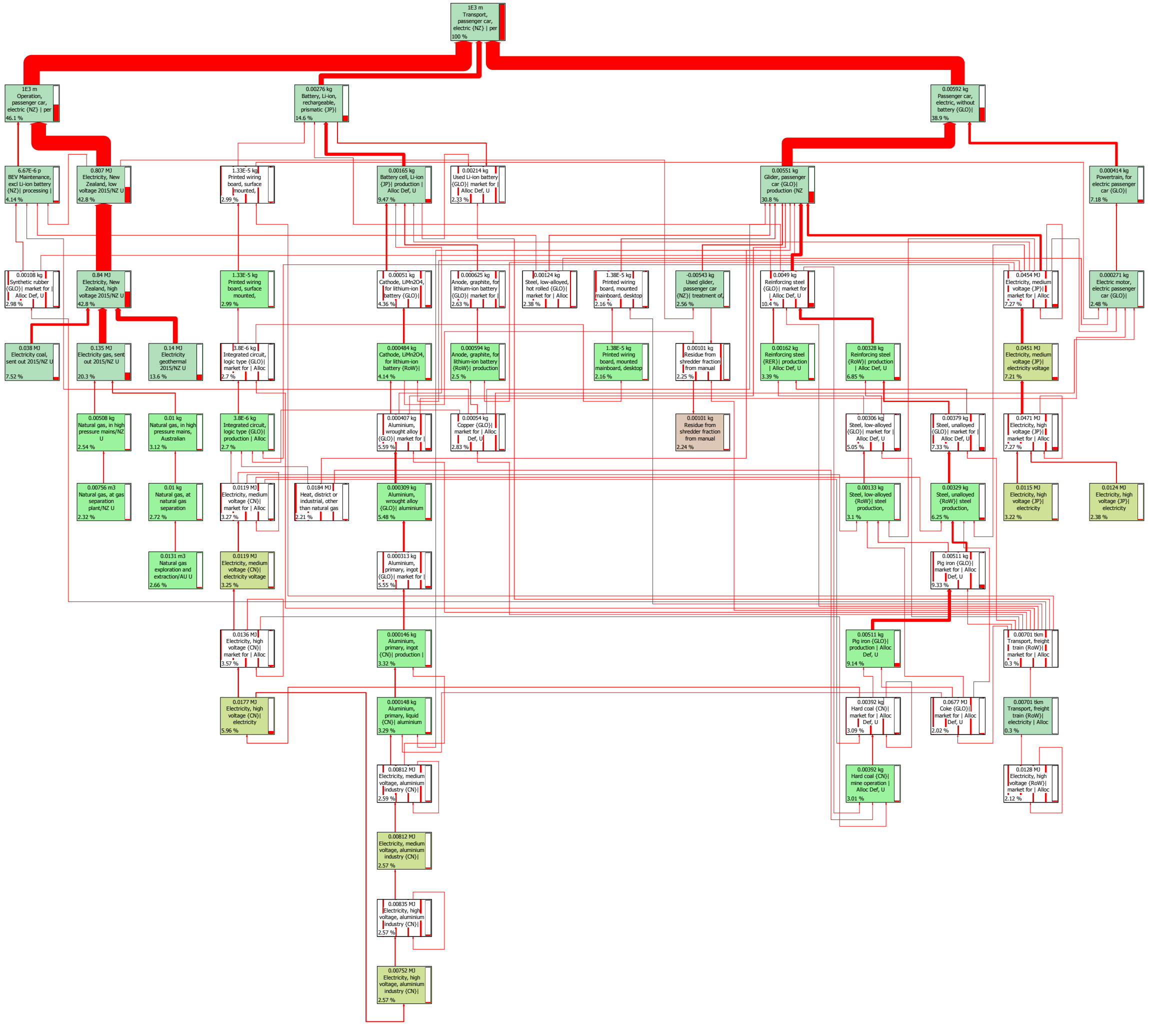


Product:	Transport, passenger car, small size, hybrid elec-petrol, EURO 5 {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator:	Damage assessment, Air Acidification (kg SO2 eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %

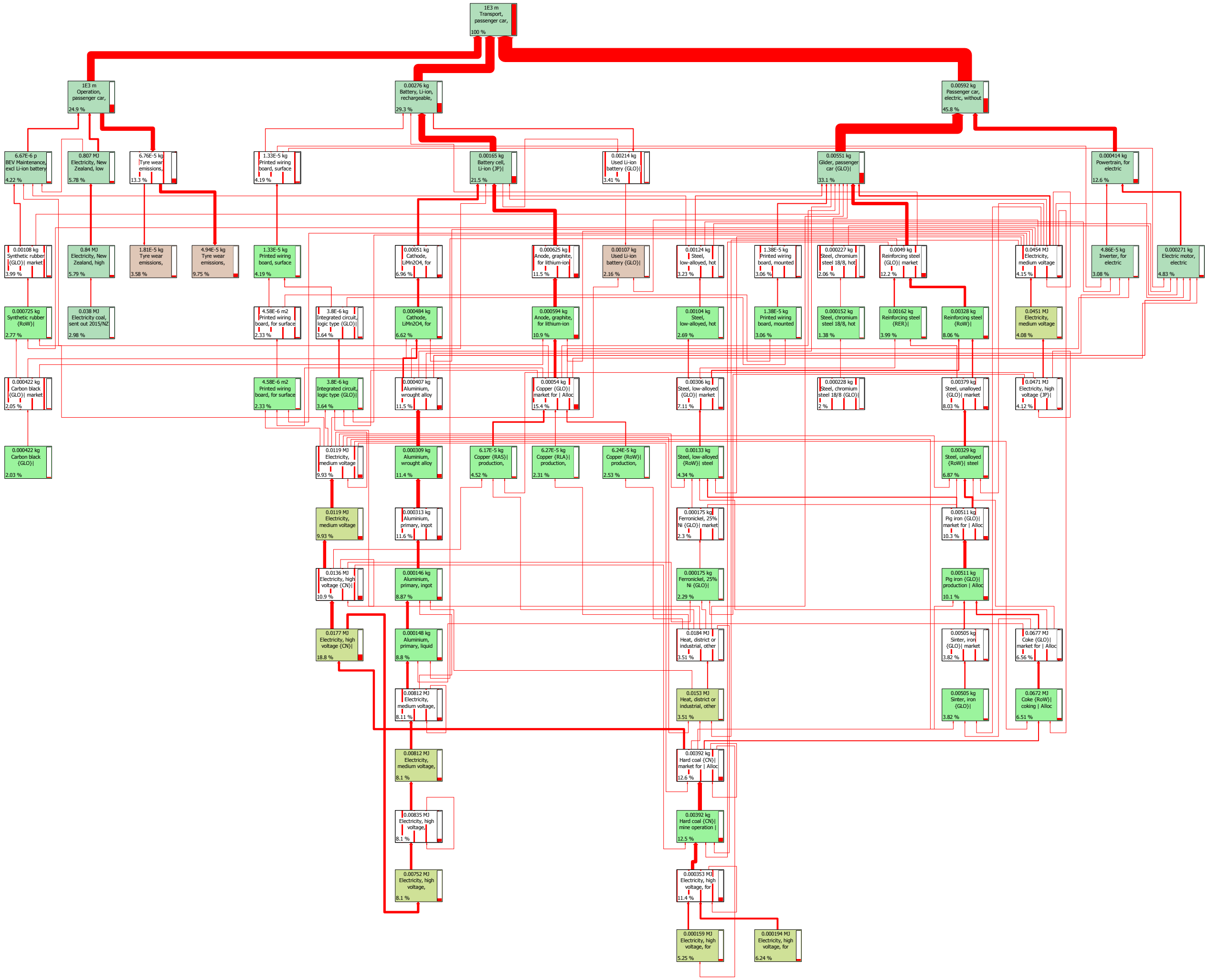


C4 Battery electric vehicle (BEV)

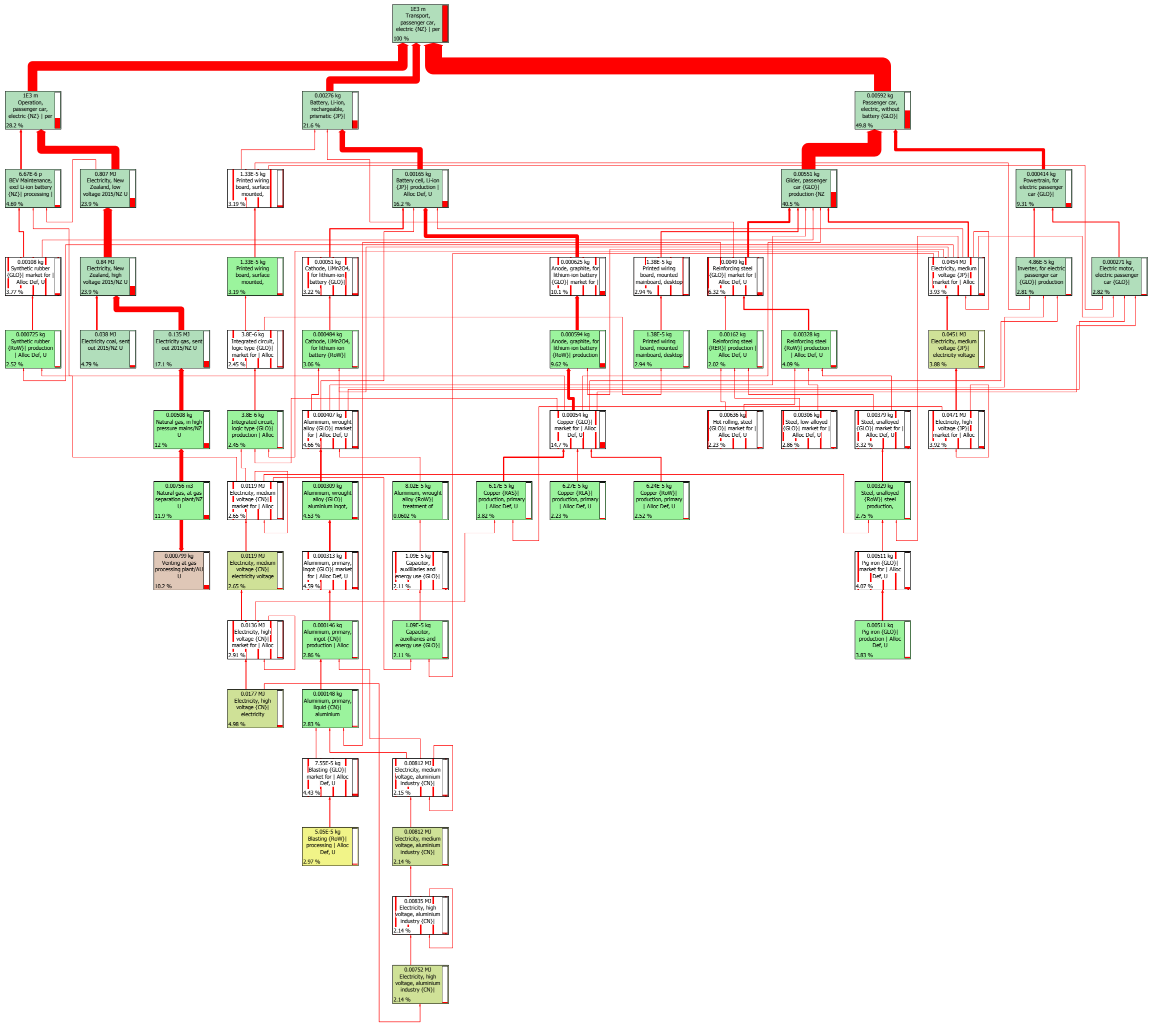
Product: Transport, passenger car, electric {NZ} | per km | Alloc Def, U
Project: NZ EECA LCA Study Oct 2015
Category: Transport\! NZ Vehicle Study
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator: Damage assessment, Climate Change (kg CO2 e)
Indicator mode: Cumulated indicator
Exclude long-term emissions: No
Node cut-off: 2 %



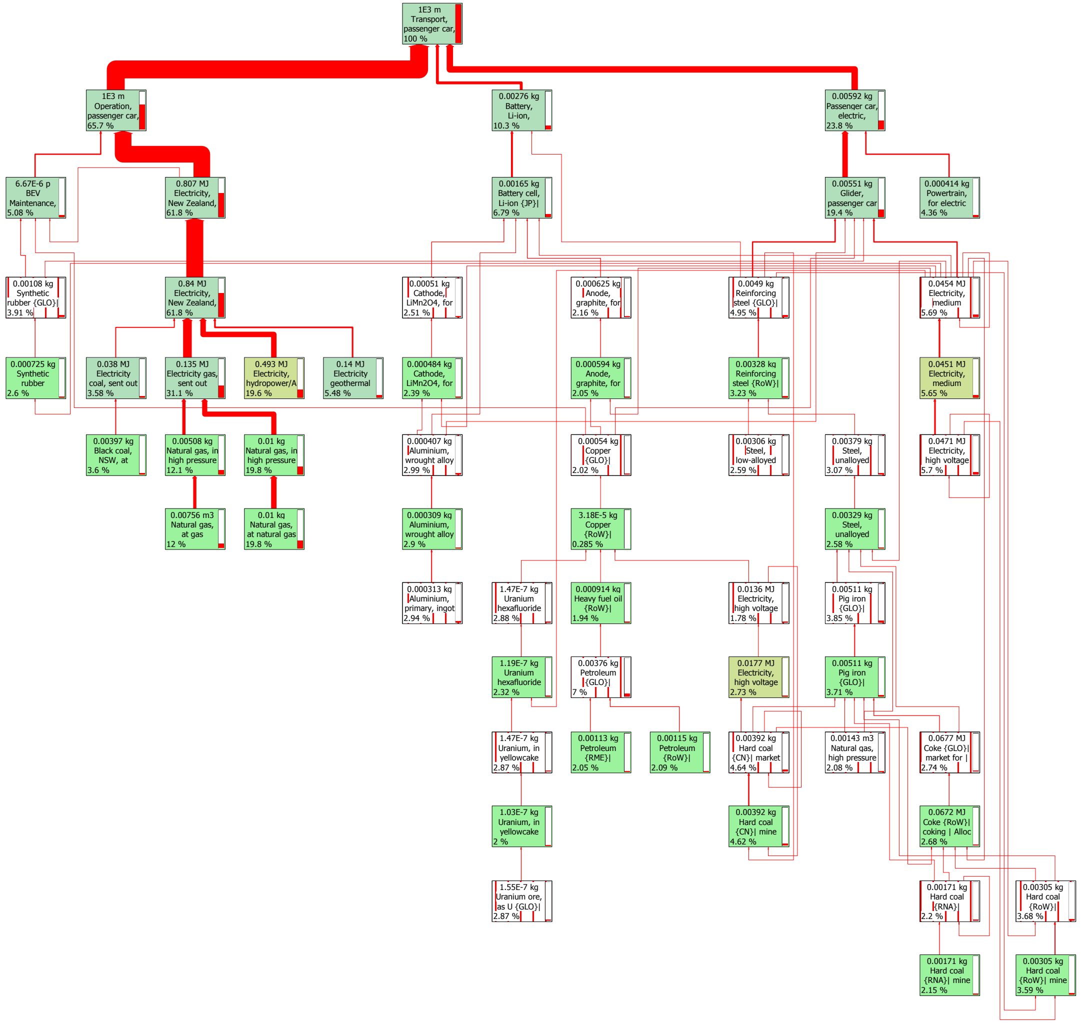
Product:	Transport, passenger car, electric {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Particulate Matter (kg PM2.5 eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



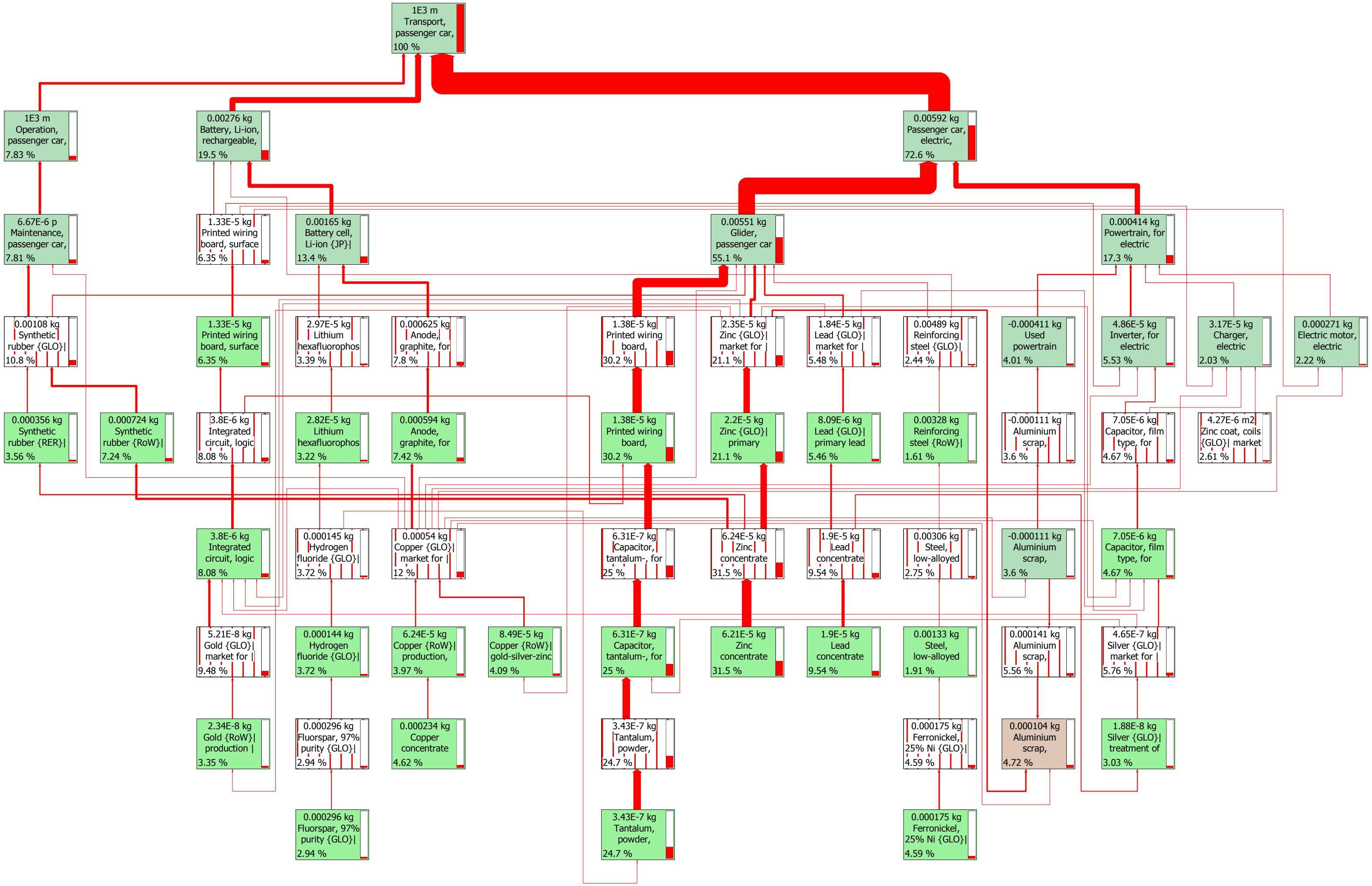
Product:	Transport, passenger car, electric {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Photochemical Oxidation (kg C2H2 eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



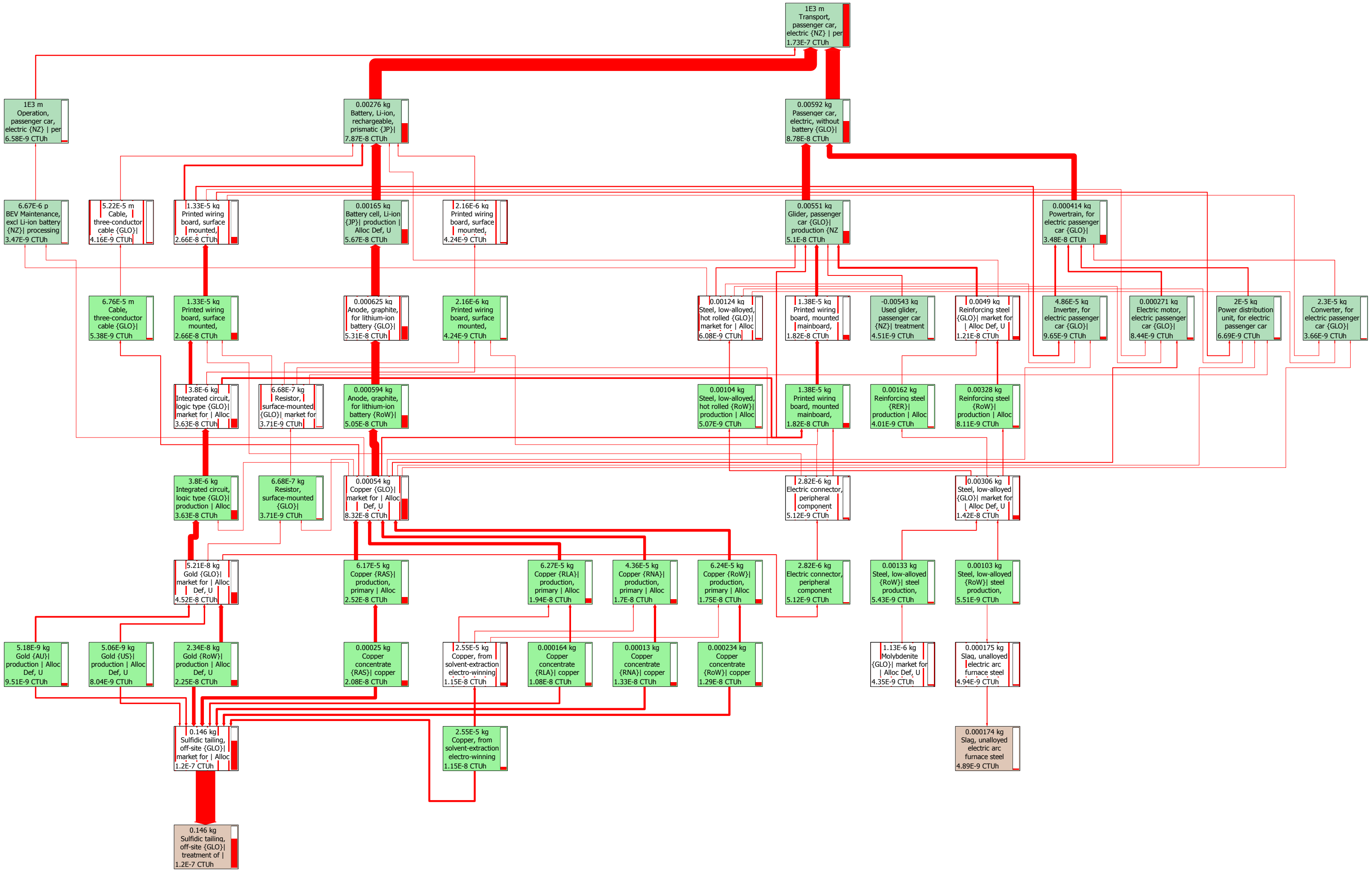
Product: Transport, passenger car, electric {NZ} | per km | Alloc Def, U
Project: NZ EECA LCA Study Oct 2015
Category: Transport\! NZ Vehicle Study
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator: Damage assessment, Cumulative Energy Demand (MJ LHV)
Indicator mode: Cumulated indicator
Exclude long-term emissions: No
Node cut-off: 2 %



Product:	Transport, passenger car, electric {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final October 2015) V4.00
Selected indicator:	Damage assessment, Resource (Abiotic) Depletion (kg Sb eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



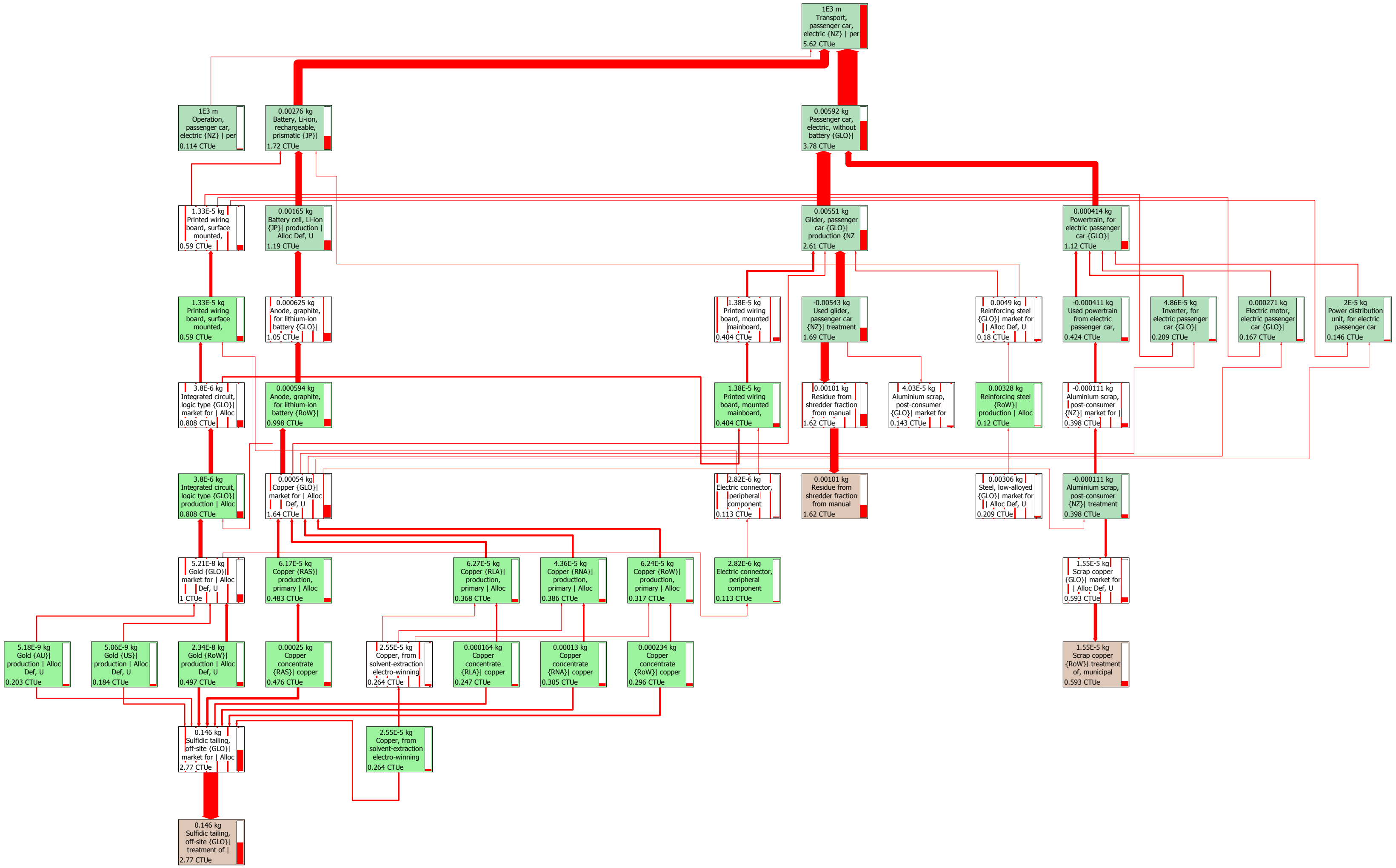
Product:	Transport, passenger car, electric {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator:	Damage assessment, Human Toxicity (CTUh)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



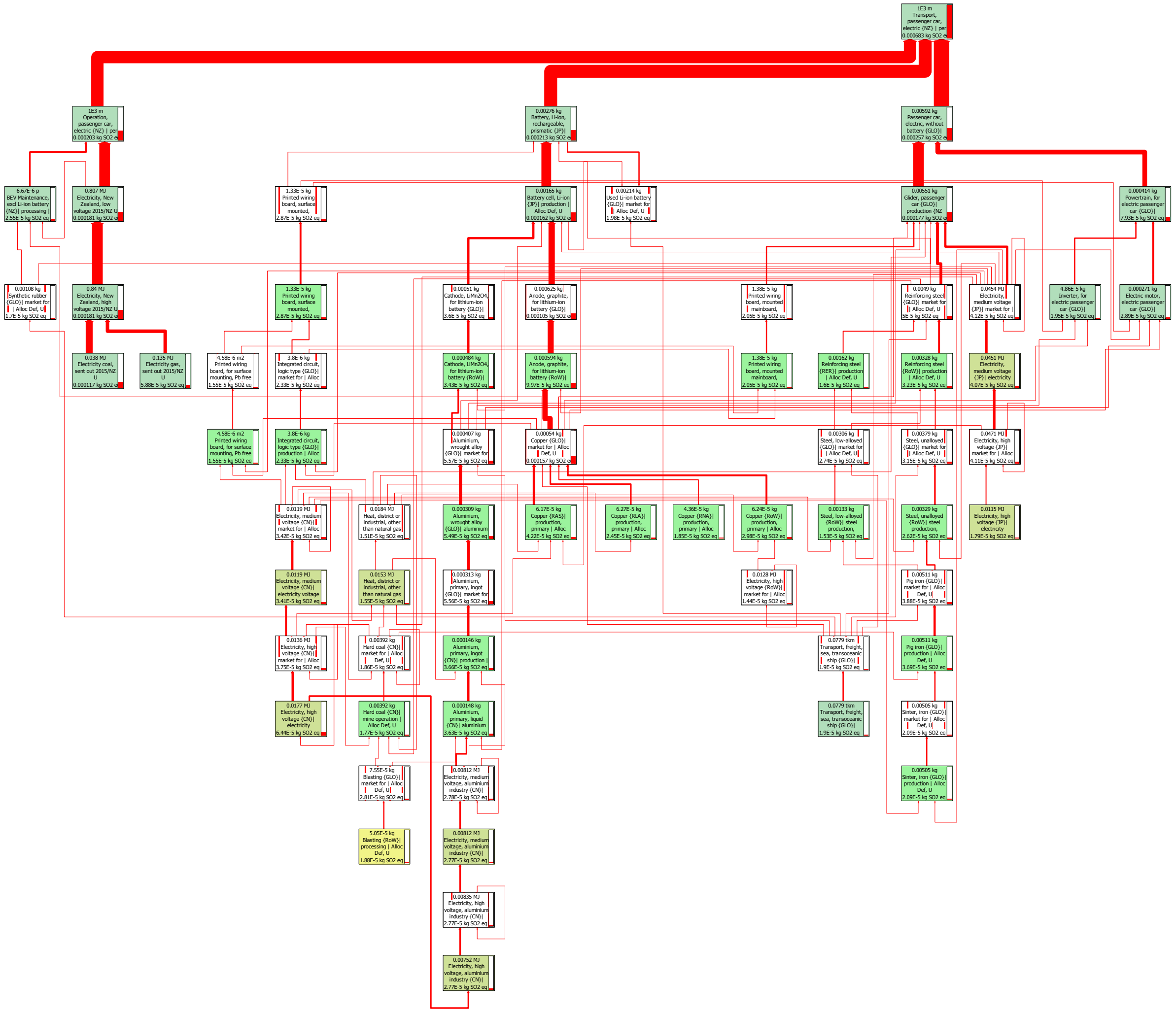
Network

Date: 10/11/2015 Time: 11:41:36 AM

Product:	Transport, passenger car, electric {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator:	Damage assessment, Ecotoxicity (CTUe)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



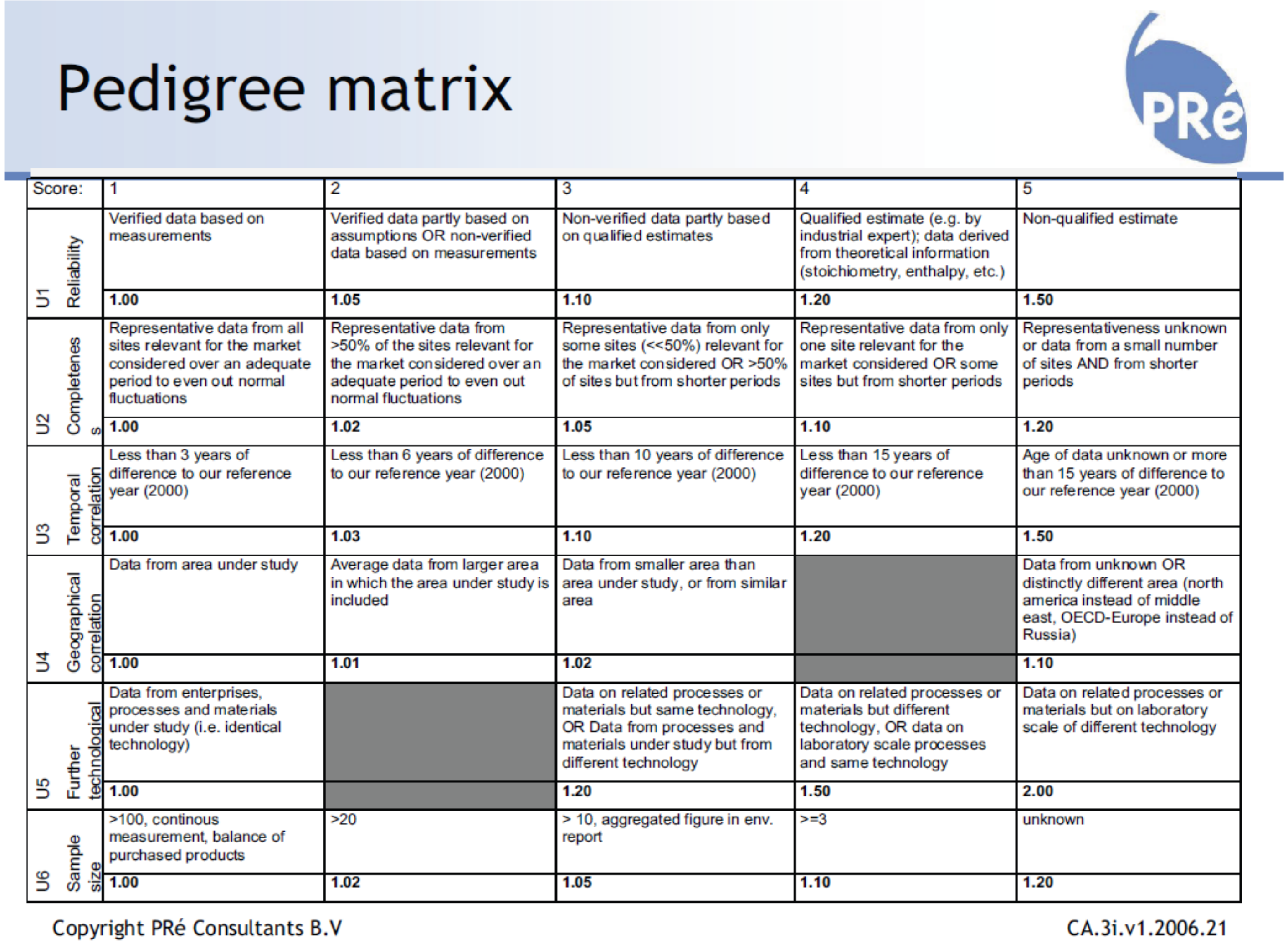
Product:	Transport, passenger car, electric {NZ} | per km | Alloc Def, U
Project:	NZ EECA LCA Study Oct 2015
Category:	Transport\! NZ Vehicle Study
Method:	NZ EECA LCA Impact Assessment (Final August 2015) V3.00
Selected indicator:	Damage assessment, Air Acidification (kg SO2 eq)
Indicator mode:	Cumulated indicator
Exclude long-term emissions:	No
Node cut-off:	2 %



Appendix D

Uncertainty analysis detailed results

D1 Pedigree matrix



Pedigree matrix

Score:	1	2	3	4	5
U1 Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)	Non-qualified estimate
	1.00	**1.05**	**1.10**	**1.20**	**1.50**
U2 Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered OR >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
	1.00	**1.02**	**1.05**	**1.10**	**1.20**
U3 Temporal correlation	Less than 3 years of difference to our reference year (2000)	Less than 6 years of difference to our reference year (2000)	Less than 10 years of difference to our reference year (2000)	Less than 15 years of difference to our reference year (2000)	Age of data unknown or more than 15 years of difference to our reference year (2000)
	1.00	**1.03**	**1.10**	**1.20**	**1.50**
U4 Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, or from similar area		Data from unknown OR distinctly different area (north america instead of middle east, OECD-Europe instead of Russia)
	1.00	**1.01**	**1.02**		**1.10**
U5 Further technological	Data from enterprises, processes and materials under study (i.e. identical technology)		Data on related processes or materials but same technology, OR Data from processes and materials under study but from different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but on laboratory scale of different technology
	1.00		**1.20**	**1.50**	**2.00**
U6 Sample size	>100, continous measurement, balance of purchased products	>20	> 10, aggregated figure in env. report	>=3	unknown
	1.00	**1.02**	**1.05**	**1.10**	**1.20**

CA.3i.v1.2006.21

D2 Pedigree assessment of study-specific data and assumptions

The following table provides the assessment of uncertainty, based on the Pedigree Matrix in Section D1. A qualitative description provides the basic rationale behind the uncertainty score applied to each assumption.

Data or assumption	Conventional	Electric	Qualitative description (rationale)
Overall vehicle weights and proportions	(3,3,1,2,3,na)	(3,3,1,2,3,na)	Estimations and own calculations, based on industry sourced data and industry-applied assumptions, described in Section 4.1. Representative of vehicles class available in NZ.
Overall battery weight and proportions		(2,3,1,1,2,na)	Industry sourced data and based on own calculations as described in Section 4.1
Importing	(3,1,1,1,2,na)	(3,1,1,1,2,na)	Estimation, based on importing distance, described in Section 4.2.
Disposal			
Aluminium scrap treatment - electricity usage	(2,5,4,3,1,na)	(2,5,4,3,1,na)	Estimation, based on ecoinvent v3.1, assumes NZ electricity usage
Copper scrap treatment - electricity usage	(2,5,4,3,1,na)	(2,5,4,3,1,na)	Estimation, based on ecoinvent v3.1, assumes NZ electricity usage
Used glider treatment - electricity usage	(3,5,4,3,1,na)	(3,5,4,3,1,na)	Estimation, based on ecoinvent v3.1, assumes NZ electricity usage
Used engine treatment - electricity usage	(3,5,4,3,1,na)	(3,5,4,3,1,na)	Estimation, based on ecoinvent v3.1, assumes NZ electricity usage
Internal combustion engine			
Overall weight	(2,3,2,4,2,na)	(2,3,2,4,2,na)	Industry sourced data and based on own calculations as described in Section 4.1
Materials and specific weights	(2,4,4,4,2,na)	(2,4,4,4,2,na)	Based on Volkswagen Golf A4, Ref: Volkswagen (2014) *LCA of e-Golf*
Glider			
Overall weight	(2,3,2,4,2,na)	(2,3,2,4,2,na)	Industry sourced data and based on own calculations as described in Section 4.1
Materials and specific weights	(1,3,4,4,2,na)	(1,3,4,4,2,na)	Based on Volkswagen Golf A4, Ref: Volkswagen (2014) *LCA of e-Golf*
Powertrain			
Overall weight	-	(2,3,2,4,2,na)	Industry sourced data and based on own calculations as described in Section 4.1
Materials and specific weights	-	(1,4,2,4,2,na)	Based on direct information from Swiss electric vehicle-parts manufacturer Brusa.

Data or assumption	**Conventional**	**Electric**	**Qualitative description (rationale)**
Battery materials			
Battery cell, Li-ion	-	(1,4,2,3,1,na)	Average from literature values, from ecoinvent v3.1
Reinforcing steel	-	(2,4,2,3,3,na)	Average from literature values, from ecoinvent v3.1
Sheet-rolling for steel	-	(2,4,2,3,3,na)	Average from literature values, from ecoinvent v3.1
Used li-ion battery	-	(1,1,2,1,1,na)	Average from literature values, from ecoinvent v3.1
Printed wiring board	-	(1,4,2,3,1,na)	Average from literature values, from ecoinvent v3.1
Metal working factory	-	(5,5,3,3,3,na)	Average from literature values, from ecoinvent v3.1
Cable	-	(3,4,2,3,1,na)	Average from literature values, from ecoinvent v3.1
Printed wiring board	-	(1,4,2,3,1,na)	Average from literature values, from ecoinvent v3.1
Electricity	-	(4,5,4,5,3,na)	Average from literature values, from ecoinvent v3.1
Specific electric vehicle components (materials and weights)			
Charger, electric passenger car	-	(1,4,2,4,2,na)	Based on direct information from Brusa.
Electric motor	-	(1,4,2,4,2,na)	Based on direct information from Brusa
Inverter	-	(1,4,2,4,2,na)	Based on direct information from Brusa
Power distribution unit	-	(1,4,2,4,2,na)	Based on direct information from Brusa
Operation			
Brake wear emissions	(2,2,3,4,1,na)	(2,1,3,4,1,na)	Industry-sourced information, literature study, from ecoinvent v3.1
Maintenance	(2,2,3,4,1,na)	(3,3,3,3,3,na)	Estimation, from ecoinvent v3.1
Tyre wear emissions	(2,2,3,4,1,na)	(2,1,3,4,1,na)	Industry-sourced information, literature study, from ecoinvent v3.1
Electricity consumption	(2,3,1,4,3,na)	(2,3,1,4,3,na)	Industry-sourced information, own calculation as described in Section 4.3.
Diesel/petrol consumption	(2,2,1,1,1,na)	-	Industry-sourced information, own calculation as described in Section 4.3.
Percent fuel split for hybrid electric	(4,3,1,4,3,na)	-	Estimation based on industry-sourced information, described in Section 4.3.
Lifetime of vehicle	(4,2,1,3,3,na)	(4,2,1,3,3,na)	Estimation based on industry-sourced information, described in Section 4.3.

Data or assumption	Conventional	Electric	Qualitative description (rationale)
New Zealand electricity			For all descriptions relating to electricity below, refer also to Appendix E1.
Coal	(2,1,1,1,1,na)	(2,1,1,1,1,na)	Data from literature-source specific to NZ electricity, described in Section 3.5 and 4.3.
Water	(3,3,1,3,1,na)	(3,3,1,3,1,na)	Estimation, based on AusLCI data
Black coal	(3,3,1,3,1,na)	(3,3,1,3,1,na)	Assumes density of coal in NZ, based on AusLCI data
Transport (trucking)	(3,3,1,3,1,na)	(3,3,1,3,1,na)	Estimation, based on AusLCI data
Transport (rail)	(3,3,1,3,1,na)	(3,3,1,3,1,na)	Estimation, based on AusLCI data
Emissions to air (carbon dioxide, methane, dinitrogen monoxide, nitrogen oxides, carbon monoxide, NMVOC, sulfur dioxide)	(2,1,1,1,1,na)	(2,1,1,1,1,na)	Calculated, data from literature-source, based on total emissions from electricity generation using coal (2013 MftE data)
Emissions to air (other Australian NPI pollutants)	(3,3,1,3,1,na)	(3,3,1,3,1,na)	Estimated, based on Australian NPI data for electricity from coal
Gas	(2,1,1,1,1,na)	(2,1,1,1,1,na)	Data from literature-source specific to NZ electricity, described in Section 3.5 and 4.3.
Water	(3,3,1,3,1,na)	(3,3,1,3,1,na)	Estimation, based on AusLCI data
Natural gas	(3,3,1,3,1,na)	(3,3,1,3,1,na)	Assumes carbon content of natural gas in NZ, based on AusLCI data
Transport (trucking)	(3,3,1,3,1,na)	(3,3,1,3,1,na)	Estimation, based on AusLCI data
Transport (rail)	(3,3,1,3,1,na)	(3,3,1,3,1,na)	Estimation, based on AusLCI data
Emissions to air (carbon dioxide, methane, dinitrogen monoxide, nitrogen oxides, carbon monoxide, NMVOC, sulfur dioxide)	(2,1,1,1,1,na)	(2,1,1,1,1,na)	Calculated, data from literature-source, based on total emissions from electricity generation using coal (2013 MftE data)
Emissions to air (Remaining Australian NPI pollutant data)	(3,3,1,3,1,na)	(3,3,1,3,1,na)	Estimated, based on Australian NPI data for electricity from coal
Hydropower	(2,1,1,1,1,na)	(2,1,1,1,1,na)	Literature source
Geothermal	(2,1,1,1,1,na)	(2,1,1,1,1,na)	Literature source

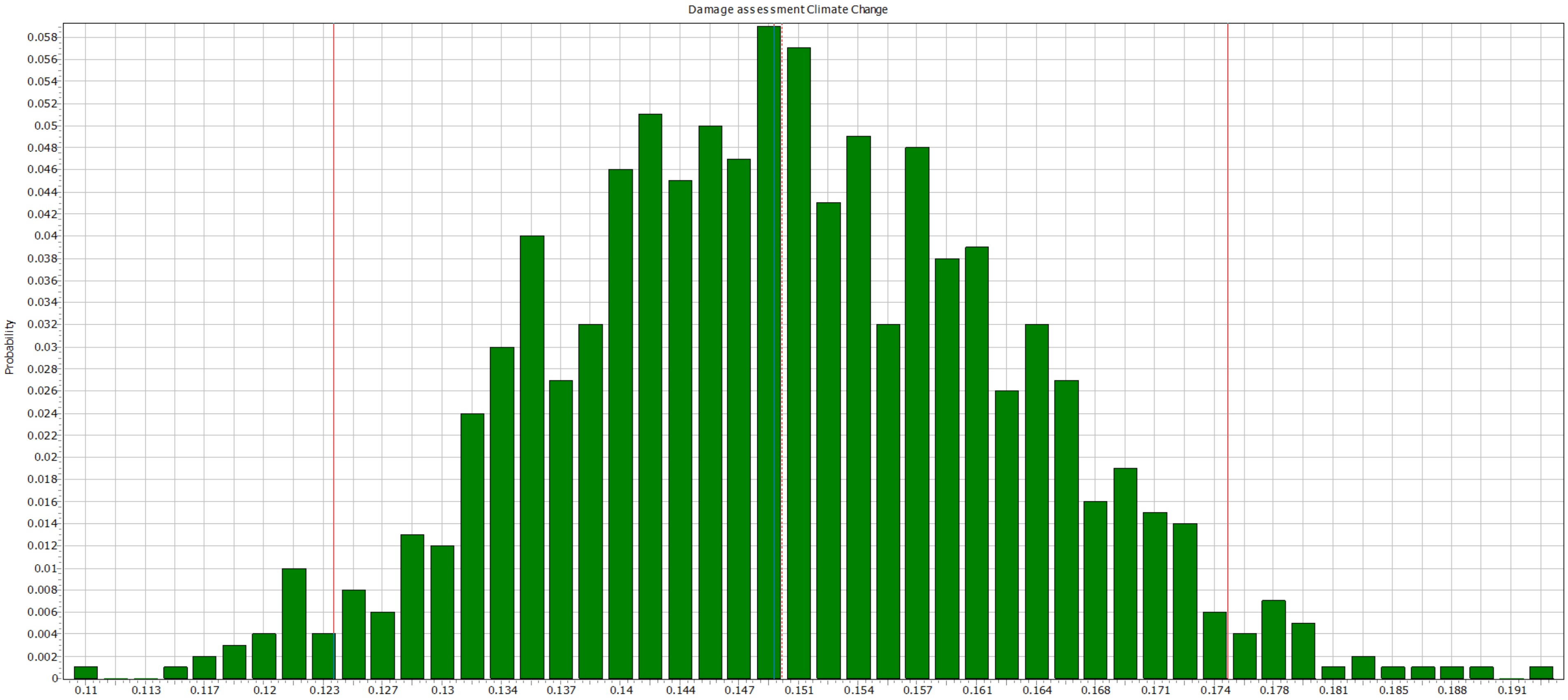
Data or assumption	**Conventional**	**Electric**	**Qualitative description (rationale)**
Emissions to air (CO2, Methane)	(2,1,1,1,1,na)	(2,1,1,1,1,na)	Calculated, data from literature-source, based on total emissions from electricity generation using coal (New Zealand's Greenhouse Gas Inventory 1990–2013 Snapshot, 2013 emissions from energy generation, tonnes)
Oil	(2,1,1,1,1,na)	(2,1,1,1,1,na)	Literature source
Wind power	(2,1,1,1,1,na)	(2,1,1,1,1,na)	Literature source
Landfill gas	(2,1,1,1,3,na)	(2,1,1,1,3,na)	Proxy for biogas and remaining
Bagasse	(2,1,1,1,3,na)	(2,1,1,1,3,na)	Proxy for wood
Losses	(2,1,1,1,1,na)	(2,1,1,1,1,na)	Literature source
Tailpipe emissions - conventional	(2,2,3,4,1,na)	-	Literature source, based on engine Euro class (EURO 5)
Tailpipe emissions - hybrid	-	(3,3,2,2,4,na)	Estimation of tailpipe emissions, pro-rated by fuel use to petrol conventional

D3 Detailed results

D3.1 Conventional petrol engine vehicle compared to BEV

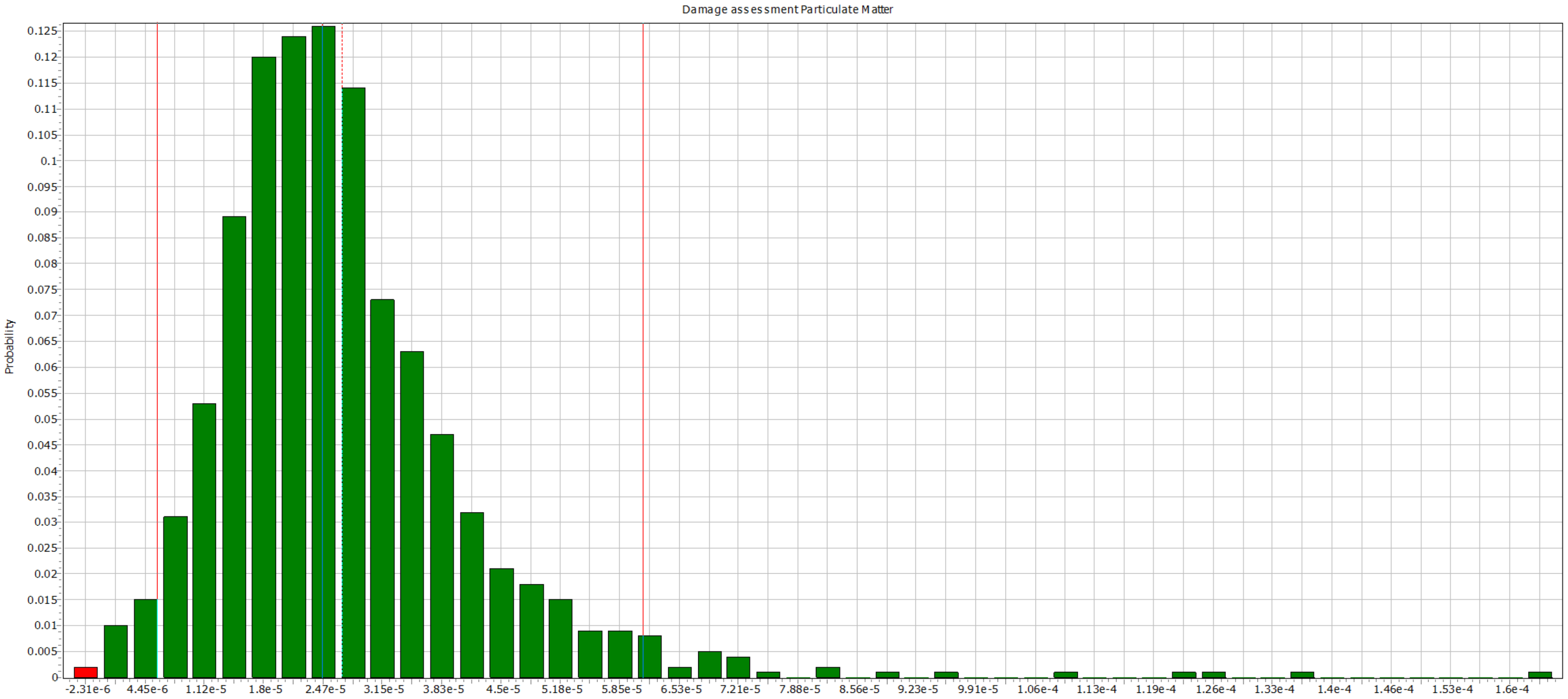
Table 24 Uncertainty Analysis – Comparing conventional petrol engine vehicle against battery electric vehicle (BEV), Confidence interval of 95%, 1000 runs performed

Damage category	**Conventional petrol engine vehicle > BEV** **(% of times)**	**Mean**	**Median**	**SD**	**Units**	**CV (Coefficient of Variation)**	**2.50%**	**97.50%**	**Standard error of mean**
Air Acidification	60.1%	6.47E-05	2.99E-05	1.87E-04	kg SO_2	289.09	-1.46E-04	4.71E-04	5.91E-06
Climate Change	100.0%	0.150	0.149	1.30E-02	kg CO_2	8.65	0.124	0.175	0.000
Cumulative Energy Demand	100.0%	1.802	1.698	7.94E-01	MJ LHV	44.05	0.552	3.633	0.025
Ecotoxicity	66.4%	0.459	0.839	2.58E+00	DAY	561.94	-5.774	4.104	0.082
Human Toxicity	45.1%	-8.53E-08	-8.48E-08	7.75E-07	DALY	-907.87	-1.68E-06	1.46E-06	2.45E-08
Particulate Matter	99.8%	2.69E-05	2.46E-05	1.51E-05	$PM_{2.5}$	56.33	5.92E-06	6.12E-05	4.79E-07
Photochemical Oxidation	100.0%	5.35E-05	5.22E-05	9.50E-06	kg C_2H_2	17.75	4.12E-05	7.35E-05	3.00E-07
Resource (Abiotic) Depletion	67.0%	3.46E-06	4.75E-06	1.54E-05	kg Sb	445.56	-3.01E-05	2.90E-05	4.87E-07



Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00, confidence interval: 95 %

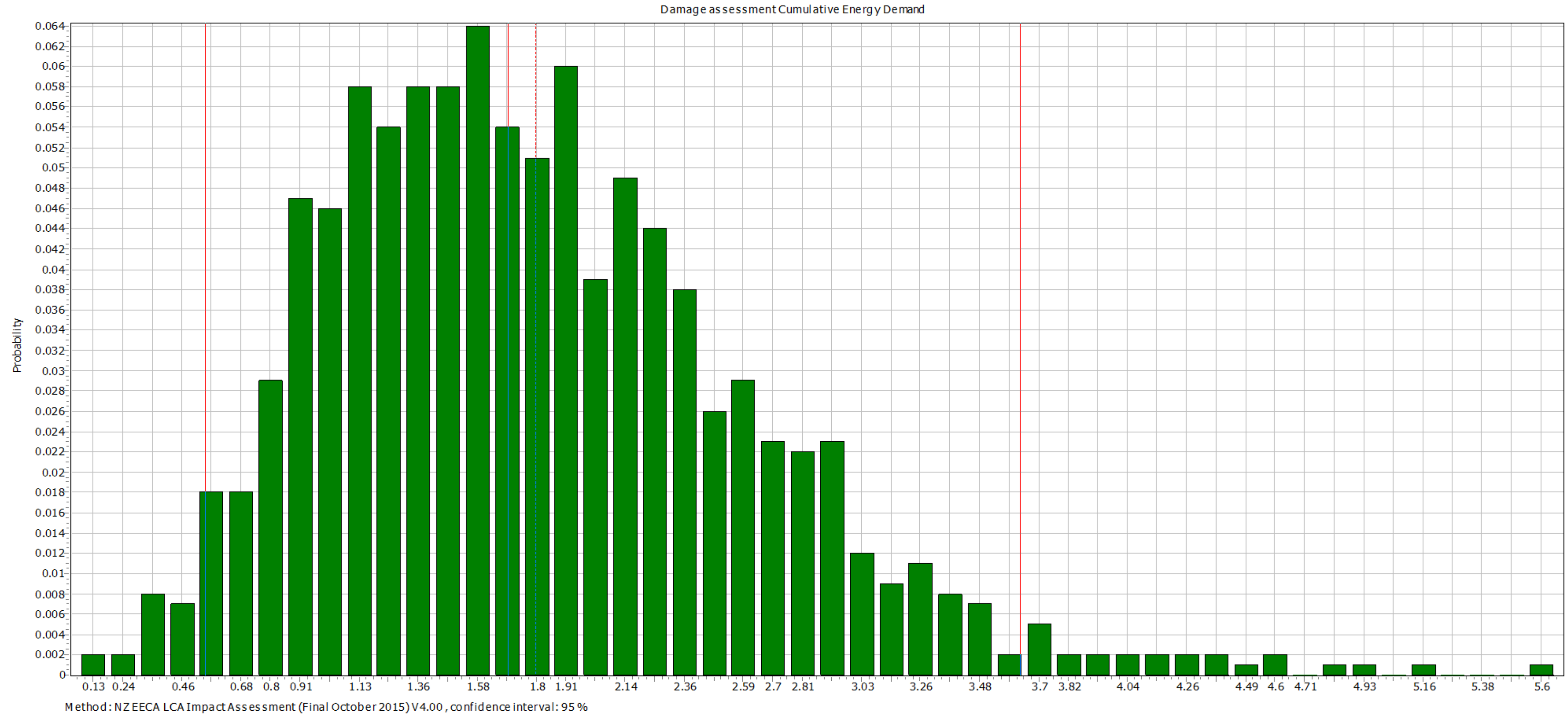
1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus



Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00 , confidence interval: 95 %

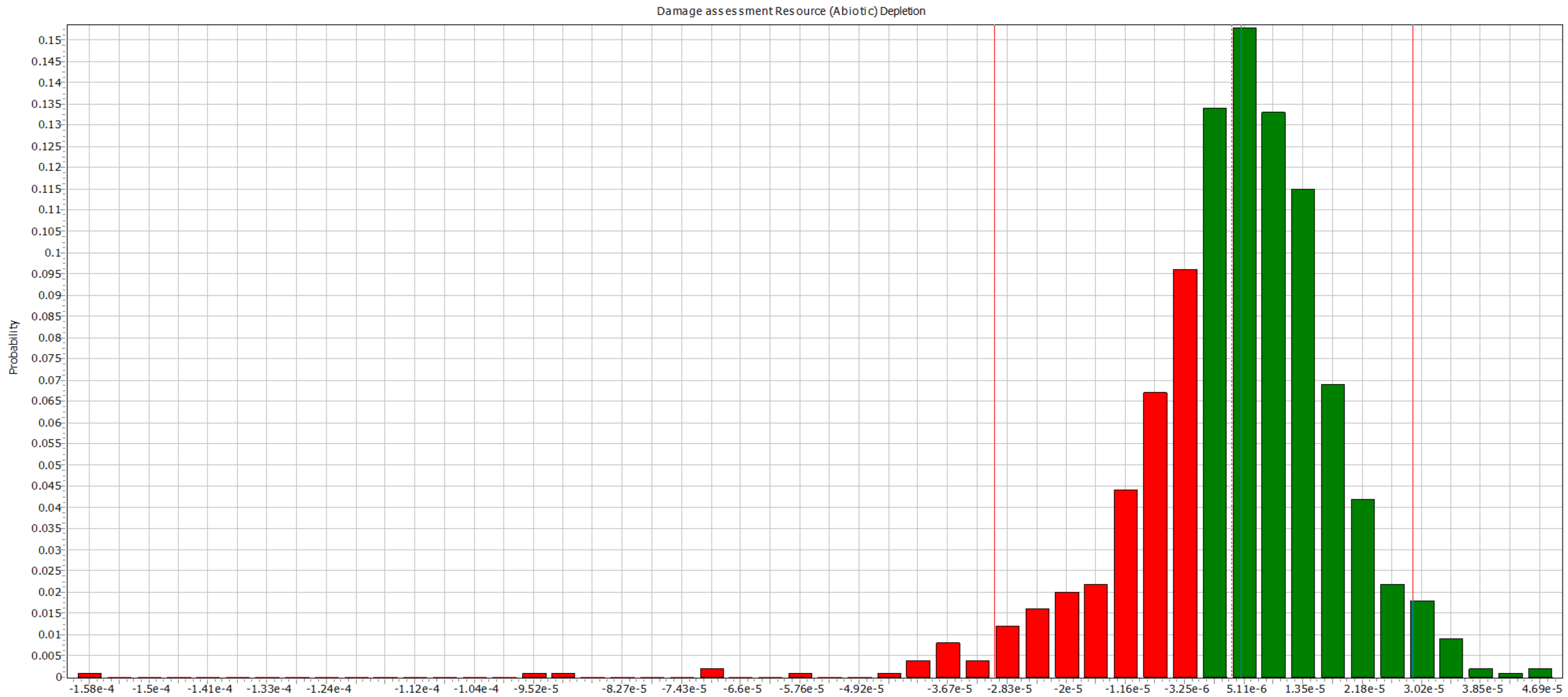
1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus

Damage assessment Cumulative Energy Demand



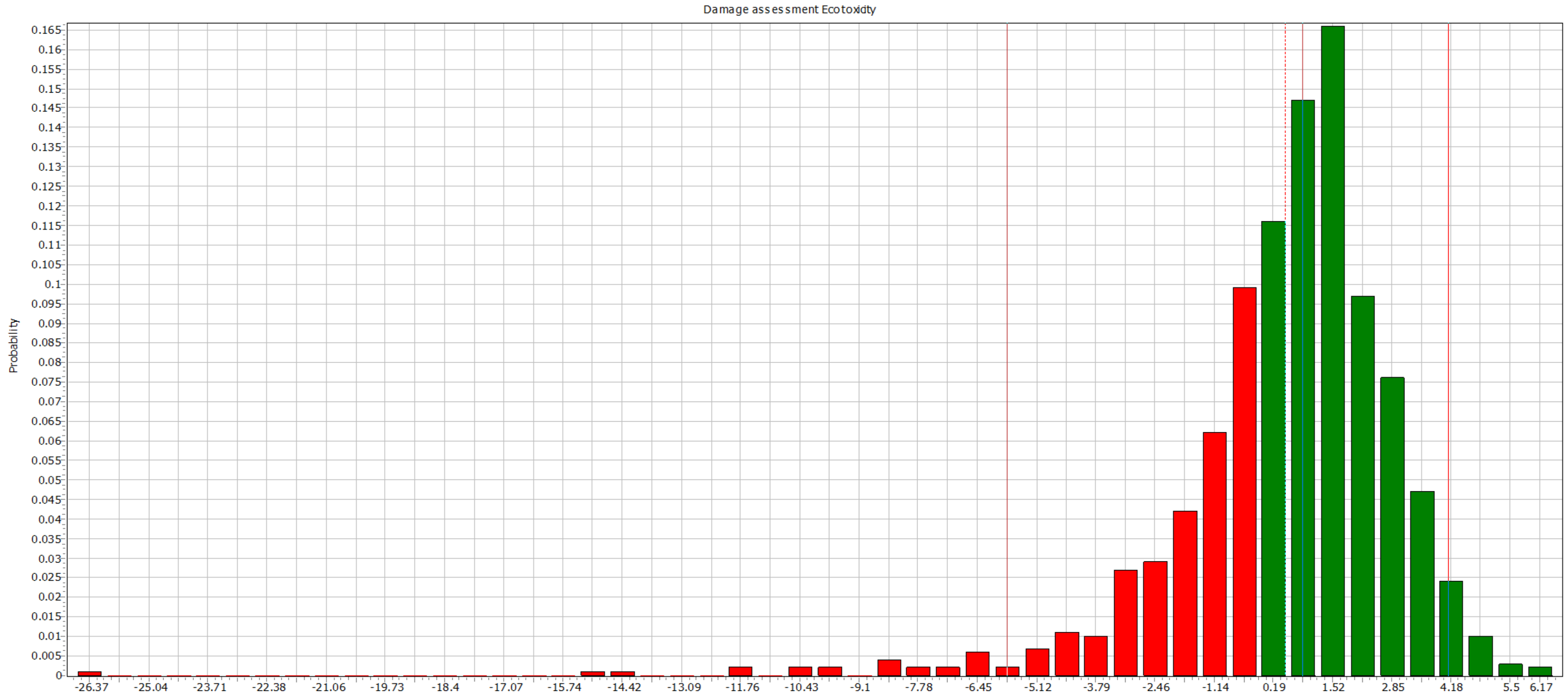
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00 , confidence interval: 95 %

1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus



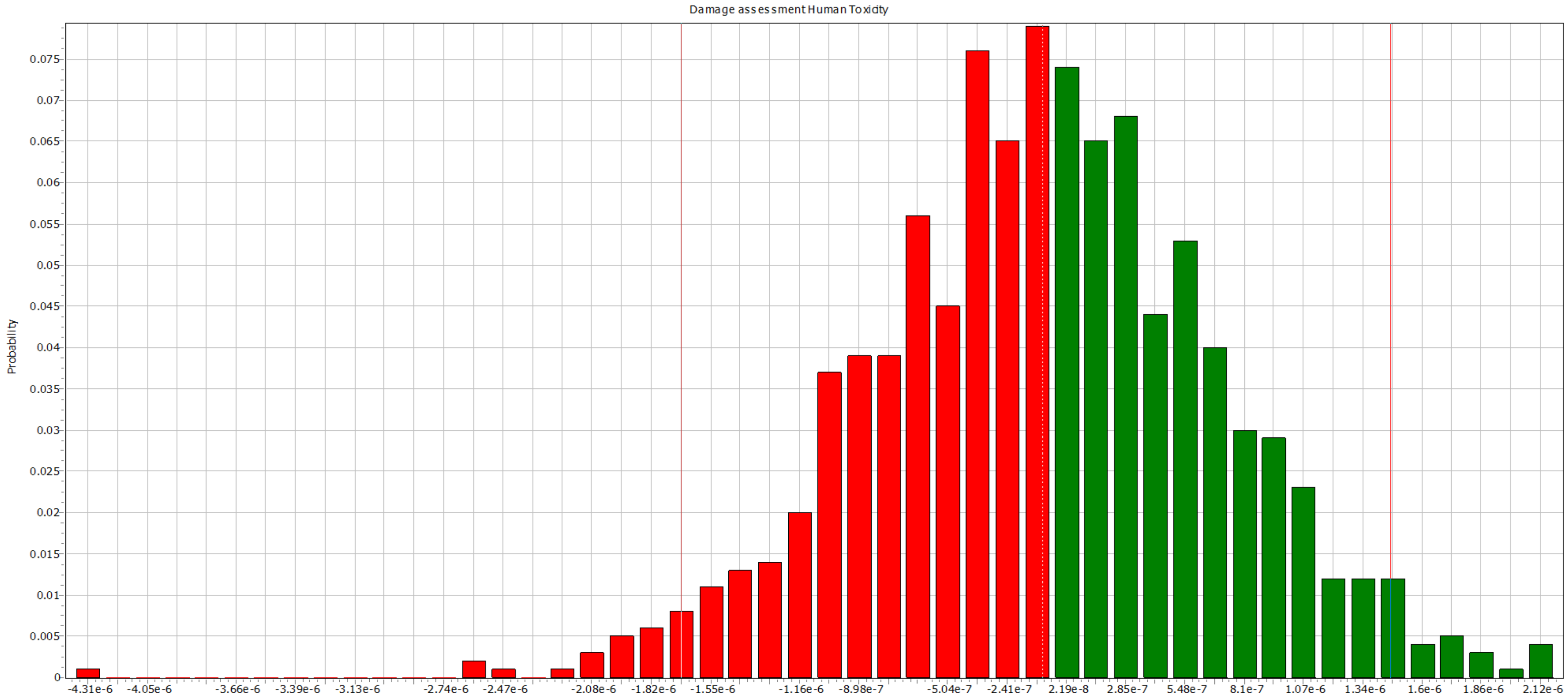
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00 , confidence interval: 95 %

1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus



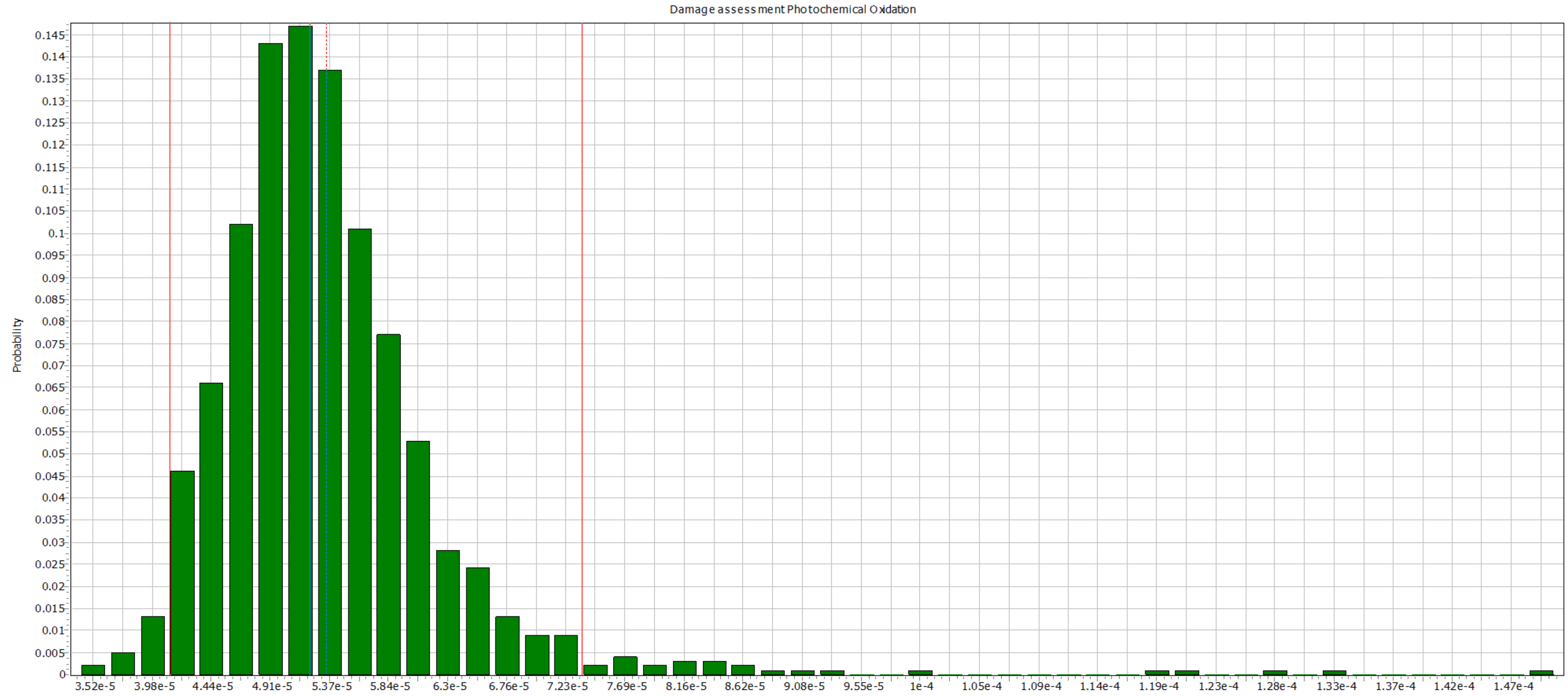
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00 , confidence interval: 95 %

1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus



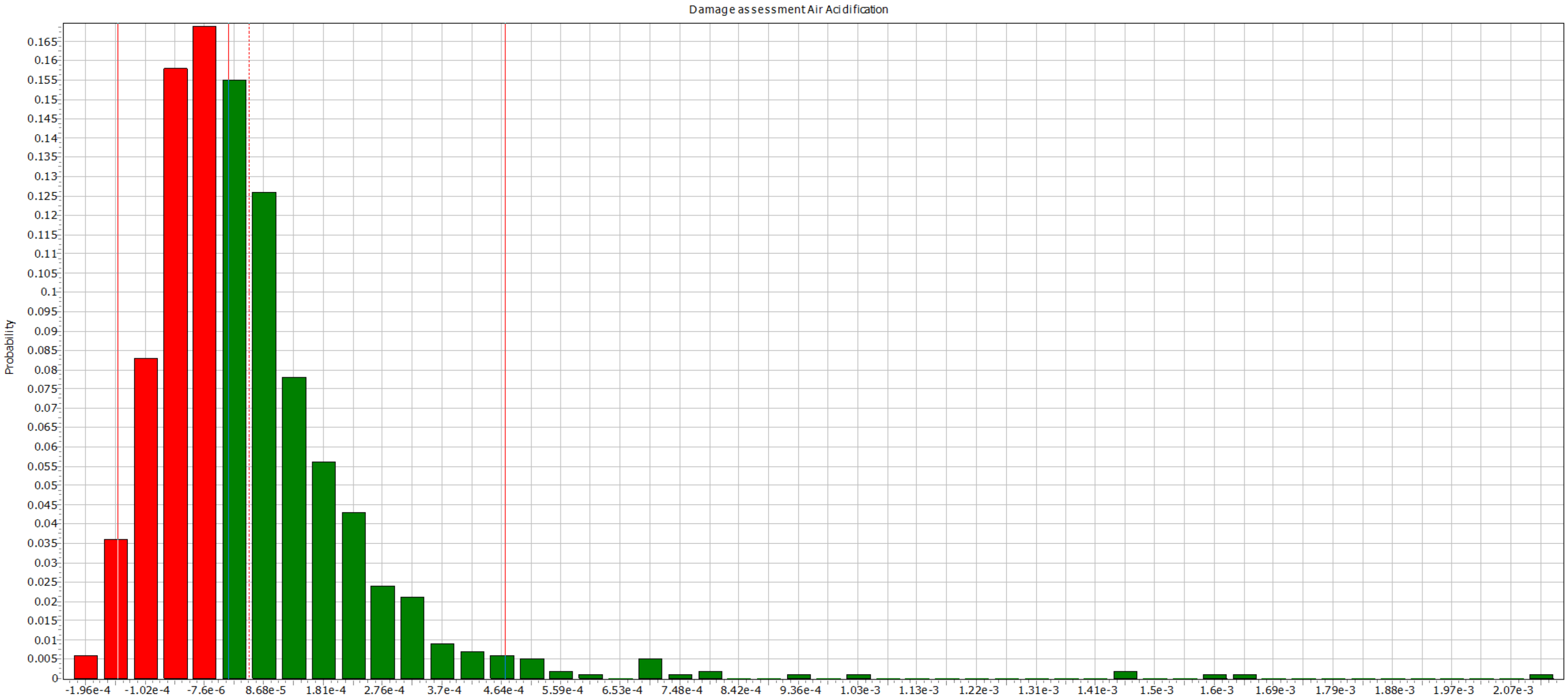
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00 , confidence interval: 95 %

1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus



Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00 , confidence interval: 95 %

1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus



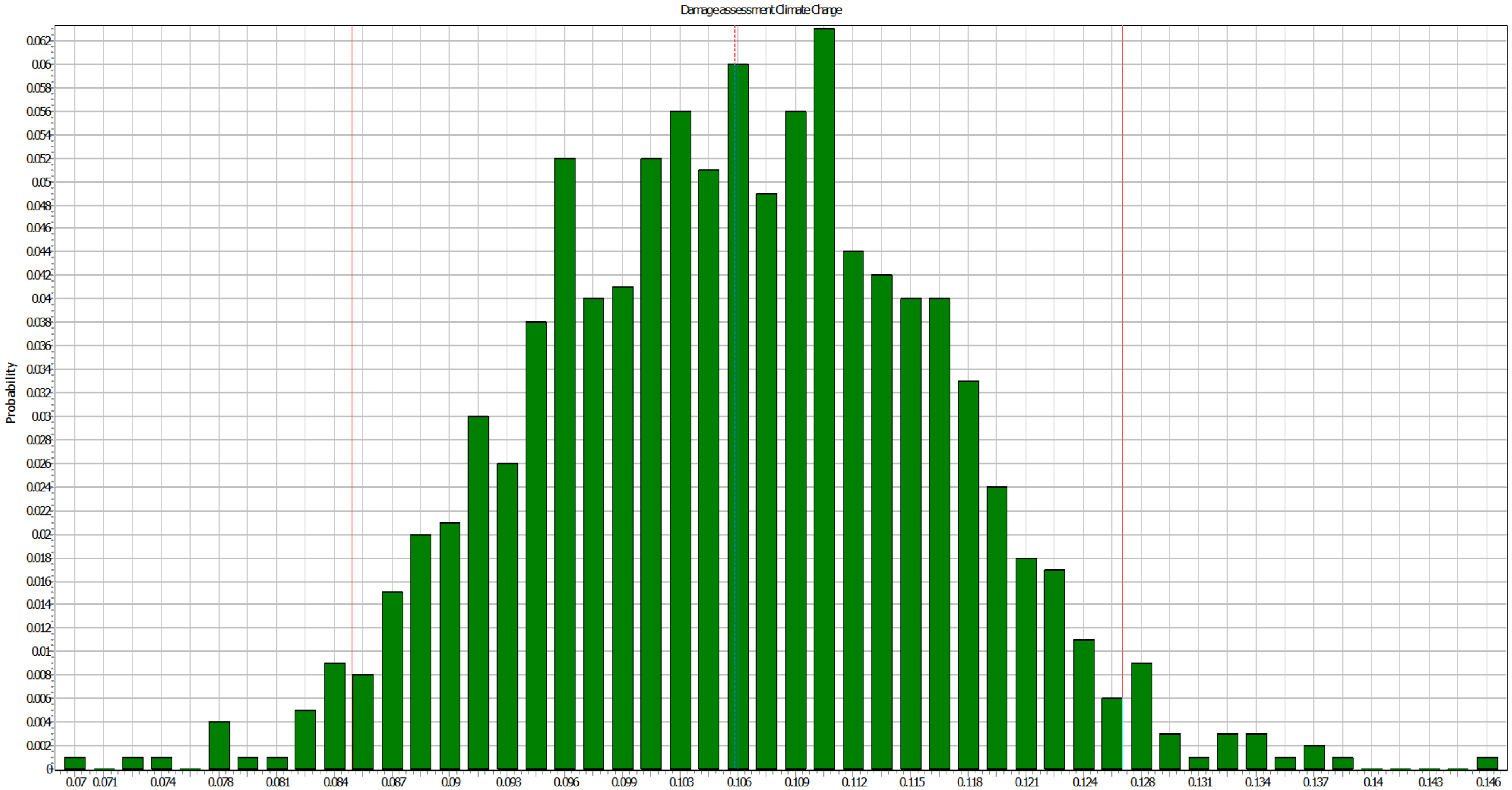
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00 , confidence interval: 95 %

1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, petrol, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus

D3.2 Conventional diesel engine vehicle compared to BEV

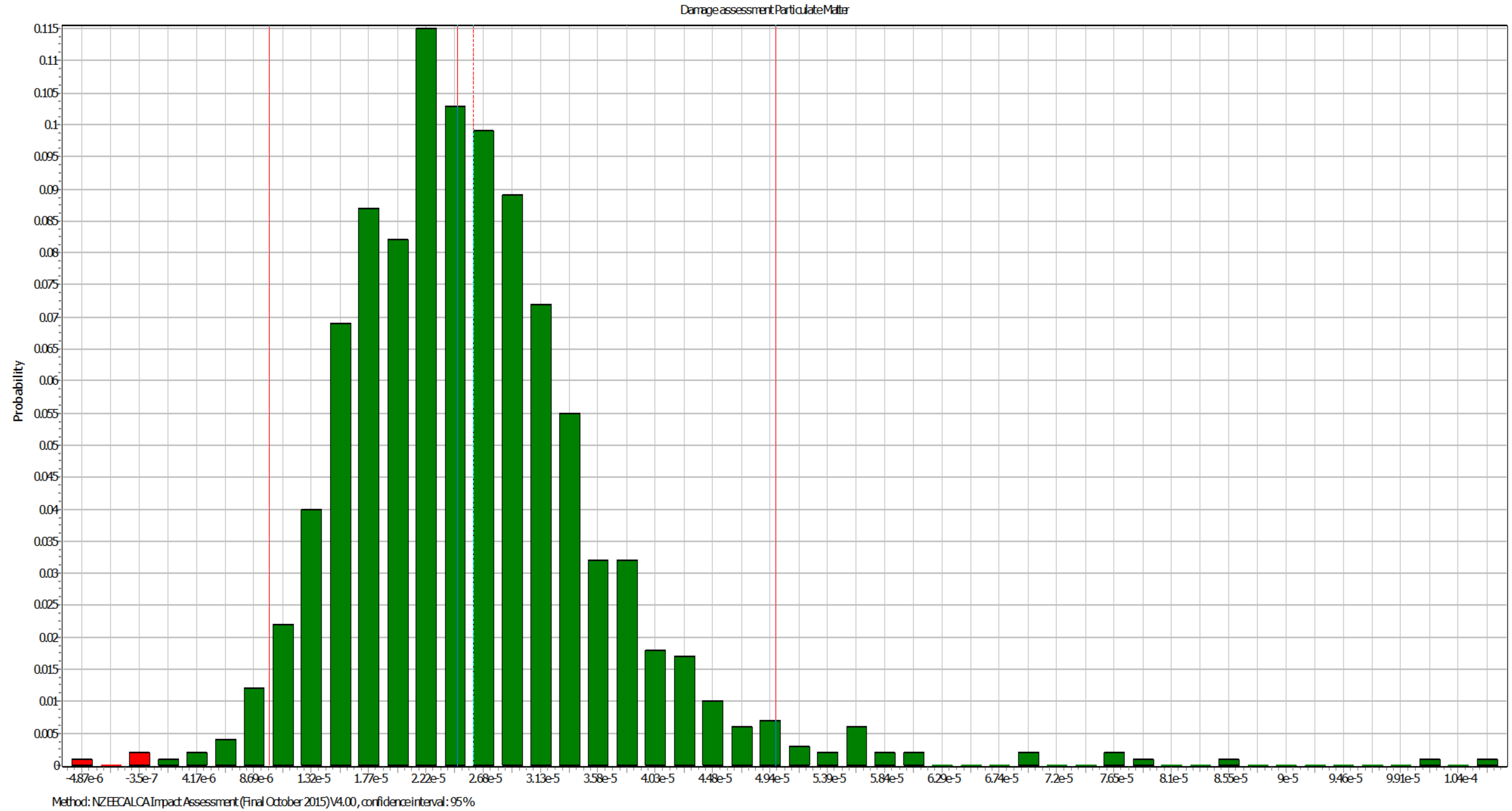
Table 25 Uncertainty Analysis – Comparing conventional diesel engine vehicle against battery electric vehicle (BEV), Confidence interval of 95%, 1000 runs performed

Damage category	**ICE (Diesel) > BEV (% of times)**	**Mean**	**Median**	**SD**	**Units**	**CV (Coefficient of Variation)**	**2.50%**	**97.50%**	**Standard error of mean**
Air Acidification	54.5%	3.04E-05	1.15E-05	1.26E-04	kg SO_2	413.59	-1.36E-04	3.54E-04	3.98E-06
Climate Change	100.0%	0.106	0.105	1.06E-02	kg CO_2	10.01	0.086	0.128	0.000
Cumulative Energy Demand	99.7%	1.648	1.576	7.84E-01	MJ LHV	47.60	0.335	3.372	0.025
Ecotoxicity	73.7%	1.050	1.284	2.30E+00	DAY	219.14	-4.273	4.899	0.073
Human Toxicity	44.7%	-1.23E-07	-7.54E-08	8.85E-07	DALY	-721.57	-2.00E-06	1.55E-06	2.80E-08
Particulate Matter	100.0%	2.54E-05	2.41E-05	1.03E-05	$PM_{2.5}$	40.32	9.81E-06	4.87E-05	3.24E-07
Photochemical Oxidation	96.4%	9.12E-06	8.54E-06	6.63E-06	kg C_2H_2	72.67	-1.10E-06	2.49E-05	2.10E-07
Resource (Abiotic) Depletion	74.0%	5.61E-06	7.07E-06	1.52E-05	kg Sb	271.76	-3.06E-05	3.42E-05	4.82E-07



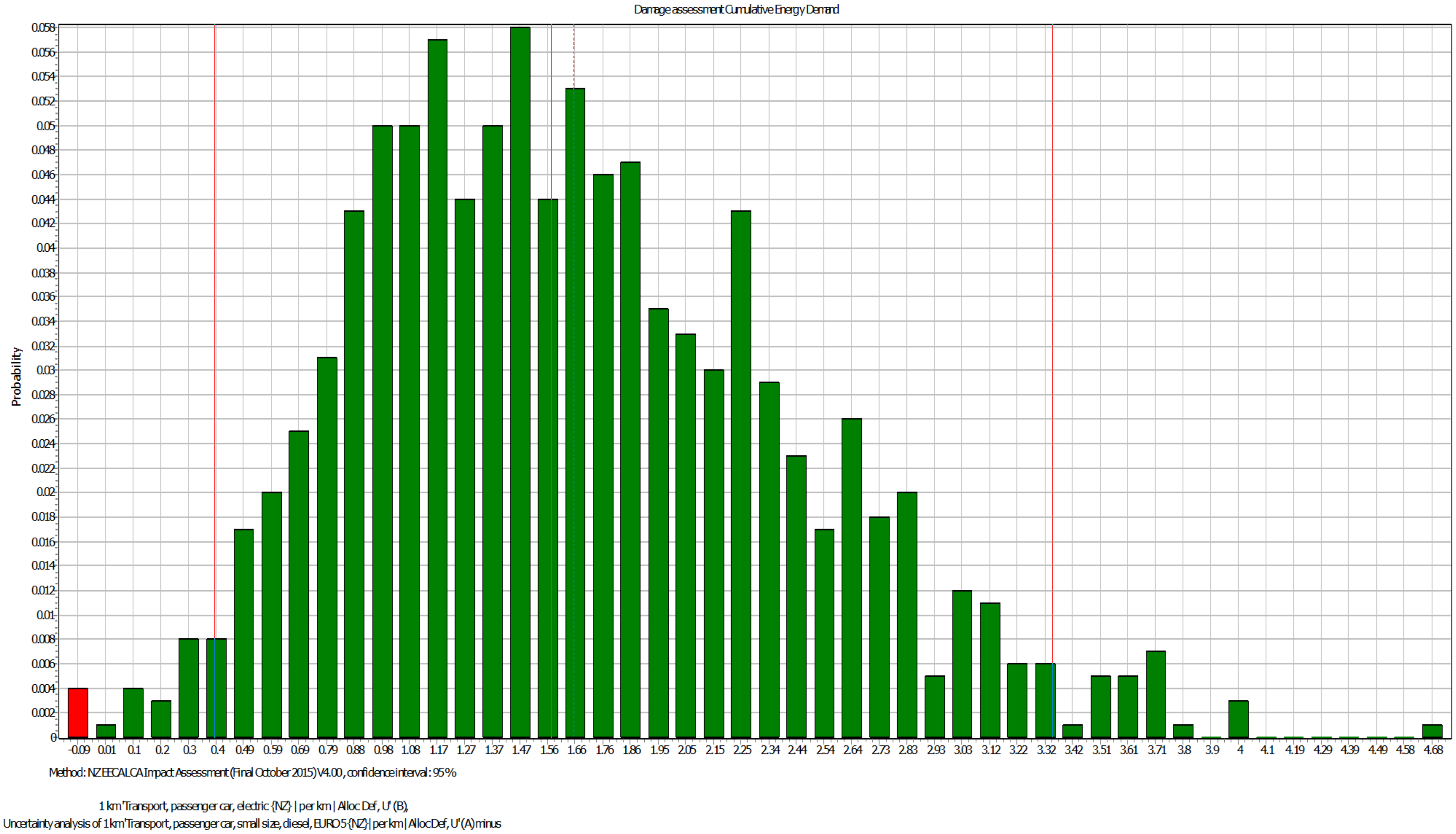
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00 , confidence interval : 95 %

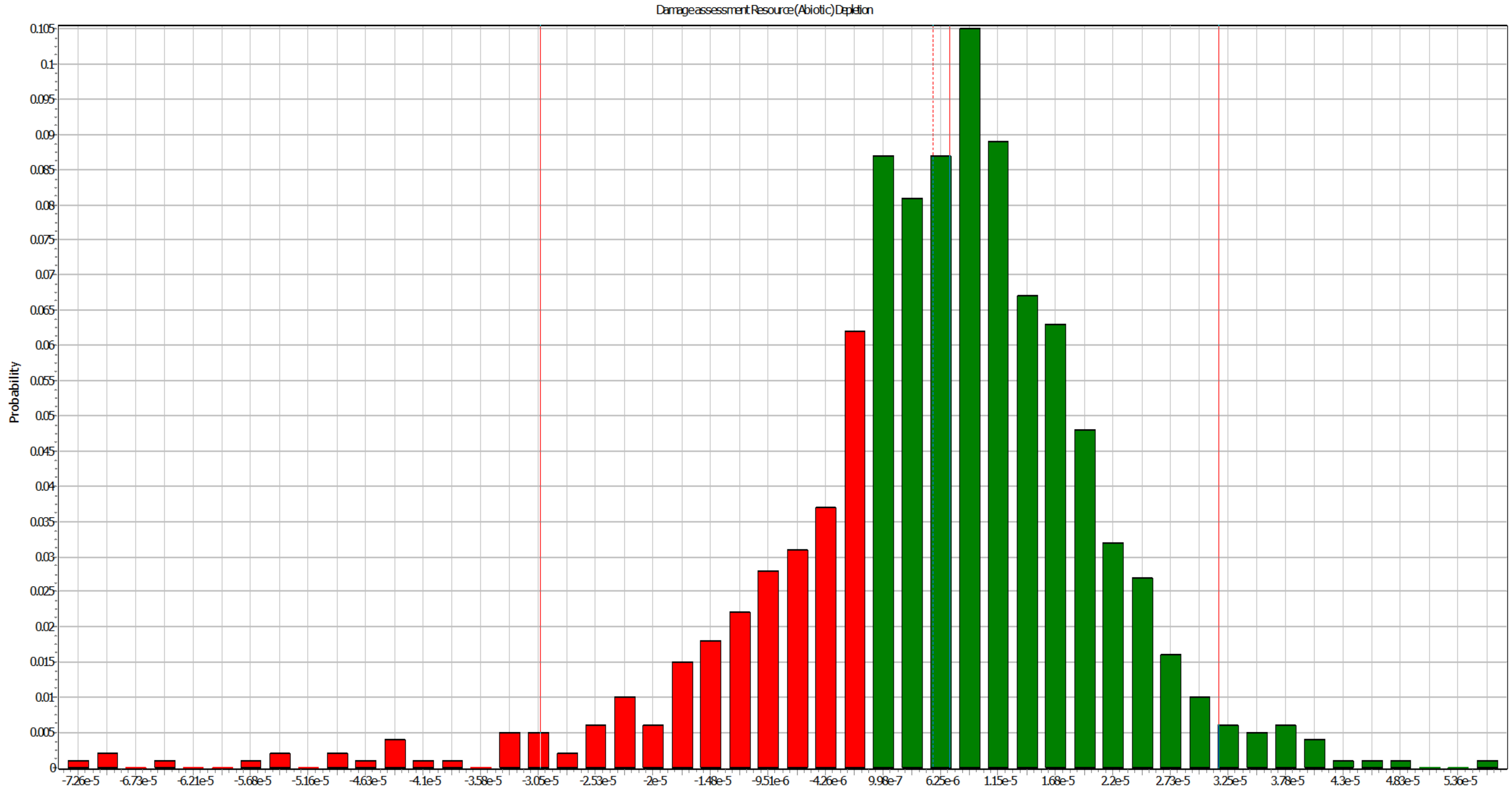
1 km 'Transport, passenger car, electric {NZ}- | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, diesel, EURO 5 {NZ}| per km | Alloc Def, U' (A) minus



Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00, confidence interval: 95%

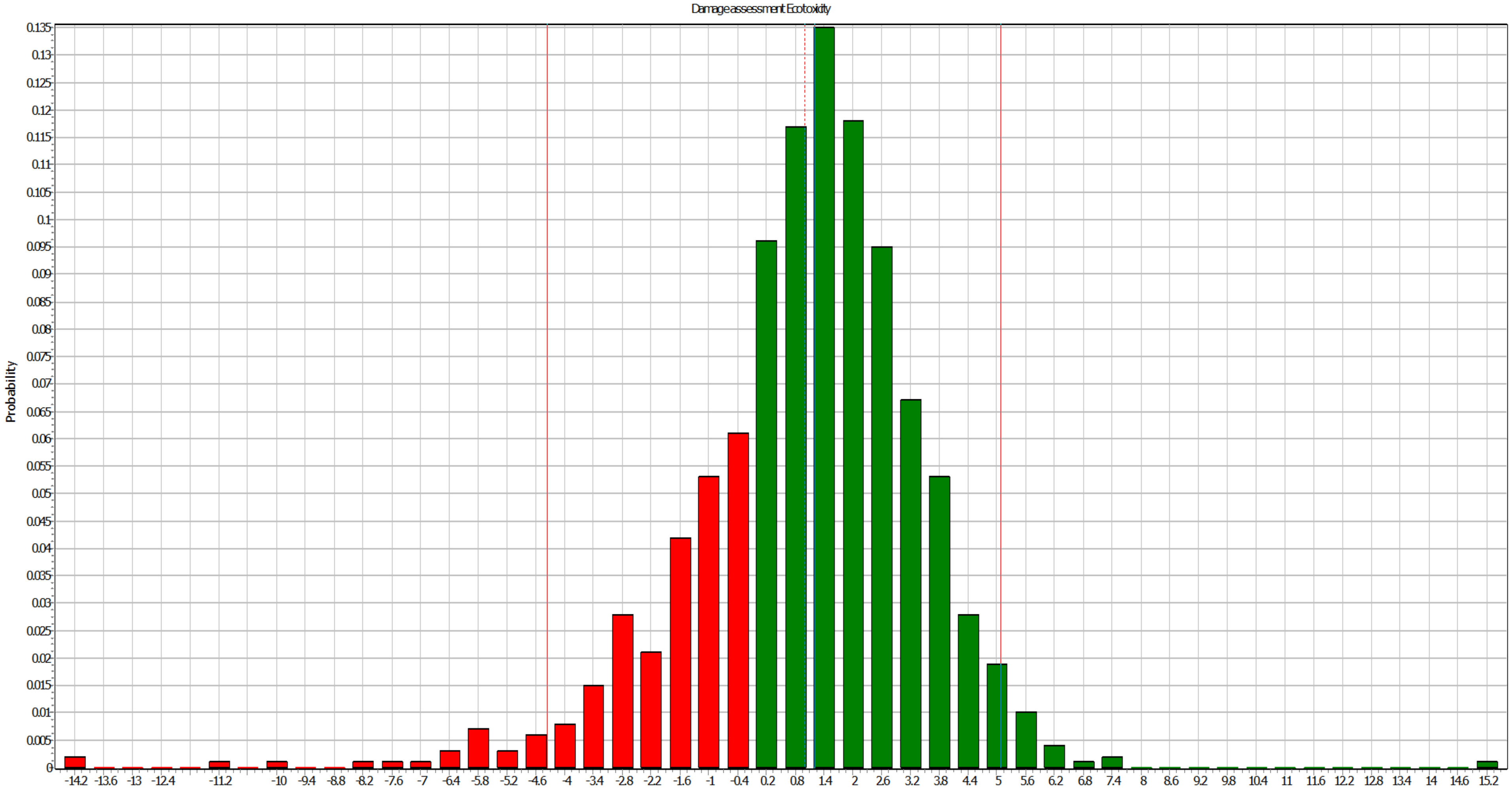
1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, diesel, EURO5 {NZ} | per km | Alloc Def, U' (A) minus


Damage assessment Cumulative Energy Demand
Probability
0.058
0.056
0.054
0.052
0.05
0.048
0.046
0.044
0.042
0.04
0.038
0.036
0.034
0.032
0.03
0.028
0.026
0.024
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
-0.09
0.01
0.1
0.2
0.3
0.4
0.49
0.59
0.69
0.79
0.88
0.98
1.08
1.17
1.27
1.37
1.47
1.56
1.66
1.76
1.86
1.95
2.05
2.15
2.25
2.34
2.44
2.54
2.64
2.73
2.83
2.93
3.03
3.12
3.22
3.32
3.42
3.51
3.61
3.71
3.8
3.9
4
4.1
4.19
4.29
4.39
4.49
4.58
4.68
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00, confidence interval: 95%
1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, diesel, EURO5 {NZ} | per km | Alloc Def, U' (A) minus



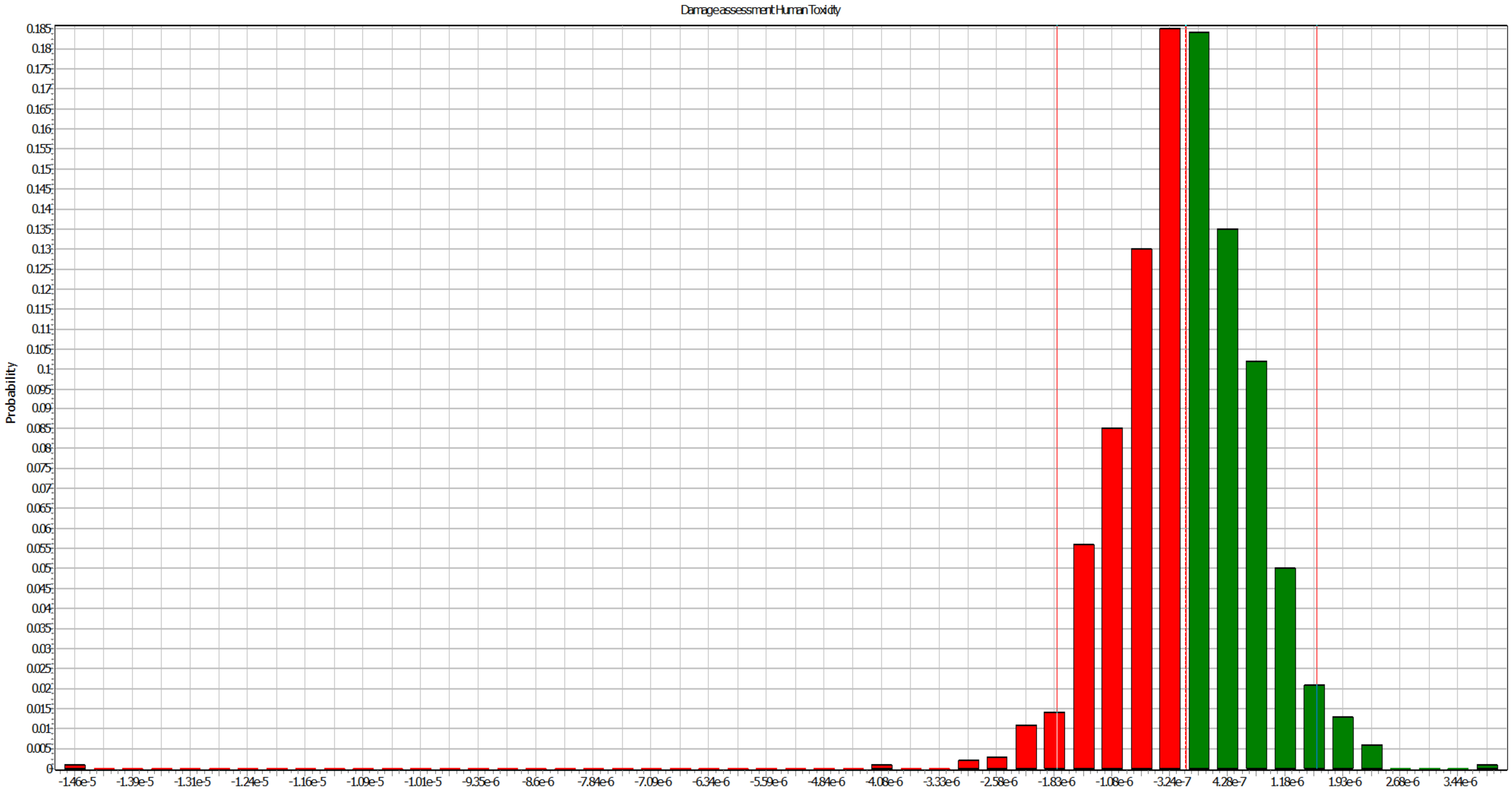
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00 , confidence interval : 95 %

1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, diesel, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus



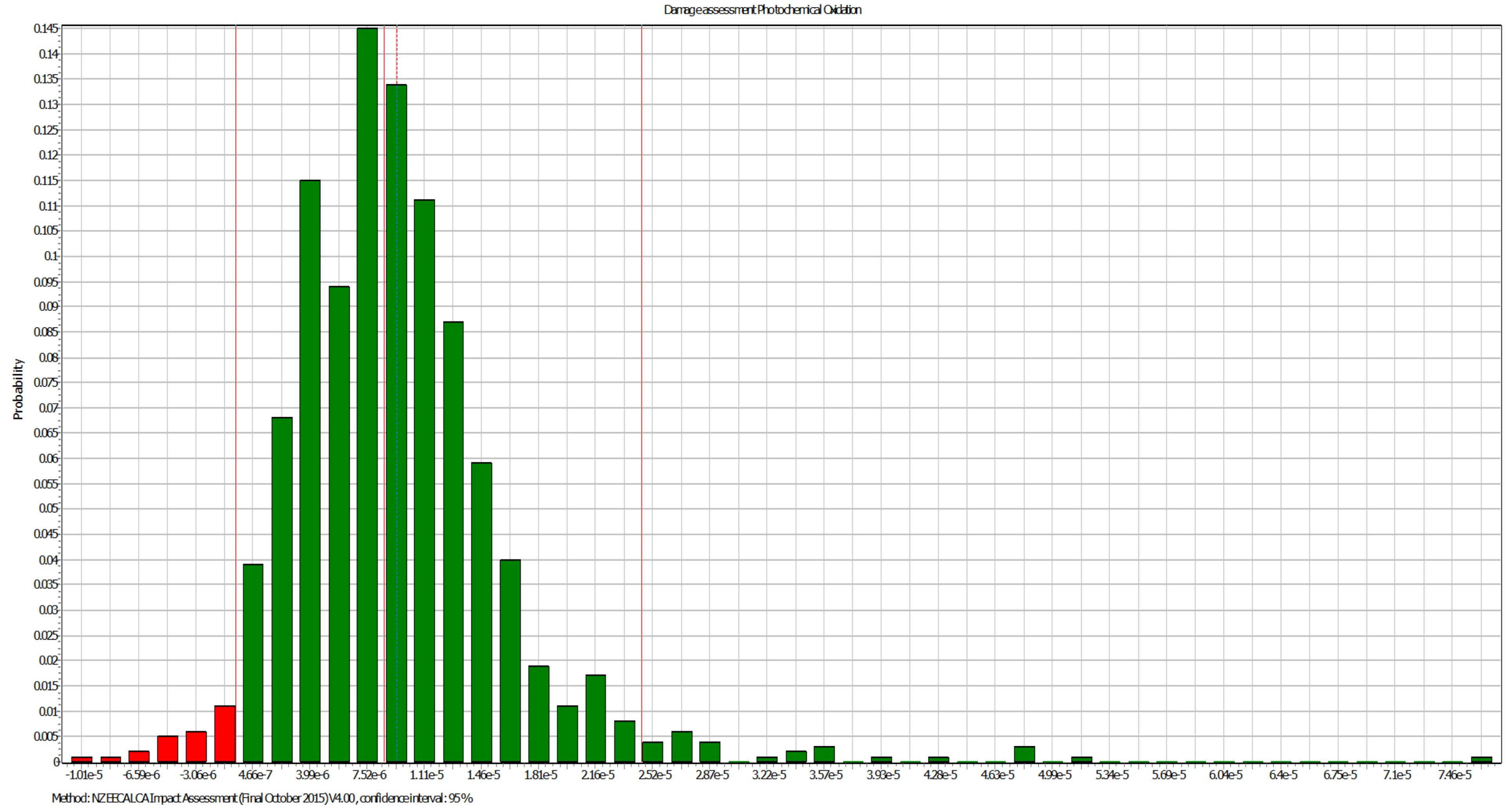
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00, confidence interval: 95%

1 km 'Transport, passenger car, electric {NZ}- | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, diesel, EURO5 {NZ}| per km | Alloc Def, U' (A) minus



Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00, confidence interval: 95%

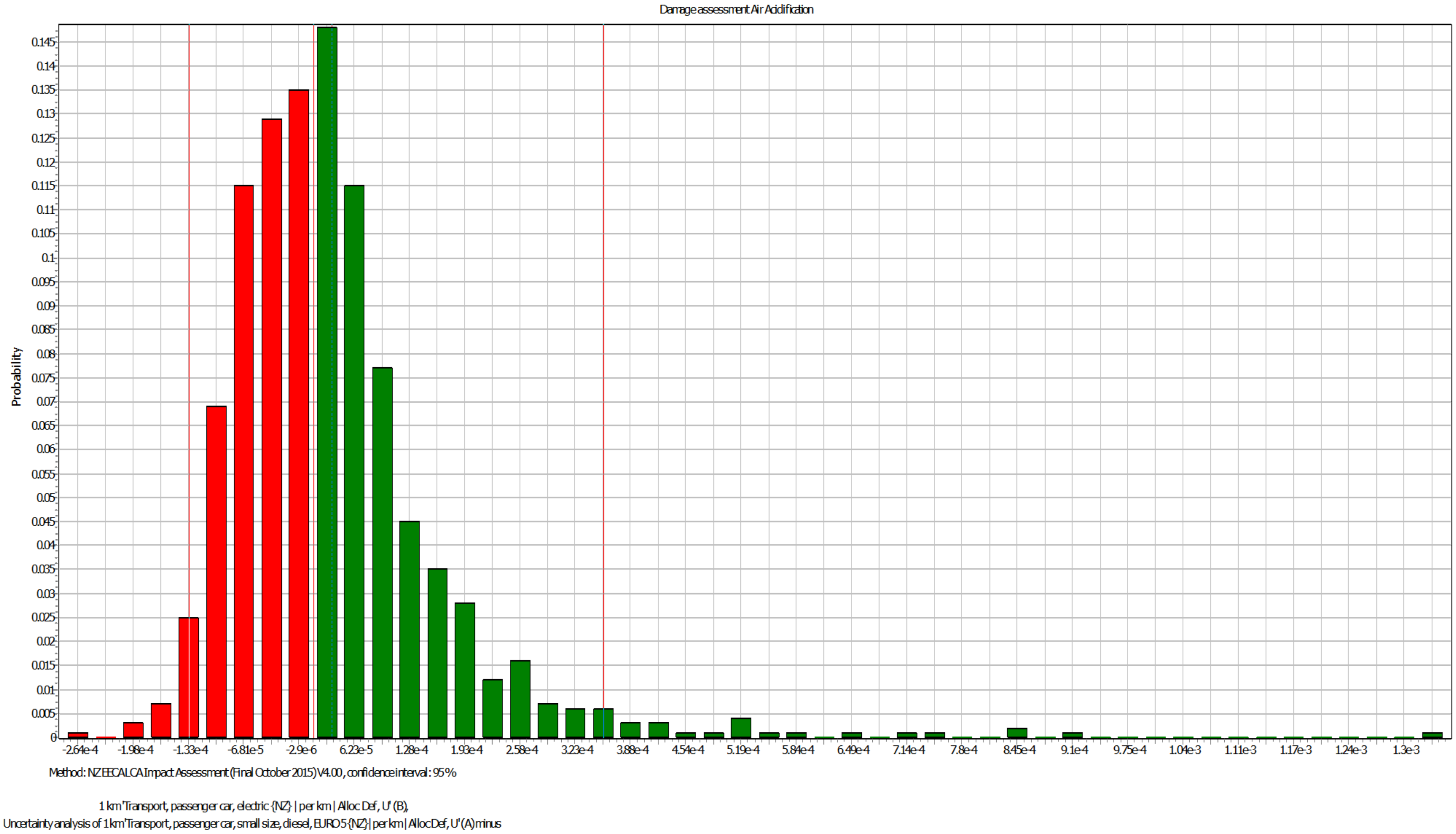
1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, diesel, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus



Damage assessment Photochemical Oxidation

Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00, confidence interval: 95%

1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, diesel, EURO5 {NZ} | per km | Alloc Def, U' (A) minus


Damage assessment Air Acidification
Probability
0.145
0.14
0.135
0.13
0.125
0.12
0.115
0.11
0.105
0.1
0.095
0.09
0.085
0.08
0.075
0.07
0.065
0.06
0.055
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-2.64e-4
-1.98e-4
-1.33e-4
-6.81e-5
-2.9e-6
6.23e-5
1.28e-4
1.93e-4
2.58e-4
3.23e-4
3.88e-4
4.54e-4
5.19e-4
5.84e-4
6.49e-4
7.14e-4
7.8e-4
8.45e-4
9.1e-4
9.75e-4
1.04e-3
1.11e-3
1.17e-3
1.24e-3
1.3e-3
Method: NZ EECA LCA Impact Assessment (Final October 2015) V4.00, confidence interval: 95%
1 km 'Transport, passenger car, electric {NZ} | per km | Alloc Def, U' (B),
Uncertainty analysis of 1 km 'Transport, passenger car, small size, diesel, EURO 5 {NZ} | per km | Alloc Def, U' (A) minus

Appendix E

Detailed assumptions

E1 New Zealand electricity

The following table provides the assumptions relating to New Zealand electricity. The assumptions have been used to modify AustralianLCI inventory data for electricity for a New Zealand context. Table 26 outlines the amount of electricity contributed by each energy technology to the New Zealand energy grid in 2014.

Table 26 Grid electricity energy mix in 2014

Source	**Electricity generated (GWh)[41]**	**Notes**
Hydroelectricity	24,093	Transmission losses: 2.8% (calculated line losses based on total transmission line losses compared to net generation)[41].
Natural Gas	6,602	
Geothermal	6,847	
Coal	1,855	
Oil	6	
Wind	2,188	
Other	33	
Wood	366	
Biogas	223	

The total emissions to air from electricity generation from coal in New Zealand for 2013 are outlined in Table 27.

Table 27 New Zealand total coal electricity emissions in 2013

Emission type	**Emissions (tonnes)[42]**	**Notes**
CO_2	1,615,903	Primary energy from coal: 17.9 PJ[43] Electricity generated from coal: 2,238 GWh[44]
CH_4	11	
N_2O	26	
CO	150	
NO_x	6,340	
NMVOC	83	
SO_2	6,800	

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[41] Data for 2014, Quarterly Electricity Graph and data tables, Ministry of Business, Innovation and Employment NZ, Table 2

[42] New Zealand's Greenhouse Gas Inventory 1990–2013 Snapshot, 2013 emissions from energy generation

[43] NZ MBIE 2015 Data, Table 4 - Annual Coal Supply, Transformation & Consumption (PJ), includes only Transformation: Electricity Generation and Production losses and own use

[44] Data for 2013, Quarterly Electricity Graph and data tables, Ministry of Business, Innovation and Employment NZ, Table 2

The total emissions to air from electricity generation from natural gas in New Zealand for 2013 are outlined in Table 28.

Table 28 New Zealand total natural gas electricity emissions in 2013

Emission type	**Emissions (tonnes)**[45]	**Notes**
CO_2	3,409,035	Primary energy from gas: 60.1 PJ[46] Electricity generated from gas: 8,134 GWh[47]
CH_4	178	
N_2O	5.8	
CO	1,866	
NO_x	12,831	
NMVOC	292	
SO_2	0	

The total emissions to air from geothermal electricity generation in New Zealand for 2013 are outlined in Table 29.

Table 29 New Zealand total geothermal electricity emissions in 2013

Emission type	**Emissions (tonnes)**[48]	**Notes**
CO_2	597	Electricity generated from geothermal: 6,847 GWh[49]
CH_4	6.1	

E2 Process flows

Appendix C provides a summary of the product and process flows for each of the vehicles used in the study. The flows provide the energy, masses and components of various unit processes into the functional unit of 1 km travel per vehicle. The cut-off for the diagrams is 2%.

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[45] New Zealand's Greenhouse Gas Inventory 1990–2013 Snapshot, 2013 emissions from energy generation

[46] NZ MBIE 2015, Gas Production and Consumption, 2013 data for Electricity generation, production losses & own use, transmission and distribution losses

[47] Data for 2013, Quarterly Electricity Graph and data tables, Ministry of Business, Innovation and Employment NZ, Table 2

[48] New Zealand's Greenhouse Gas Inventory 1990–2013 Snapshot, 2013 emissions from energy generation

[49] Data for 2014, Quarterly Electricity Graph and data tables, Ministry of Business, Innovation and Employment NZ, Table 2