Transportation CO_2 Emissions in Automotive Life Cycle Assessments of Electric Vehicles – a Systems Theory Evaluation.

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ABSTRACT

Electric vehicles are widely viewed as having the potential to reduce global carbon emissions because they effectively produce no carbon emissions to operate when powered by a low carbon electric energy source for charging their batteries. Given that transportation activities account for around a quarter of global carbon emissions, a societal switch to electric vehicles appears to offer significant potential in reducing global carbon emissions as most transport emissions are caused by internal combustion engines which burn fossil fuels.

However, when viewed from an overall systems perspective (i.e. the entire “cradle to grave” life cycle of an electric vehicle – spanning from raw materials mining and extraction to final disposal and recycling) it transpires that significantly more carbon emissions are generated in order to manufacture electric vehicles, compared to traditional internal combustion engine vehicles.

Taken over the whole life cycle of the vehicle, it can be several years of operation before the anticipated lower carbon emissions of electric vehicles are realised. Indeed, in some countries which rely on fossil fuel electric power generation, a traditional internal combustion engine vehicle produces lower carbon emissions over its life cycle.

Significant research has already been conducted by others on the whole life-cycle carbon emissions of both electric vehicles and internal combustion engine vehicles. However, within that research, there has been no visible scrutiny of the CO_2 emissions arising from the logistics transportation activities which are needed in order to produce these vehicles. This apparent omission in the existing research is surprising considering that transportation carbon emissions account for such a large proportion of global carbon emissions. Thus, there is a risk – if these transportation emissions are significant – that the anticipated environmental benefits of electric vehicles may be less than thought.

Addressing this gap in the literature, this research examines, calculates and compares the carbon emissions arising from transportation activities in electric vehicle supply chains, comparing them with internal combustion engine vehicle supply chains and thereby provides an original contribution to knowledge.

This was done via a case study simulation of supply chains of vehicle production in Germany for both types of vehicle, spanning from raw materials extraction to the completed vehicle manufacture. A proxy model of supply chains of vehicle materials was developed specifically for this research. It was found that electric vehicle supply chains give rise to 72% more carbon emissions in their transportation activities than equivalent internal combustion engine vehicles.

Notwithstanding this, these emissions remain modest compared to carbon emissions in the rest of the vehicle life cycles and it was calculated that including these emissions in life cycle calculations typically delays the anticipated environmental benefits of electric vehicles by a mere few months of typical usage.

Moreover, in the case of internal combustion engine vehicles this figure remains insignificant compared to the carbon emissions produced by years of burning fossil fuels during their usage phase, justifying this omission from the historical research literature.

In the case of electric vehicles though – where these emissions during the usage phase are potentially eliminated – these emissions become comparable in size to their end of life and recycling emissions, and are around half the magnitude of the manufacturing emissions (both of which typically *are* considered in electric vehicle life cycle assessments). Thus, this research demonstrates that the impact of supply chain transportation emissions can no longer be omitted in the life cycle assessment literature. This is of specific importance to the wider research body in electric vehicle emissions, and thus relevant to academics, consultants and researchers who engage in this area of work.

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Super omnia, soli Deo gloria. Caelitus mihi vires.

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LIST OF ABBREVIATIONS

C2G	“Cradle to Gate”
BEV	Battery electric vehicle
EV	Electric Vehicle
EVs	Electric Vehicles
ICE	Internal Combustion Engines
ISO	International Organization for Standardization
LCA	Life Cycle Assessment or Life Cycle Analysis
LCI	Life Cycle Inventory
TTW	Tank to wheel or wake
WTT	Well to tank
WTW	Well to wheel

1. INTRODUCTION

As government organisations endeavour to reduce carbon emissions, electric vehicles have been identified as a key part of their strategy to achieve this. For example, in the European Union where transportation activities are recognised as contributing around a quarter of total carbon emissions, road transport is identified as contributing the greatest share of this, at 72% transportation emissions figures (European Environment Agency, 2022). Within this context, the EU has prioritised an increase in electric vehicles (EVs) in the European-wide vehicle stock as a key strategy to achieving its climate targets. This is because - when powered by low carbon energy sources, such as electricity generated by wind power – electric vehicles produce significantly fewer carbon emissions per mile compared to internal combustion engine (ICE) vehicles (Pridemore *et al.*, 2018).

Notwithstanding this apparent advantage of EVs, greenhouse gas emissions arising from raw materials extraction and production activities are notably higher for EVs compared to ICE vehicles. Thus, the environmental benefit of EVs is only realised after a period of time when the potential lower usage emissions of an EV offset the higher emissions which arise to produce them (Pridemore *et al.*, 2018).

This research focuses on the transportation emissions that arise during the raw materials' extraction and subsequent manufacturing activities required to produce EVs – in other words, the transportation activities that arise across their supply chains. Given that transportation activities give rise to such a high proportion of overall carbon emissions – a quarter in the case of the EU as noted above - it would be expected that they contribute a significant proportion of the carbon emissions arising when manufacturing an EV. Yet, this research has found that when examining the literature on carbon emissions arising from making EVs, this source of carbon emissions is scarcely mentioned (or is considered to be negligible).

This research examines this apparent omission from the literature on carbon emissions arising in the manufacture of EVs and sets out to provide quantifiable figures as to the scale of these emissions in EV manufacture, thereby addressing this gap in the literature. This will allow for more accurate whole life cycle assessments of carbon emissions arising from EVs, which in turn allows vehicle manufacturers to focus their efforts to reduce carbon appropriately, and for governments to refine legislation in this area as appropriate. It will also qualify the expected environmental benefits of EVs compared to ICE vehicles.

Moreover, the impact of EVs - *compared to ICE vehicles* - on the supply chain transportation emissions has also not been evaluated in the research literature and this research will - for the first time[1] - provide a clear comparison between the transportation emissions arising from EV supply chains compared to ICE vehicles. Thus this research presents the magnitude of transportation carbon emissions in supply chains in the automotive industry – considered to be the world's largest single manufacturing sector (Orsato and Wells, 2007).

1.1. Background

Before discussing the research aims and objectives, a number of concepts and foundational principles require introduction and are outlined next.

1.1.1. Global transportation carbon emissions

It is not only in Europe that transportation activities give rise to a quarter of total carbon emissions. This figure is echoed by the United Nations to be valid for global carbon emissions too – their estimate is that global transportation activities account for approx. 23% of total man-made carbon emissions (United Nations, 2021) with developed countries contributing a greater proportion at a typical 30% of their carbon emissions (with Europe being the notable case where transportation carbon emissions have actually reduced in the last 20 years (European Commission, 2023)). They note that transportation is the largest source of energy related emissions for almost half of the world's countries[2] and for other countries, transportation is the second largest source. Thus, opportunities to reduce transportation carbon emissions offer significant potential to reduce overall global carbon emissions, providing a compelling motivation for research in this specific area.

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[1] As will be demonstrated in the literature review chapter, various authors have documented transportation emissions from individual segments of supply chains. However, this investigation has found that to date, a study spanning supply chains from raw materials extraction all the way to manufacturing a vehicle has not been presented in the life cycle assessment literature published prior to July 2023.

[2] A figure of 45% is reported in by the UN (United Nations., 2021)

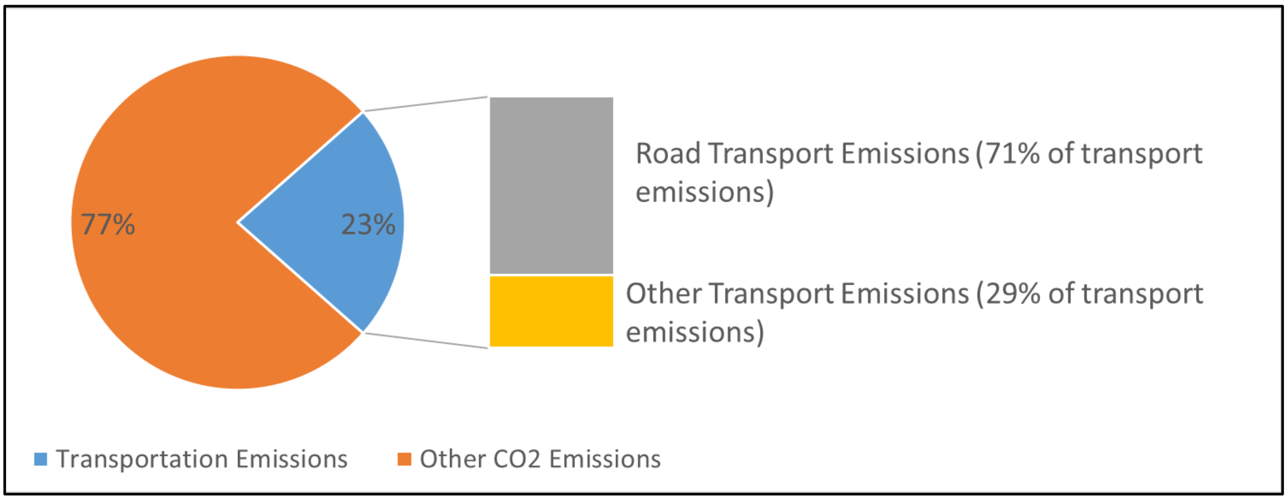

Figure 1-1: UN Figures for Transport CO_2 Emissions as a proportion of global emissions, showing proportion that road transportation contributes (Data source UNECE (2023))

As shown in Fig 1-1 above (and echoing the European environmental agency's figures on road transportation's contribution to these emissions) the UN estimates inland *road* transport as contributing over 71% of these transportation emissions (UNECE, 2023) - the source of these being internal combustion engines which predominantly propel road transportation, and which are discussed next.

1.1.2. Electric Vehicle CO_2 emissions compared to Internal Combustion Engine Vehicles'.

ICE vehicles use fossil fuels as their energy source, which when burned in an internal combustion engine release energy in the form of heat which is converted to motion - used to propel the vehicle's wheels. The byproducts of this combustion process are water vapour, CO_2 and minor traces of other gases which are ejected from the vehicle in gas form into the atmosphere (US Govt. Vehicle Technologies Office, 2013; Bieker, 2021). It is this CO_2 which is produced when using internal combustion engine vehicles - during the combustion process - that produces the carbon emissions associated with road transport.

In contrast, EVs use electric motors to propel their wheels which do not produce carbon emissions in this process. The electric energy driving these motors is stored in a large battery on board the vehicle which is charged periodically from an electricity supply. In this way, the emissions from an EV are zero at the point where it is being used. However, to evaluate overall carbon emissions one has to take into account the source of the electricity used to power the EV. Where the electricity supply is from a low carbon source of electricity (such as wind power) the associated carbon emissions are reduced by as much as 90%[3] (Pridemore *et al.*, 2018; US Govt. Vehicle Technologies Office, 2022).

In reality however, low carbon electricity sources such as wind power only represent a small proportion of the "energy mix" (a term referring to the proportion of different primary energy sources that generate the electricity supply in a given location, which may include fossil fuel generated power as well as nuclear, solar or hydroelectric sources for example (Planete Energies, 2023)). Notwithstanding this, using the average European energy mix for example, EVs have the potential to reduce carbon emissions by as much as 30% compared to ICE vehicles over the entire life cycle of the vehicle (Pridemore *et al.*, 2018).

Note however, that in countries where the energy mix generating electricity is made-up of a high proportion of fossil fuel based power generation (such as arises from coal or natural gas power stations), EVs may actually be worse for the environment in terms of carbon emissions then ICE vehicles over their life span (Kawamoto *et al.*, 2019). In such a case, this occurs because in both types of vehicle, fossil fuels are burned to provide the energy for propulsion - but in the case of EVs, electric transmission losses between the power station and the vehicle charging point mean that EVs actually give rise to more carbon emissions to perform the same transportation function. Thus, the energy mix[4] supplying an EV is central to its effectiveness in reducing carbon emissions (Del Pero, Delogu and Pierini, 2018; Jing *et al.*, 2020).

1.1.3. A systems perspective

As the paragraphs above demonstrate, the benefits of EVs depend to a large extent on the parameters with which they are viewed and the context in which they are used. For example, when viewed at the point at which they are used, EVs have zero carbon emissions. However, if the scope of analysis includes the generation of the electricity used to propel them, they may actually produce more carbon emissions then an equivalent ICE vehicle if the electricity is generated by a coal-fired power station (Kawamoto *et al.*, 2019). Thus, in order to confirm the potential benefit of EVs, all contributing factors need to be taken into account and viewed from a "systems perspective" (Pridemore *et al.*, 2018).

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[3] even with a low carbon source of electricity such as wind power some carbon emissions do arise which are associated with creating and maintaining the infrastructure required to generate this power.

[4] the "energy mix" refers to the proportion of electricity generated by different electric generation methods which can include coal fired power stations, nuclear power stations, wind power, solar power etc. This combination of electricity sources impacts the carbon emissions associated with electricity usage in a country.

This "systems perspective" has its roots in a wider school of thought known as "systems theory" - which originated in the early 1900's - which advocates that for an issue or problem to be adequately addressed, it needs to be viewed from and overall and holistic perspective (Ackoff, 1994; Ramage and Shipp, 2009) and that viewing an issue or problem locally and applying a local solution may not actually produce the overall improvements anticipated (Meadows and Wright, 2008). An example of this could be an EV being used to reduce carbon emissions when propelling it by electricity generated by a coal-fired power station (Kawamoto *et al.*, 2019).

Thus, in order to evaluate the overall CO_2 emissions associated with of EVs, a "systems" perspective will be used in this research - the foundation and justification of which is discussed in detail in Chapter 2 of this document. Similarly, when comparing EVs and ICE vehicles, a "systems" perspective will be taken.

1.1.4. Life Cycle Analysis introduced.

Thus, when evaluating carbon emissions, the method used should span the entirety of the product's contribution to carbon emissions[5]. Although not overtly acknowledging the principles developed by systems theorists, during the late 1960s and early 1970s an approach was developed to evaluate the overall environmental impact of products from a "cradle to grave" perspective which was specifically based on an overall "systems analysis" of the product "life cycle" as it has now become known (note that the term "life cycle analysis" only became prevalent in the decades that followed (Guinée *et al.*, 2011)).

A life cycle analysis endeavours to avoid exactly the localised view described in section 1.1.3. above (applied to EVs in that case). Early life cycle assessments typically compared the overall environmental life cycle impacts of consumer products - a noted early study compared fluorescent light bulbs with traditional incandescent light bulbs: while fluorescent light bulbs consume less electricity and last longer than incandescent light bulbs, they require more material to produce and contain heavy metals. Thus to evaluate if they actually were of environmental benefit across their lifetime, an analysis was performed which spanned the entire product life taking into account the environmental impact at every stage of the product's life, from raw materials to final disposal, known as a "cradle to grave" analysis (Guinée *et al.*, 2011).

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[5] In this section, the Life Cycle Analysis approach was found to fit this requirement. However, other methods which could be used were also found in the literature, for example "material flow analysis" as well as "product energy analysis" (Finnveden and Moberg, 2005; Ness *et al.*, 2007). These concepts are noted in Chapter 3.3 and discussed more fully in Appendix G

In due course the methods and approaches of life cycle analysis were standardised, and in 1994 the International Standards Organisation (or "ISO") became involved and formally developed standard methods and procedures of life cycle "assessment" (a term used interchangeably with life cycle "analysis" – both abbreviated as "LCA"), documented in ISO 14040 and ISO 14044 (Guinée *et al.*, 2011) (which will be discussed in greater detail in chapter 3.6. of this document).

While a "cradle to grave" span is the ideal scope for a lifecycle analysis, there may be instances where uncertainty of the data used or limited information make a study of this scope unfeasible. Thus, it may be desirable to study a portion of a product's life cycle and so other terms to describe the span of a life cycle assessment are also common. For example, a "cradle to gate" study will span environmental impact from raw materials extraction up to and including the factory where a product is made (Klöpffer and Grahl, 2014). This span of life cycle assessment is useful when evaluating the environmental impact of creating a product, but where the usage and disposal of the product are not known or unfeasible to accurately evaluate (for example if a product is used in an unknown mix of different countries where the usage and disposal practices differ). Other life cycle analyses concern themselves with a "cradle to customer" scope, which spans from the raw materials extraction to the customer, including usage by the customer. However, recycling and disposal are not included in this analysis (Azapagic, 2004). This type of LCA is useful where the recycling and disposal conditions are not known – for example if a product is shipped to several different unspecified countries where recycling and disposal practices differ.

While this research will focus on carbon emissions, an LCA can focus on any environmental impact which may arise from a given product and some analyses may focus on multiple types of environmental impact. For example, life cycle analyses may evaluate water usage, toxic wastes, air pollution or any other type of environmental impact (Guinée *et al.*, 2011) including greenhouse gas emissions which is the focus of this analysis.

It is important to note that the exact contribution that the different phases of a life cycle will make to carbon emissions (in the case of this research) will vary from case to case, depending on the geographical and other parameters of any given LCA. As noted by Del Pero et al (2018), the results of lifecycle assessments for seemingly similar products (in this case, automobiles) can vary considerably and are influenced by geographical location, the source of the electric energy used across the life cycle, a product's typical use, as well as other assumptions made during a life cycle assessment. The results of any life cycle assessment therefore need to be considered within the context of where the life cycle assessment was conducted. Where comparisons are made between different lifecycle analyses – even of the same product - the different assumptions and the context of those lifecycle analyses need to be taken into account.

Having introduced the general topic of life cycle analysis, the discussion will now return to the focus of this study – namely carbon emissions of EVs compared to ICE vehicles. The topic of life cycle analysis in the automobile industry will be discussed again in greater depth in the literature review, Chapter 3. Further critical reflections on the Life Cycle Analysis approach are also included in Appendix G.

1.1.5. Transportation Emissions in Automotive Life Cycle Analyses

As will be noted in the literature review chapter, there has been extensive research and multiple life cycle analyses evaluating the environmental impact of automobiles across their life cycles, and it remains an area of increasing research.

However, upon examining the LCA research, it transpired that transportation emissions during the "cradle to gate" phases of a LCA tend not to be discussed[6] (this is also noted by Bobba et al (2020)). The reasons for this are explained below.

While it was found that some research claims that transportation emissions are included in their LCA, on closer scrutiny of the publications, no evidence, data or discussion was presented on this topic making it difficult to confirm that their evaluation of transportation carbon emissions is valid (for example Bhosale and Mustad (2023) Yan and Sun (2021) and Guo et al (2022). See section 3.7. for further examples and discussion). Most frequently though, transportation carbon emissions were found to be left out of LCAs for reasons such as:

- It is considered unfeasible to evaluate due to the difficulty and span of the task – for example Mares and Flannery (2022) state transportation energy is not accounted for in their studies "because of the enormous administrative difficulty of determining and verifying such usage".
- Transportation carbon emissions are considered to be insignificant

The reason for the above appears to be because in the historic case of ICE vehicles, the usage phase of the vehicle's life cycle dominates the carbon emissions created to the extent

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[6] See Section 3.7 and as shown in Fig 3.6

that lesser contributions to carbon emissions such as transportation become insignificant (as seen in the LCA by Maclean et al (1998) for example).

To illustrate this by example, consider the “cradle to customer” study by Jing et al (2020) comparing EVs and ICE (or “ICE”) vehicles in the USA which shows this clearly (Fig 1-2 below).

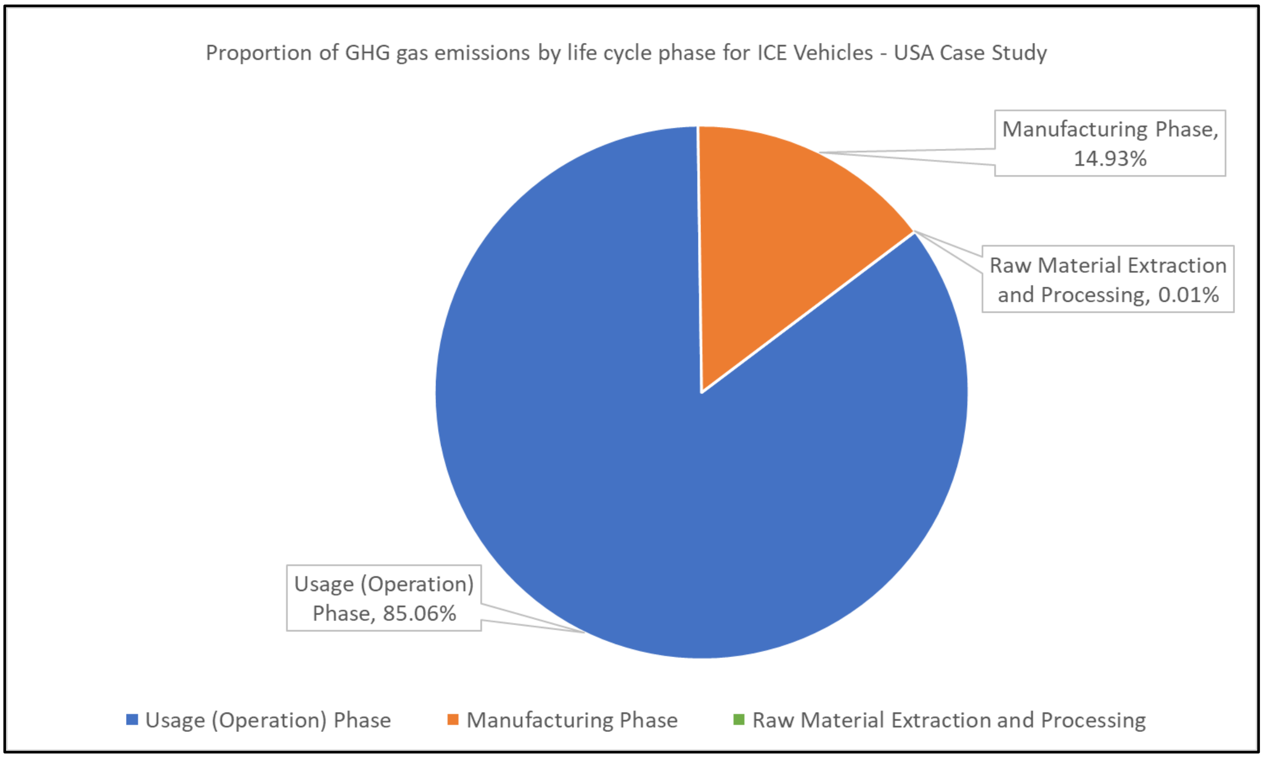

Figure 1-2: Proportion of GHG gas emissions by life cycle phase for ICE Vehicles - USA Case Study (source Jing et al (2020)).

As can be seen in Fig 1-2, compared to the emissions arising from the usage phase of an ICE vehicle’s life cycle, other factors contributing to greenhouse gas emissions will appear to be comparatively small and may thus be considered negligible by some researchers. Note that (like many other researchers), Jing et al (2020) have not stated that they included “cradle to gate” carbon emissions arising from transportation in their figures.

However, in the case of an EV, the usage phase carbon emissions can be reduced drastically and therefore the remaining carbon emissions become more significant. Again, consider the results in the same study by Jing et al (2020), shown in Figure 1-3 below:

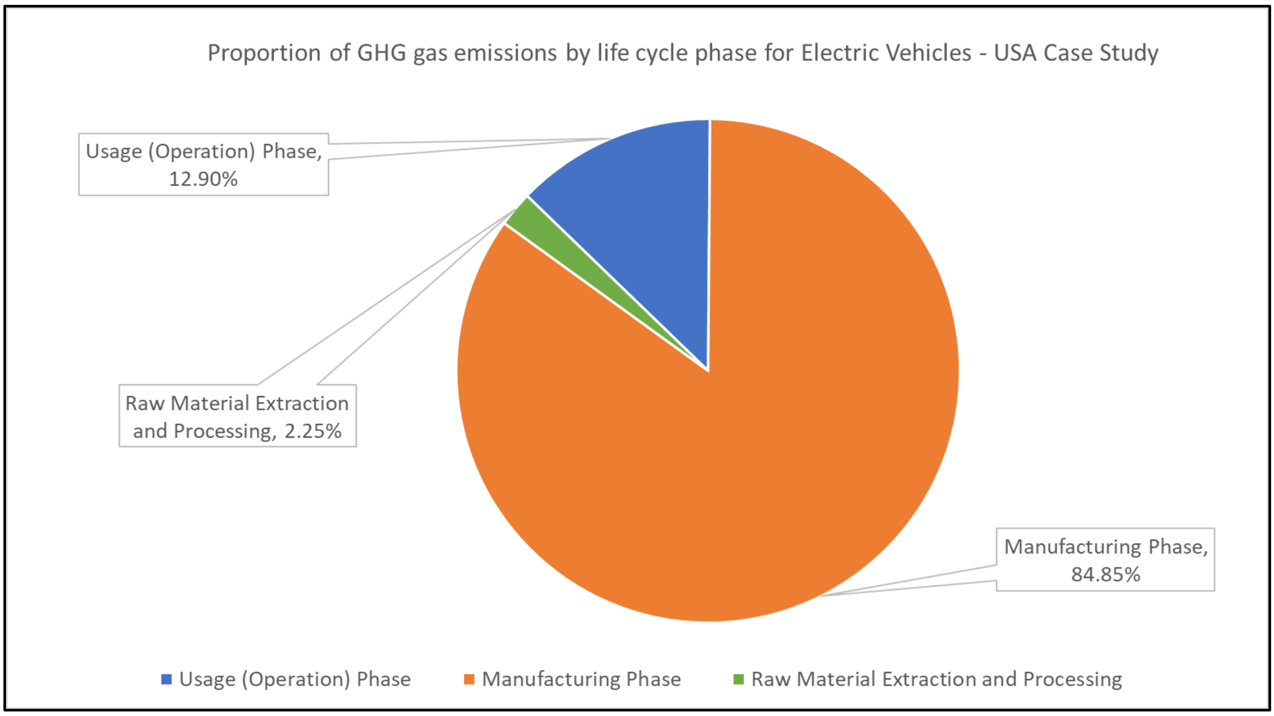

Figure 1-3: Proportion of GHG gas emissions by life cycle phase for EVs - USA Case Study (source Jing et al (2020)).

As can be seen in figure 1-3 above, because the usage phase has diminished considerably as a proportion of emissions, the remaining manufacturing and raw materials phases increase significantly as a proportion.

Thus, in the case of an ICE vehicle, it might be argued that as a proportion of overall emissions, the transportation emissions which occur within the other phases are comparatively low and may therefore be ignored (note that this argument was however not actually substantiated by any sort of calculations in any literature which asserted this).

However, in the case of EVs, the manufacturing and raw materials extraction phases of the lifecycle now comprise the majority of the emissions: it cannot therefore be assumed that the transportation emissions are so small that they can be ignored as may have been previously thought in the case of ICEs.

1.2. Research aims, objectives and research questions.

As introduced above, it has been found that transport emissions in cradle to gate automotive life cycle analyses tend to be largely ignored or dismissed as of insignificant magnitude, which seems to be in contradiction with the wider global figures that report that transport emissions account for approximately one quarter of global carbon emissions.

Thus, there is the risk that total carbon emissions across the life cycle of EVs have been under reported, and therefore the anticipated overall benefits of EVs (compared to ICE vehicles) in reducing carbon emissions may be less than thought.

To evaluate if this actually has occurred, this research will seek to calculate and compare the actual transportation carbon emissions in the raw materials and manufacturing phases of these two types of vehicle, and also thereby evaluate the validity of the current practice of omitting specific consideration of transportation emissions in life cycle analyses.

In order to achieve this, the research aims, objectives and questions that follow have been defined.

1.2.1. Research aim

To evaluate the impact of EVs' manufacturing supply chain "cradle to gate" CO_2 emissions arising in transportation, compared to traditional ICE vehicles. This is to be done via a systems theory based evaluation of automotive life cycle assessments to ensure that an equitable comparison is made.

1.2.2. Research questions

To fulfil the research aim stated above, two research questions have been formulated which will guide the path of this research, and the answers to which will constitute this research's contribution to knowledge and to practise.

The research questions are as follows:

> **Question 1.** What is the relative impact of EV supply chains compared to ICE vehicle supply chains on transportation emissions when calculating "cradle to gate" automotive lifecycle analyses?
>
> **Question 2.** What is the relative contribution of supply chain transportation activities compared overall "cradle to gate" CO_2 emissions in automotive life cycle assessments?

The reason for having a second research question is that it provides context to, and demonstrates the significance and impact of, the findings of the first question. Given the systems paradigm of this research, this additional context provided by the second research question is appropriate and is needed.

1.2.3. Research objectives

To achieve the research aim stated above, and answer the research questions, the following objectives are identified.

> **Objective 1.** To trace the “systems” concepts used in the life cycle analysis approach back to their origins in the systems theory literature, and outline systems thinking principles for this research.
>
> **Objective 2.** To critically evaluate the extent to which emissions due to transportation activities are accounted for in the life cycle assessment literature for both EV and ICE vehicles.
>
> **Objective 3.** In order to build a model to evaluate and calculate carbon emissions arising in transportation, identify the main factors which influence the transportation energy usage across the automotive supply chain from “cradle to gate”.
>
> **Objective 4.** Taking these factors into account, develop a model for calculating transportation CO_2 emissions in automotive supply chain logistics.
>
> **Objective 5.** Using the model built, evaluate EV supply chains’ CO_2 emissions arising in cradle to gate transportation activities, compared to traditional ICE.

1.3. Contributions to knowledge, practice and theory.

The answers to the two research questions above will provide the following contributions to knowledge and to practise:

1.3.1. Contribution to knowledge

As will be demonstrated in the literature review chapter, there is currently no presented research which specifically documents the transportation carbon emissions arising in “cradle to gate” activities in automotive manufacture. This research will calculate and present figures for these emissions for both EVs and for ICE vehicles. This in turn will allow the anticipated benefit of EVs to be critically evaluated. This is the focus of the first research question.

While the primary contribution to knowledge is to provide figures for the above emissions, these in turn have potential to provide two further contributions to knowledge as a consequence, which are:

- A *comparison* of CO_2 emissions for “cradle to gate” transportation emissions for electric and ICE vehicles
- A *comparison* of total life cycle emissions for these two types of vehicle, *including the cradle to gate transportation emissions.*

To date neither of the above comparisons have appeared in the literature.

1.3.2. Contribution to practice

As noted above, the emissions arising due to cradle to gate transportation activities tend to be omitted, ignored or considered to be negligible in the automotive life cycle assessment practice.

This research will confirm or challenge the validity of this practice, based on the figures calculated. The second research question provides the numerical results to do so.

In order to address the above research questions, a unique transportation carbon emissions model will need to be developed – because existing models are unable to simulate the scope undertaken in this research[7]. The development of this new model forms an innovation in modelling and a contribution to practise.

The model will be of benefit to practitioners, consultants and academics who undertake life cycle analyses both in automotive and other manufacturing contexts.

1.3.3. Contribution to theory

In the course of this research, a theoretical basis – grounded in Systems Theory - for evaluating transportation carbon emissions in supply chains has been developed and documented[8]. This “systems theory” based approach ensures that the overall (global) impact of transportation emissions is evaluated, and seeks to avoid the risk of evaluating a localised portion of the supply chain, thereby risking incorrect conclusions and decision

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[7] This is discussed in section 4.2.

[8] In sections 2.3 and 2.4

making – as discussed in section 2.1.. This paradigm is also applied and noted in the literature review, section 3.1..

As above, this theoretical foundation – underpinned by systems theory - will benefit practitioners, consultants, and academics conducting life cycle analyses in the automotive industry and as well as other manufacturing sectors (including manufacture for retail and consumer supply chains where the assumptions in that context are comparable to this boundaries stated for this research, as outlined in section 2.4.).

1.4. Description of research approach

As will be discussed in the methodology chapter, a case study approach has been taken to address the research questions. As noted above, the automotive LCA literature is virtually silent on transportation emissions and no usable data or discussion is available from the existing literature.

Even If however, some usable data had been available on ICE vehicles or EVs, unless the data (or results) on both types of vehicle arise from the same life cycle assessment study, they cannot be meaningfully compared as the assumptions and context underlying any two lifecycle analyses would almost certainly be different (as discussed above).

Therefore, for meaningful results to be presented and compared, the cradle to gate transportation emissions for both an EV and an ICE vehicle need to be calculated using the same assumptions and context in each case with only the actual physical components of the vehicle differing where this occurs.

Thus, this research will model and calculate the transportation supply chain emissions of two equivalent EV and ICE vehicles, using all the same underlying assumptions for the supply chains but noting the different component composition between the two vehicles.

Since no model or calculation tool previously existed for doing this, the author has developed and created a computational model for doing so. The data from the selected case study was then entered into the model, and the results presented and compared.

1.5. Triangulation of the literature, research questions and findings.

Goodman and Johnson (2020) identify the practice of “triangulation” as a credible strategy which can be used to confirm the rigour of research, and as argued by Creswell and Miller (2000), can reenforce the findings of a research study by providing supporting convergence from multiple sources. In other words, if aspects of a study are consistent with other similar studies, they are thereby supported. Conversely, if aspects of a study differ significantly from other studies it potentially signals the need for greater scrutiny and justification of these.

Throughout this research, its data, analysis and results have been compared and tested against published research and best practice to confirm its credibility and the subsections below signpost the reader as to where this is found in this document.

1.5.1. Triangulation to the literature

Hussein (2009) identifies several different types of triangulation, which provide useful categories when triangulating this research to the literature. Firstly, in regard to “Data Triangulation” the data used for this research is from the GREET database (published by the Argonne national laboratory) is widely regarded in the LCA literature to be one of the most credible data sets available for the materials composition of automobiles, and correspondingly widely used in the life cycle analysis literature (Wang, 2022). This is discussed in Section 4.4. in more depth.

The “Theoretical Triangulation” of this research is grounded in the Systems Theory approach – introduced above in section 1.1.3. and which is discussed in detail in Chapter 2 and thus not repeated here. The “Data Analysis Triangulation” is seen in that the formula used when calculating the carbon emissions is widely used in the literature as well as by the UK Department for transport (Leonardi *et al.* 2010; A. McKinnon *et al.*, 2015) and thus confirmed as a credible basis for comparing carbon emissions – discussed in depth in Section 4.3..

Lastly in respect to “Methodological triangulation”, three different modelling methods – namely discreet event simulation, system dynamics and proxy modelling - were initially used to calculate the carbon emissions on a test case and all gave the same results when the same data was entered – thereby triangulating and confirming the chosen method of analysis – as discussed in section 4.2. Moreover, the results were triangulated to commercial calculation tools’ results for the same test case and similar results obtained as documented in Section 4.7..

Lastly with respect to gaps in the literature, section 3.7. carefully analyses the relevant current publications on LCA’s using criteria underpinned by Systems Theory as discussed in section 3.1.

1.5.2. Triangulation of the research questions

The research questions can be triangulated to two areas of the literature. Firstly, as discussed in Section 3.6. the ISO standards specifically identify transportation as a source of emissions and thereby provide a basis for the first research question's validity and relevance. Secondly the "Systems Theory" paradigm of this research – discussed in chapter 2 – provides the need for context to the results of the analysis which arise for the first research question, and thereby providing the basis for the second research question.

1.5.3 Triangulation of the findings

The second research question provides the triangulation of the findings. In isolation, the results of the first research question can be taken out of context, and potentially lead to conclusions which may not be credible. The second research question however required that the results of the analysis be taken in the context of overall carbon emissions – this giving them credibility and perspective – as discussed in Section 7.2.. Lastly when comparing the results of the analysis with other comparable studies in the literature (for example to Kasai (1999), Xiong et al (2019), Kawamoto et al (2019)) they are of a similar magnitude although it is in this research that for the first time the transportation emissions of EV and ICE vehicles are compared, thereby confirming the novelty of the work.

1.5.4. Summary

The above sections highlight individually, the triangulation in the literature, research questions and the findings of this research. When taken together however, they provide a logic and rationale for this research. The chapters that follow will show how - beginning with Systems Theory as a paradigm for this research, the ISO standards which describe the LCA approach identify LCA's as a compatible method for assessing carbon emissions from a systems theory point of view. The ISO standards will in turn document the need for transportation carbon emissions to be include in LCA's. However, when the LCA literature is scrutinised, it emerges that transportation carbon emissions are largely omitted, which in turn identifies a gap in the existing research which the research questions will address. Finally, the results of the modelling - undertaken in order to answer the research questions – fill the gap in the literature identified.

1.6. Dissertation Structure.

Having introduced the topic and rationale for this research, this subsection will provide an overview of the rest of the document.

Having introduced the case for taking a systems theory approach to this research, Chapter 2 provides an in-depth discussion concerning systems theory and the systems theory based principles which guide the route taken in this research.

In Chapter 3, the literature review evaluates the existing automotive life cycle assessment literature and robustly demonstrates the gap in the existing literature which this research contributes to. This chapter also introduces the ISO standards which guide lifecycle assessment practise, which also in turn informs the approach taken in this research. Lastly, the literature review chapter explores the wider literature which focuses on carbon emissions in logistics and transportation - which again informs this research and in particular provides a theoretical foundation for the modelling undertaken in this study.

The methodology discussion which follows is divided into two sections, each comprising a separate chapter. Chapter 4 discusses - in general terms - the approach taken the modelling performed in the automotive context and presents the model built for the purposes of this research. Having done this, the Chapter 5 specifically focuses on the case study chosen to model in order to answer the research questions.

Chapter 6 presents the final results which the modelling has calculated. Note however that the calculations themselves span several pages and thus are included in the appendices for reference if needed.

The discussion chapter which follows in Chapter 7 is structured according to the research questions, stating each in turn and demonstrating how the results of the modelling have provided answers for these research questions – in line with the contribution to knowledge that this research has achieved. Having done this, this chapter revisits the issues raised in this introduction regarding the anticipated benefits of EVs and - based on the results of the modelling - provides answers to these questions as well as discussing related insights which the results provide.

Chapter 8, the conclusion chapter, discusses in detail the contributions to knowledge and practice achieved by this research. It also discusses limitations of the research conducted, many of which form the basis for potential future work. Finally, the chapter concludes by revisiting the research objectives, the research questions and the research aim confirming that in each case they have been addressed.

The above structure is shown diagrammatically below in Fig 1-4 below.

Chapter 1. INTRODUCTION	Introduces the research and its rationale
Chapter 2. SYSTEMS THEORY: A BASIS FOR CRITICAL EVALUATION OF CARBON EMISSIONS AND AN UNDERPINNING CONCEPT OF LIFE CYCLE ANALYSIS	Provides the underpinning systems theory foundations of this research
Chapter 3. LITERATURE REVIEW	Evaluates existing research and provides further foundation for this research
Chapter 4. METHODOLOGY PART 1 – THE TRANSPORTATION CARBON EMISSIONS MODEL	Describes the approach to modelling taken and the model built for evaluating transportation carbon emissions
Chapter 5. METHODOLOGY PART 2 – CHOICE OF CASE STUDY AND SCOPE OF MODELLING	Applies the model developed to the case study chosen for this research
Chapter 6. RESULTS	Presents the summarised results of the modelling undertaken
Chapter 7. DISCUSSION	Discusses the results and thereby addresses the research questions
Chapter 8. CONCLUSION	Confirms the outcomes of the research and reflects on further opportunities.

Figure 1-4. Dissertation Structure

1.7. Chapter Conclusion

This chapter has introduced the scope of the research conducted and made an argument for pursuing it. It has identified an omission in the current practice of calculating carbon emissions in automotive life cycle assessments which, if significant, has the potential to lessen the anticipated positive environmental impact of EVs.

This chapter has also documented the research aims, objectives and questions arising in this area and identified the potential contribution to knowledge and practice which this research provides.

Having outlined the case study approach which this research adopts, and having outlined the document’s structure, the next chapters will now turn to in depth discussions of the concepts presented above, starting with Systems Theory.

2. SYSTEMS THEORY: A BASIS FOR CRITICAL EVALUATION OF CARBON EMISSIONS AND AN UNDERPINNING CONCEPT OF LIFE CYCLE ANALYSIS

“Systems thinking is a discipline for seeing wholes”

(Senge, 1997)

As noted in the Chapter1, apparent paradoxes present themselves when approaching this research area. For example, some sources suggest that carbon emissions caused by transportation are a major contribution to global CO_2 emissions. Yet, studies dealing with CO_2 emissions associated with manufacturing vehicles appear to omit the contribution arising from transportation activities or consider them to be negligible. Another example would be that EVs appear not to produce CO_2 emissions, as they do not burn fossil fuels and are thus considered to reduce carbon emissions. Yet - when viewed from a different perspective - EV manufacturing produces significantly more CO_2 than traditional ICE vehicle production.

Systems theory provides principles which can be used when evaluating these apparently conflicting positions and which can also be used to critically evaluate the literature which documents them.

It should be mentioned however that there is no clear consensus, or universally agreed upon definition for “systems theory” (sometimes called “systems thinking”) (Forrester, 1994; Adams and Hester, 2014). In fact, one of its key proponents, Jay Forrester (1994) lamented that for many people “systems thinking implies a rather general and superficial awareness of systems”. Thus, one of the purposes of this section will be to build a set of principles which encapsulate a “systems theory” approach to guide this research.

A second purpose of this chapter is to note the language and concepts of systems theory which are heavily used in the LCA literature and ISO documentation (and which typically do not acknowledge its roots and associations[9]).

The key ideas of systems theory (as applied to this research) are documented in the sections that follow – citing the key originators of these concepts. In particular, authors have

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[9] demonstrated in the literature review, Chapter 3

been chosen because their contributions impact the “operations management” and “operations research” applications of systems thinking - areas more applicable to this research[10]. They are listed in table 2.1:

Table 2.1: Key contributors to systems theory used in this research

Author(s)	Key contribution	Section
Von Bertalanffy*	Founder of Systems Theory.	2.1, Appendix A
Vickers*	Extending Von Bertalanffy’s concepts to societal, business and social contexts.	2.1, Appendix A
Ackoff*	Systems thinking as a problem solving tool	2.1, Appendix A
Forrester*, Meadows, Sterman	Counter intuitive systems and unintended consequences	2.2, Appendix A

*For the sake of completion, a historical overview elaborating on the contribution of the above authors and their context - is presented in Appendix A.

2.1. Systems Theory Introduced

The commonly cited principle of systems theory, that “the whole is greater than the sum of the parts” - attributed to Aristotle (Von Bertalanffy, 1972) - is hardly a new concept. Indeed, “Systems theory” has been described by one of its founders as a “contemporary expression of perennial problems which have been recognised for centuries” (Von Bertalanffy, 1972). However, this commonly cited principle – while useful - is merely a starting point in understanding what is considered to be “systems theory”.

“Systems theory” originated in the early 1900’s, developed by Ludwig von Bertalanffy who is acknowledged as the founder and creator of the discipline (Ramage and Shipp, 2009). Rejecting the “reductionist” view popular at the time[11], he proposed the discipline of “General Systems Theory”. He argued – in contrast to a “reductionist” approach – that the correct way to understand the behaviour of an “element” (a part of a “system”) was in the context of

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[10] Systems theory has been applied to a considerable spectrum of other fields too - highlighted for example by Adams & Hester (2014).

[11] The “reductionist” approach argued that the way to understand phenomena is to break them down into ever smaller constituent parts and to “analyse them in terms of the properties of those isolated individual components” (Lewis 2015)

a “system”. (Von Bertalanffy 1968). In its simplest form, he defined a system “as a set of elements standing in inter relations” whereby the relations between the elements influenced how they behave. This was formulated in the context of the physical and scientific realms – being a biologist himself. In addition to this, he formulated the language of “systems”, “boundaries” and “systems theory” whose usage endure to the current day, beyond the their original scientific context (Ramage and Shipp, 2009; Adams and Hester, 2014).

Evolving and applying Von Bertalanffy’s systems theory to social, business and societal systems, Sir Geoffrey Vickers evolved the use of systems theory to an “epistemological” tool – a philosophical tool for understanding what we see in the world. This became known as “soft” systems[12] thinking as opposed to “hard” systems which focus on scientific reality and naturally occurring systems in biology and the sciences as originally developed by Von Bertalanffy (Vickers, 1983; Brocklesby, 2007; Ramage and Shipp, 2009).

Building on the above, Russell Ackoff was instrumental in promoting and spreading the use of systems thinking as an approach not just for *understanding*, but also for *solving* societal and business problems. Ackoff refined the definition of a system, stating that “A system is more than the sum of its parts; it is an indivisible whole. It loses its essential properties when it is taken apart. The elements of a system may themselves be systems, and every system may be part of a larger system” (Ackoff, 1973).

Ackoff especially warned against the tendency to focus on (or attempt to improve on) individual elements of a system in the hope that it would necessarily improve the overall system performance[13] (Allio, 2003). Instead, Ackoff argued, the *overall system* needs to be optimised rather than attempting to optimise individual (local) elements (Ackoff, 1999) - and thereby avoid optimising a solution for a *local* element which may actually worsen the *overall* situation[14]. Ulrich (2005) similarly later argued that improvement “is an eminently systemic concept, for unless it is defined with reference to the *entire* relevant system, *sub-optimisation will occur*” (italics added).

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[12] This “soft” view of systems theory would prove influential on later systems thinkers, notably Peter Checkland, who would directly reference and quote Vickers’ work when distinguishing between “hard” and “soft” systems in his work on soft systems methodologies (Checkland, 1985).

[13] He used the analogy that taking the very best parts and components from the world’s top automobiles and trying to put them together to form a “best” automobile would clearly not work very well – not least because they would not fit

[14] Goldratt et el (1992) echoed this concept (in is best-selling book “The Goal”) by arguing that a series of local optimums does not constitute the optimum for the system.

2.2. Current discussions in systems theory.

The fundamental “first principles” described above – some of which arose almost a century ago - are for the most part still used and supported by more recent literature on systems theory (for example Flood (2010)). When systems theory is mentioned in current literature, the context is usually in the area of application rather than its fundamentals – indeed it has been applied to a myriad of disciplines as diverse as medical, agricultural, political and environmental sciences (these examples are a small selection of those listed in Adams et al.. (2014)).

This section will focus on current systems thinking discussions in two areas specifically relevant to the present study, namely “system boundaries” and “unintended consequences”.

2.2.1 System Boundaries.

The concept of a system “boundary” was defined by Von Bertalanffy as noted above. Building on this concept, Ulrich (2010) pointed out that the choice of where the boundary lies is of great importance and can affect one’s understanding of the system being studied. He warned that to avoid misunderstanding, a clear reference system must be defined, and that the boundaries selected are important in defining the system being considered. He developed a technique known as “Critical Systems Heuristics” to “support boundary critique – a systematic effort of handling boundary judgements critically” (Ulrich, 2005).

The choice of boundary is of importance for two reasons:

In the first instance a careful choice of boundary is important to avoid optimising “subsystems” at the expense of the whole – which has the potential to create a “counterintuitive” system (a concept which is discussed in the next section).

In the second instance, the choice of boundary may affect how the problem is dealt with: widening boundaries may provide options not previously available. Therefore, part of trying to solve a problem may be to consider the implications of moving the boundaries of the system being considered and the associated impact on possible solutions. This however may introduce considerations not part of the initial system.

To illustrate this concept in the context of this research, consider the example of an automotive designer selecting a battery system to power an EV. It may be that the designer has been given specific limits to which batteries are available for the design – perhaps due to agreements made by the procurement department. Their mandate may be to provide the materials and components needed to sustain vehicle production, and to do so in a reliable, cost effective way (Van Weele, 2018). This "boundary" would then define which raw materials are needed by the supply chains, leaving no flexibility to avoid materials with especially environmentally damaging supply chains. If however the "boundary" of which batteries are available is lifted, it would leave the designer free to consider products with supply chains that are less environmentally damaging.

Applied to the current research specifically, the application of boundaries is twofold. As will be discussed in Section 2.4, the boundary of the environmental impact will be defined as the "cradle to gate" emissions of the automotive supply chain logistics activities. However, there is a further set of boundaries which impact the system being modelled, which includes the potential influences on the *causes* of the "problem" – the impact of this will be seen in the discussion, Chapter 7.

2.2.2. "Counterintuitive behaviour" and "Unintended consequences".

Forrester (1971) (who was based at the Massachusetts Institute of Technology (MIT) and acknowledged to be one of the leaders of systems modelling) coined the phrase "counterintuitive behaviour of systems" to describe the frequently occurring phenomenon where taking a specific course of action to solve a problem often makes the problem worse[15] (Sterman, 2000; Ramage and Shipp, 2009).

Forrester's successors at MIT, John Sterman and Donella Meadows, have continued this theme in their work do develop what Sterman (2000) calls "the Law of unintended consequences" and which Meadows (2008) called "System Traps" . In both these cases the point is that systems can produce results other than those expected or desired. They draw a distinction between a system's overall "purpose" or "function" and the "sub purposes" of its sub systems. Meadows (2008) points out that a sub-system might be the source of the unintended consequences as it strives to satisfy its own individual sub-purpose which may not be immediately aligned with the overall purpose of the system.

The application to this research is immediate: EVs have been embraced as a potential way to reduce CO_2 emissions - yet in some contexts EVs may actually be worse for the environment over the course of their lifetime (Kawamoto *et al.*, 2019).

Another example might be the "low emissions" zones in large cities such as London in the UK. This policy – which promotes the use of electric vehicles, hybrid electric vehicles and

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[15] An example used to illustrate this by Sterman (2000) is that in spite of the widespread utilisation of labour saving household appliances, Americans currently have less leisure time than 50 years ago.

low emissions ICE vehicles - has resulted in reduced pollution and improved air quality in the London area (Ma, Graham and Stettler, 2021). Thus – if the system boundary under consideration is the London area – it might be considered to be a success. However, if the system boundary is extended to include the geographic areas where the electric power is generated as well as the locations which manufacture the electric vehicles, the conclusion is not necessarily the same. Indeed, some sources report significant increase in pollution and CO_2 emissions in locations such as China arising from manufacturing electric vehicle batteries (MIT Climate Portal, 2022).

These examples can be thought of as “system traps” or showing “unintended consequences” where the very actions taken to reduce CO_2 emissions (by embracing EVs) actually may have the overall effect of increasing CO_2 emissions globally.

2.3. Summary of systems theory for this research

Drawing on the preceding overview, the following defining principles of systems theory (as applied to this research) can be distilled:

1. A system can be defined “as a set of elements standing in inter relation”. These “elements” can be systems themselves.

2. The boundary of the system under discussion is a device used by the observer to demarcate the system under consideration.

3. The overall system needs to be considered when addressing an issue or endeavouring to optimise a situation - not the individual elements of the system themselves.

4. “Systems” can be thought of as actual representation (or model) of the “system” under scrutiny, or as an etymological device for understanding it.

5. Optimising individual elements of a system does not necessarily result in an overall improvement in the system’s performance. In some cases it may worsen overall system performance.

These principles underpin the approach taken in this research both as a criteria of how the literature has been selected and reviewed as well as the way that the modelling has been undertaken and the parameters selected.

2.4. Defining the boundaries for this research.

While the focus of this research was introduced in the research “aims and objectives”, having now discussed the concepts of boundaries and systems it is appropriate to clearly state the “system boundaries” - in other words – the scope of this research.

The following boundaries for this research are therefore defined:

- **Global CO_2 emissions:** where emissions are evaluated, this research will endeavour to evaluate the impact on global CO_2 emissions as opposed to local optimums.

- **Transportation CO_2 Emissions:** as will be demonstrated in the literature review section, the gap in the literature is specifically in the area of transportation emissions in the supply chain. Thus, the research will focus on this area to contribute to knowledge in this area.

- **Passenger vehicles:** The focus of this research will be in the area of passenger electric and ICE vehicles. However, it is anticipated that the findings of this research so are transferable to other types of vehicle.

- **Cradle to gate emissions:** To fully evaluate global CO_2 emissions would require a “cradle to grave” evaluation. However, taking a span of this breath introduces considerable uncertainty in the robustness of any results.

  The reason is that after a vehicle leaves the automotive plant there is limited certainty as to it's geographical destination for the usage stage. Since this research focuses on transportation emissions in the supply chain, variance between the distance a finished vehicle is transported to customers from the automotive plant introduces significant uncertainty on the transportation emissions incurred.

  If data is available for where customers are geographically located, a “cradle to customer” or “cradle to grave” evaluation becomes feasible as the distances to customers from the automotive plant would be known, and therefore transportation emissions can be calculated. Knowing the destination countries would also enable estimation of recycling practices.

However, without this data a “cradle to customer” or “cradle to grave” evaluation would introduce significant opportunity for uncertainty. Thus, this research will focus on a “cradle to gate” evaluation because there is reliable data which allows for consistent assumptions on transportation activities and distances from the location of raw materials extraction all the way to the factory gate.

- **Entire vehicles, not just parts or subsystems.** In order to evaluate and compare the carbon emissions arising from transportation in ICE vehicles compared to EVs, the manufacture of the whole vehicle needs to be evaluated. As will be noted in Chapter 3, some studies endeavour to optimise transport emissions associated with individual subsystems. However, the impact on other subsystems is not considered and risks actually worsening transportation emissions overall.

  For example, it may be tempting to only evaluate the vehicle powertrain in each case (the parts of a car which propel the vehicle). It may be argued that much of the rest of the vehicle is the same in both cases and thus can be ignored. However - as will be demonstrated and discussed later in this document - this assumption is not correct because the powertrain (including the batteries) is significantly heavier in the case of EVs. This therefore requires that the vehicle body is significantly heavier in the case of an EV to support this extra weight. As a result, more steel (or aluminium) is needed to produce these vehicles and so if a supply chain was optimised just for the powertrain it may well worsen supply chain emissions for steel (or aluminium) and thereby not have the anticipated benefits. The results of the modelling conducted in this research demonstrate and discuss this topic further with appropriate citations in Chapters 6 and 7.

- **Entire vehicles – not just individual materials** As will be noted in the literature review below, many life cycle assessments focus on the benefits of a new or novel material and there is again the temptation to embrace these innovations and optimise supply chains around one material. Once more however this may well result in worsening supply chains for other materials and unless the entire vehicle his modelled one cannot confirm an actual benefit for individual materials.

2.5 Chapter Conclusion

This chapter has discussed and formulated a systems thinking paradigm for this research. It began by noting the need for a way to evaluate apparently conflicting factors which confront research of this nature and argued that a systems theory paradigm provided a credible way to evaluate carbon emissions arising from transportation. A historic overview provided the theoretical foundation of this paradigm from which several principles were distilled to guide this research. From this, the boundaries and remit of this research have been refined.

This foundation now established, it will be used in Chapter 3 to evaluate the relevant body of knowledge in the literature review.

3. LITERATURE REVIEW

This literature review provides the theoretical foundation and principles for this research and also demonstrates the “gap” in the literature - and thereby the novelty of the work undertaken.

It is made up of several sections. In section 3.1. the way that a systems theory paradigm is applied to the literature review is discussed. Three case study papers dealing with carbon emissions will be appraised in section 3.2. using a systems theory paradigm to demonstrate it’s application. Section 3.3. argues that the “life cycle assessment” literature is based on a systems thinking approach and thus becomes the focus of the literature review for the current study.

Section 3.4. discusses the literature review methodology used and presents an initial summary of the literature search conducted.

The qualitative analysis of this literature search is divided into three sections:

- Subsection 3.5. provides the historical foundation for LCA methods and provides the principles, definitions and terminology used across this research.
- Subsection 3.6. summarises the ISO standards which are frequently used as a framework for performing LCA’s.
- Subsection 3.7. evaluates recent LCA’s which have been performed since the year 2000 applicable to this research.

Section3.8. then summarises the gap identified in the literature. The chapter concludes with section 3.9. which introduces the foundational concepts from the wider logistics literature which underpin the model created for this research and which also underpin the methodology section.

The literature review spans publications which have been written in or translated into English.

3.1. Systems Thinking: a basis for selecting and appraising automotive supply chain emissions literature.

The previous chapter concluded by listing principles of systems theory which would be applied to this study. This subsection will outline the way in which these principles have been applied to the literature review, both in terms of how literature has been selected for inclusion as well as noting how a systems thinking paradigm has been used in critically evaluating the literature considered.

When selecting which literature to include, the key consideration from a systems perspective is to evaluate if the work being considered spans or includes a whole system. As will be demonstrated below, works which deal only with specific components or limited sections of a supply chain, risk presenting findings based on local optimums. As noted previously, these local optimums may in fact be worse for the overall system - which in this research concerns global CO_2 emissions. Thus, the system boundary being considered in any work being evaluated needs to be sufficiently wide and able to evaluate overall impact to global CO_2 emissions. Works whose system boundaries risk a local optimum are not suitable for inclusion in a systems wide evaluation - as is the case in this research - and are thus not included in this literature review.

Note that many publications considered do not explicitly articulate what their system boundaries are - however this does not mean that system boundaries have not been applied. Instead, this suggests that the authors who produced such a study operated within certain system boundaries (perhaps without being aware that they were doing so). In other words, the existence of a system boundary is not dependent on an author clearly stating what the system boundary is.

The second way that the systems principles are applied is to evaluate if the *relevant* elements of the system have been included in the work being evaluated.

3.2. Case studies demonstrating a systems thinking appraisal of CO_2 emissions in automotive transportation.

The purpose of this subsection is to briefly demonstrate examples where recent journal papers - taken from across the automotive or logistics literature - have been found unsuitable for inclusion in this literature review as they have not taken a systems thinking approach to their work. It is therefore not intended to be a comprehensive discussion on the topic.

This subsection focuses on three recent journal papers (from 2010 onwards), which pertain to automotive supply chains, and which consider logistics carbon emissions, and which might be – at first glance – potentially relevant to this research.

3.2.1 Example 1 - Nieuwenhuis et al. (2012)

Nieuwenhuis et al. (2012) discuss the “CO_2 Impact” of a (presumably hypothetical) “strategic decision” which Hyundai and Kia Motor corporations might take when deciding where to manufacture their vehicles in relation to their customers in the USA and Europe. They focus specifically on the logistics of *completed* vehicles, and provide a comprehensive and informative study of the CO_2 per car produced in this area. Of specific interest is that they contrast the transport of finished vehicles from Korea to the USA & Europe, with that of local production, and find that shipping completed vehicles from one continent to another produces considerably higher emissions, providing an analysis of the emissions across the different modes of transport.

While it is difficult to fault the analysis of this paper within the boundaries set (i.e. the transportation of finished vehicles) it provides a good example of where the “boundaries” selected affect the assessment of the carbon footprint. While it is difficult to dispute that transporting a vehicle produced locally will generate fewer carbon emissions than if it were transported across continents, when considered from a “systems thinking” point of view, the paper does not take into account the “upstream” transportation carbon emissions which occur before the factories. They seem to assume that the “cradle to gate” carbon emissions will be the same regardless of the factory location which cannot automatically be assumed, as will be demonstrated in the modelling section of this research.

Thus, because the boundaries of these results are only relevant to a small part of the supply chain, it does not qualify for inclusion in a systems paradigm analysis of CO_2 emissions literature.

3.2.2 Example 2 - Tognetti et al (2015)

Tognetti et al (2015) explore the tension between economic and environmental priorities in supply chains. Their simulations suggest that automakers could reduce CO_2 emissions associated with manufacturing activities by up to 30% with minimal financial impact, by changing their energy supply mix. However, to achieve a similar reduction in *transportation* emissions would require significant cost increases. Their suggested opportunity to reduce transportation emissions lies in sourcing from more localised suppliers (suggesting a potential 50% reduction in inbound logistics emissions albeit with an associated cost increase). However, a close scrutinization of their model indicates that they have only considered “factory to factory” emissions, which implies that the original raw materials’ supply chain logistics have not been included.

This anticipated 50% opportunity for reducing inbound logistics emissions is a good example of a "local optimisation" which may have minimal or no impact once the raw materials' supply chains (potentially from other continents) have been considered. Their limited span of study has excluded this paper from the literature considered.

3.2.3 Example 3 - Sim and Sim (2017)

Sim and Sim (2017) performed a comprehensive audit on harmful emissions arising from transportation activities of completed vehicles in the South Korean Automotive industry noting the South Korean Government's concern with these emissions. Their focus is on the transportation of completed vehicles – in particular to the United States, noting the significant impact of these activities. As the "boundary" of their study does not include raw materials or transportation across the supply chain, their conclusion implies that the "cradle to gate" transportation emissions would be identical for a vehicle manufactured in the United States which is not necessarily the case.

Again, in this case because the boundaries of the system being studies are localised, it means a local optimum. Indeed in the case of EVs, there is a concentration of EV battery manufacture local to South Korea (Bunting *et al.*, 2023) (discussed in detail in the methodology and results chapters). Thus, moving vehicle production to the USA in the hope of reducing the transportation CO_2 emissions may not have the desired overall effect if key battery components are potentially shipped from South Korea or its neighbours to the USA.

Thus, the limited scope of the above study means that its results and conclusions may not be relevant to this research.

3.3 – The systems thinking paradigm found in the Life Cycle Assessment approach.

During the course of the initial survey of the literature, the body of literature concerned with Life Cycle Assessment *was* found to take a systems based approach when viewing CO_2 emissions and other environmental impacts. However, it was noted that other methods – including "material flow analysis"" as well as "product energy analysis" can also be applied when evaluating the environmental impact of a product (Finnveden and Moberg, 2005; Ness *et al.*, 2007). However the life cycle assessment approach was found to be closest to a systems theory paradigm – pls see Appendix G where these are discussed in more detail and where this is demonstrated.

Thus, the focus of the literature reviewed for this research moved to the life cycle assessment area. Not only is it grounded in a systems approach but many of its authors specifically use the systems principles discussed in section 2. Two introductory examples illustrate this (note that a more comprehensive uncovering of this follows in the literature review below).

First, consider Lehman et al (2018): in this paper they endeavour to develop and present policies which would enable a credit-based system for potential use in governmental legislation for CO_2 emissions. They specifically discuss the risk of focusing only on improving CO_2 emissions in the usage phase of an automobile's life cycle. Indeed, they specifically use the words "unintended consequences" when discussing CO_2 emissions which may arise in other phases of a vehicle's life cycle such as the production or end of life phases and thus argue that a "life cycle thinking" approach is required (as occurs in the LCA approach). They argue that policies which promote local optimization of CO_2 emissions risk the "unintended consequences" of increasing overall carbon emissions. Although the paper does not use the specific term of "boundaries" it is clearly argued that any effective CO_2 emission credit system cannot limit its "scope" (i.e. boundaries) to tail pipe emissions: instead its scope needs to include upstream processes such as vehicle manufacturing and the energy mix supporting these activities for example. Without specifically acknowledging it, the authors of this paper have used the systems paradigm and language (developed decades before) to approach this problem.

A second example can be found in Rodger et al.'s (2018) approach to reducing CO_2 emissions in automated car body manufacturing. They place their approach within a lifecycle assessment context arguing that this is required in order to achieve an overall improvement. They specifically caution against the risk of local optimums (they use the term "sub optimization" to describe this) and argue that "life cycle thinking" approach is needed - and specifically note the importance of appropriate boundaries when determining an overall strategy. Again, without specifically referencing or acknowledging its origins, these authors are using a systems thinking approach.

In summary, the systems thinking approach taken by the life cycle assessment methodology - which will be discussed and demonstrated in more detail below- makes it an appropriate match for this research and thus becomes the focus of this research's literature review.

3.4. The literature review strategy used.

In this section, the strategy of the literature review is discussed and a numerical summary of the literature searches conducted is presented.

3.4.1 An overview of potential approaches to literature review.

Since its publication, Snyder (2019) has been widely used as a guide for literature review in the supply chain management literature (for example by Yang et al (2021), Novoszel et al (2022) and Shaharudin et al (2022)) and was chosen as a guide appropriate for this research too.

In her overview and guidelines of types of literature review applicable to business research, she documents several approaches to conducting a literature review, providing a number of strategies which include the following summarised options[16]:

- A "systematic" literature review. Considered by some to be the "gold standard" among review methods, this involves a rigid process and method for identifying and including material relevant to the research being conducted – using a defined search method and search terms and database selection criteria. She argues that the merits of this approach include its repeatability as well as minimising bias on the part of researchers. However, she notes the challenge in assessing the quality and applicability of the results which arise from a purely systematic literature review.
- A "qualitative systematic" review. In this variation of a systematic literature review, a rigid systematic process is used to collect works for inclusion but then a qualitative analysis is performed on these results to evaluate them.
- A "semi systematic" review. In this case inclusion for selection his based on a thematic emphasis, often considering how a topic has evolved over time and across different research fields. Such a review seeks to identify and precis potentially applicable works about a topic from across several different disciplines noting how each discipline views, understands or applies a concept and then comparing them to provide an overall synthesis. This is often used when identifying common themes or theoretical perspectives and issues across different research disciplines.

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[16] these options precis the strategies discussed by Snyder (2019) and thus the citation of Snyder (2019) is not repeated for every paragraph.

- Integrative review. Similar to a semi systematic review this review has a different purpose: namely to develop new conceptual frameworks or models (as apposed to synthesising or comparing existing ones) – she notes that these are rarely used.

Of the options above, none specifically describe the approach taken for this research - rather the approach taken is underpinned by the principles of the second option: using a defined set of criteria for selecting relevant papers but will then following with a qualitative analysis and commentary on the papers selected.

3.4.2. Search terms and initial results.

Using the SCOPUS database[17], the following keywords were selected to identify works for consideration in the literature review. Permutations of the keywords below were also used to ensure potential matches were included. The search was within article title, abstract and keywords.

The keywords used were:

- Automotive Life Cycle assessment
- Automotive Life Cycle Analysis
- Automotive Life Cycle Inventory

The above terms were also applied with permutations of:

- Emissions
- Carbon
- CO_2
- EV
- Powertrain

This was applied for publications up to and including April 2024.

After removing duplications which arose through the various searches, as well as restricting the eligible material to peer reviewed journals and books, the number of items to be examined numbered 1514.

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[17] Scopus was chosen for this purpose as it is widely considered to be a leading tool for this purpose – especially in scientific journals, which is relevant to this area of studies, for example as discussed by Baas et al (2020).

These however covered a wide variety of topics, many of which were outside the “cradle to gate” scope of this research, for example:

- end of life recycling
- the impact of various vehicle design improvements
- the environmental impact of different vehicle fuel or - in the case of EVs - electricity mix options
- the potential environmental impact of optimising transportation or logistics operations

Having narrowed the papers down to those within the scope of the current study, the publications to be reviewed numbered 307.

These were divided into two broad categories:

- publications presenting actual models and their results as well as frameworks or philosophies (i.e. articulating a specific approach to LCA) – which numbered 206
- publications dealing with the LCA of specific individual material(s) in a vehicle - which numbered 101 items.

The above split in LCA literature highlights that almost one third of the LCA literature reviewed dealt with the life cycles (or the impact thereon) of specific individual materials. While these may provide useful data in the modelling activities of this research, they do not in most cases help to understand the overall CO_2 emissions of a *whole* vehicle’s life cycle. Therefore – except where noted - they have not been included in the scope of this literature review although where used in the modelling undertaken in this research, they are referenced there.

As shown in Figure 3-1. below, there has been an increase in the literature in recent years dealing with this subject area:

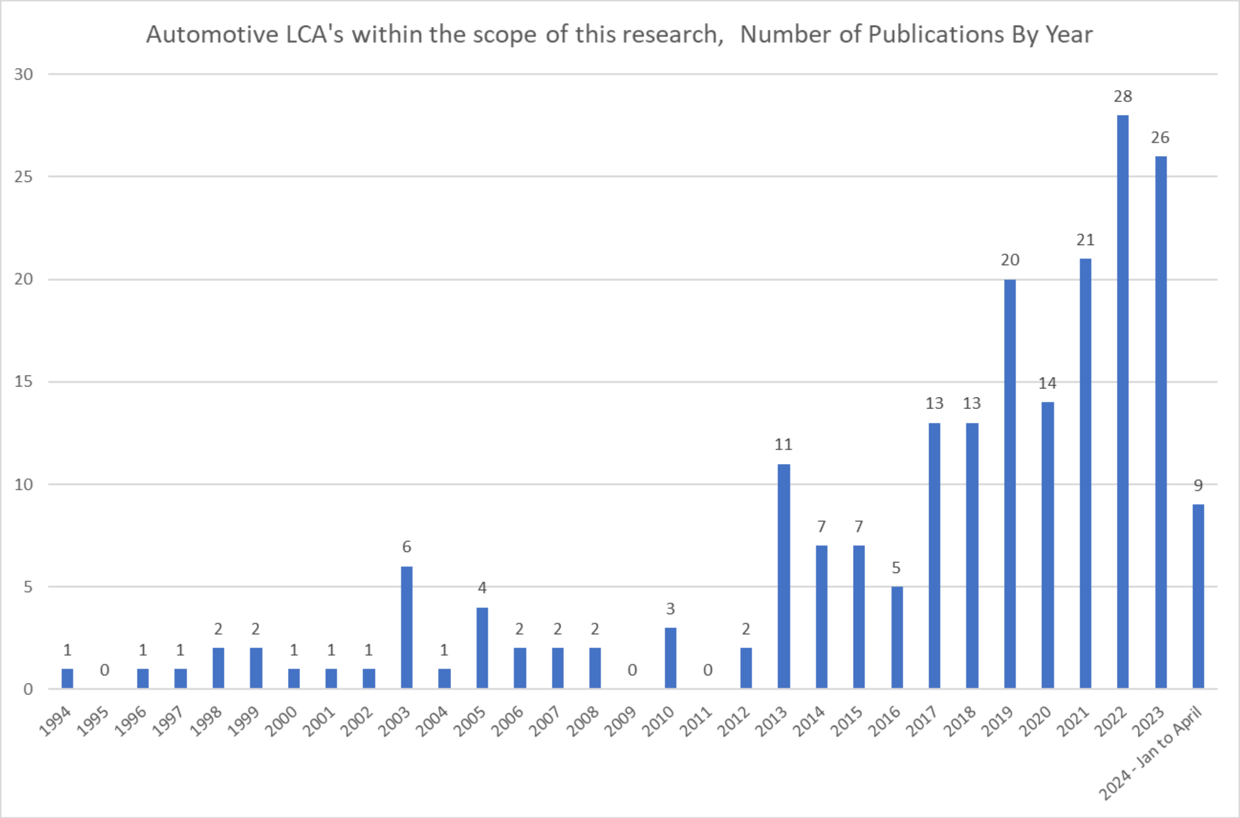

Figure 3-1: Automotive published life cycle assessments by year.

The sections that follow are a review of this material. Where publications which may incorporate relevant LCA discussion which have already been mentioned in preceding sections, they are not repeated here.

3.5. Life Cycle Assessment Principles, Definitions and Terminology

This section provides the historical foundation for LCA methods and provides the definitions and terminology used across this research. It also makes comment on where systems theory principles have been used.

This section does not therefore specifically seek to document the actual numerical results found in the publications (except where noted due to their direct relevance to this research), but rather seeks to identify LCA principles that emerge in the early LCA works. Numerical results which were used as data in the methodology section of this document are cited therein.

Throughout this section, comment is made on the extent to which transportation emissions have been considered thereby highlighting the potential novelty of this research in the light of the existing literature.

3.5.1. 1994-2000 – Introductory papers in the LCA literature

The first mentions of life cycle assessment in the automotive context appear in the years preceding and including 2000. The early LCA publications often took great care to outline the LCA philosophy and methodology, perhaps because at the time this was a new approach. Thus, they provide a useful starting point for analysing LCA methodologies as used today.

Young and Vanderburg (1994) are the first authors found who discussed LCA in an automotive context. They do however start their paper by noting that environmental life cycle analysis has been used as a tool for assessing environmental impact of products for the "last several years" prior to their publication in in 1994[18]. In this paper they provide an introduction for LCA which is noted here to provide parameters and *de facto* definitions used in this research[19].

They define LCA as "as a tool to systematically measure and assess any environmental impact attributable to a product and its supporting product system".

Immediately, this aligns the LCA approach with the systems approach taken in this research. Whether deliberately or otherwise[20], the paper uses the language of systems theory including discussing the "system boundary", defining the product "system", "system inputs and outputs" and even "negative feedback[21]" within the analysis.

They argue that over the lifetime of a product spanning from its manufacture to its disposal, inputs such as raw materials and energy are required. Consequently, various outputs arise as a result of this (including wastes and air emissions). Figure 3-2. below documents this.

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[18] Their references and citations on the topic (including from other disciplines) in this paper date back to 1991.

[19] Subsequent publications tend to use the same or similar definitions and parameters and will therefore not be repeated as each publication is noted.

[20] The authors do not make specific reference to systems theory in their publication.

[21] See the discussion on Jay Forrester in the appendices for more information on feedback in systems.

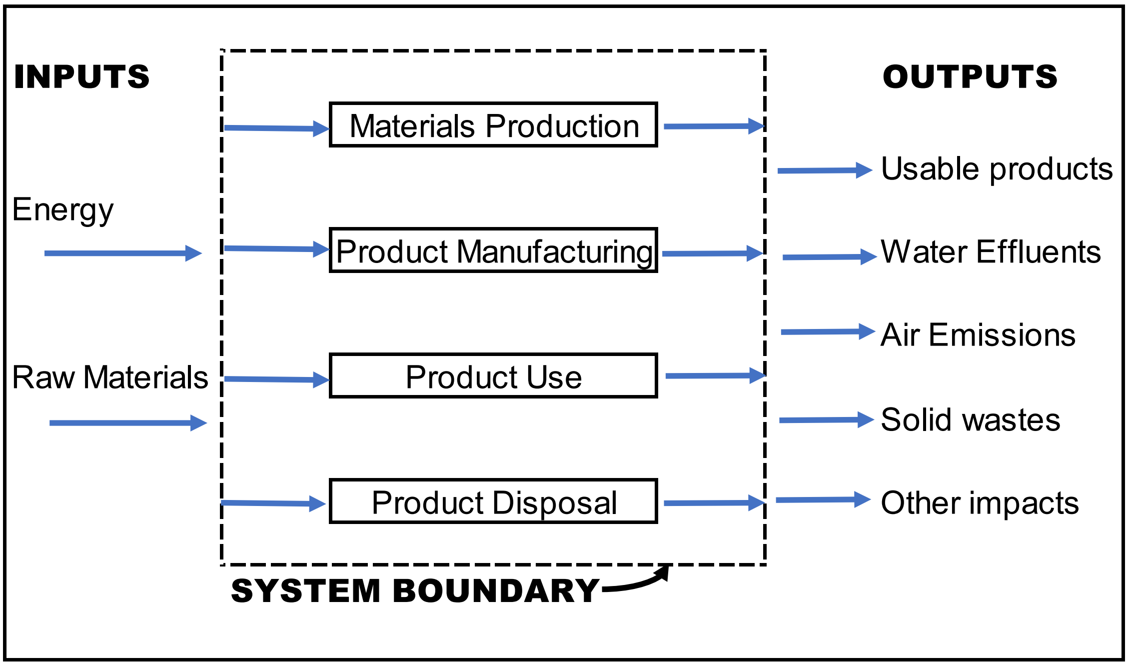

Figure 3-2: Inputs and outputs associated with a product's life cycle (reproduced from Young & Vanderberg (1994)).

They discuss three types of environmental impact which may arise:

- Gross energy requirement (GER)
- Global warming potential (GWP)
- Solid waste burden (SWB)

While they acknowledge raw materials depletion, it is not a topic of analysis in their paper (which is a concern of subsequent authors (Fleisher and Schmidt (1997) for example)).

With regards to their method and approach, they argue that the LCA of a product can be determined by performing a LCA on each of a component (or vehicle's) constituent materials. This is of direct relevance to this research insofar that the modelling performed in the methodology section specifically uses this approach as it traces the supply chains of the different materials which make up a vehicle.

They also argue that the choice of material at the design stage will have a significant influence on the LCA of a product. To illustrate this point, they then perform a LCA of a hypothetic automotive structural part, and compare the results based on if it was constructed of steel, aluminium or HDPE, noting in turn the relative impact on GER, GWP and SWB of each material. Thus, they imply that there may be an impact on transportation emissions due to material selection. They do make mention that the transportation involved in producing the product will contribute to the energy used, but they do not discuss or quantify the proportion of energy used attributable to transportation and the reader assumes that this is somehow included in the overall energy figures quoted. As they do not specifically deal with the transportation emissions directly, useful data or figures relevant to this research was not found in this paper.

Following a similar approach of evaluating individual material choices, Harsch et al.. (1996) perform a LCA on an automotive fender, this time comparing the impact of using steel sheet; aluminium sheet; an injection-moulded polymer blend (of polypropylene oxide and nylon), and a glass-fibre reinforced polyester resin.

They describe a four step process for performing a LCA which can be summarised as follows:

- Defining the scope of the analysis, and the “boundary conditions” (again using system theory language)
- An “Inventory” stage where all the environmental impacts are calculated and noted
- An assessment of the impact of the factors noted in the “inventory” stage
- An analysis of any weaknesses in the preceding steps.

They then discuss the relative advantages and disadvantages of each material for differing environmental impacts.

They acknowledge that transportation is a factor contributing to the environmental impact, and indicate that it has been included in the calculations, but do not disclose or discuss the relative magnitude of its contribution.

Stressing the importance of considering environmental impact during the design phase, Fleisher and Schmidt (1997) document a collaboration between six German Research institutions whereby they developed a tool and methodology known as “euroMAT”. Their paper demonstrates this in the context of a car body component – analysing the relative impact of using a six different materials (steel, aluminium as well as two composites and two plastics). In this paper however they do not specifically mention whether transportation emissions are incorporated into their calculations.

Maclean and Lave (1998) perform a LCA in the American context using the case study of a 1990 Ford Taurus vehicle which has a fuel consumption of 21.8 mpg. In a similar conclusion to authors above, they conclude that the significant majority of the environmental impact of the vehicle (by means of energy usage) arises during the usage stage of the vehicle (see fig 3-3 below).

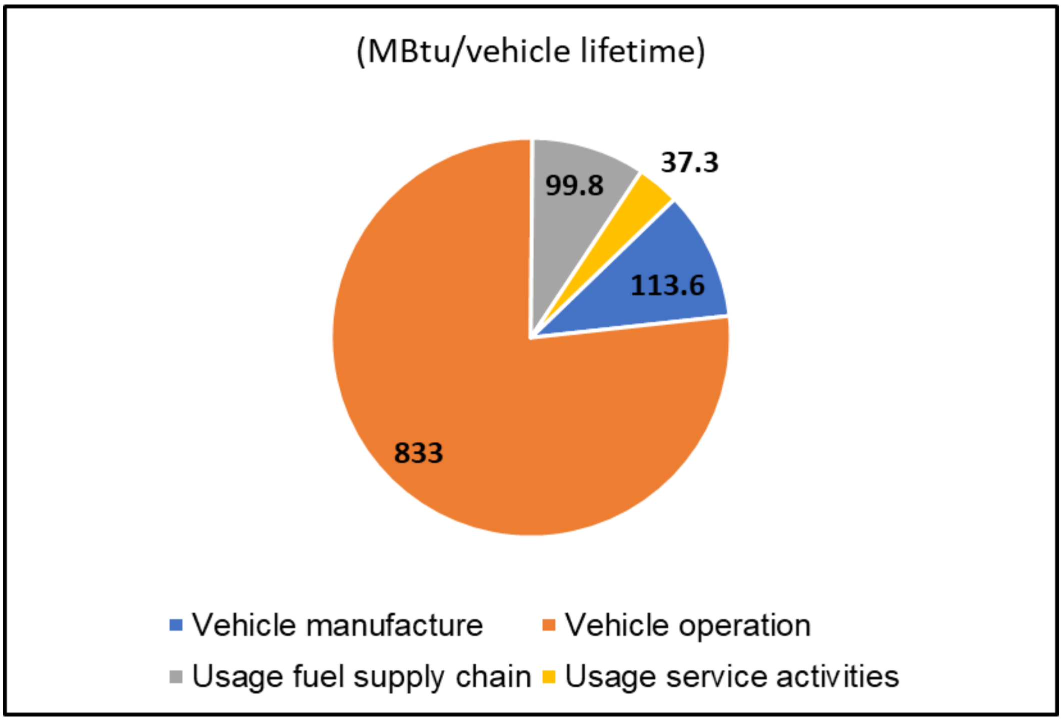

Figure 3-3: 1990 Ford Taurus - Manufacture and Use Stage Energy Consumption Estimates (Maclean and Lave, 1998).

While this deals with energy usage (rather than carbon emissions) it can be argued that the above closely represents carbon emissions: although they do not discuss the energy mix involved with the energy supply it is most likely – given the date of the study - that the majority of the energy usage was fossil fuels. Moreover, all of the vehicle operation emissions would be caused by burning petrol. They estimate that 83000 kg of CO_2 are produced from the vehicle's usage phase of 13.74 years covering 143000 miles (but do not suggest figures for other phases of the vehicle life cycle).

It is notable that they specifically assert that a "systems approach" is needed when considering environmental impact, noting the risk that an apparent local benefit (i.e. a local optimisation) may be perceived "from a change that simply transfers discharges elsewhere". In line with their finding that most of the environmental impact arises during the usage stage, their publication focusses the usage stage with brief consideration to the manufacture stage. As with other authors, they assert that energy of transportation is included in the manufacturing phase, but details of this are not given.

Kasai (1999) documents the awareness and evolution of LCA thinking and approaches in Japan. Published in English, this publication provides a valuable overview to the English reader of Japanese publications preceding it. It documents awareness and efforts dating as far back as 1981 [22] focussed on what would be termed LCA today. This awareness followed the "Oil crises" of the 1970's and endeavoured to reduce vehicle weight as a means to reduce fuel consumption during a vehicle's lifetime. He cites an increase in public concern with environmental protection[23] as a "strong" motivator for the development and activity of LCA evaluations in the 1990, citing a number of industrial evaluations performed by vehicle manufacturers as examples. He notes a difference between Japanese LCA studies at that time compared to those performed in other countries: Japanese LCAs tend to focus specifically on energy usage and CO_2 as these areas tend to have high quality data available. He indicates that Japanese studies tend to be "very cautious" when it comes to life cycle inventory (i.e. which deal with other types of environmental impact such as resource depletion, other types of pollution and impact on human health for example[24]) data and the consequent results.

Following the above overview, he summarises three case studies providing LCA calculations on a lorry propellor shaft, an "average passenger vehicle", a light "truck" and finally an Isuzu instrument cluster. Of specific interest is that he does provide energy usage summary documenting the relative contributions of different phases of the vehicle life cycle and notably includes transportation – shown in figure 3-4 below.

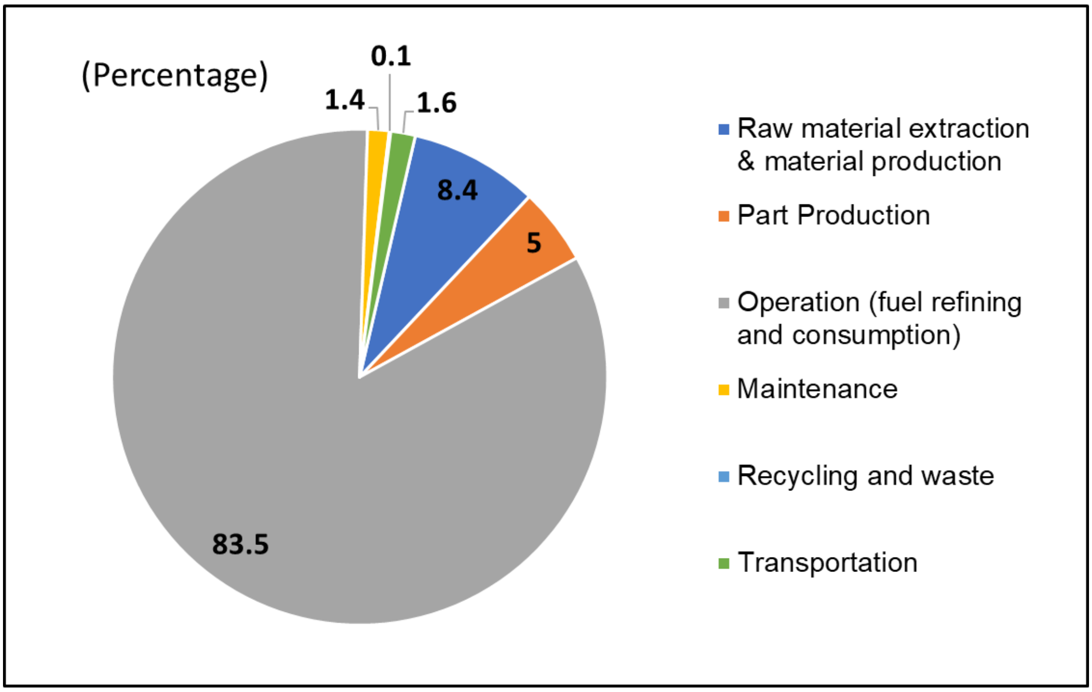

Figure 3-4: Relative energy usage across the life cycle of a light passenger vehicle (Kasai, 1999).

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[22] Kasai cites a "famous report" entitled "Energy Saving Effect lead by Introduction of Newly Developed Materials" published by "the Chemical Economy Research Institute" in 1981.
[23] Notably citing Donella Meadows (1972) "The Limits to growth"
[24] Please see the ISO standards below for information on life cycle inventory

However, he does not give absolute figures for this (only percentages) and does not discuss in any depth how it was calculated or the assumptions behind it. It is nonetheless significant to this research as it unusually provides a figure for transportation across the life cycle documented as being 1.6% of energy used in a vehicle's life cycle. It is the first specific figure provided for this in the literature surveyed.

In a follow up publication, Kasai (2000) notes the three types of LCA prevalent in Japan at that time. They are documented as:

- LCAs based precisely on the ISO 14040 standard (prevalent in industry wide or nationwide research)
- LCAs which don't adhere strictly to the ISO 14040 standard (typical of LCA's performed by individual businesses for their own internal purposes)
- An abbreviated or "streamlined" LCA used by a company as part of a specific project or incentive and focussed on a very specific or narrow set of criteria or outcomes.

Kasai's paper has two points of application to this research: firstly he specifically notes the ISO 14040 standard as a reference for LCA activities – the first specific mention of ISO standards in the literature surveyed. ISO standards become the benchmark for many LCA assessments to follow in the literature and will be discussed separately below in Section 3.6.. Secondly, Kasai again does make mention and gives figures for "all transportation" in his case studies (presenting again the figures from his previous paper). But as before, he does not elaborate on how it was calculated, or assumptions made.

The final publication noted in this section is by DeCicco and Thomas (1999). Written in the USA, (and in parallel to Kasai's publications at the same time) they propose a method for "green rating" automobiles in the light of increasing consumer awareness as to the environmental impact of vehicles, which would allow consumers to compare the environmental impact of different vehicles when considering a potential vehicle purchase. They too note the "streamlined" LCA mentioned by Kasai (2000) - describing an "often" used approach where not every aspect of the life cycle is included and where "expert judgement" is used to determine what is included in the LCA.

Focussing on air pollution impacts, they discuss and quantify three contributors to Greenhouse Gas emissions:

- "Tailpipe emissions" arising from fuel combustion during a vehicle's life cycle (accounting for an average[25] of 68% of GHG emissions). This is based on an average fuel consumption of 20.0 MPG.
- "Fuel cycle" emissions which arise from fuel exploration, extraction, refining and distribution - (accounting for an average of 21% of GHG emissions).[26]
- "Embodied" Emissions – arising from obtaining and producing materials as well as vehicle manufacture (accounting for an average of 11% of GHG emissions)

While they do not present overall figures in this publication, they do provide "per mile" CO_2 emissions for these categories based on an "average 1998 vehicle" which weighs 1674kg and covers 100000 miles allowing – for the first time in the literature reviewed – CO_2 emissions to be noted. From these numbers the figures in Figure 3-5. can be calculated:

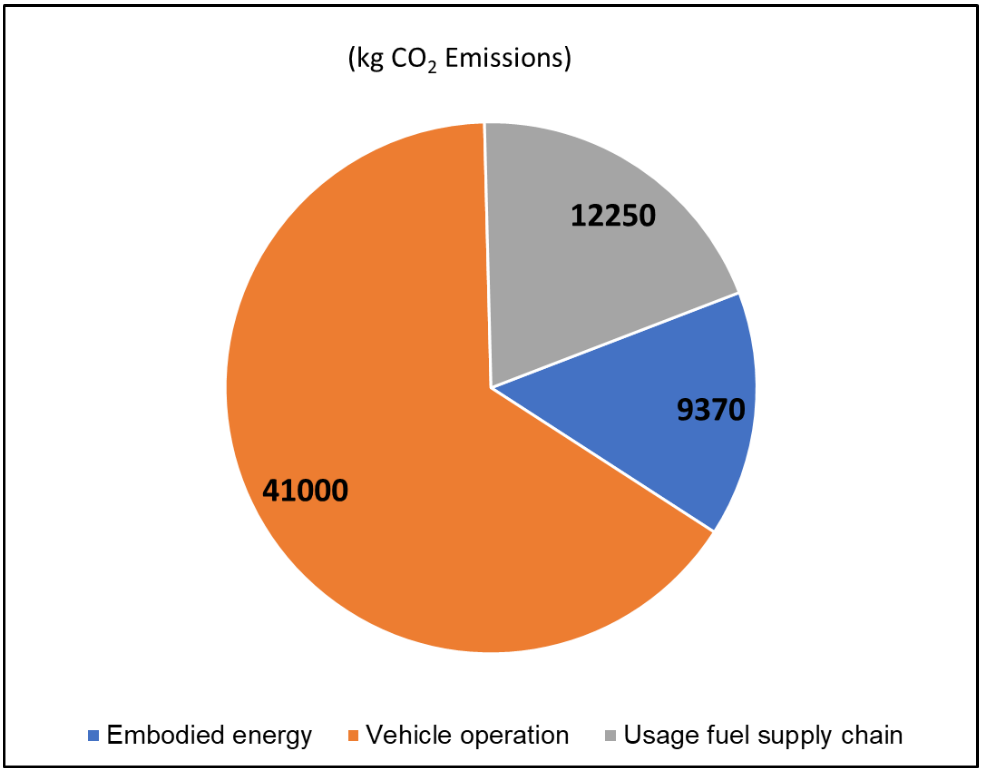

Figure 3-5: CO_2 Emissions across vehicle manufacture and usage stages (calculated from DeCicco and Thomas (1999)).

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[25] This average is based on their survey of vehicles in 1998 in the USA. The paper does provide further breakdown showing the different percentages by vehicle type.

[26] Note that this is an average across both petrol and diesel vehicles, where it appears that the majority of vehicles have petrol engines. They note that diesel in comparison has a Fuel cycle contribution of around 8%. A specific number is not given for petrol, but it is presumably near or just over the 20% average.

They do not make specific mention of whether transportation emissions are included in their “embodied” emissions.

Note that the figures above are for vehicles with ICEs. They note that in the case of EVs the embodied emissions are a much higher 21%. This increase is due to a higher absolute value for embodied energy (EVs requiring more energy to produce).

Significantly, they note an absence of “tailpipe emissions”[27] in EVs – a point central to the opportunity and importance of this research. As has been noted already, transportation emissions are either not discussed or are considered to be a very minor part of emissions, given the magnitude of the emissions that arise in the usage phase from fossil fuels being burned. However, if EVs are *without* tailpipe emissions, and if the electricity used is from low emissions sources, then the importance and proportion of the embodied emissions (that remain) becomes much greater if *operating* emissions have the potential to be eliminated. In which case, it may no longer be assumed that transportation emissions - which fall within the manufacturing phase – can be ignored when performing an EVs LCA.

3.6 A review of relevant ISO standards

As noted by Kasai (2000), the ISO14040 standard forms the basis of many LCAs. Therefore, before continuing with the literature review which includes several works which use this standard, it is useful to consider these ISO standards and note the extent to which they require the inclusion of transportation emissions when performing a LCA.

ISO 14040 was first published in 1997 (British Standards Institution, 1997). This edition provided the “Principles” and “Framework” for performing an LCA. It describes an LCA as “a technique for assessing the environmental aspects and potential impacts associated with a product” and describes three steps which are performed in order to do so:

“ - compiling an inventory of relevant inputs and outputs of a product system
- evaluating the potential environmental impacts associated with those inputs and outputs
- interpreting the results of the inventory analysis and impact assessment phases in relation

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[27] Notwithstanding this point, they do show a continued contribution due to the “fuel cycle” (i.e. emissions which arise to generate electricity to propel EVs). They specifically note that the absence of tailpipe emissions does not necessarily mean no emissions, but merely displaced emissions where the electricity used is generated by fossil fuels.

to the objectives of the study"
(Quoted directly from ISO 14040:1997 (British Standards Institution, 1997))

While these provide a useful basis for performing a LCA, they also do provide considerable scope for what is included and excluded from a LCA. As is confirmed later in the standard, a LCA can be restricted to "relevant" inputs and outputs of a system, and the "objectives of the study" might determine if a specific factor (such as transport emissions for example) are included or not. Thus, relevant to this research, the 1997 version of this standard does not specifically require that transportation emissions are taken into account (indeed they are not mentioned in the document).

A supporting document to the above, ISO 14041:1998 (Britsh Standards Institution, 1998) provides specific guidelines as to what factors should be included within the "system boundary" when performing the first step (above) of "compiling an inventory of relevant inputs and outputs of a product system" (British Standards Institution, 1997). It recognises that when modelling a system, it may not be practical, possible or relevant to include every possible contributing factor. It also states that inputs which "will not significantly change the overall conclusions of the study" can be omitted. Thus, as relevant to this research, if it is deemed that transportation emissions are of minimal impact, then they can be omitted from a study, and the study would still remain compliant with ISO 14040:1998.

This standard does however state that "Any decisions to omit life cycle stages, processes or inputs / outputs shall be clearly stated and justified" (Britsh Standards Institution, 1998). Moreover, in this document, it repeatedly states that the impact of distribution or transportation *should* be taken into account when performing the first step of an LCA. Indeed, the document even provides a template for recording transportation data when performing an LCA[28]. ISO 14047:2003 (British Standards Institution, 2003) which provides examples and case studies of LCAs follows this practice, and where transportation impact is deemed negligible, the exclusion of that factor *is specifically stated*.

ISO 14040:2006 (which superseded ISO 14040:1998) and ISO14044:2006 (which superseded ISO 14041:1998) retain the key points taken above and again, specifically states that where an input does not materially impact the result it can be excluded (British Standards Institution, 2006) and that where inputs *are* excluded, it should specifically be mentioned and justified (Britsh Standards Institution, 2018). Of note however, is that in this later edition, transportation is now specifically noted in ISO14040 as an example of environmental impact which should be considered.

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[28] On page 13

Thus, in this research, it will be assumed that where an LCA claims to be ISO14040 complaint, that transportation emissions have been accounted for unless the study specifically states that transportation impact has not been included.

What is notable in both editions, is the use of systems theory language – the documents make frequent use of terms from systems theory and system dynamics[29], and refers to models of "product systems" with detailed discussions on points such as defining the system boundary, as well as input and output flows of materials and energy.

Having confirmed that accounting for transportation emissions is a requirement of the ISO standards, the literature review is resumed.

3.7 2000 – 2023: Applications, case studies and the gap in the literature.

Having established the basic definitions and parameters though these initial papers, the literature review will focus on papers which specifically discuss or quantify transportation impact.

It was found that only 33 of 199 papers published after 1999 and reviewed actually mentioned or discussed transportation impact – suggesting a significant potential gap in the literature. To emphasise the point, papers which include parts or subsystems of a vehicle are also noted, even though they fall outside the boundaries previously stated for this review.

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[29] Please see the appendix summarising the works of Jay Forrester for more information on system dynamics.

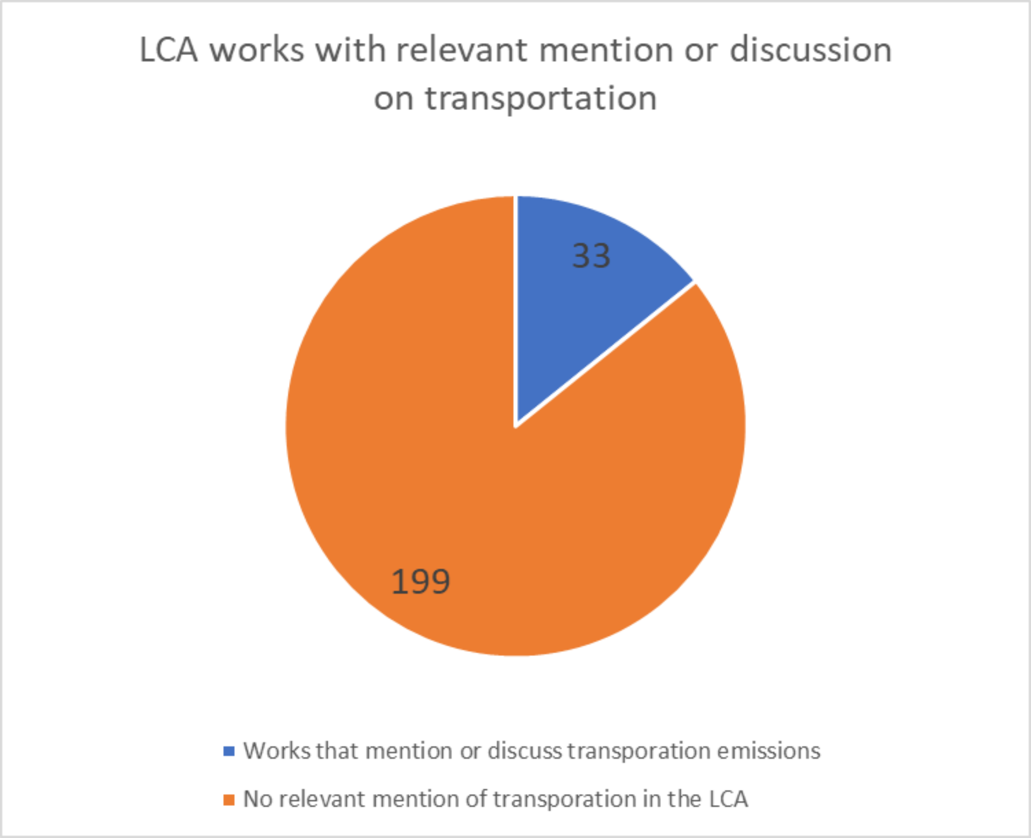

Figure 3-6: LCA works with relevant mention or discussion on transportation.

Works that do mention or discuss transportation emissions are reviewed below.

Using the ISO 14040 standard, Smith & Keoleian (2004) evaluated the economic value and environmental impact of re-manufactured engines compared to new engines. In accordance with the ISO standard, they did include transportation emission in their analysis. Existing data from a previous study[30] was used for to quantify transportation impact. While the purpose of the publication was to compare the impact of remanufactured engines compared to new engines, they found that the environmental burden due to transportation was similar in both cases. They assumed that all transportation was conducted by diesel truck. A figure of 600 miles' transportation was used, and they indicated that in both new and remanufactured engines, the transportation CO_2 emissions were less than 8% of the overall CO_2 emissions involved. Note that their study did not include the usage phase or disposal

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[30] The study cited was presented at a conference: Keoleian, G. A., G. Lewis, R. B. Coulon, V. J. Camobreco, and H. Teulon. 1998. LCI modelling challenges and solutions for a complex product system: A mid-sized automobile. Paper presented at Total Life-Cycle Conference, Graz, Austria, 1 to 3 December 1998. This study used the Database for Environmental Assessment and Management (DEAM). This was a life-cycle database created by Ecobilan, an LCA consulting firm (Smith and Keoleian, 2004).

of a typical LCA (assuming that these would be similar for new and remanufactured engines) – it dealt only with the environmental impact of providing the engines.

Subic et al. (2010) performed a comprehensive LCA on different BMW passenger seats based on the relevant ISO standards, and do state that transportation is included within their "system boundary" for their LCA. They document that transportation between automotive suppliers has been included but do not comment on whether transportation during the raw materials and steel manufacture phases has been accounted for. They cite the sources of their data as being various databases and supplier information, but do not document the contribution that transportation makes to their overall numbers.

Notter et al. (2010) perform a thorough LCA, comparing lifetime GHG emissions between an electric and ICE vehicle, using the Golf 4 as a case study. While they note that EV production is more energy intensive – especially in producing the batteries - they conclude that the key difference in lifetime CO_2 emissions arises in the usage stage, and the potential advantage which EVs may have in lower emissions depends on the type of electricity being used to power it. They calculate that based on the average electricity production mix at the time of publication (with a share of fossil fuels >50%) that EVs and ICE's produce similarly high emissions, except in the case of very fuel efficient ICE's[31] which may even produce lower emissions. This paper is notable in that they – unusually - do provide full transparency on their data used, and provide a comprehensive "supporting information" document which shows their calculations and data used. Notably, they do provide figures for transportation distances and assumptions for the *manufacturing* phase. However, transportation emissions for the supply chains are not dealt with separately to other sources of emissions, and thus it is not possible to determine the separated impact of the transportation activities. However the availability of some data regarding transportation distances informs assumptions made in the methodology section of this research.

Mayyas et al. (2012) – in their comprehensive literature review of automotive environmental impact – affirm that the literature supports the inclusion of transportation emissions when evaluating of automotive environmental impact. While they do provide representative figures on emissions caused by factors such as manufacture, use, and end of life disposal, they do not however attempt to quantify the relative impact of transportation and also do not

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[31] They indicate that the break even point is at 3.9 l/100km fuel consumption, and cite vehicles produced by VW and Ford which achieve this.

comment on the extent to which the literature specifically accounts for transportation emissions.

Arena et al. (2013) propose a “streamlined” LCA framework which treats transportation as a specific “lifecycle stage” affirming the need to account for it. However, they do not suggest a method or guidance for calculating it and do not provide a case study demonstrating how their model might be applied (and consequently no indication of the relative impact).

Andriankaja et al. (2013) also endeavour to simplify performing an LCA. They argue that where an LCA might be used to guide design decisions, the complexity of performing a full LCA and the amount of effort required to do so may be an obstacle to performing an LCA as part of an automotive design process. They propose a “simplified” simplified LCA method, which also treats transportation as a separate lifecycle stage. They indicate that their method has been used to evaluate dashboards and door panels but do not include the results of their evaluation or specifics of their calculations in their publication.

Busch and Schwarzkopf (2013) examine five major automakers[32] to evaluate the extent to which they incorporate strategies to reduce or manage their carbon emissions. Amongst the strategies noted, a focus was found which refers to transportation related carbon emissions in their supply chains. They found that the main tactic employed was to optimise choice of transportation to lower carbon modes of transport (for example using rail or ship instead of road transportation, or maximising the use of carbon neutral trains). However the analysis is at a company level, and don’t provide any sort of figures for the impact at a vehicle level.

Nakano (2013) outlines and discusses the extent of sustainability efforts in supply chains with a focus on Japan, noting the extensive work and progress in this area there. While he does specifically note that logistics transportation contributes to energy use in the overall product life cycle, he does not quantify its relative contribution. He is the first author found in this review who notes the conflict found in “just in time” (JIT) delivery systems, a widely employed “lean manufacturing” technique in the automotive industry. He notes that as a general principle, a “lean” approach to manufacturing - which focuses on eliminating waste (Liker, 2020) – results in reduced energy consumption. However, in contradiction to this, he notes that the JIT philosophy (which encourages frequent deliveries of smaller numbers of parts) actually increases the energy consumption and CO_2 emissions of the overall system. However, he does not discuss if this increase in environmental impact due to JIT is greater than the other positive impacts arising elsewhere in a lean manufacturing system, although

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[32] BMW, Daimler, Renault-Nissan, Toyota Motor Corporation and Volkswagen AG

he does provide a case study which demonstrates how to minimise the impact of a JIT system from an emissions point of view.

Using the data published by Notter et al. (2010) (discussed above), Hutchinson et al. (2014) compare the LCA's of electric hybrid and LCA vehicles, concluding that the key differences lie in vehicle utilisation phase and the energy mix used. Notably, for their calculations, they assume that the vehicle and powertrain production emissions are the same for the two types of vehicle, with the only difference being the battery which the hybrid vehicle would have. As they use the data of Notter et al. (2010), as discussed above the transportation emissions would be included - although not shown separately.

Shama et al. (2015) perform both a LCA as well as a Life Cycle Costing analysis to explore opportunities to reduce environmental impact as well as cost in the case study of a vehicle steering column assembly, manufactured in India[33]. Their system boundary spans the manufacturing and assembly processes, and they note transportation activities between the stages of manufacturing facilities (totalling 170 km) as being a contributing factor to greenhouse gas emissions, but do not provide their relative contribution compared to other contributing factors. They conclude by suggesting three potential ways to optimise cost and environmental impact, one of which is reducing transportation emissions by machining and assembling components at the same geographical facility resulting in a reduction of 30km transportation of the product. This scenario is calculated to provide a 0.08% reduction in green house gasses for the system studied. While this may appear to be a very small impact, when one considers the very modest distance change (compared to other supply chains which may span continents) it does suggest a potentially significant greenhouse gas impact arising from transportation activities in supply chains which span greater distances.

Kim et al. (2016) performed a "cradle to gate" LCA on Li-Ion batteries as used in a Ford Focus battery EV, using primary data from the vehicles actual bill of materials. They calculated that transportation related activities in manufacture contributed 3% of the 3.4 metric tonnes of CO_2-eq GHG emissions associated with producing the 24 kWh lithium-ion battery. While providing a useful benchmark for this research, they do not provide comparative figures for transportation of an equivalent conventional ICE.

Hao et al. (2017) compared the LCA GHG emissions associated with vehicle production in China and the USA. Their research concluded that similar vehicles produced in China resulted in 54% more GHG emissions than in the USA. This was attributed mainly to the carbon intensive power generation typical in China. They state that transportation in supply

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[33] Made in Tiruchirappalli, Tamil Nadu, India

chains is accounted for, and appear to assume a uniform average distance of 200km travelled as part of the materials transformation processes and assume that all road transportation is undertaken by 9.3t diesel trucks. These distances do appear to be conservative given the size of both China and the USA (in the light of modelling done later in this research), and the 9.3t truck chosen represents at best an "average" vehicle. However even if these estimates are accurate, the relative contribution of transportation is not stated in the publication.

Ameli et al. (2017) have developed a model which sums both the financial cost as well as the environmental impact of design decisions, allowing designers to optimise their designs accordingly. Transportation is included in the calculations of both, and a case study calculation on an automotive dashboard made in Iran is analysed using the tool. However, the transportation figures are not listed separately compared to other contributing factors and so, its significance does not emerge in the paper's results or conclusions.

Similarly, Schöggl et al. (2017) have developed a comprehensive checklist to support sustainable product development in the automotive context, and specifically note transportation and logistics activities as one of the "key categories" that should be considered. However, as in other cases no actual figures related to these areas are documented in the results of their case studies.

Continuing this trend, Sangwan et al. (2018) published their criterion for assessing sustainability in manufacturing, and listed transportation as a factor which needs to be incorporated. But, as with previous papers, actual figures were not presented, and thus the relative significance of the contribution by transportation remains a question.

Yu et al (2018) compared the life cycle carbon emissions of electric and petrol vehicles in China and specifically state that transport is included in their calculations. However the only detail on this states that the vehicle power system is transported from the manufacturer to the automotive assembly plant across a distance of 1500 kilometres being carried by a "heavy truck". When discussing the environmental impact of different stages of the vehicle's life cycle they do not provide an actual figure for the transportation, instead stating that the impact of the transportation activities are "too low to be determined".

Using a case study of an automotive steering component, manufactured in Tamil Nadu state in India, Thirupathi et al. (2019) evaluated the environmental effect of reducing raw materials waste in a manufacturing process. This was done using a LCA approach which yielded a positive reduction on environmental impacts as a result. Among the benefits listed, a reduction in environmental impacts due to transportation and logistics activities associated with raw materials procurement is noted, but as in other cases it is not quantified.

Xiong et al (2019) compare life cycle greenhouse gas emissions for EVs and plug in hybrid vehicles and consider both lithium ion based and lithium nickel manganese cobalt oxide based batteries in each case. While they do not account for cradle to gate transportation emissions when manufacturing the vehicles, they do include a transportation phase for the *completed* vehicle assuming a distance of 1600 kilometres between the automotive assembly plant and the customer dealer. They also account for a 500 kilometre journey to recycling and dismantling sites - in both cases assumed to be by diesel fuelled road transportation. Of interest to this research are the results for lithium iron based battery vehicles for which case they calculate this transportation in the latter life cycle phases to contribute 2.5% of the "vehicle cycle" greenhouse gas emissions which total 11,712 kg CO_2-eq / vehicle (this excludes vehicle usage and fuel consumption).

Kawamoto et al (2019) perform a LCA comparing ICE vehicles with EVs, also taking into account regional variations considering vehicles in the USA, the EU, Japan, Australia and China. They demonstrate that the perceived benefits of EVs' lower emissions are only realised in some parts of the world where the electricity mix is from low CO_2 sources. But, in regions dependent on fossil fuel-based electricity generation the CO_2 emissions for EVs are significantly worse. Overall these results question the current global benefit to overall greenhouse gas emissions in the case of EVs compared to ICE vehicles - especially when battery replacement is taken into account due to the significant greenhouse gas emissions generated in battery production. Their only mention of transportation emissions, however, is in the disposal phase where they note a greenhouse gas emissions contribution of 4 kg per vehicle.

Zackrisson et al. (2019) performed a LCA on a "Structural" EV battery – whereby the EV battery is incorporated into the structure of the vehicle (in this case the roof). While they do not provide separate figures for emissions associated for transportation during manufacture, they do disclose their assumptions used for transportation distances associated with the battery manufacture that can be summarised as follows:

- Transportation of raw materials (e.g. from mines to refineries) was not considered separately, as they assumed that this impact was already included in the raw materials emissions data they used.
- Distance from raw material producer (refinery) was 11000 km in total (10000 km boat + 1000 km by HGV)
- Distance from battery manufacturer to car plant – 200km, by HGV

These distances provide a useful benchmark for the present study.

Both Yin et al (2019) and Arambarri et al (2019) focus on EV battery manufacturing for their LCA's, both referencing the GREET database. In both cases, they do state that transportation emissions are included but the specific contribution of these are not disclosed.

Bobba et al (2020) discuss how calculating carbon emissions is central to achieving EU carbon emission targets set for 2030 and 2050. They argue that no single approach adequately provides a complete overview of the complex systems that produce EV batteries and conclude that more than one approach may be needed to provide a complete picture (for example using lifecycle system assessments together with material flow analysis techniques). Of significant interest to this research is that they specifically identify a lack of data and information on the environmental impact of transportation activities when undertaking the approaches they discuss. Importantly, this paper has specifically identified and confirmed the gap in the literature being demonstrated in this chapter and underscores the need for the contribution to knowledge that this research provides.

Although not published in an academic peer reviewed journal, the automotive manufacturer Volvo has published their own LCA, comparing the ICE and electric versions of the XC40 model which is available in both options (Egeskog *et al.*, 2020). While the results and methods form an extremely useful benchmark for this research (as documented in later chapters) their results do not include "cradle to gate" transportation emissions for these vehicles. Instead, they only account for emissions arising between Tier 1 suppliers and their manufacturing facilities.

Xiong et al (2021) evaluate the impact of large scale adoption of EVs and although they do a life cycle assessment, they elect to exclude transportation activities due to the non-availability of data (due to the variation of specific locations involved and also cite Xiong's 2019 publication (noted above) which considers the contribution of transportation emissions to be insignificant).

Ibarra-Gutierrez et al (2021) evaluate the potential GHG emissions impact from establishing local EV battery production capacity near to Quebec 's considerable lithium natural reserves. They evaluate the impact of three scenarios whereby lithium raw materials could be supplied locally, from the USA and from China and contrast the greenhouse gas emissions in each scenario. They provide clear data and assumptions for transportation emissions as well as their transportation emission results (although these locations are different to the scenario modelled in this research). Of significance though is that their assumptions and methodology support and confirm the methodology take in this research. Their scenario however is only for a few materials used in lithium production and does not include the rest of the vehicle.

Puig-Samper Naranjo et al (2021) evaluate differences in life cycle emissions for electric, hybrid and ICE vehicles in Spain. While they do note some transportation emissions they only include transportation of some completed components to the vehicle assembly plant from the component manufacturer and distribution of the completed vehicles, omitting emissions associated with raw materials extraction, refining and supply to the component manufacturers.

Raugei et al (2021) use an LCA to evaluate the impact of the UK's ambitions to move to only EV sales by 2030. However transportation is only accounted for in the EV battery manufacturing and distribution activities, but not for the rest of the vehicle.

Shu et al (2021) use a life cycle assessment to evaluate the environmental impact of batteries used in EVs focusing specifically on two leading types of technologies currently used (namely $LiFePO_4$ and $Li(NiCoMn)O_2$) batteries. They usefully note the impact of these different technologies' emissions both during the manufacturing stage and usage stage. While they state that transportation is included in the LCA and they do provide specific transportation results, scrutiny of the boundaries they have implemented reveals that raw materials acquisition lies outside of their study and therefore an overall CO_2 emissions are actually not necessarily represented.

Yan and Sun (2021) and Guo et al (2022)[34] both perform lifecycle analyses to assess the impact of the growing EV adoption on green house gas emissions in China. While in both cases they specifically state that transport emissions are included in their calculations, no specifics or transport specific numbers are given in their results.

Bhosale and Mustad (2023) provide a similar analysis but in their case focusing on India. They specifically state that transportation emissions during vehicle manufacture need to be included in calculations, including for raw materials extraction. However no mention of the contribution that transportation emissions makes is stated in their results.

Shang et al (2024) evaluate the atmospheric environmental impact of large scale adoption of electric vehicles in China and perform a “cradle to grave” life cycle analysis on two of China's bestselling electric and ICE vehicles. Both vehicles (the BYD Qin plus EV and the Volkswagen Lavida ICE vehicle) are manufactured in China, although assembled in facilities over 1300km apart. Their publication shares several aspects of the current research in that they endeavour to compare similar EV and ICE vehicles and notably do mention transportation as part of the production stage of both. However, the specific numbers on

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[34] Guo et al do this by system dynamics modelling

transportation are not published in the paper and are not discussed as being key contributors to carbon emissions.

However it is unlikely that their transportation emissions - if published - would necessarily provide a close replication of the results in the current study because they model vehicles not manufactured in the same location and thus the road transportation carbon emissions (which are the largest contributor) would vary considerably between the two locations and thus not give a precise comparison as has been done in the current research. Yet their paper does echo many other aspects of the current research's figures, potentially offering transferability to a supply chain transportation carbon emissions case study in China – potentially reinforcing the results of this research in a different location.

3.8 The gap in the literature: Transport emissions in "cradle to gate" LCA's

Having analysed the literature in the preceding sections, a clear gap in the literature has emerged. As has been demonstrated above (and noted by Bobba et al (2020) (above)) there is an absence of clear, specific and quantified research on overall carbon emissions which arise as a result of the transportation activities spanning the cradle to gate phase of the life cycle of an entire passenger vehicle. While some authors have documented parts of this information or provided it for specific materials, no author has documented this for an entire ICE or EV and provided actual numerical results in units of actual CO_2 emissions.

Several authors have instead simply stated that it is insignificant. However, this assertion is made without numerical evidence or actual calculations: rather authors cite other authors who take the same position. In other cases, authors simply state that it is difficult to calculate, or cite uncertainty around the location from which raw materials are sourced, processed and made into parts. Most authors however simply do not even mention transportation emissions even though they claim to be doing whole life cycle assessments.

Only one author, Kasai (1999), has presented any figure for these transportation activities and this was for an ICE vehicle manufactured in Japan - and in this case *energy consumed* was calculated rather than carbon emissions and this was presented as a percentage and no absolute figure was given. Moreover this percentage was given in the context of an overall life cycle assessment, and no supporting assumptions, calculations or data were provided to support the percentage figure provided.

To date, no author has presented a comprehensive calculation of "cradle to gate" carbon emissions arising from transportation activities in the life cycle of a passenger vehicle. This research will therefore address this gap in the literature by modelling and calculating these emissions for both an ICE and an EV (in this case, manufactured in Germany[35]) and thereby provide an original contribution to knowledge.

3.9. Carbon emissions arising in transportation activities – fundamental concepts.

Having identified a gap in the literature, the next section introduces fundamental concepts which are involved when modelling carbon emissions.

Thus far, this literature review has focussed on publications focussed on the automotive sector. However, in order to develop a model to calculate CO_2 emissions in transportation, the body of research on logistics has been consulted.

As documented by McKinnon et al. (2015) there is a significant body of work described as “Green logistics” which endeavours to evaluate the environmental impact of logistics activity, and research focussing on ways to reduce it. This body of work provides a useful framework for evaluating environmental impact of transportation activities, and is thus used as the approach for this research.

3.9.1. Factors impacting transportation carbon emissions.

Historically, there are three areas by which “green logistics” research and studies (dating from the 1990’s) have focussed upon in order to evaluate the environmental impact and (potentially) reduce the amount of freight traffic on roads (A. McKinnon *et al.*, 2015). These three areas (or factors) are still used in current thinking including at an international strategy level (for example: Edenhofer et al. (2014) or Zhang (2020)) and therefore are still considered relevant for use in this research.

Although the three factors were formulated in the context of road freight, they are transferrable to other modes of transport (Woodburn and Whiteing, 2015) and are thus considered relevant for this research.

These three factors are “transport intensity” (incorporating the distance travelled), “modal split” (referring to the type of transportation used) and “vehicle utilisation” (which incorporates the weight transported) (A. McKinnon *et al.*, 2015). The model built for this

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[35] Please see Section 5.1. which provides an in depth discussion on why Germany has been selected.

research has – as appropriate - taken these factors into account. These factors are discussed in the sub sections which follow.

3.9.1.1. Transport intensity – incorporating distance travelled.

“Transport Intensity” refers to the *amount* – or total distance - of transportation needed in order to maintain a given economic output (A. McKinnon *et al.*, 2015). Research into “Transport intensity” endeavours to reduce or avoid the need for transportation in the first place while still maintaining the same economic input[36], for example by identifying opportunities to reduce transport distances. (Bongardt, Breithaupt and Creutzig, 2010).

In the automotive supply chain context, the occurrence of transport intensity is a stubborn problem: limited opportunities exist for completely avoiding the transportation requirements of automotive supply chains when one considers the entire supply chains. The design choices of the automotive engineers in terms of vehicle materials dictate the various supply chain transportation requirements if one views it from a “cradle to gate” span.

For example: if a designer chooses steel for a particular body panel’s material (perhaps a door panel), it will necessitate the corresponding supply chain activities to provide the steel in the specified grade and thickness of sheet metal to arrive at the automotive press shop in order to manufacture the door panel. Following the supply chain to its source, this therefore necessitates the mining of iron ore (typically in Australia or Brazil (Comtois and Slack, 2016)) which needs to be transported by bulk carriers across land to a local refinery or harbour - this would typically occur by rail (Comtois and Slack, 2016). Because the iron ore needs to be transported anywhere, this immediately dictates the need for a means of transportation (see section 3.9.1.2 for a discussion on different types of transportation, or freight modes) as well as the associated freight “density” of iron ore (see section 3.9.1.3 for a discussion on freight or “packing” density).

In this example, while the existing body of logistics research may equip one to evaluate and attempt to optimise the situation, because the vehicle designer chose to use *steel* as a material, the “problem” of transporting the iron ore remains – and thus producing the associated carbon emissions.

In addition to this, the geographical span of the supply chain is most likely influenced by procurement and financial considerations (Harris *et al.*, 2011).

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[36] In other words, simply *NOT* undertaking the business (in our case manufacturing vehicles) is not one of the options available.

Thus, the opportunity for reducing the need for the transportation is constrained by design and procurement decisions made by vehicle manufacturers.

The main opportunity to reduce the amount of transportation required lies in geographically "shorter" supply chains. While the model built for this research cannot make materials or manufacturing location choices, the results from this model (for different scenarios) can provide decision makers with results which can inform these choices as will be shown in the discussion chapter.

3.9.1.2 Modal Split – the type of transportation needed.

In a logistics context, the transport "mode" refers to the freight transport medium (such as road, rail, sea, air and pipeline) (Rushton, Croucher and Baker, 2017). Of interest to this research is that each of these transport modes produces different CO_2 emissions per tonne of freight moved per kilometre (measured in the units: gCO_2/ tonne-km – in other words the mass of CO_2 produced to transport one tonne of freight for one kilometre) – this figure is known as the "emissions factor". Using the applicable "emissions factor", the model built for this research takes account of the CO_2 emissions associated with different freight modes.

Note that while air freight is considerably more polluting than any of the other modes, it is not included in this discussion or in the model built as it is not routinely used for freight in an automotive context (Automotive logisitics, 2013).

Before concluding this point, it is appropriate to discuss how the above units gCO_2/tonne-km are derived.

In assessing these CO_2 emissions, two factors need to be taken into account: namely the "well to tank" (or "WTT") emissions as well as the "tank to wheel/wake" (or "TTW") emissions (McKinnon and Piecyk, 2010).

3.9.1.2.a. "Well to tank" emissions

The WTT emissions are those associated with the energy supply chain (for example distribution, production and extraction of a fuel or energy source (Andersen *et al.*, 2010) and are "upstream" relative to the transport vessel or mode.

As stated above, the "well to wheel" emissions must include the "well to tank" emissions which arise due to the activities needed to provide the fuel at the point of use. These arise due to variations in the carbon emissions which arise during the various stages of the fuel supply chain including the extraction, transportation, refining and distribution of different fuels associated with different transport modes (Andersen *et al.*, 2010). Figure 3-7. provides “well to tank” emissions associated with different fuels commonly used in logistics activities.

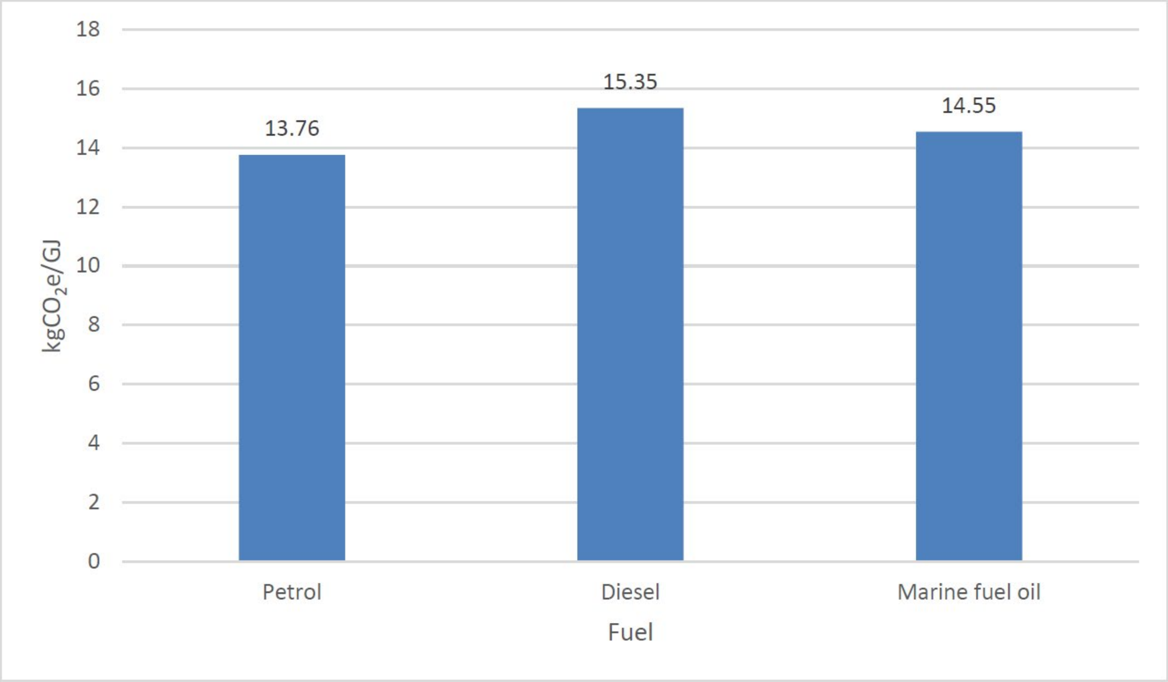


Figure 3-7: Well to tank emissions for fuels used in logistics (Data Source: GOV.UK (2016))

3.9.1.2.b “Tank to wheel” emissions

The TTW (“tank to wheel” (road and rail) or “tank to wake” (aviation and ships) (Klein *et al.*, 2021)) emissions relate to the fuel consumption on board the vehicle – such as those shown in figure 3-7. Note that different transport modes produce varying CO_2 emissions. Moreover, this figure is influenced by the type of product carried due to variations in packing densities and product weight (McKinnon & Piecyk 2010). For example, the values in figure 3-8 below are for transporting chemicals which typically have relatively high load densities .

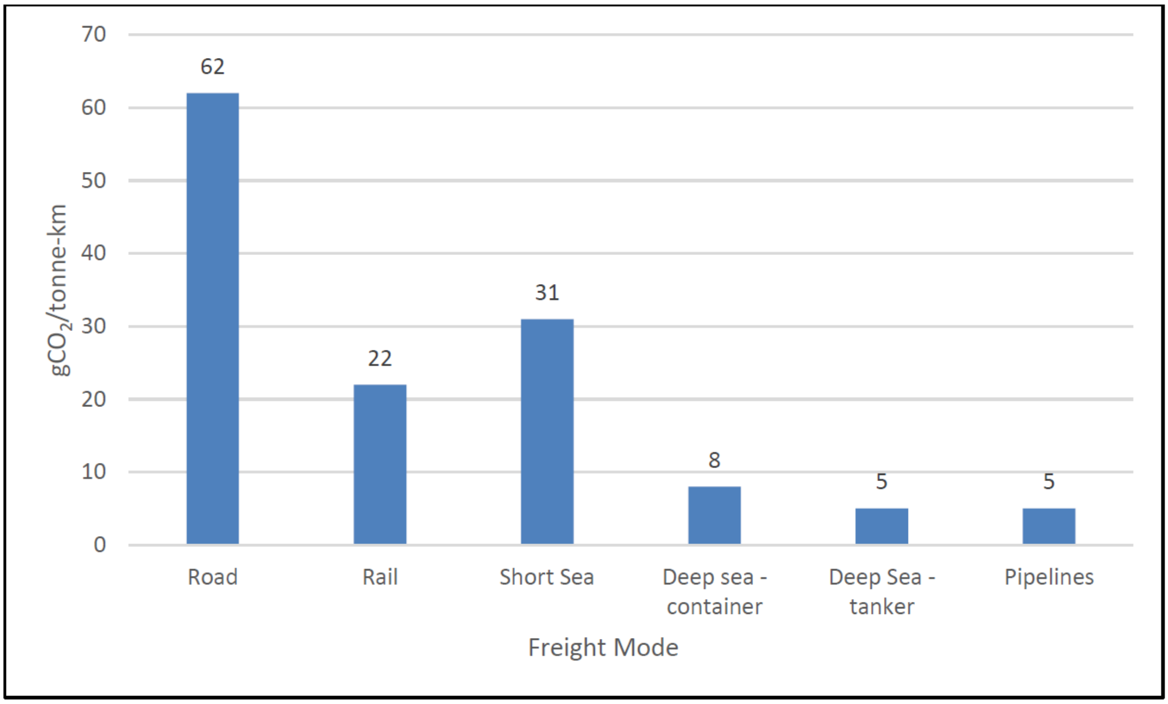


Figure 3-8: Average emissions by transport mode in chemical transport operations (Data source: McKinnon & Piecyk (2010) .

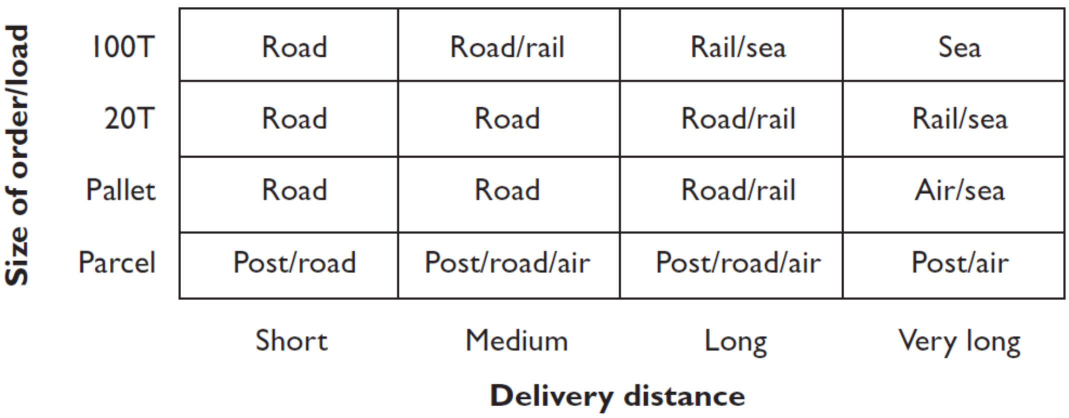
3.9.1.2.c. “Well to wheel” WTW emissions.

To calculate the total emissions, the WTT emissions are added to the TTW figure to provide the “well to wheel” (WTW) emissions (McKinnon and Piecyk, 2010). The model built in this research reflects this “well to wheel” figure.

3.9.1.2.d. Choice of Mode

The choice of mode is influenced by cost of transportation, operational considerations and the capability of a mode to perform its required function. (Rushton, Croucher and Baker, 2017). It is outside of the scope of this research to investigate potential opportunities available to reduce emissions by using different modes although they are easily simulated in the model built. Instead, it is the aim of this research to calculate CO_2 emissions based on the most likely mode of transport used in each situation. Thus, for the purposes of this model, the “modal choice selection matrix” documented by Rushton, Croucher and Baker (2017) will be used:

Table 3.1: Modal choice matrix. (Rushton, Croucher and Baker, 2017)



Size of order/load	Short	Medium	Long	Very long
100T	Road	Road/rail	Rail/sea	Sea
20T	Road	Road	Road/rail	Rail/sea
Pallet	Road	Road	Road/rail	Air/sea
Parcel	Post/road	Post/road/air	Post/road/air	Post/air

Delivery distance

The above matrix will be taken as a default when modelling transport emissions in this research - unless other evidence is available in specific instances.

3.9.1.3 Vehicle utilisation – incorporating the mass transported.

The third consideration is has the objective of evaluating and improving vehicle utilisation (McKinnon 2015). Methods to achieve this include techniques to improve vehicle routeing, improving vehicle fuel efficiency and improving vehicle loading as this influences the loading factor, and therefore emissions generated.

A key contributor to the efficiency of vehicle utilisation is the vehicle loading – i.e. the mass transported, which is closely related to the “packing density” or “freight density” of the vehicle. The carbon emissions generated by a vehicle depend on the weight of the vehicle and the load which it is carrying. Once a vehicle has been purchased, there is limited scope to improve its weight and this weight will need to be propelled in any journey undertaken. However, what can be influenced is the packing density of a vehicle. Where products can be packaged with a minimum of space between them, more weight of product can be moved in each journey thereby improving the relative emissions (per unit weight) of loads with a higher packing density (A. McKinnon *et al.*, 2015). Note however that the packing density may be inherent in the product being transported: Some products such as sand can be moved with a minimum of air in the load. However once the same sand has been transformed into glass containers for example, the shape of the container limits the weight of glass which can be transported in a given space, thus worsening the packing density and thus increasing the relative emissions per unit of weight transported.

However, influencing or improving vehicle utilisation is beyond what this research will attempt to analyse. Financial pressures from increasing transport and fuel costs imply that transport companies will seek to find the cheapest way to move materials to satisfy their customer needs (Harris *et al.*, 2011). However, the problem of transportation remains: the materials specified to make the vehicle need to be transported - and thus create carbon emissions.

3.9.2. CO_2 Equivalence

CO_2 is not the only gas produced by transport activities which has a “greenhouse” effect (A. C. McKinnon *et al.*, 2015) and the manner that this research addresses this issue is now discussed.

A historic milestone in the United Nations history of action on climate change was the Kyoto Protocol. This was is an international treaty aimed at mitigating climate change by reducing greenhouse gas (GHG) emissions and was adopted in Kyoto in 1997 during the Third Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations, 2023).

The main objective of the Kyoto Protocol was to combat global warming and stabilize greenhouse gas concentrations in the atmosphere to prevent further damage to the climate system. It recognized that developed countries, as major contributors to historical emissions, bear a greater responsibility in addressing climate change and set binding targets for the EU and 37 industrialised countries on GHG emissions (United Nations, 2023).

Defined in this protocol, are six greenhouse gasses which became know as the “Kyoto basket” (European Union: Eurostat, 2015) which are:

- carbon dioxide (CO_2)
- methane (CH4)
- nitrous oxide (N2O)
- hydrofluorocarbons
- perfluorocarbons
- sulphur hexafluoride (SF6)

While CO_2 is perhaps most widely known for its GHG impact, other gasses on this list (notably methane (CH4) and nitrous oxide (N2O)) have significantly higher global warming potential. Notwithstanding this, CO_2 is produced in significantly higher quantities and thus contributes the most to global warming (A. McKinnon et al., 2015; U.S. EPA, 2015).

Thus, to account for the *overall* greenhouse gas impact of the above six gasses a measure known as “carbon dioxide equivalents” or $C0_2e$ has been developed (European Union: Eurostat, 2015). This is done by weighting each gas by its global warming potential and aggregated, providing the overall greenhouse gas emissions in *CO_2 equivalent or CO_2e.*

The model developed for this research accounts for these *CO_2 equivalent* emissions and all CO_2 emissions stated in this document refer to CO_2 equivalent figures, unless otherwise stated.

3.10 Literature review precis and conclusion.

This concludes the literature review section of this dissertation. In it, the systems theory approach to evaluating the literature has been formulated and documented. Arising from this, the life cycle assessment approach has been identified as being aligned with a systems thinking paradigm and in turn therefore becomes the focus of this research.

Using a systems thinking paradigm, the results of the literature review on the life cycle assessment literature which deals with automotive manufacture of passenger vehicles has been documented. This literature review has in turn provided the theoretical background and foundations required to evaluate overall CO_2 emissions associated with automotive manufacture.

The literature review has also revealed that the carbon emissions arising from transportation activities during vehicle manufacture (including those associated with raw materials extraction and refining) is largely ignored in this body of literature and even where it is acknowledged there is a complete absence of actual results, thus confirming a gap in the literature which this research is able to fill and thereby provide an original contribution to knowledge.

The chapter concluded by consulting the wider literature on logistics and transportation (and in particular focusing on the “green logistics” body of knowledge) providing fundamental concepts which underpin research and modelling in carbon emissions arising from transportation activities. These concepts form the foundation of the model developed for this research which is introduced and discussed in Chapter 4.

4. METHODOLOGY PART 1 – THE TRANSPORTATION CARBON EMISSIONS MODEL

The methodology section of this document is divided into two chapters. The first chapter - Part 1 - describes the approach taken to the modelling and describes the Transportation Carbon Emissions (or "TCE") model built for this research. The second chapter - Part 2 - then moves on to describe the specific case study which is used to meet the aims and objectives of this research.

This chapter - Part 1 - guides the reader through the assumptions, theory and processes used to construct the model used to fulfil objectives 4 and 5 of this research. It consists of several sections which are introduced here.

The chapter starts with an introduction to the methodology approach taken (section 4.1.), using Saunders et al (2023) as a framework for the discussion. Note that some topics discussed in that section are revisited in greater detail later in the chapter.

Next, potential approaches to modelling are discussed in section 4.2. , followed by an analysis of the calculation methods and theory used to build the model built for this research in section 4.3..

The potential sources of data available for this research are then discussed in section 4.2. followed by an introduction to the GREET database chosen for this research in section 4.5..

The model built for this research is then described in detail as well as defining the boundaries and assumptions used in section 4.6.. The testing and validation undertaken to confirm the veracity of the model is documented next in section 4.7.

The chapter concludes with documenting general assumptions and default choices which would be applicable to whatever scenario is modelled in sections 4.8 to 4.10.

4.1. Methodology Introduction – Saunders et al 2023

Now in its 9th edition, Saunders et al (2023) is widely used in supply chain management research[37] as a framework for research methods, and thus forms a useful structure to introduce the approach taken in this research. Using their well-known "research onion" as a guide therefore, the next subsections follow accordingly. In some cases, the criteria or "layer" of Saunders' framework is discussed in this introductory section. However, in other cases ("data collection" for example) the subsections below are merely brief introductions to the criteria because some topics merit their own section and are thus dealt with in significant detail later in the chapter.

In the interests of conciseness, not every option outlined by Saunders' "research onion" is discussed below: rather the categories which are most relevant and applicable to this research form the focus of this subsection. The options in each "layer" as applicable to this research are illustrated below in Fig 4-1..

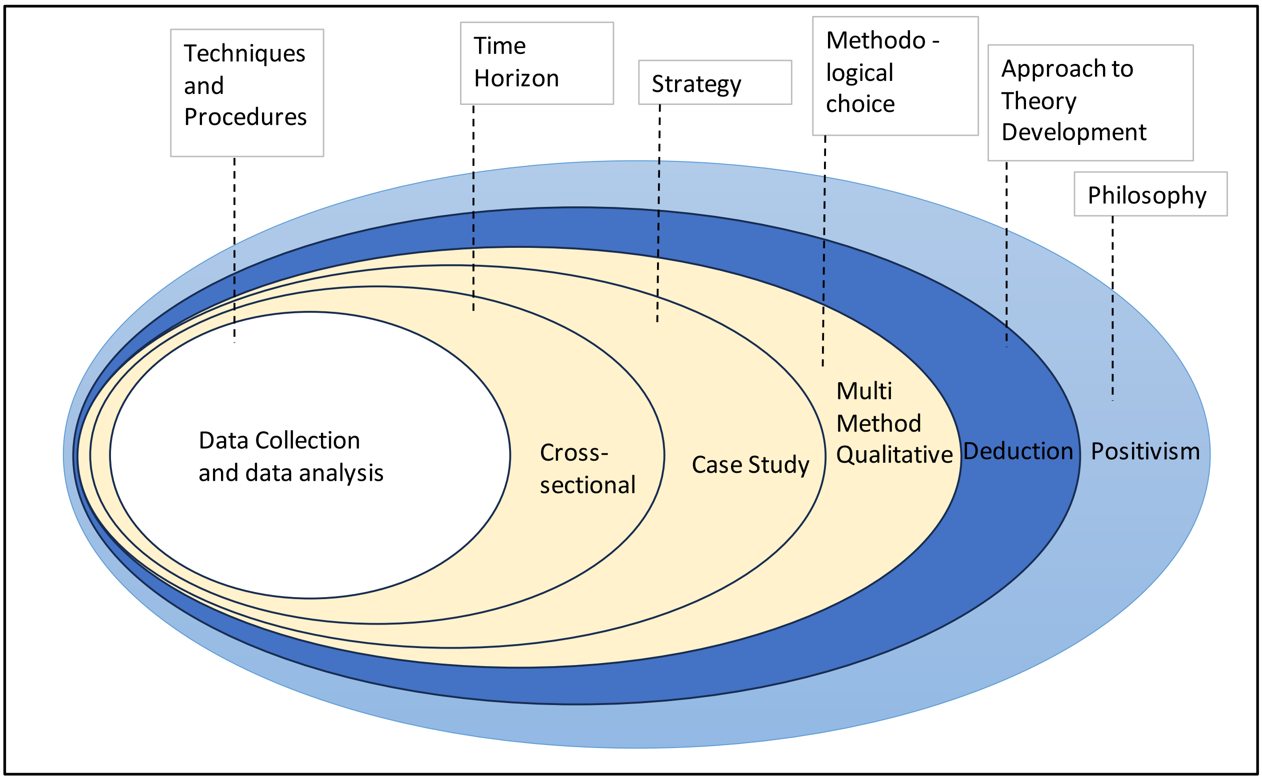


Figure 4-1:   Saunder's "research onion" categories as relevant to this research (redrawn from Saunders et al (2023) omitting descriptors not applicable to this research).

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[37] To confirm its applicability to this area of research, a brief literature search was performed. Over 100 publications in the area of supply chain management and logistics published since 2022 alone were found which cite Saunders' "onion" as a guide to their methodology.

4.1.1. Research Philosophy (or “Paradigm”)

Aspects of the philosophical approach – or paradigm[38] – chosen for this research have already been introduced in the Systems Theory chapter (Chapter 2), which document a range of systems thinking approaches ranging from the positivism[39] of Van Bertalanffy and Forrester the to the interpretivism[40] which characterised “soft systems” thinking.

Of interest is that Saunders traces the history of positivism to - amongst others - the “Vienna circle” (Saunders, Lewis and Thornhill, 2023). It is perhaps significant that systems theory can also be traced back to the Vienna circle because (as previously noted) Von Bertalanffy’s PhD supervisor - Moritz Schlick - was a founding member of this “Vienna circle”. However (as was noted previously) Von Bertalanffy felt that the reductionist approach taken by the Vienna circle was inadequate and this led to the formulation of Systems Theory.

The approach to addressing the aims and objectives can be considered to be described by positivism. Throughout this research the endeavour has been to follow a quantifiable and evidence-based argument and to use scientific and numeric arguments to address the research questions. The model built performs an expansive set of calculations based on quantifiable, credible data. Where such data is not available, defendable assumptions are made to estimate the values used for the modelling process.

This scientific approach also supports the LCA principles prescribed in ISO 14040 (which are used in the modelling of this research) which specifically require “priority of scientific approach” when performing a life cycle analysis (Finkbeiner *et al.*, 2006).

Lastly, the impact and significance of this research will be defended based on the numeric results arising from the modelling undertaken again underscoring the positivism underlying this research.

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[38] Saunders et al (2023) acknowledges that the terms “philosophy” and “paradigm” are commonly used interchangeably in this context.

[39] Saunders et al (2023) describes positivism as typical of the scientific method of the “natural scientist” which works with an observable reality, which allow “law like” generalisations and in turn results un influenced by the researcher.

[40] In contrast to positivism, interpretivism acknowledges the “human” influence of the researcher and human systems being studied and allows for differences in reality perception both in the case of the researcher and the humans being studied (Saunders et al 2023)

4.1.2. Theory Development

The next “layer” of Saunders’ “research onion” concerns the method by which a theory is formulated. When discussed in his guide to research methods, Saunders (2023) assumes that a theory or thesis has been developed and therefore needs to be tested or confirmed in some way. In this case however, this is not the course that this research has followed - rather than positing that EVs will definitely increase (or alternately decrease) carbon emissions in transportation this research has not taken a position to confirm or invalidate one of these positions - rather it seeks to via the modelling process discover the impact of EVs.

Notwithstanding this, a deductive approach – which involves using a logical approach using general principles to provide specific conclusions (Saunders et al, 2023) - is followed to address to the research questions formulated. Typical of the more scientific method used in this research, (and considering the expansive existing technical knowledge and theory already available), the conclusion and discussion of this research are derived logically from modelling a known set of assumptions which typify the case study being considered – as befits a deductive approach. This is in contrast to an inductive approach whereby there are gaps in the theory or assumptions made for the research and the results endeavour to provide a foundation to fill these unknown areas of theory (Saunders et al, 2023).

Finally, as is typical in deductive approaches, the approach taken is highly structured and is easily replicated if improved data becomes available or if it is desirable to repeat this analysis on a different case study or in the future. A clear scope of the modelling undertaken is defined and clear assumptions have been stated under which the outcome of the modelling is considered valid. This allows the findings of the model to be generalised to other sectors which share the fundamental criteria against which this modelling has been conducted.

4.1.3. Methodological choice

Saunders et al (2023) discuss a variety of research approaches from quantitative studies to qualitative approaches (and various variations of these) as may be commonly performed by business researchers which is the audience of his book. However, in the case of this research - while in the broader subject area of supply chain management - the approach taken in this modelling is typical of engineering or scientific research which relies on measurable data and applying known theory or calculations upon this data.

Thus, the clear choice of approach for this research undertaken is a *quantitative*[41] one. Within this, a "multi method" quantitative approach[42] is taken. In some cases, secondary data has been used directly from the GREET database or other sources. In other cases where this is has not been readily available, data has been gathered from sources such as industrial research reports, government statistics and trade body publications (to mention a few sources). Nonetheless, in each case, the source of the data has been clearly cited and where it was not available the assumptions made which underlie the values used are underpinned by current literature or best practice.

4.1.4. Research Strategy

Saunders outlines several potential research strategies among which some lend themselves particularly to the more scientific and deductive approach taken in this research ("experimental" or "survey" research as examples). However, because this research endeavours to model a global phenomenon arising from a trend in the activities of humankind, constructing an experiment or some sort of survey spanning the scope of this research is unfeasible.

Moreover as noted in Section 1.4 above, taking a case study approach is required to allow comparable scenarios to be modelled, and thereby provide results in each case which allow for an equitable comparison between the scenarios modelled and considered.

Thus, this research is conducted by a "case study" approach - modelling two case studies and comparing the results. The case studies of both internal combustion and EVs manufactured in a specific location are modelled – details and the rationale of which are discussed below in section 5.1. The results which arise from modelling this case study allow the research questions to be answered and the aims and objectives achieved.

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[41] i.e. reliant on measurable data and applying known theory or calculations (Saunders et al, 2023).

[42] Saunders et al (2023) describe situations where more than one data collection technique is used as being "multi method"

4.1.5. Time Horizon

Saunders discusses two potential time horizons:

- a cross-sectional study which provides a “snapshot” of a given point in time
- longitudinal study which evaluates changes over time perhaps due to an intervention or similar.

In the case of this research, a cross-sectional study is made as it models data based on current supply chains and will not evaluate the evolution over time of carbon emissions being studied. Note however that the model built is flexible enough to be easily updated should new data emerge over time (and if it should be desirable to compare the current results sometime in the future).

4.1.6. Data Collection and analysis

The centre of Saunders’ “research onion” deals with data collection and analysis. In this research the data requirement arises from the formulas and logic used to model the scenario being examined (discussed below in section 4.3.). Given the scope of this topic, it warrants a separate subsection, and it is thus not discussed here, and the reader is directed to sections 4.4 and 4.5 below that follows for a comprehensive discussion on this topic.

4.1.7. Ethical considerations and processes followed.

As will be noted in Section 4.4 below, this research is based on publicly available data and no human subjects or involvement was required to obtain the data used other than the input of the researcher performing the research. Having reviewed the University of Hertfordshire’s research ethics documentation and processes, no activities during this research required specific ethics approval from the university, or accommodations to comply.

4.1.8. Chapter conclusion

Having used Saunders et al.’s framework as a high level introduction to describe the methodology approach, the next sections discuss in greater detail how the modelling in particular was undertaken.

4.2. Modelling options & techniques

The model built for this research is needed to address the research questions by providing a quantifiable comparison between ICE and EVs' carbon emissions arising from "cradle to gate" transportation activities. Several modelling options exist within operations and systems research which are discussed in this section.

As discussed by Auvinen et al. (2014), several models already exist for calculating carbon emissions in transportation. While these are regarded as credible, they are typically "Point A to Point B" calculators, allowing the user to calculate the carbon emissions of a shipment between two locations – in some cases across multiple freight modes (examples that were evaluated for potential use in this research but found unsuitable were the "NTMCalc" and "EcotransIT World"[43]). However, they are limited in that they do not allow the user to model the entire supply chain *system* of a product which may be made up of a number of supply chains combining at various stages. Moreover the product under scrutiny might undergo various stages of refining or processing - thus changing its weight and shape[44] as it progresses – again something which these existing models are unable to account for.

Thus, in order to progress with this research, it has been necessary to develop a model which can not only replicate the commercially available models in their calculations, and but also represent a supply chain *system* as described above.

In their survey of 127 peer reviewed papers which simulate logistics and supply chain systems, Tako and Robinson (2012) identify the two widespread modelling techniques in logistics systems as being "system dynamics" and "discreet event simulation". Thus, this section begins by examining the appropriateness of these two options for this research, followed by a discussion of the "proxy modelling" approach ultimately chosen for this research.

4.2.1. Discreet event simulation.

Using computer software, discrete event simulation replicates the behaviour of individual items in a system referring to each occurrence as a "discrete event". Several commercial software packages are available (such as "Witness", "Flexsim" and "Arena") as well as open source

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[43] These tools are discussed in greater detail in the "Testing and Validation" section below.

[44] The shape of a product impacts the packing density: for example how many products can be fitted into a container. This has a direct impact on the carbon emissions of transportation.

versions (such as JaamSim) and form an ideal platform to replicate the movement of individual vehicles or items being shipped through a system. (Robinson, 2005; A. Tako and Robinson, 2012; Lang *et al.*, 2021).

Using the computing power available in modern computers, these discrete events (for example individual vehicles travelling in traffic) can be simulated and the overall effect of all the individual occurrences determined. For example, if traffic is being modelled, the software could show the total individual distances travelled by vehicles, identify where traffic jams might occur or model the impact on traffic flow of slow heavy vehicles travelling on the same road as faster vehicles.

The suitability of discrete event simulation for this research was evaluated using Flexsim whereby a basic journey of a generic material from “cradle to gate” across several steps in manufacture was modelled. However, this was not found to be useful because while the software was capable of modelling the distances travelled by the material it did not have easily accessible functionality to convert the distance travelled to carbon emissions (taking into account the mode of transport associated with various packing densities of the load) as required by this research. Moreover, it proved unfeasibly complicated to account for a reduction in raw material as the material moves from one phase to the next as is typical through a manufacturing journey due to waste, offcuts etc.

Notwithstanding the above - even if this functionality was easily available, this research only requires the journey of a single vehicle to be modelled and so the type of modelling done by this software – of a continuous flow of vehicles - is not needed or suitable. It was also found that the scalability needed to accommodate the scope of this research appeared unfeasible.

Lastly, in the context of this research, discreet event simulation seems less appropriate because it models a system by breaking it into its individual components (or “events”) and modelling their individual performance - thereby taking a reductionist approach which goes against one of the principles of systems theory outlined above.

Thus, discreet event simulation appeared unsuitable for this research.

4.2.2. System dynamics

As noted in Appendix A, system dynamics is a modelling technique developed by Jay Forrester specifically for the purpose of modelling systems and so would appear to be an ideal choice for this research. System dynamics - again through utilising modern computing power - simulates systems by modelling flows of items through a system (as opposed to individual items as is done in discrete event simulation) and is able to simulate of different parts of a system and the way in which they affect one another (Sterman, 2000).

Again, several system dynamic software packages are available: the prominent packages include "Vensim"[45] "Powersim"[46] and "Stella"[47]. All are powerful and widely used for modelling complex systems, although may require a significant investment in training and time to adequately master the software. Some have free editions for academic use, albeit with some restrictions in some cases.

The software finally chosen to evaluate the suitability for this research was "SYSDEA", which was a web based product from Strategy Dynamics Ltd. It was considered ideal for this research due to its intuitive nature – which does not require in-depth programming knowledge as in the case of some other packages. Moreover, it was available free of charge for academic teachers and PhD students (without restrictions), and with UK based support and assistance. It is acknowledged that other software packages may have more features (at a premium price), but SYSDEA was found to be adequate to evaluate the suitability of system dynamics modelling for this research.

Initially, SYSDEA appeared ideal, and a model was built to simulate the cradle to gate journey of a steel car door panel. The SYSDEA software gave excellent options to customise the journey of the material and the carbon emission calculations required were easily incorporated. Reducing the amount of material as the steel moved through the production journey was again easily incorporated. Indeed this preliminary model built was presented at the 2018 System Dynamics Society conference in Cardiff (Baker, 2018) and received an excellent reception from the delegates attending.

Notwithstanding this, there were two issues which prevented the system dynamics model initially built from being further developed for this research. The first issue was that of scalability - while building a model of an individual component consisting of a single material was feasible, building an entire vehicle appeared unfeasible from both a time and complexity point of view.

Secondly, system dynamics modelling specifically deals with flows of material and is excellent at modelling dynamic systems where the flows might fluctuate over time and be influenced by other factors over time. But, in the case of this research only a single vehicle is being simulated in a stable "non dynamic" journey and only a single occurrence of the material journey is simulated (as opposed to a *flow* of material). Therefore, in order for this single

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[45] See: http://vensim.com/
[46] See: http://www.powersim.com/
[47] See https://www.iseesystems.com/store/products/stella-architect.aspx

journey to be modelled, the system dynamics software had to be used in a way other than for which it was designed making the simulation unnecessarily cumbersome.

Thus, despite spending considerable time developing an initial system dynamics model for this research it was ultimately deemed unsuitable. Notwithstanding this though, valuable modelling experience was gained through this exercise and the system dynamics process of modelling proved useful when constructing the model ultimately used for this research as will be documented below.

4.2.3 “Proxy” Modelling

As discussed above, the first two approaches to modelling appeared unfeasible when it came to scaling them to the extent required to become useful for this research.

In this case the concept of a “proxy model” became useful. As discussed by Hursey et al. (2015) a proxy model can be considered as a model “approximating a more complex model”, and within an acceptable margin of error, rather than attempting to model reality exactly.

The benefit of taking this approach is that it allows for a more simple, agile model, compared to a “heavy” model which would require extensive resources in order to be a more precise replication of reality (Hursey, 2015; Alenezi and Mohaghegh, 2016).

Consequently, it is used in an extensive variety of fields: including being suitable for LCA’s - as discussed by Masnadi et al (2020) . Thus, the model constructed for this research can be thought of as a *proxy model*, in that it does not attempt to model the supply chains exactly as would be the case in discreet event simulation or system dynamics. Please see section 4.3.5 which expands on the “proxy” nature of the model built and which also discusses the transferability of the model developed to other products.

Note that the proxy model built did accurately replicate the system dynamics model developed (discussed above) because - given the same inputs - it exactly replicated the results of the system dynamics model built for a vehicle door. Moreover, using a simplified approach to modelling allowed the model to be built using Microsoft Excel which provided excellent scalability and customisation.

It may be argued that discreet event simulation may be *capable* of providing higher resolution results. This would however only be true in this capability was utilised – for example if the data entered into a discreet event simulation model was of a higher “resolution” or granularity than could be accommodated in a proxy model. In the case of the proxy model built for this research however, the model could be customised to calculate the full granularity or resolution of the data set available. This allowed it to account for – for example – factors such as the different packing densities of steel door panels compared to steel engine blocks[48], as a discreet event simulation would also be able to do. Thus, because the proxy model built was able to match the resolution of the data available, there was no disadvantage to using it compared to using a discreet event simulation method.

Lastly, because this research endeavours to *compare* the carbon emissions arising from "cradle to gate" EV transportation activities with those of ICE vehicles, a proxy model allows for an acceptable comparison of the *relative* impact. Even if the *absolute* results have a margin of error within them, this will be consistent - and of the same magnitude - for *both* vehicles being modelled and thus the *relative* impact can be usefully determined and thereby usefully address the research questions.

As noted though, the model was built using the modelling process typically taken when building a systems dynamic model, discussed in the next section.

4.2.4. The Modelling Process

"Modelling is the art of simplification" (Sterman 2000)

Although a "proxy" model was ultimately built, the modelling process used in this research is based on the process outlined as "best practices in systems dynamics modelling" as collected by Martinez and Richardson (2013). They form the steps summarised below, and which were followed in developing the model for this research.

The activities are:

- **Problem identification and definition.**
  This step, done at the outset of this research, culminated in the research questions, aims and objectives.

- **System conceptualization and model formulation.**

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[48] Pls see section 4.3.5. which expands on this example

This step is discussed in the Section 4.3. where the calculation methodology of the model is examined.

- **Model testing and evaluation,**
  This step is discussed in section 4.7. where a test case of the model is compared with the results arising from commercial software.

- **Model use, implementation and dissemination.**
  Having built the model, it is used to model the scenario arising in this research described below and discussed in the latter chapters of this document

Having built a model using the above modelling process, the remainder of this methodology chapter describes in detail how the above steps were achieved.

4.3. Calculation methodology for the model built.

The model built for this research bases its approach on the UK Department for Transport's "Guidance on measuring and reporting greenhouse gas emissions from freight transport operations" (Leonardi, McKinnon and Palmer, 2010). While this guidance extends to all modes of freight transport, there is a focus on road transport in particular in this guidance.

Thus, the work by McKinnon and Piecyk (2010) is used as a further reference as they also acknowledge the Department of Transport's methodology, but go into greater depth when dealing with other modes of transport.

Both of the above documents discuss two methods which can be used to quantify carbon emissions arising from transportation activities. They are:

- An "energy based" approach: considering that CO_2 emissions primarily arise from fuels and other forms of energy which power transportation, this approach simply records the fuel (or energy) used for transportation and uses these figures to calculate the corresponding carbon emissions.

  This approach is useful in cases where companies operate their own logistics operations and would have accurate records of fuel used (or financial records of fuel purchased) in which case these figures can be used to calculate carbon emissions arising.

- An "activity based" approach. Where energy data is not available, the carbon emissions can be calculated by taking into account the distance travelled, the mass of cargo moved and the typical CO_2 emissions arising from the mode of transportation used.

  This approach is however considered to be the less accurate of the two approaches (McKinnon and Piecyk, 2010).

4.3.1 Calculation of activity based transportation

Because energy and fuel figures described in the first approach are not available in this research, the second approach is used. In this case the following formula applies:

$$\textbf{CO}_\textbf{2}\ \textbf{emissions} = \textbf{mass transported} \times \textbf{distance travelled} \times \textbf{CO}_\textbf{2}\ \textbf{emissions factor}$$

Units:

CO_2 emissions: g CO_2

Mass Transported: tonne

Distance travelled: km

CO_2 emissions factor: gCO_2/tonne-km

Source: McKinnon and Piecyk (2010)

This formula is embedded in the model built and provides the CO_2 emissions which correspond with the inputs provided.

The three elements of the calculation above – mass, distance and emissions factor (arising from a given mode of transport) reflect the three factors identified in section 3.9.1. which impact transportation carbon emissions.

4.3.2. Multiple journeys from "cradle" to "gate"

The above formula calculates the carbon emissions for a single journey. However, in this research multiple journeys are considered. Thus, using the above formula, the model built allows the user to define multiple sequential journeys as would be typical in a "cradle to gate" transformation of raw materials to finished parts.

Mathematically expressed, the total across a component's journey will be:

$$\text{Total Carbon emissions} = \sum (\text{CO}_2\ \text{emissions for each transportation stage}).$$

4.3.3. Multiple supply chains for each material

It is typical that several raw materials may be required to produce a material used in automotive parts. For example, to make the steel used in a vehicle door panel, iron ore, metallic coal (or "coke") and scrap metal[49] (Worldsteel.org, 2019) all form part of the wider supply chains which feed a steel refinery.

Using this example, the supply chain to a steel mill can be represented graphically as follows:

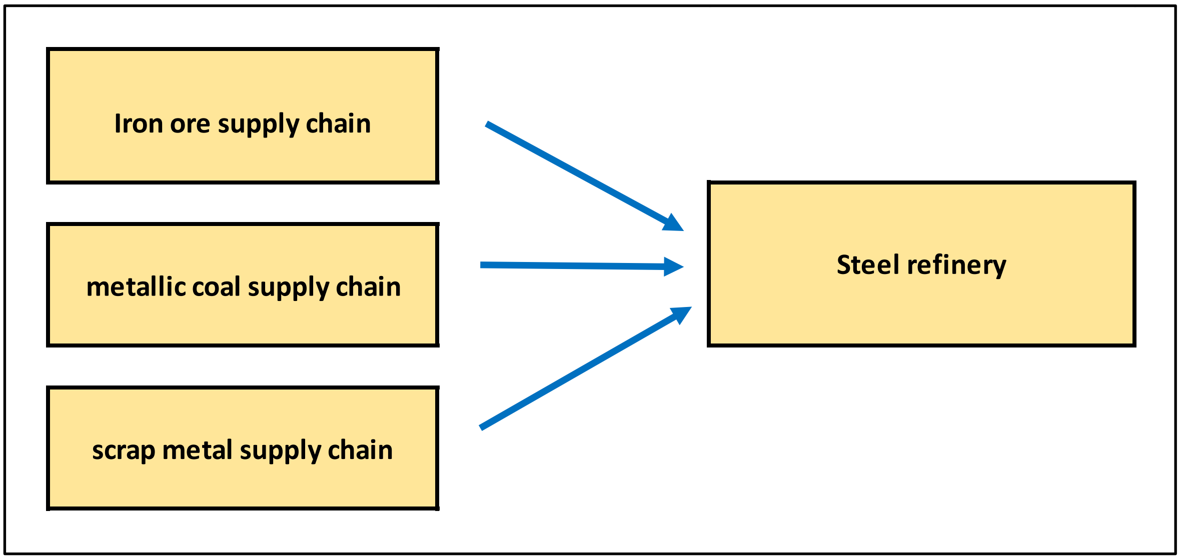

Figure 4-2: Raw materials supply chains to a steel mill.

The model constructed allows the relative proportions of these materials to be defined. In the example above, the associated transportation carbon emissions are automatically calculated from this and summed to find the total transport emissions associated with supplying the steel mill.

4.3.4. Waste and unused raw materials

The mass of the material transported may change from one manufacturing stage to the next. For example, in the case of the journey of a car door, in the initial stages of the journey, the

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[49] The proportions of these are documented and cited accordingly on the calculations shown in Appendix C.

material will be in the form of iron ore. However, after the refining process, a fraction of the original raw material will continue on the next leg of the journey[50], in the form of sheet metal.

Similarly, after being processed at the automotive press shop, only a fraction of the material will continue the journey as a car door, due to the waste in offcuts remaining at the press shop.

The model built allows the user to specify the final weight of the product, as well as the proportion of weight lost at each stage, and it automatically calculates the weight being transported in each leg.

Thus, for a car door weighing 50kg for example, this weight can be entered and the model automatically calculates that the raw materials that started the journey weighed 130.4kg in the raw materials state (see Appendix F for the calculation sheet for this case[51]).

Accordingly, the model built calculates the CO_2 emissions of each stage of the supply chain using the corresponding weight, mode of transportation and distance.

4.3.5 A life cycle assessment approach to modelling.

Because this research has identified a gap in the *life cycle assessment* literature, in order to “fill” this gap it is important that the modelling performed is done in a manner consistent with a lifecycle assessment approach - as if it were being done as part of a greater life cycle assessment study.

Thus, consistent with the life cycle assessment approach (as discussed in the literature review chapter) the phases performed in accordance with ISO 14040 can again be listed as:

- Compiling an inventory of *relevant* inputs to a system (in this case raw materials at the “cradle” stage) and outputs of a system (in this case completed parts delivered to the “gate” stage)
- evaluating the potential environmental impacts associated with those inputs and outputs (in this case focussing on CO_2 emissions arising from transportation)
- interpreting the results in relation to the objectives of the study (as will be discussed in the chapters that follow).

In the case of this research, the LCA will follow the approach endorsed by Young and Vanderberg (1994), whereby the environmental impact (on emissions arsing from

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[50] Again, these percentages are stated and cited in the calculation sheets, in Appendix C as applicable.

[51] The 130.4kg is obtained by adding each of the raw materials weights used in making the steel shown on this case study calculation sheet.

transportation in this case) will be calculated by tracing the life cycle of the vehicle's constituent materials – an approach seen across the LCA literature. Importantly this approach is also used by Argonne National Laboratory in their LCA work and upon whose secondary data this research is based (please see section 4.4.4. below for more information on the work of Argonne National Laboratory). Maintaining this consistency of approach allows for an aligned "contribution to knowledge" in this field and potentially even to the work of the Argonne National Laboratory.

Herein lies the proxy model nature of this modelling. It is not feasible to perform an individual life cycle assessment on each of the thousands of components which make up a vehicle. However, it can be argued that in the case of similar components, each material transformed to make it undergoes a similar cradle to gate journey. For example: in the case of steel used in a car body, regardless of which body panel is considered, in every case the steel needs to be mined, refined into steel, pressed into a body panel, welded together and fitted to a car body. Thus, the proxy nature of this model is that all of the steel that makes up a the car body will be modelled together, rather than the individual body panels.

Thus, the proxy model built will model subsystems of a vehicle (for example the car body, glass and windows or powertrain subsystems) tracing the individual materials' supply chains which make up these subsystems: assuming that within each subsystem the manufacturing processes and transformations for each material will be of a similar nature. While it may be tempting to simply model the overall mass of the different materials in a vehicle, modelling by subsystem allows the typical packing density of different subsystems to be taken into account (for example, steel used in vehicle body panels has a different packing density to steel used in engine blocks).

This approach makes the model developed highly transferrable to other products: as long as the manufacturing location and the composition of a product's materials are known, the model built for this research can be used to evaluate the transportation carbon emissions of any product being considered. This can be especially useful when considering the environmental impact of decisions concerning potential manufacturing locations of a new product. Similarly, it allows designers to evaluate the transportation emissions implications when selecting different materials for a product being designed.

While it is acknowledged that - typical of a proxy model - the precision of the results may not be as accurate as a more granular approach, any inaccuracies will affect the figures for the two types of vehicle (or manufacturing location as noted in the paragraph above) being considered in the *same way*.

Therefore – in the case of this research - the model provides a useful comparison between EVs and ICE vehicles even if the results may have a margin of error within them.

4.3.6. Summary

This subsection has discussed the principles and methodology upon which the model developed for this research has been built. Having started with the basic calculation used for transport emissions the subsection has discussed how the model built has been developed to include functionality not available on commercial or existing modelling facilities.

The subsection has concluded with noting its consistency with a life cycle assessment approach and further acknowledging the proxy nature of the modelling conducted. This being done, the next subsection will discuss sources of data available with which to conduct the modelling.

4.4. Data required and data sources

Having established the approach to modelling that would be undertaken the next step was to identify which data was needed as well as a credible source of this data.

4.4.1 Specific data needed

For this modelling to be undertaken the materials composition of the parts or at least subsystems of an entire vehicle was needed with the corresponding weight of each component or subsystem.

Knowing the materials used allows for the supply chain to be modelled - which involves both the origins of the raw materials as well as the geographical distances across which the materials would be transported.

Combining the typical material with a knowledge of the component or subsystem being modelled allows for the modelling to account for typical packing density and likely transportation modes associated with these parts. This established, the weight of the materials used allows for the carbon emissions to be calculated.

To summarise, the following vehicle data is needed for a whole vehicle:

- details of the materials used, by subsystem.
- weight of each of the above materials used, by subsystem.

For this research, using secondary data was utilised as discussed next.

4.4.2. The choice of secondary data

For this research, it was decided to use secondary data, as it has several advantages over using primary data in the context of this research. While primary data may initially seem preferable as it allows the researcher to collect data specifically suited to the research question (Saunders, 2019), it was unfeasible (from a time, resource and access point of view[52]) to collect the volume of data needed to model this research.

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[52] Without having access to individuals who deal with this data obtaining primary data from a vehicle manufacturer was unfeasible.

Saunders (2019) notes several advantages to using secondary data. Relevant to this research is that secondary data may be available and accessible, and can be thus be utilised without the time and resource requirements associated with collecting primary data.

However, of greatest value is that where the source of secondary data has been collected by a "reliable and valid" source[53] (using the terminology of Saunders et al (2019)) and whose use and validity can be triangulated via the existing literature, it lifts the rigour of the data above what might be achievable in collecting primary data by a single researcher (Johnston, 2014; Saunders, 2019) – this was true in this research's time and resource constraints.

One potential risk to the applicability of using secondary data is that it may have been collected for a purpose different to the study to which it is subsequently applied as secondary data (Saunders, 2019). Compounding this, where there may be an element of subjectivity or bias inherent in the primary data collected – even if it is disclosed at the point of applying it as primary data, these considerations may be overlooked or not known where the data is used as secondary data (Johnston, 2014), this leading to potential errors in results of its analysis. In the case of this research, data sets were identified which were compiled for the specific purpose of life cycle analyses and thus are perfectly aligned with

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One manufacturer however - namely Volvo - has recently published life cycle assessments (or "Carbon footprint reports") comparing the overall life cycle emissions of some of their vehicles (the XC40 and the C40) and in the case of the XC40 specifically comparing vehicles which have both electric and ICE options within the same model range (Egeskog *et al.*, 2020; Evrard *et al.*, 2021).

The results of these were publicly made available but on closer examination did not fully account for transportation activities in the life cycle assessments[52]. The reports revealed contact details of the lead author who coordinated and lead these LCA's and contact was made with this person to enquire if access to collect primary data might be possible. This request was declined although interest was expressed in the eventual outcome of this research being conducted. However, even if this access had been allowed it would likely have proved unfeasible to use this access from resource point of view.

Notwithstanding the above, the well documented and detailed XC40 LCA (Egeskog *et al.*, 2020) has been used as a useful benchmark and discussion for this research and noted accordingly in sections that follow.

[53] As has been done in this research – see section 4.5.

the way they are used in this research (this will be highlighted where the data sources are discussed individually).

Lastly – as is the case in this research – where the contribution to knowledge rests not on the uniqueness of the data collected but on the results of modelling the data, secondary data was a preferable choice to using primary data.

Finding a complete data set for this research did however prove challenging as researchers do not in general share their data sets, and where they do, it may not span the breadth of this research (as in the case of Notter et al (2010) and Ibarra-Gutierrez et al (2021) for example). Notwithstanding this, two potential sources of secondary data were identified for this research, which are discussed next.

4.4.3. Caresoft Global

Describing themselves as a “market challenger” (Caresoft Global, 2021), Caresoft Global are a company which specialise in - among other activities - completely dismantling EVs to provide what is known as a “teardown analysis”, documenting - *inter alia* - materials used, weight and functionality of individual parts. This information allows companies to benchmark their own products with those of competitors.

Access was gained to the full vehicle tear down secondary data of a Tesla Model X and permission was obtained to use this data for this research. While this data appeared initially to be suitable for this research, closer analysis of the data revealed that the components’ materials were not consistently documented and, in many cases, absent from the data. Thus, unfortunately this potentially excellent source of data was ultimately not suitable.

Note however that even if it was suitable, Caresoft Global specialise in EVs and thus data for an ICE would still need to be found.

4.4.4 Argonne National laboratory – the GREET model and database.

Upon studying the LCA literature, it was noted that the GREET life cycle models and accompanying data sets developed by Argonne National Laboratory are frequently cited - some examples of which are mentioned in literature view chapter.

Argonne National Laboratories is a research facility of the United States Department of Energy, employing over 3500 staff and provides research facilities in a variety of disciplines which include the “Energy Systems and Infrastructure Analysis Division” which specialise - *inter alia* - in Life Cycle Analysis (Wang, 2022; Argonne National Laboratory, 2023).

Described as “the gold standard for life-cycle analysis of technologies and energy systems” and available for open access use[54], their GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) models provide thorough LCA tools which allow a user to perform LCA on over 80 types of vehicle covering over 65 materials used in vehicle production across all four major transport modes (road, rail, marine and air). It allows the user to assess energy consumption, fossil fuel use, greenhouse gas emissions (and other air pollutants) as well as water consumption if desired (Argonne National Laboratory, 2020). As at 2022, there are over 50 000 registered GREET users globally, with approximately half of which are from academia and education (Wang, 2022).

Among the tools available are two models known as “GREET1” and “GREET2” models. GREET1 focuses on fuel cycle analysis or “well two wheel” modelling of transportation fuels. The second model - GREET2 - specifically considers the vehicle manufacturing life cycle.

While these tools allow for in-depth in depth “cradle to gate” LCA of several types of vehicle - close scrutiny of the underlying data upon which the model draws revealed that “cradle to gate” *transportation* emissions are only occasionally found in the data – further re-enforcing the potential contribution to knowledge that this research provides.

Importantly, the underlying data sets of the GREET2 model are also made publicly available. This includes comprehensive data on materials used in each subsystem as well as the comparative weights of material in each case, making this data set ideal for the modelling undertaken for this research. Moreover, this data is available for a variety of ICE, hybrid and electric vehicles of varying sizes. Supporting this data is extensive documentation and reporting which outlines in detail the methodology used to derive this data. This documentation provides an excellent starting point for modelling the transport emissions as it outlines the supply chains which underpin the values they have calculated for energy of manufacture and materials extraction which are provided in their results (but, as noted above transportation is largely omitted from this documentation).

As noted in section 4.4.2. above, a potential risk of using secondary data is that it may have been originally collected for a purpose other than its “secondary” application, and may contain bias or subjectivity, not accounted for in its secondary application. However in the case of the GREET database, it has been specifically collected for the purpose of Life cycle assessments, and its results are objective and measurable (example weights measured and

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[54] registration is required

materials identified) thus negating the above risks of secondary data because it is used in this research for exactly the purpose for which it was gathered.

Thus, due to the suitability, credibility and comprehensiveness of this data set, it was selected for the modelling undertaken in this research.

4.4.5. The Volvo XC40 case study.

In order to address the second research question, a life cycle assessment case study is needed which addresses the carbon emissions from the other cradle to gate activities and which is compatible with the case study modelled in this research[55]. Only one life cycle assessment was found which satisfied the requirements of this research - published by Volvo which documents their XC40 passenger vehicle's life cycle, and thus it was used for this research. Please see Section 7.2.1 which provides a comprehensive justification of this choice of case study.

4.5. Selection of Data

This subsection describes the decisions taken and rationale for the data used in modelling as well as a summary of sources used in this modelling.

Saunders et al (2019) provide guidance and criteria to ensure credibility of data sources which include evaluating the authority of the data source, transparency of methodology, and objectivity of the information. They advise that prioritizing peer-reviewed data from reputable institutions further ensures reliable and relevant information. These criteria have been applied when selecting data for this modelling.

As noted above (in section 4.3.1.) transportation carbon emissions are dependent on:

- the weight being transported
- the emissions factor of the transportation mode used
- the distance covered.

Discussing each in turn, the specific data source(s) chosen for each of these are described below.

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[55] Pls see the introductory paragraphs of section 7.2. which provide the rational for this requirement.

4.5.1. Weight of material: The GREET2 Data Sets Chosen

Having identified the GREET2 sources of data (in section 4.4.4 above) the next step was to identify the specific subsets of data required to do the modelling. As noted above, the data for several vehicles is available spanning from ICEs, hybrid vehicles as well as EVs and an assortment of vehicle sizes large and small.

For this modelling the following vehicles were selected from the 2021 edition of the GREET2 data set for comparison: "ICEV: Conventional Material" and the "EV: Conventional Material".

Their overall weights are as follows:

Table 4.1: Overall weights of vehicles selected for modelling (Data Source: Argonne National Laboratory (2021)).

Vehicle Descriptor	Data subset	Weight (kg)
"ICEV: Conventional Material"	Car without battery	1444.00
"ICEV: Conventional Material"	Lead acid battery	16.33
"EV: Conventional Material"	Car without battery	1741.65
"EV: Conventional Material"	Li-ion battery	391.65

The detailed values for weights and materials of the subsystems of the above vehicles are documented in Appendix E "Weights by Subsystem for ICE and BEV from GREET Data Set".

Notably, the GREET dataset lists the vehicle batteries separately. This conveniently allows the impact of the battery system to be highlighted.

4.5.2. Transport Emissions data – "STREAM Freight Transport 2020".

For modelling accuracy, the transport emissions data need to match the scenario being modelled – in the case of this research this needs to be based on northern European roads and vehicles. As discussed in section 5.2.4. below, the data set entitled "STREAM Freight Transport 2020" report prepared by CE Delft (Klein et al., 2021) was selected as an excellent match for this research.

4.5.3. Distance covered data.

While the GREET and "STREAM Freight Transport 2020" data sets provide consistent and accurate figures for materials used and emissions factors across all the elements being modelled, no single data source was found which provides the needed information to model the distance covered for each material on each leg of the journey from the "cradle to gate" scenario being modelled.

Thus, a combination of the following sources were used for data, as might be typical when collecting secondary data (Saunders, 2019):

- Published sources (including books, text books and peer reviewed journals)
- Government reports and figures (including European Union figures and reports)
- Research organisation reports and figures (example: Argonne National Laboratory)
- Trade organisation reports and figures (example: World Steel.org or the Aluminium Association)
- Company reports and figures
- Trade publications
- Commercial consultancies
- Specialist Websites (including websites which calculate shipping distances e.g. ports.com).

As far as possible, data has been used from the first five sources due to the increased credibility of these sources (Saunders, 2019). In every case the sources have been cited in the calculation sheets (as explained in detail in section 4.6.1.).

4.5.4. Summary of data sources utilised.

As noted above, various data sources were used for the modelling - Table 4.2. below shows the different data sources utilised – arranged according to the categories described above.

Table 4.2. Analysis of data sources.

Source	Count
GREET Data Sets	2
STREAM Freight Transport 2020	1
Published sources	17
Government reports and figures	3
Research organisation reports and figures	11
Trade organisation reports and figures	21

Company reports and figures	14
Trade publications	6
Commercial consultancies	3
Specialist websites	7

The above table does not however account for the frequency with which a data source is utilised. For example, where several figures from a single source are used, this is not reflected, and similarly, where a figure is used multiple times in different situations, the priority of that type of source is not reflected. Thus, the reader might – incorrectly – conclude from table 4.2. that company reports and figures provided a significant portion of the data, whereas they were actually one of the least utilised sources in the modelling. Similarly, the reader might assume that the "STREAM Freight Transport 2020" data set was used only once, when it was in fact used in every calculation made.

Thus, to reveal the utilisation of the different sources, Table 4.3. below counts the number of times a data source was used in the modelling, providing a more representative picture.

Table 4.3. Analysis of data sources showing number of times used in modelling.

Source	Count
GREET Data Sets	65
STREAM Freight Transport 2020	458
Published sources	195
Government reports and figures	66
Research organisation reports and figures	75
Trade organisation reports and figures	199
Company reports and figures	38
Trade publications	163
Commercial consultancies	26
Specialist websites	211

The figures in table 4.3 confirm that the data is sourced from sources which would be considered "reliable and valid"[56] – such as from credible research organisations, publications and international trade organisations (evaluated using the criteria described by Saunders et al (2019), noted above).

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[56] Using Saunders et al (2019) terminology

4.6. Description of the Transportation Carbon Emissions (“TCE”) model built

Using the values in the above GREET data sets, the associated transportation CO_2 emissions were calculated separately for each material for each subsystem.

The model was constructed using Microsoft Excel which provided excellent computational power as well as customization and graphical representation facilities.

The paragraphs below provide a detailed guide to the model built and how it was used. The detailed sheets for every calculation are documented an Appendix C.

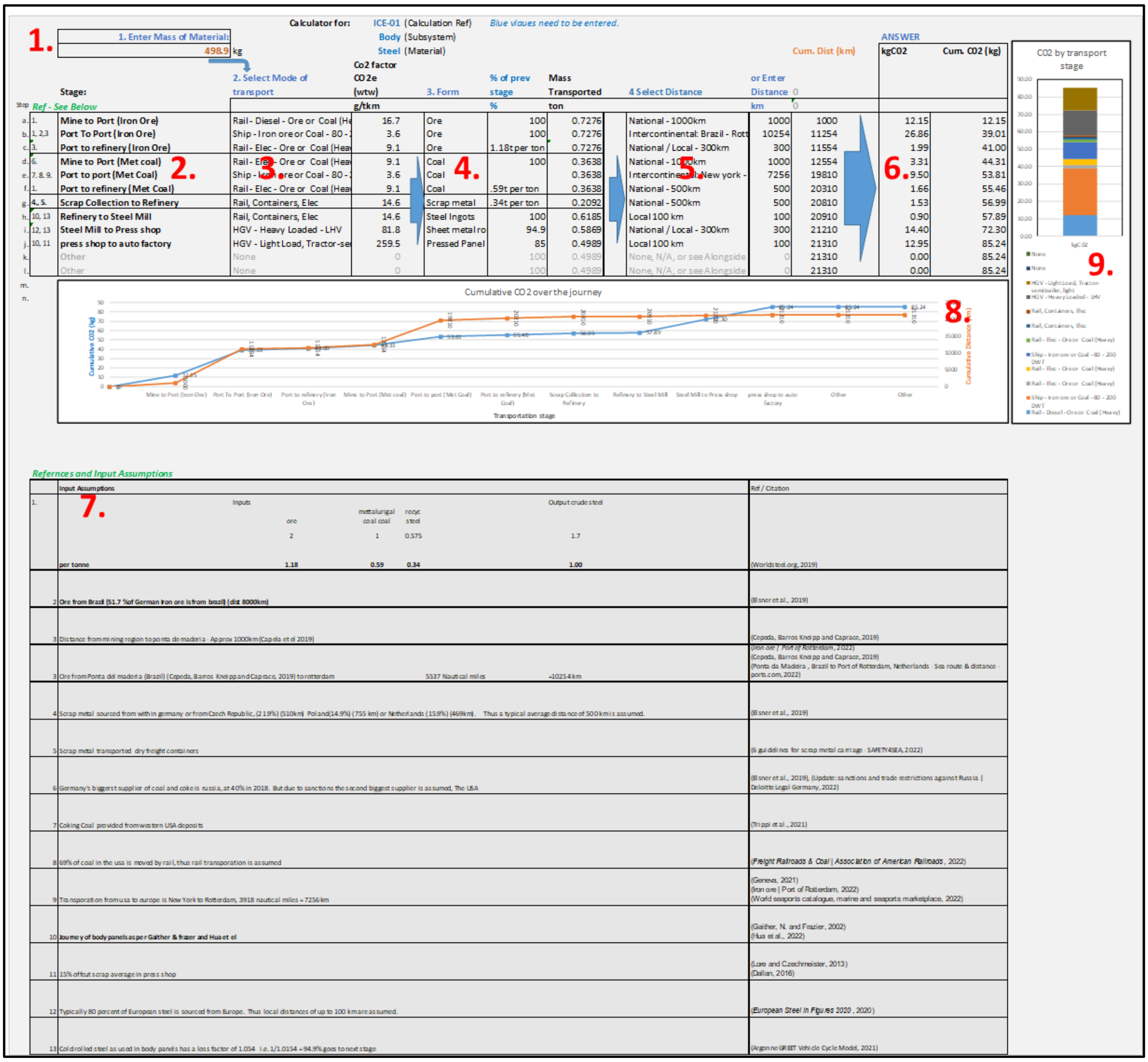
Note that the spreadsheets built span entire screens which - if simply reproduced below - would be difficult to read. Thus while a full screen view is shown by way of introduction below, the description is done by magnifying specific areas to improve readability.

4.6.1. Calculation Sheets

The transportation emissions for each material for each subsystem are calculated on a separate sheet in the model - a total of 29 sheets for an ICE vehicle and 38 sheets for an EV – these are all reproduced in Appendix C. Each has a reference number corresponding to its material and subsystem, also listed in Appendix C.

To illustrate the structure of each calculation sheet, sheet reference “ICE-01” is discussed below as an example (This sheet models the transportation emissions for *steel* components in the *vehicle body* subsystem for *an ICE vehicle*)

To allow for readability, separate areas of the calculation sheet are discussed individually, corresponding to the labels on figure 4-3. below. Red text labels are overlaid on the model layout corresponding to the description numbering below.



Calculator for: ICE-01 (Calculation Ref)
Body (Subsystem)
Steel (Material)

Blue vlaues need to be entered.

1. Enter Mass of Material: 498.9 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist (km)	kgC02	Cum. C02 (kg)
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (He	16.7	Ore	100	0.7276	National - 1000km	1000	1000	12.15	12.15
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 2	3.6	Ore	100	0.7276	Intercontinental: Brazil - Rott	10254	11254	26.86	39.01
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Hea	9.1	Ore	1.18t per ton	0.7276	National / Local - 300km	300	11554	1.99	41.00
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Hea	9.1	Coal	100	0.3638	National - 1000km	1000	12554	3.31	44.31
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 2	3.6	Coal		0.3638	Intercontinental: New york -	7256	19810	9.50	53.81
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Hea	9.1	Coal	.59t per ton	0.3638	National - 500km	500	20310	1.66	55.46
g.	4., 5.	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.2092	National - 500km	500	20810	1.53	56.99
h.	10, 13	**Refinery to Steel Mill**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.6185	Local 100 km	100	20910	0.90	57.89
i.	12, 13	**Steel Mill to Press shop**	HGV - Heavy Loaded - LHV	81.8	Sheet metal ro	94.9	0.5869	National / Local - 300km	300	21210	14.40	72.30
j.	10, 11	**press shop to auto factory**	HGV - Light Load, Tractor-se	259.5	Pressed Panel	85	0.4989	Local 100 km	100	21310	12.95	85.24
k.		Other	None	0		100	0.4989	None, N/A, or see Alongside	0	21310	0.00	85.24
l.		Other	None	0		100	0.4989	None, N/A, or see Alongside	0	21310	0.00	85.24
m.												
n.												

Refernces and Input Assumptions

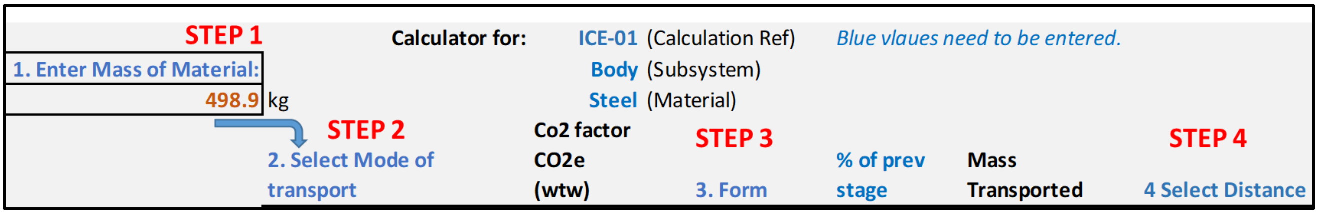
	Input Assumptions	Ref / Citation
1.	Inputs: ore 2; mettalurigal coal coal 1; recyc steel 0.575; Output crude steel 1.7 **per tonne** **1.18** **0.59** **0.34** **1.00**	(Worldsteel.org, 2019)
2	**Ore from Brazil (51.7 %of German iron ore is from brazil) (dist 8000km)**	(Elsner et al., 2019)
3	Distance from mining region to ponta de maderia - Approx 1000km (Capela et el 2019)	(Cepeda, Barros Kneipp and Caprace, 2019)
3	Ore from Ponta del maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to rotterdam 5537 Nautical miles =10254 km	*(Iron ore / Port of Rotterdam*, 2022) (Cepeda, Barros Kneipp and Caprace, 2019) (Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)
4	Scrap metal sourced from within germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500km is assumed.	(Elsner et al., 2019)
5	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
6	Germany's biggerst supplier of coal and coke is russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA	(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)
7	Coking Coal provided from western USA deposits	(Trippi et al., 2021)
8	69% of coal in the usa is moved by rail, thus rail transporation is assumed	(*Freight Railroads & Coal | Association of American Railroads*, 2022)
9	Transporation from usa to europe is New York to Rotterdam, 3918 nautical miles = 7256 km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Journey of body panels as per Gaither & frazer and Hua et el**	(Gaither, N. and Frazier, 2002) (Hua et al., 2022)
11	15% offcut scrap average in press shop	(Lore and Czechmeister, 2013) (Dallan, 2016)
12	Typically 80 percent of European steel is sourced from Europe. Thus local distances of up to 100 km are assumed.	(*European Steel in Figures 2020*, 2020)
13	Cold rolled steel as used in body panels has a loss factor of 1.054 i.e. 1/1.0154 = 94.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)

Figure 4-3: Layout of calculation sheet.

The areas of the layout can be described as follows:

1. Sheet Title and Reference
2. Supply chain stages
3. Mode of transport
4. Material form and weight transported
5. Distance transported
6. Calculation results – numerical
7. Comments and References
8. Cumulative CO_2 emissions across the journey
9. Summary of CO_2 emissions by transportation stage

Note that the model is laid out to allow the user to sequentially input information for each step of the supply chain leg being considered, as shown in fig 4-4.



STEP 1
Calculator for: ICE-01 (Calculation Ref) *Blue vlaues need to be entered.*
1. Enter Mass of Material: Body (Subsystem)
498.9 kg Steel (Material)
STEP 2
2. Select Mode of transport
Co2 factor CO2e (wtw)
STEP 3
3. Form
% of prev stage
Mass Transported
STEP 4
4 Select Distance

Figure 4-4: Steps to input information to the TCE model

The user inputs information for each line of the calculation as follows:

STEP 1 First, the user enters the mass, material and the subsystem being calculated as well as the corresponding calculation reference.

Next, the user enters details for each leg of the supply chain journey. The user is able to enter (or select) values for the following:

STEP 2 - Mode of transport corresponding to the weight, distance and packing density of freight being transported.

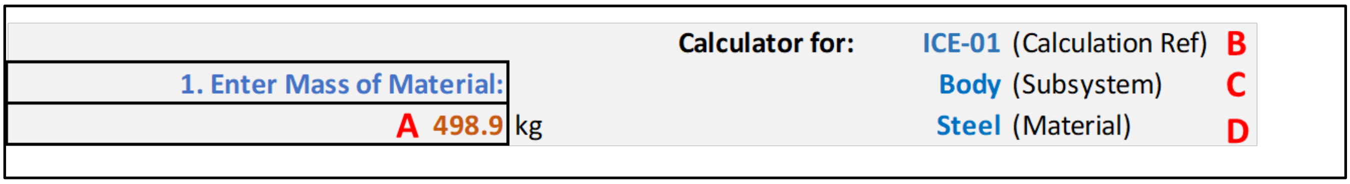
STEP 3 - Form of material being transported

STEP 4 - Distance of each leg of the journey.

Steps 2-4 are repeated for each leg of the supply chain.

The areas of the calculation sheets are described in detail next.

4.6.1.1 Sheet Title and Reference.



Calculator for: ICE-01 (Calculation Ref) B
1. Enter Mass of Material: Body (Subsystem) C
A 498.9 kg Steel (Material) D

Figure 4-5: Sheet Title and Reference

The applicable information from the “Vehicle weights and materials by subsystem” data set (Appendix E) are entered into each sheet as follows:

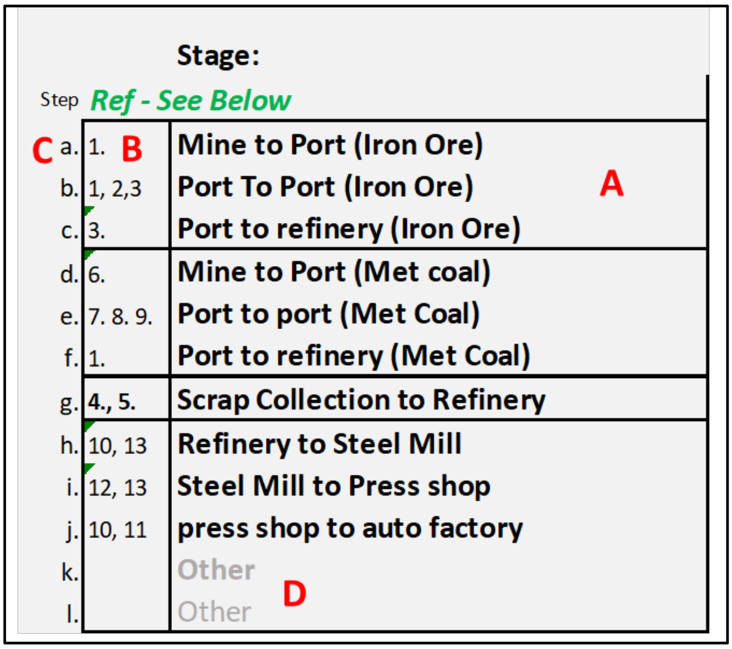
A. **Mass of material.** The mass of the material being modelled is entered here.

B. **Calculation Reference**. Each sheet has a calculation reference which cross references the calculation to the results summary page.

C. **Subsystem.** Vehicle subsystem is entered here

D. **Material.** The material of the subsystem being modelled is entered here.

4.6.1.2. Supply chain stages



Step	Ref - See Below	Stage:
a.	1.	Mine to Port (Iron Ore)
b.	1, 2,3	Port To Port (Iron Ore)
c.	3.	Port to refinery (Iron Ore)
d.	6.	Mine to Port (Met coal)
e.	7. 8. 9.	Port to port (Met Coal)
f.	1.	Port to refinery (Met Coal)
g.	4., 5.	Scrap Collection to Refinery
h.	10, 13	Refinery to Steel Mill
i.	12, 13	Steel Mill to Press shop
j.	10, 11	press shop to auto factory
k.		Other
l.		Other

Figure 4-6: Supply Chain Stages

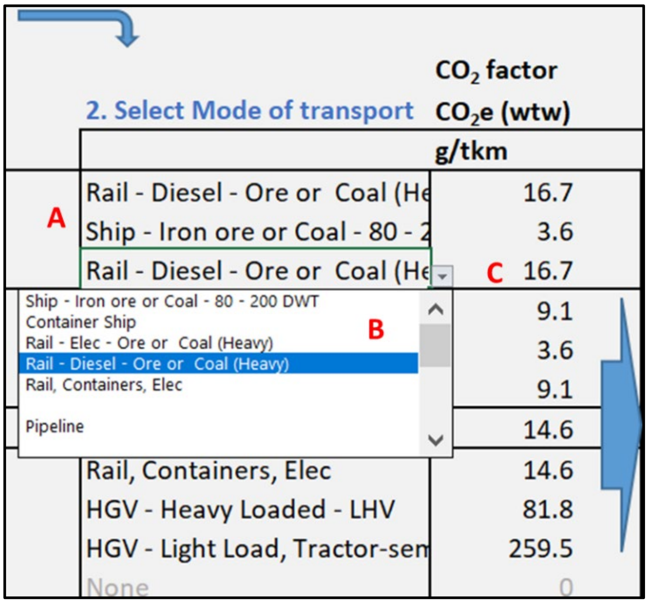
This area allows the user to provide the narrative of the journey taken by the materials in the supply chain journey.

The areas of the layout can be described as follows:

A. Here, journey of each step of the supply chain of each material is listed. Each different raw material is bordered with a solid line. In the above example iron ore, metallic coal and scrap metal (each with a solid border) are transported to a steel refinery. After that, the steps of the refined steel (steps h. , i., and j.) are documented from the refinery to the automotive factory.

B. Each step of the journey is supported by a citation and / or comment as needed. These are listed as footnotes below (see section 4.6.1.7), and area “B” directs the user to the corresponding citation(s), comments or assumptions underpinning the values in that row.
C. The journey of the supply chain is represented diagrammatically when discussed in section 5.3. below. The letters here correspond to the supply chain diagrams in that section.
D. Lines of the sheet not used are shown in grey text.

4.6.1.3. Mode of transport



2. Select Mode of transport	CO$_2$ factor CO$_2$e (wtw) g/tkm
Rail - Diesel - Ore or Coal (He	16.7
Ship - Iron ore or Coal - 80 - 2	3.6
Rail - Diesel - Ore or Coal (He	16.7
	9.1
	3.6
	9.1
	14.6
Rail, Containers, Elec	14.6
HGV - Heavy Loaded - LHV	81.8
HGV - Light Load, Tractor-sem	259.5
None	0

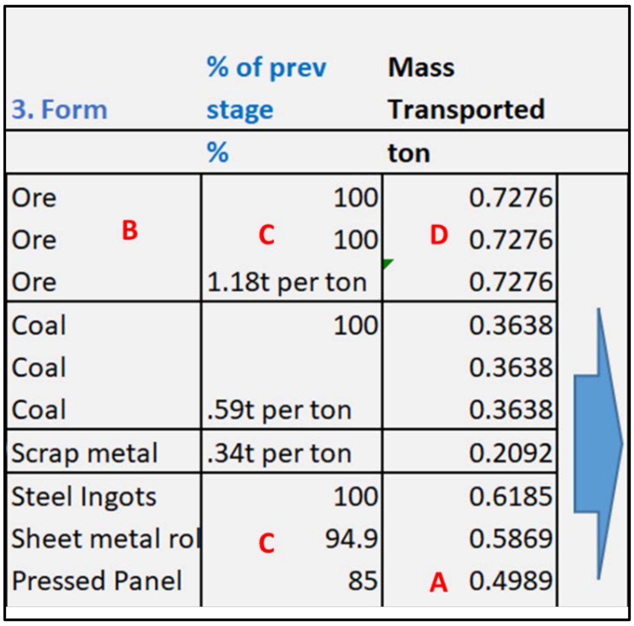
Figure 4-7: Mode of transport selection

This area allows the user to select the mode of transport associated with any leg of the supply chain journey.

The areas of the layout can be described as follows:

A. The mode of transport associated with each journey is recorded here.
B. Clicking on each cell activates a “drop down” box with a choice of modes of transport.
C. Once the appropriate mode of transport is selected the corresponding carbon emissions factor is automatically provided for the calculation.

4.6.1.4. Material form and weight transported



3. Form	% of prev stage	Mass Transported
	%	ton
Ore	100	0.7276
Ore	100	0.7276
Ore	1.18t per ton	0.7276
Coal	100	0.3638
Coal		0.3638
Coal	.59t per ton	0.3638
Scrap metal	.34t per ton	0.2092
Steel Ingots	100	0.6185
Sheet metal rol	94.9	0.5869
Pressed Panel	85	0.4989

Figure 4-8: Material form and weight transported.

As materials move through the supply chain they may change form and in some cases a percentage of the material at each stage is lost due to scrap or refining. This area allows the user to document the evolution of the material as it progresses through the supply chain journey. The areas of the layout can be described as follows:

A. This is the final mass of the material which ultimately is in the subsection, in tons[57]. It corresponds to the figure entered in the “Sheet Title and Reference” area discussed in section 4.6.1.1 above.

B. The form of the material transported, for example “ore” or “steel ingots” is recorded here. This information is needed to confirm the packing density and thereby select the appropriate mode of transport in section 4.6.1.3. above.

C. The user can enter the percentage of material which progresses to the next leg of the journey. Alternately the user can note the proportion of each material that is used in the next step.

D. Using the percentage (entered above) or by custom formula, the actual mass transported in this leg of the journey is calculated in these cells. This value is used for the emissions calculation.

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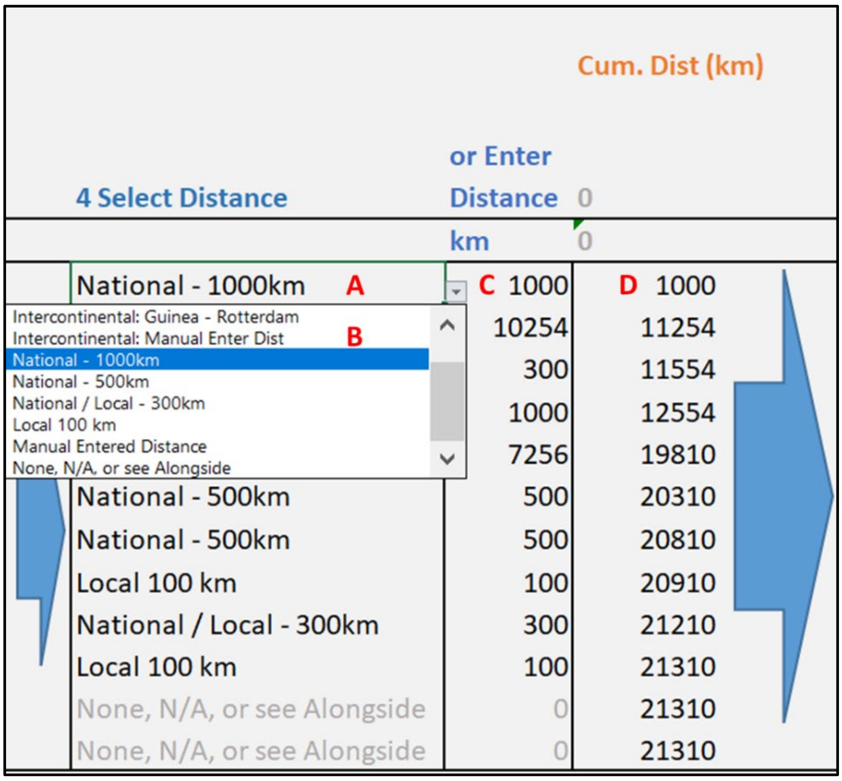
[57] tonnes are the unit required in this value because the transport emissions values in the preceding section are in units of “tonne kilometres”.

4.6.1.5. Distance transported



		Cum. Dist (km)
4 Select Distance	or Enter Distance 0	
	km 0	
National - 1000km	1000	1000
	10254	11254
	300	11554
	1000	12554
	7256	19810
National - 500km	500	20310
National - 500km	500	20810
Local 100 km	100	20910
National / Local - 300km	300	21210
Local 100 km	100	21310
None, N/A, or see Alongside	0	21310
None, N/A, or see Alongside	0	21310

Intercontinental: Guinea - Rotterdam
Intercontinental: Manual Enter Dist
National - 1000km
National - 500km
National / Local - 300km
Local 100 km
Manual Entered Distance
None, N/A, or see Alongside

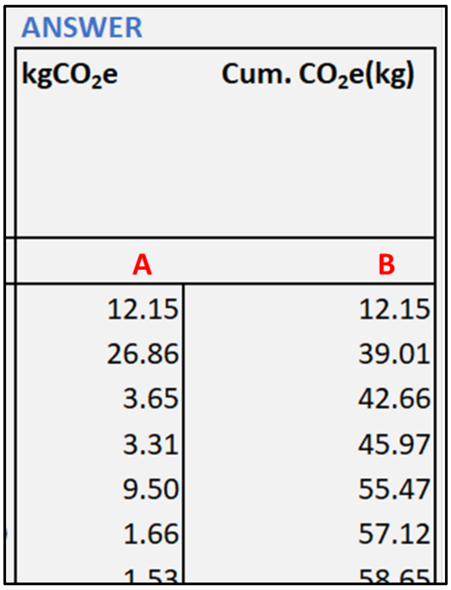
Figure 4-9: Distance transported.

This section allows the user to enter the distance travelled in each leg of the journey or alternately select assumed distances as appropriate.

The areas of the layout can be described as follows:

A. The distance of each journey is entered here.
B. Clicking on each cell activates a “drop down” box with default choices of distances which are discussed below in section 5.2.1..
C. Once the appropriate distance is selected the corresponding value is automatically populated here. Alternately the user can enter a specific distance if desired.
D. The cumulative distance covered by the supply chain journeys is automatically calculated in this column. Note that this however is purely for discussions’ sake if it might be needed – it does not form part of any CO_2 calculation.

4.6.1.6. Calculation results – numerical



kgCO$_2$e	Cum. CO$_2$e(kg)
12.15	12.15
26.86	39.01
3.65	42.66
3.31	45.97
9.50	55.47
1.66	57.12
1.53	58.65

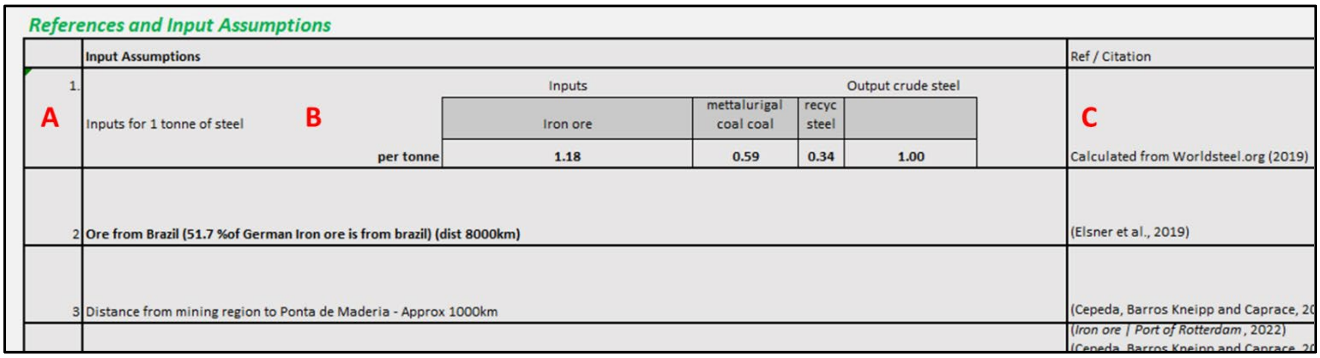
Figure 4-10: Calculation results – numerical

This area presents the results of the calculations using the formula documented in section 4.3.1., which is automatically performed based on inputs in the preceding sections.

The areas of the layout can be described as follows:

A. The CO$_2$e emissions for each section of the journey are calculated in this column.
B. The cumulative CO$_2$e emissions for each section of the journey are calculated in this column. The last figure in this column is used in the results summary sheet.

4.6.1.7. Comments and References



References and Input Assumptions

	Input Assumptions	Ref / Citation
1.	Inputs for 1 tonne of steel Inputs: Iron ore, mettalurigal coal coal, recyc steel; Output crude steel per tonne: 1.18, 0.59, 0.34, 1.00	Calculated from Worldsteel.org (2019)
2	**Ore from Brazil (51.7 %of German Iron ore is from brazil) (dist 8000km)**	(Elsner et al., 2019)
3	Distance from mining region to Ponta de Maderia - Approx 1000km	(Cepeda, Barros Kneipp and Caprace, 2 (*Iron ore | Port of Rotterdam*, 2022)

Figure 4-11: Comments and references

As noted above each leg of the journey is supported by a brief explanation, assumptions and / or citations. This area documents them.

The areas of the layout can be described as follows:

A. The reference number as corresponding with the above (area B described in section 4.6.1.1.).
B. Comments and assumptions made
C. Citation(s) supporting comments and assumptions

4.6.1.8. Cumulative CO_2 emissions across the journey

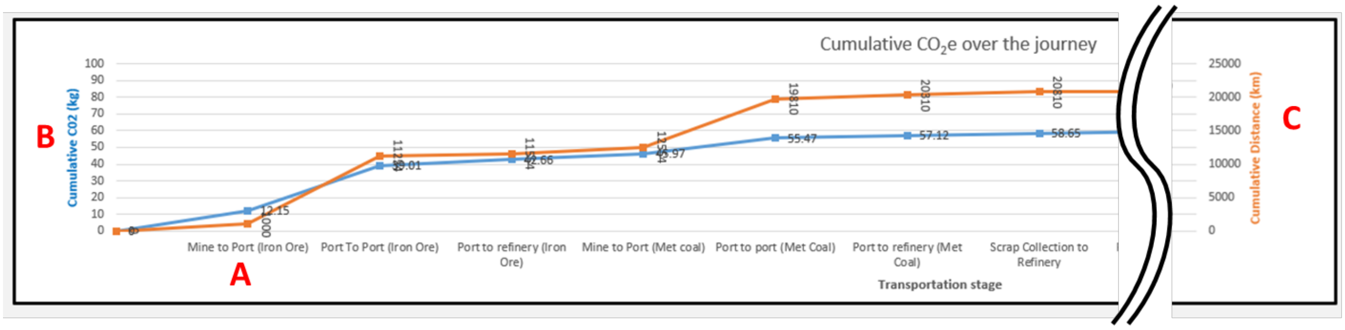


Figure 4-12: Cumulative CO_2 emissions across the journey (section removed for readability).

This chart helps to visualise the increasing CO_2 emissions and distance as each journey's contribution is added.

The areas of the layout can be described as follows:

A. The leg of the journey shown here
B. Cumulative CO_2 emissions shown by blue line
C. Cumulative distance shown by orange line

4.6.1.9. Summary of CO_2 emissions by transportation stage

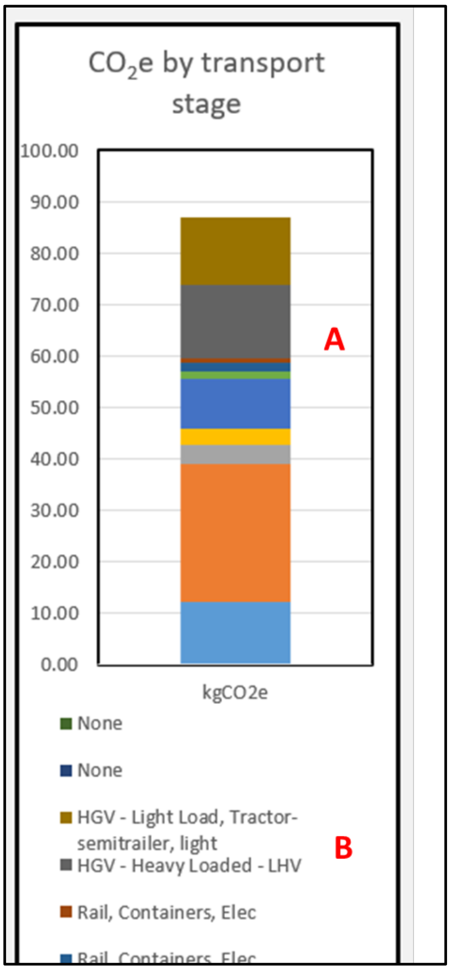


Figure 4-13: Summary of CO_2 emissions by transportation stage

This area enables the reader to visually note the relative CO_2 emissions contribution of each phase of the transportation. For example, in the case shown in figure 4-13, this bar chart highlights how much more emissions the heavy goods vehicles contribute compared to the rail journeys which are across similar distances.

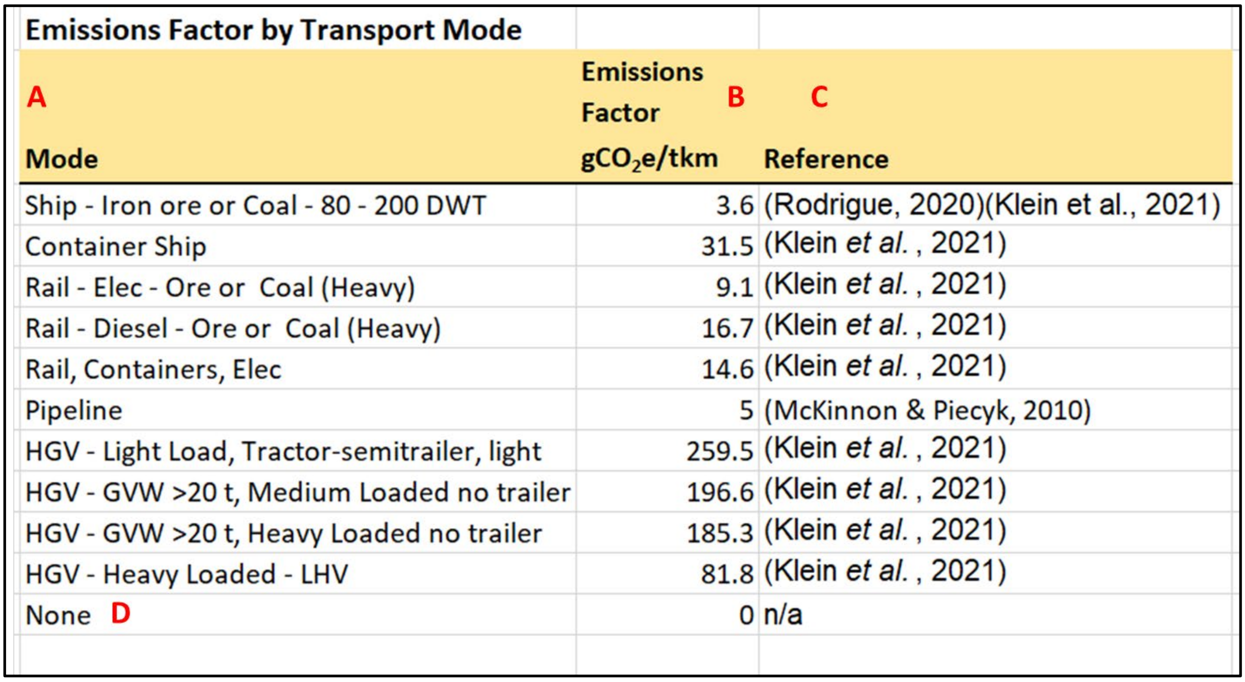
The areas of the layout can be described as follows:

A. Relative contribution of each leg of the journey shown here
B. Corresponding description. Note that lines not used in the calculation are listed as “none” with a zero value

4.6.2. Shipping Input Data

In Sections 4.6.1.5. and 4.6.1.3. above, “drop down boxes” allow the user to quickly select values for those cells, for commonly used values. The subsections below outline the “Shipping Input Data” information embedded in the calculation spreadsheets.

4.6.2.1 Emissions Factor by Transportation Mode



Emissions Factor by Transport Mode

Mode	Emissions Factor gCO_2e/tkm	Reference
Ship - Iron ore or Coal - 80 - 200 DWT	3.6	(Rodrigue, 2020)(Klein et al., 2021)
Container Ship	31.5	(Klein *et al.* , 2021)
Rail - Elec - Ore or Coal (Heavy)	9.1	(Klein *et al.* , 2021)
Rail - Diesel - Ore or Coal (Heavy)	16.7	(Klein *et al.* , 2021)
Rail, Containers, Elec	14.6	(Klein *et al.* , 2021)
Pipeline	5	(McKinnon & Piecyk, 2010)
HGV - Light Load, Tractor-semitrailer, light	259.5	(Klein *et al.* , 2021)
HGV - GVW >20 t, Medium Loaded no trailer	196.6	(Klein *et al.* , 2021)
HGV - GVW >20 t, Heavy Loaded no trailer	185.3	(Klein *et al.* , 2021)
HGV - Heavy Loaded - LHV	81.8	(Klein *et al.* , 2021)
None	0	n/a

Figure 4-14: Emissions Factor by Transportation Mode

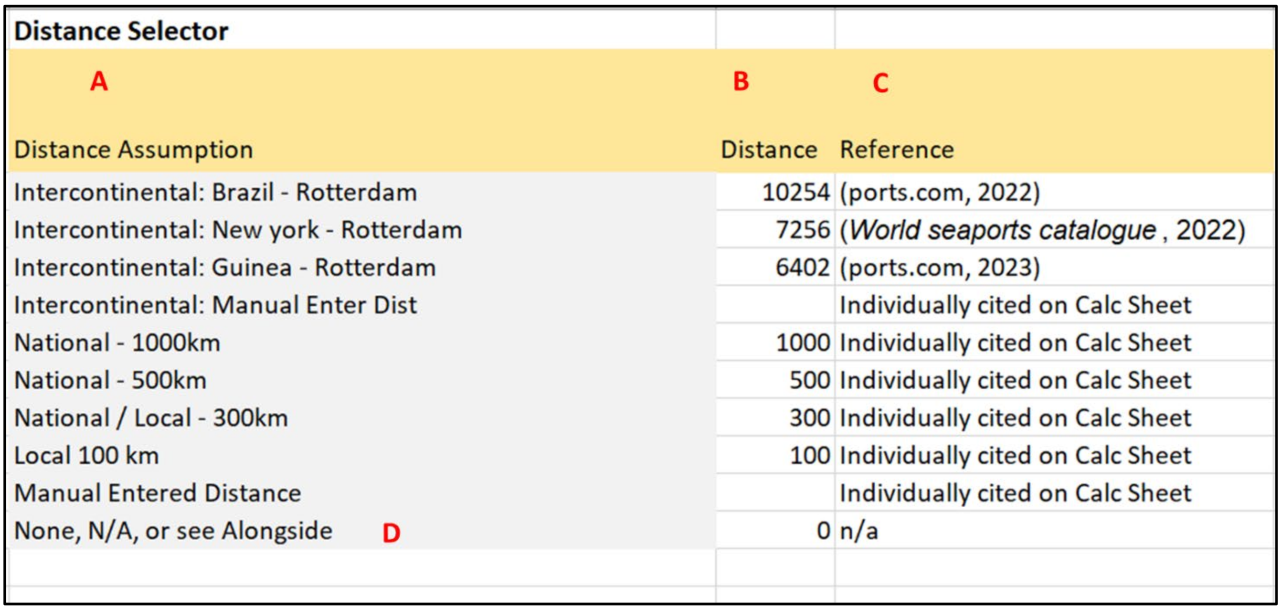
These figures underpin the drop down selection values from section 4.6.1.3. above.

The areas of the layout can be described as follows:

A. Commonly used values for the drop down options
B. Corresponding emissions factor
C. Citation for emissions factor
D. If user wishes to enter their own value, or if the line is not used, “none” can be selected.

Please see section 5.2.4. “Choice of Transportation Emissions Factors Data” below which discusses the source of data used for the various transportation modes.

4.6.2.2. Distance Selector Values



Distance Selector

Distance Assumption	Distance	Reference
Intercontinental: Brazil - Rotterdam	10254	(ports.com, 2022)
Intercontinental: New york - Rotterdam	7256	(*World seaports catalogue* , 2022)
Intercontinental: Guinea - Rotterdam	6402	(ports.com, 2023)
Intercontinental: Manual Enter Dist		Individually cited on Calc Sheet
National - 1000km	1000	Individually cited on Calc Sheet
National - 500km	500	Individually cited on Calc Sheet
National / Local - 300km	300	Individually cited on Calc Sheet
Local 100 km	100	Individually cited on Calc Sheet
Manual Entered Distance		Individually cited on Calc Sheet
None, N/A, or see Alongside	0	n/a

Figure 4-15: Distance Selector Values

These figures underpin the drop down selection values from section 4.6.1.5. above.

The areas of the layout can be described as follows:

A. Commonly used values for the drop down options
B. Corresponding distance
C. Citation for value
D. If user wishes to enter their own value, or if the line is not used, this option can be selected.

4.6.3. Results Sheet

The outputs and reference numbers for each calculation sheet are automatically displayed on a combined results sheet. This sheet is reproduced in Appendix B and is self-explanatory and therefore not discussed here, although excerpts of it may be reproduced in the results and discussion section.

4.7. Testing and Validation

In order to confirm the validity of the TCE model built, the results from the model have been checked against those calculated by two organisations' online emissions calculation facilities – namely the Swedish based "Network for transport measures" and the German based "EcotransIT World". Both are considered to be credible and are widely used outside[58] and within academia and cited in academic literature (Auvinen *et al.*, 2014).

As noted previously, both were considered as potential tools with which to model this research, but were found unsuitable as they don't allow for combining multiple supply chains, and don't allow for reducing weight of product as the supply chain continues, as they are designed to model single journeys.[59]

The "Network for transport measures" (NTM) is a Swedish based non-profit organisation established to provide an impartial facility to "enable credible calculations of transports' environmental, climate and energy performance" (transportmeasures.org, 2017). Two versions for their NTMCalc 4.0 tool are available – a "basic" edition which is free of charge and an "advanced" version which requires a paid membership to NTM – the basic version was used for validating this model.

Based in Germany, EcotransIT World describes itself as a "project" which "identifies the environmental impacts of freight transportation in terms of direct energy consumption and emissions". It is supported by various research institutions as well as a number of national European rail companies (ecotransit.org, 2017). Of specific interest is that it highlights in its documentation that it uses the same formula and method of calculating emissions as the one described by McKinnon & Piecyk (2010) and used in this research, (described in section 4.3.).

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[58] For example in the Volvo XC40 LCA (Egeskog *et al.*, 2020) which is discussed and used as a benchmark later in this document.

[59] While they could theoretically be used for calculating the individual journeys documented in this research it is practically not feasible. This is because this would require manually entering the individual parameters of every journey modelled in this research (after having separately accounted for combining supply chains and / or reducing weight of product as the supply chain continues) in to their website and then manually recording the results for each journey – an approach unfeasibly time consuming and at risk of error due to the high level of manual transferring of inputs and results.

4.7.1 Comparison of results

A number of “single leg” journeys were entered into the three calculators and the results were - in every case - in close agreement. To illustrate this point, the results are shown in Fig. 4-16 below. The journey represents a hypothetical journey of 1 tonne of generic material from the port of Santos in Brazil to Port Talbot in the UK, across three modes of transport: sea, rail and road respectively . It assumes that this is transported in a container – this is chosen to obtain a “like-for like” comparison between all three models – all of which allow for transportation by shipping container (this constraint was needed to accommodate comparison with the NTMCalc calculator which has limited opportunity for the user to modify the packing densities and other parameters (EcotransIT allows for more customisation)).

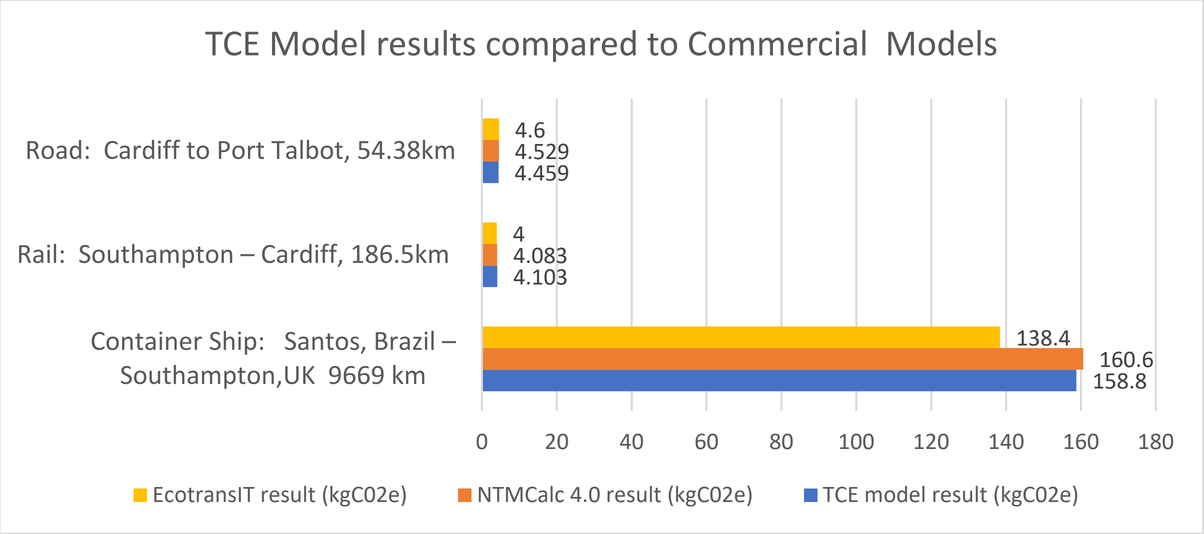

Figure 4-16. CO_2e Emissions as Calculated by three different models

Table 4.4. below re-states these results, also providing the percentage variation between each model’s results.

Table 4.4: CO_2 equivalent emissions as calculated by three different models

Mode of transport	**Journey:**	**TCE model result ($kgC0_2e$)**	**NTMCalc 4.0 result ($kgC0_2e$)**	**% difference NTMCalc-TCE**	**EcotransIT result ($kgC0_2e$)**	**% difference EcotransIT - TCE**
Ship, (container)	Santos, Brazil – Southampton , UK 9669 km	158.8	160.6	+1.0%	138.4	-14.7%
Rail	Southampton – Cardiff 186.5km	4.103	4.083	-1.0%	4.0	-2.5%
Road	Cardiff to port Talbot 54.38 km	4.459	4.529	+1.6%	4.6	+3.2%
Total for journey		167.362	169.212	+1.1%	147.0	-13.9%

As can be seen from the above, the TCE model produces results which are very close to NTMCalc and of similar magnitude to EcotransIT. This is accounted for by the fact that NTMCalc lists its assumed emission factors on the website, allowing the same values to be used in the TCE model - the emissions factors for EcotransIT were not found on its website.

The greater variance found with the EcotransIT numbers is attributed to the fact that instead of inputting a generic distance for the journey (as allowed by NTMCalc, and TCE) they require the geographical start and end point, and the distance is calculated automatically. While the same distance was then used on all three models, EcotransIT takes into account local variabilities of well-to-tank emissions for different countries, whereas the TCE and NTMCalc models use a generic value incorporated into the emissions factor for that mode of transport.

Notwithstanding the above (and taking the reasons for the variations into account) the TCE model is deemed to be satisfactory in terms of accuracy: in every case of an individual transport journey tested it was within 5% of the commercial models, and in instances where it was NOT (explained above), the result fell between the two values (for example in the shipping leg shown above).

Since the purpose of the TCE model will be to *compare* the two types of vehicle modelled, the *relative* impact of these choices will be of concern. As long as the values used in the model are consistent in every scenario tested, the results will remain meaningful.

4.8. Modelling accuracy and “cut-off rules”

While the testing against commercial modelling tools has shown that the TCE model’s results align with their results, in neither case did it produce exactly the same results. Moreover, these two respected commercial great tools varied from one another considerably in some cases.

Thus, it must be accepted that the results obtained from this type of modelling are not perfectly accurate – indeed McKinnon and Piecyk (2010) describe results achieved from an activity based approach as providing merely a “rough estimate” of carbon emissions. This can be attributed to the generic nature of the CO_2 emissions factor associated with different modes of transport. These emissions factors will by their very nature be *typical* emissions factors of the mode of transport being considered - there is no feasible way to determine the exact vehicle model (and performance characteristics) that transported the individual product being modelled.

Thus, the generic nature of the CO_2 emissions factors will limit the accuracy of any modelling done via the activity based approach. Indeed, this accounts for the differences in results seen between the commercial modelling tools noted above. Even in the best cases where the TCE model was compared with NTM calcs results there was as much as a 2.6% spread across different modes of transport even though the final result (where the positive and negative spreads cancelled one another out) was within 1.1%. However when compared to the EcotransIT model the variance was over 15% in some journeys.

With this being the case, it also therefore places a limit on the extent to which extremely accurate inputs to the model are useful or meaningful and it is useful to define “cut off rules” to avoid pursuing a level of accuracy which will not contribute meaningfully to the result.

Therefore, in line with accepted LCA modelling practice (for example as is used in the GaBi commercial LCA software[60] which is ISO 14044: 2006 compliant (Kupfer *et al.*, 2021)) a 1% cut-off will be applied to inputs to this modelling, and where inputs of a given material to the model comprise <1% of the overall product mass or <1% of a journey distance, they will be omitted unless there is a specific reason for their inclusion.

The effect of this is that the results obtained may have a corresponding level of error or uncertainty. This will have differing impacts on the results depending on if the cutoff rule is applied to distance or to product mass weight.

In the case of *distance*, if for example a product's transportation carbon emissions are calculated to be 100.00 kg of CO_2 after having applied the cutoff rules for a "cradle to gate" journey, this means that the actual emissions may be as much as 100.99 kg if a distance of up to 1% was omitted. Therefore, the results of this model may under represent the overall carbon emissions to this extent. However, since this research is to *compare* the transportation emissions for the two types of vehicle to the same location, this error will be found in both vehicles' figures, to the same extent. Thus despite this, a meaningful comparison can still be made despite the applied cutoff rules.

In the case of the *mass* of individual materials, this may give differing results, as the two vehicles' materials are not identical and the materials to which the cutoff rules are applied are not necessarily the same. The numerical impact of this is recorded in table 6.8. below in the results chapter of this document, where it is shown that the weight of material not modelled due to the cutoff rules being applied is of a similar magnitude (and also in line with other LCA's in the literature). As above, it therefore suggests that the model may under represent the carbon emissions accordingly in each case. Thus, if the materials representing less than 1% were taken into account we would expect the results of the model to be increased accordingly albeit of very small magnitude compared to the rest of the vehicle (see Table 6.8). Again however, since the research seeks to *compare* the emissions of the two types of vehicle – and this occurs in both types of vehicle and to a similarly small magnitude compared to the rest of the vehicle - the results remain meaningful for the purposes of comparison.

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[60] The GaBi LCA software was in turn used in the Volvo XC40 LCA (Egeskog *et al.*, 2020) noted above.

4.9. Default Transportation mode choices.

Wherever possible, the modelling process uses supporting evidence when selecting transportation mode according to the freight being moved. However, where this information has not been available, Rushton et al's "Modal choice selection matrix" (Rushton, Croucher and Baker, 2017)[61] is used to guide the choice of transportation mode. It is reproduced – adapted for this research - below:

Table 4.5: Modal Choice matrix (adapted from Rushton et al (2017))

Size of order /Load	**Transportation Mode**			
100T	Road	Road / Rail	Rail/Sea	Sea
20T	Road	Road	Road / Rail	Rail/Sea
Pallet	Road	Road	Road / Rail	Rail Sea
	Short <300km	Medium <500km	Long <1000km	Very Long >1000km
	Delivery Distance			

Note that Rushton et al do not specify exact distances for their matrix other than to state that "very long" distances refer to thousands of kilometres. Thus, the values in this table have been added to correspond with their categories. The distances above have been chosen to be typical and representative of comparable supply chain distances found in the LCA literature and have been benchmarked against LCAs such as the one published by Notter et al. (2010) (who provide typical transportation emissions for isolated parts of a VW Golf).

Some of the categories in Rushton et al.'s matrix are however not applicable to this research (for example "parcel deliveries") and are omitted above.

4.10 A typical two stage supply chain from raw materials to assembly plant.

Because this model is constructed using secondary data it is seldom possible to have definitive information on how many steps of a supply chain are involved preceding the automotive factory gate.

However upon studying the LCA literature a trend is noted: many authors assume two stages in the supply chain between raw material availability and the factory gate. While there may be multiple stages recorded in the supply chain of the actual raw materials (for example steel parts in the GREET documentation (Burnham, A, Wang, M, Wu, 2006) or by

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[61] (discussed in section 3.9.1.2.d)

Hua et al (2019)), once the raw material is available, a “tier 2” supplier typically processes the raw materials into components which are then sent to a “tier one” supplier who uses the components to make sub-assemblies, which are then supplied to the auto manufacturer (see for example Deng Et al (2019)).

Thus, unless otherwise noted (for example in the case of steel vehicle body panels which are typically not sub assembled before reaching the automotive factory), the TCE model will assume the following supply chain as the default:

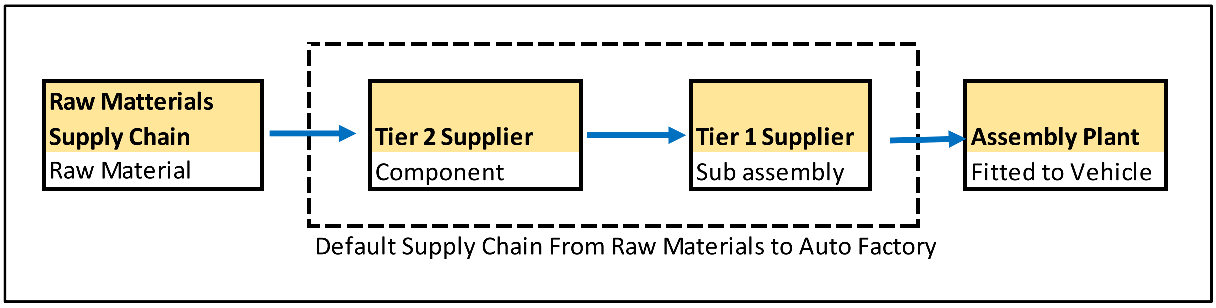

Figure 4-17: Default supply chain from raw materials to Automotive Factory (adapted from Deng et al (2019)).

4.11. Methodology Part 1 – Conclusion

This chapter has described the approach taken to modelling and the model built to address transportation carbon emissions in an automotive context to compare ICE and EVs.

However, thus far the model has complete flexibility as to the geographic location of manufacture as well as which supply chains supports the vehicle manufacturer. The next chapter discusses which case study is chosen as appropriate to meet the research aims and objectives.

5. METHODOLOGY PART 2 – CHOICE OF CASE STUDY AND SCOPE OF MODELLING

The TCE model described in the previous chapter can be used to evaluate automotive transportation carbon emissions from any geographical location where adequate information is available to do so.

However, in order to address the research questions posed, the case study selected for modelling needs to be sufficiently representative of actual automotive supply chains.

Thus, this section begins with a discussion supporting the choice of case study location and is followed by an overview of automotive supply chains which correspond to this choice of geographic location for the automotive assembly plant. Because adequately granular data indicating precise locations is not available, several assumptions need to be made for this modelling: the locations of the case study need to be such that the assumptions made remain credible.

5.1. Choice of Case Study – Vehicle Manufacture in Germany

When modelling this research, the choice of case study needs to be made in such a way as to minimise the uncertainty of the results.

The formula used for this modelling – discussed in section 4.3.1. - relies on three components: the mass being transported, the distance travelled, and the CO_2 emissions factor associated with the transportation used. Each will have a level of certainty or confidence associated with the values used, which are now considered in turn.

The mass being transported will have a very high level of confidence: as discussed in section 4.5. the values in the GREET data set are obtained by a rigid and objective method by the highly respected Argonne national laboratory and are widely used and cited in the LCA literature. Similarly, the CO_2 emissions for each mode of transport are well documented and the source used - the "STREAM Freight Transport 2020" report prepared by CE Delft - has been triangulated with other sources (discussed in section 5.2.4 below) and thus there is a high level of confidence in its values.

It is however in the transportation distances that potential uncertainty lies as there is no existing data set that can provide precise “cradle to gate” transportation distances for the materials flow from around the world to a specific manufacturing location. With this being the case, several assumptions need to be made regarding transportation distance, and thus the choice of location must be carefully chosen in order to ensure that the assumptions made remain valid.

Following a systematic process for selecting a location, Germany was chosen as a case study scenario for this research. The sections that follow describe the process by which this location was chosen.

5.1.1. Criteria for choosing a location to model

To construct a credible model, a location needs to be identified which enables assumptions made to reflect a feasible scenario with the least uncertainty.

When considering the choice of location to model, the following two criteria which minimise the uncertainty in transportation distances have been identified:

- **A significant, concentrated and established automotive industry** with significant capacity to produce both EVs and ICEs vehicles.

  As several of the supply chains modelled will be assumed to be similar for the two types of vehicle (for example steel used in vehicle bodies) the location chosen needs to have established capacity for manufacturing both types of vehicles.

  Secondly in the absence of primary data, a general assumption will be made that tier one suppliers will be within a certain (typical) distance from the automotive factory. For this to be credible a location for the automotive factory needs to be chosen where this scenario is highly likely.

- **Information availability:** to construct a credible model, it is essential to have as much information and specific secondary data available as possible. While peer reviewed academic publications are desirable as data sources, it was found that comparatively few academic publications provide useful secondary data. Therefore the availability of alternative information sources such as government statistics, trade bodies, industrial consultancies and trade publications is essential[62].

5.1.2. Regions meeting the above criteria.

Having established the criteria by which to choose a location, four global regions were identified which broadly meet the above criteria.

They are:

- The USA
- China
- Japan and / or South Korea
- Europe

These are discussed briefly in turn below:

5.1.2.1. The USA

Given that the GREET LCA model and database are American based and that their LCA values are based on American automotive manufacture, the USA would appear to be the obvious choice as much of the data is already available in the GREET database values. Moreover, it was found that the American government publishes extensive information and data on its automotive industry - in English - and this is supported by numerous industrial bodies and trade organisations. Furthermore, the American automotive industry is well established and produces significant volumes of both internal combustion and EVs, again making it appear to be the obvious choice.

Notwithstanding the above however, it was found that there was considerable geographic dispersion across locations in vehicle manufacture. Thus, without specific data on distances and supply chains to known automotive plants, there was not sufficient consistency to make reliable assumptions on distances between suppliers in the supply chain and the automotive plant.

Secondly it was found that the USA has extensive natural resources making it a feasible possibility that raw materials could be sourced from within the USA. However, it was found that - in reality - many supply chains rely on imported raw materials due to favourable

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[62] In the limited cases where useful figures are provided in academic publications they are often out of date and usually based on the alternative sources listed above anyway.

economic considerations. Given this potential paradox, sufficient data was not found to reliably assume that raw materials were sourced one way or the other (i.e. from within the USA or internationally) for any specific geographic location within the USA.

Given this uncertainty the USA was not chosen as the most reliable location to model.

5.1.2.2 China

Like the USA, it was found that China has an extensive automotive industry producing both internal combustion and EVs - indeed China was noted as having significant growth in producing EVs. However - like the USA - it was found that the automotive industry has considerable geographical dispersion across this very large country. Lastly, the availability of information published in English was not as widespread as in the case of the USA making it a less suitable location for building a reliable model for this research.

5.1.2.3 South Korea and Japan

These two locations are discussed together as they fared similarly when evaluated against the above criteria. Firstly both were found to have extensive and established automobile industries manufacturing both internal combustion and EVs. Moreover it was found that due to the significantly smaller size of both of these countries that there was a much higher geographical concentration of vehicle manufacture, and supply chains making assumptions on these distances more likely to be credible. Unfortunately however, the availability of information published in English was not as widespread as in the above case of the USA.

5.1.2.4. Europe

As in the cases above, Europe was found to have extensive automotive manufacturing activities in both internal combustion and electric vehicles. Moreover, due to the relatively smaller geographical size of Europe (compared to the USA or China) there was a significantly higher relative concentration of automotive manufacture and supply chains - particularly in northern Europe. In addition to the above, extensive data was available published in English by the European Union, by local governments and by European industrial bodies and trade organisations.

Thus, of the four options discussed above, modelling a vehicle production facility in Europe presents the best opportunity for improved accuracy of the model.

5.1.3 The choice of Germany as a location to model

Within Europe, it was found that Germany presented the highest high level of confidence with regards assumptions that are made when modelling distances owing to the especially high concentration of automotive supply chain in that country:

- Germany has the highest concentration of automotive manufacturers and supply chains in Europe, generating 27% of total EU turnover in this sector. 15 of the world’s top 75 automotive suppliers are German companies.(GTAI, 2022)
- Germany produces the highest number of vehicles in Europe, (more than double the volume of Spain in second). See Appendix H for production volumes in Europe’s top 10 counties by automotive manufacture (ACEA, 2023).
- There are approx. 900 Automotive suppliers located in Germany (GTAI, 2022).
- There are 44 OEM sites in Germany (i.e. Automotive manufacturing plants), higher than any other European country and produce 25% of vehicles made in Europe (GTAI, 2022).

The above are illustrated in Figure 5-1, with Manufacturing locations shown as green circles (grey circles show supplier head quarters):

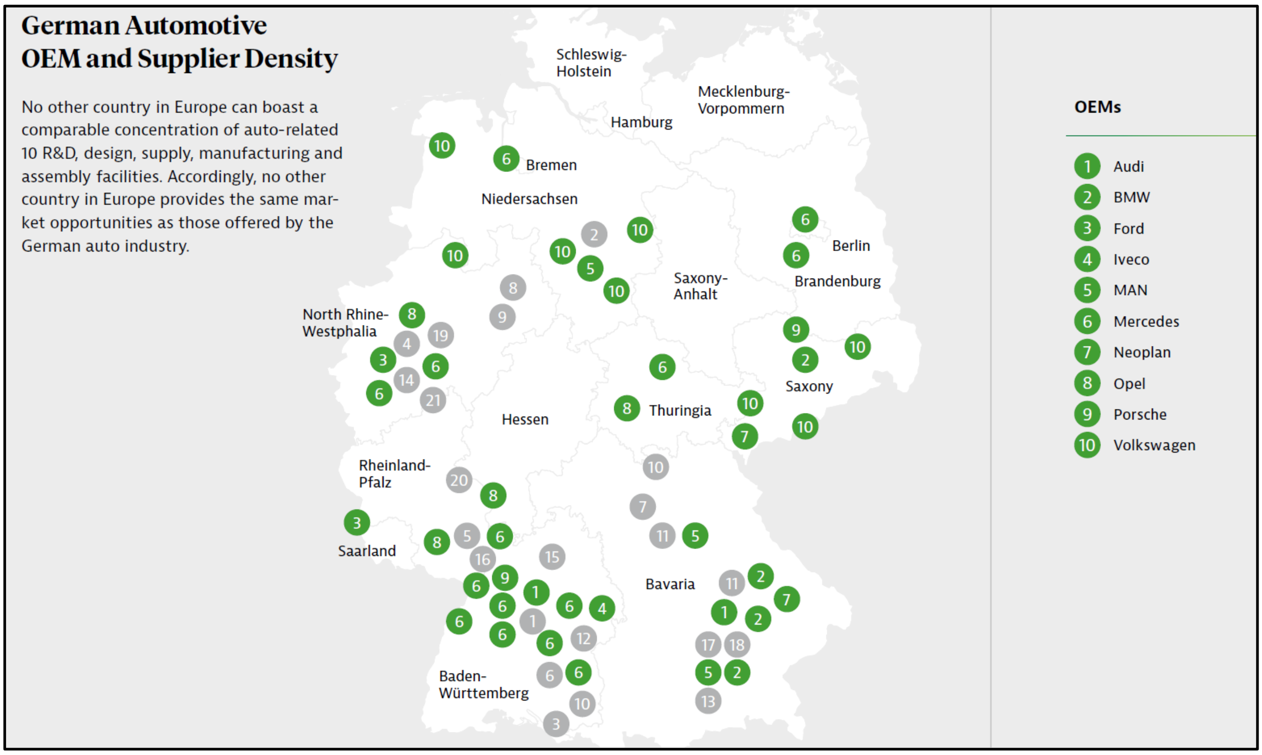

Figure 5-1 German Automotive OEM Density – Source GTAI (2022).

Thus, having the highest concentration and volume of automotive manufacture and supply chains in Europe, combined with extensive information and data availability[63] has made Germany the optimum location for this modelling, which gives the highest level of confidence in European locations that the research model's assumptions will be valid.

5.2. Assumptions and Information supporting a TCE model of German Automotive Manufacture.

With Germany identified as an optimum location for this modelling, it allows the modeller to define a number of assumptions and scenarios consistent with the geographic location chosen.

The sections below outline discuss and support these assumptions which can be used as default scenarios where specific information is not available. Note however that where specific information is available, it was used in preference.

Topics discussed below include the case for European based automotive supply chains, the transportation implications of a German based production facility and identifying an emissions data set appropriate to this scenario.

5.2.1. Supplier locations within Europe – Generic Components.

Without access to the actual list of suppliers to a specific automotive plant, assumptions need to be made about the location of tier 1 suppliers (and their supply chains in turn) who supply automotive production plants in Germany.

Automotive production in Germany is well supported by European based suppliers: Workman (2021) indicate that 80.5% of the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries.

Thus it is assumed that - unless otherwise noted - German automotive parts are sourced from Germany or Europe. The specific choice of distance is noted on individual calculation sheets.

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[63] As the author of this research has a basic German fluency, this also widened the scope of information accessible.

For the purposes of a generic supply chain, the TCE Model therefore allows the user – guided by the “Modal Choice matrix“ discussed in section 4.9. above - to select generic distances where a general location of a supplier is known but a specific address is not known (for example if a raw material typically originates in a particular European country – in which case a centre point of that country will be assumed in the absence of other information). These generic distances are documented in Table 5.1..

Table 5.1: Generic Distances in the TCE Model:

Label For Fig 5-2.	**Supplier Location relative to Germany**	**Generic distance option on TCE Model**
A	Cross border, within greater Europe	1000km
B	National within Germany or cross border to neighbouring countries	500km
C	National within Germany	300km
D	Local to Automotive Factory	100km

To illustrate this, the straight line radius distances are shown below in Figure 5-2., relative to Wolfsburg in Germany, the Headquarters of VWAG and where both ICE and BEV Vehicles are produced (Volkswagen AG Werk Wolfsburg, 2021). It is acknowledged that the actual road or rail distances will be further.

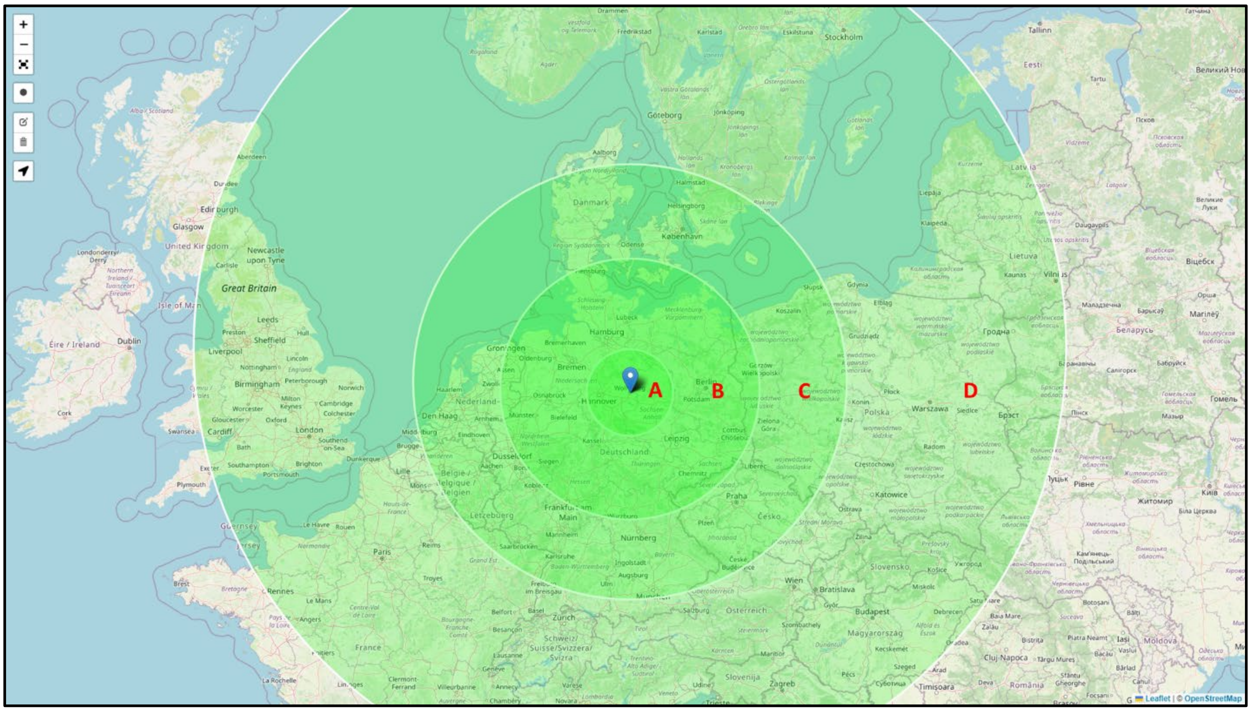

Figure 5-2: Distances from Wolfsburg Shown by straight line radius – map and distance circles generated by Freemaptools.com (2023).

5.2.2. Specific Case: EV Batteries

The possible significant exception to the above general case (described in subsection 5.2.1) is that of the EV batteries, as China is produces 76% of all EV Li-ion Batteries globally as at 2022 (International Energy Agency, 2022). Thus, a model representing current EV production would model batteries supplied from China as the most likely scenario.

Having said this, the European Union's Industrial strategy has prioritised a growth of EV battery production in Europe and development of supporting supply chains to support European demand for batteries (in 2022, European battery manufacture accounted for 7% of global manufacture). Significant funding has been provided for this purpose by the European commission as well as from governments like Germany and France (Eddy, Pfeiffer and van de Staaij, 2019; International Energy Agency, 2022) and this has seen several large European EV battery production facilities opened or announced[64]. Indeed, an EU press release hints at up to 40 "Gigafactories" being built to support European battery demand (European Union, 2022).

With this being the case - in the interests of ensuring longevity of the results of the model built for German automotive production - the modelling in this research has assumed a European based manufacture of the EV batteries[65] themselves as well as European based supply chains unless otherwise noted.

5.2.3. Default European Distances.

While the generic distances discussed above provide convenient default values where supplier locations are known, there remains a question about cases where specific supplier locations are not known other than the assumption that they are European based.

Secondary data on typical European supplier distances was not found although a number of LCA's published do state an assumed typical supplier road distance, some of which are listed below in table 5.2.

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[64] For example a Northvolt Facility in Germany (Bloomberg.com, 2023), a Production plant in Dunkirk France (Mukherjee and Waldersee, 2023), a CATL facility in Germany (Kane, 2022) and an Automotive Cells Company factory in France (Euronews.com, 2023).

[65] A report by Transport & Environment estimated that by 2027 Europe will have sufficient capacity to produce 100% of its EV battery requirements(Transport & Environment, 2023).

Table 5.2: Typical distances cited in LCA publications

Typical distance	Context	Reference
1000km	Raw materials road transportation for an EV battery in "western Europe"	(Zackrisson *et al.*, 2019)
200km	Distance from EV battery manufacturer to car plant in "western Europe"	(Zackrisson *et al.*, 2019)
170 km	Typical distance between suppliers in an Indian Automotive supply chain	(Shama, Vinodh and Jayakrishna, 2015)
200km	Average distance between manufacturing processes in Chinese automotive supply chains	(Hao *et al.*, 2017)
1500km	Distance a vehicle powertrain is transported in a Chinese supply chain	(Yu *et al.*, 2018)

As can be seen from the figures above there is no consistent figure which can be taken from these publications. However there does appear to be a distance in the region of 200 kilometres which typifies the distance from a tier one supplier to an automotive plant.

Thus, for the purpose of this research a figure of 300 kilometres will be assumed to be the default (in order to err on the conservative side) and also taking into account that many suppliers will be significantly further than the 200 kilometre typical number seen above in table 5.2.. While this does constitute a significant uncertainty in the absolute values of the results of modelling based on these assumptions, these assumed values will be equally applied to EVs and ICE vehicles modelled meaning that a meaningful comparison can still be obtained. However, wherever more detailed evidence is available regarding distances these will be used instead.

There are however two cases where different distances will be assumed.

Firstly there is significant automotive part manufacture in Eastern Europe which needs to be accounted for. Brown et al (2021) indicate that 47% of employment in the European automotive supplier network is found in Eastern European Countries (such as Poland, Czech Republic, Slovakia, Hungary, and Romania) and so it is reasonable to assume that there could be at least one journey in the component supply chain of each product that was of a distance to pass through these areas. Thus the TCE model will assume one leg of 1000km during the course of the supply chain network in each subsystem modelled.

Secondly, in the case of materials which utilise recycled material within the supply chain (such as recycled steel or aluminium) it will be assumed that this has been sourced *nationally* (as suggested by Elsner et al (2019)) i.e. within a 500km radius, rather than the more local 300km radius assumed above.

Having established a typical distance between suppliers it is useful to also define a default mode of transport for each leg of the journey - these are shown in table 5.3. below. The logic underpinning the assumed choice of vehicle is that raw materials (for example steel or aluminium billets) would be transported with a minimum of packaging suggesting a higher packing density which would imply transportation by a heavily loaded heavy goods vehicle. However, as these raw materials are transformed into parts and sub-assemblies the amount of packaging and space between each will increase thereby suggesting smaller heavy goods vehicles (which also facilitate more frequent deliveries as might be expected when supplying the automotive manufacturing facility).

Table 5.3: Default Road Vehicle choice matrix.

Transportation Leg	**Default mode of transport**	**Reference**
Raw materials to Tier 2 Supplier [66]	HGV - Heavy Loaded - LHV	Rushton, Croucher and Baker (2017)
Tier 2 Supplier to Tier 1 Supplier[67]	HGV - GVW >20 t, Heavy Loaded no trailer	Notter et al (2010)
Tier 1 Supplier to Auto Plant	HGV - GVW >20 t, Medium Loaded no trailer	Notter et al (2010)

As before, wherever more detailed evidence is available regarding transportation modes these will be used instead.

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[66] Since raw materials (such as steel or aluminium) tend to be transported in bulk with minimum packaging (Rushton, Croucher and Baker, 2017), a HGV, Heavily loaded is assumed for raw materials transportation.

[67] Notter et al (2010) is one of the very few life cycle analyses found which provide the supporting data for their analysis. Since their reference ICE vehicle is a German produced VW Golf, their values are useful in estimating transportation emissions factors, and the values above are directed by their figures.

5.2.4 Choice of Transportation Emissions Factors Data.

As part of the calculations, the WTW emissions factor (measured in gCO_2e /tkm) needs to be included for the modes of transportation used to move freight.

There are several sources of this data[68] but for consistency of calculations and to ensure a consistent comparison across the transportation modes, a single source of this data was selected: the “STREAM Freight Transport 2020” report prepared by CE Delft (Klein *et al.*, 2021).

Besides providing a comprehensive set of values for every likely mode of transportation, this data set also acknowledges the range of potential values in different transportation modes and uniquely provides specific values for “light”, “medium” or “heavily” loaded vehicles of the same class (whereas other sources merely offer an average value).

The significance of this is that using these values for different vehicle loading allows one to account for the typical packing density of components being transported. For example, a vehicle transporting steel engine blocks (which typically have a high packing density) might be classed as “heavily” loaded while another vehicle of the same size transporting plastic dashboard panels (with packaging to keep them separated) might be a “light” load (Klein *et al.*, 2021). As the above report provides this level of detail it was the most desirable choice of data.

Another factor which makes this report especially suitable for modelling a German manufacturing scenario, is that the data is based on figures from the neighbouring country of the Netherlands. The report documents a certain quality of roads and vehicles compliant with European emissions standards – as would also be found in Germany. Data sources pertaining to other continents may have different emissions due to local phenomena (for example American transportation figures would assume different speed limits and road conditions[69] in the case of road transportation).

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[68] For example:
NTM calc: https://www.transportmeasures.org/en/wiki/evaluation-transport-suppliers/road-transport-baseline-2020-global-average/
DEFRA: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

[69] and a potential local preference for larger engined vehicles - as might be the case in the USA where fuel is cheaper.

Lastly, their values are comparable with other sources[70] (typically within 5%) and tended to be slightly above the figures from other sources, in other words more conservative.

Thus, the above data set for transportation emissions is used wherever possible. Where a value is not available in their data set, an alternate European based value is used.

5.2.5. Rotterdam the Default Port for Sea Cargo to Germany

Unless otherwise known – Rotterdam, Europe's largest port (Portofrotterdam.com, 2023) will be assumed to be the port used to transport raw materials to suppliers in Europe (including suppliers in Germany given that over two thirds of freight passing through Rotterdam is destined for Germany).

While there may be an intuitive case to argue that Hamburg - Germany's largest port – may be a more likely choice for a typical shipment to Germany, Rotterdam remains the primary port for bulk raw materials such as metallic ores and coal in Europe (Statistics Netherlands, 2018; hafen-hamburg.de, 2023). Given the above assumption that components are sourced from within Europe (not only Germany), and that the likely use of seaports will be for raw materials in bulk - Rotterdam remains the most likely default choice for European suppliers (including those in Germany) for this type of shipping.

5.3 Raw material supply chains to Germany by material type.

As discussed above, supply chains for raw materials can consist of several steps and may comprise of several separate supply chains. This section discusses and documents the supply chains encountered in the course of the modelling in this research.

In section 4.4. it was argued that because primary data was not available from automotive manufacturers (i.e. who their supplies were) that secondary data and assumptions became necessary regarding the location of tier 1 and tier 2 suppliers. However in the case of raw material sourcing, even if an automotive manufacturer had provided a comprehensive list of the tier one supplies, it would remain unfeasible to expect to obtain primary data regarding the origins of the raw materials used unless each supplier was contacted and also was

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[70] Compared to:
NTM calc: https://www.transportmeasures.org/en/wiki/evaluation-transport-suppliers/road-transport-baseline-2020-global-average/
DEFRA: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021.
While a comprehensive comparison of every value was not feasible, typical classes of transportation and loading were compared to find values typically within 5% of each other.

willing (and even able) to share this information. This is a highly unlikely scenario given that raw materials are typically traded as commodities and supply origins will vary according to fluctuating prices and availability at the time of purchase (as discussed for example by Rechtsteiner et al (2023)).

Therefore, regardless of the availability of primary data regarding tier one suppliers, any modelling of this type will need to make general assumptions regarding origins of raw materials. Indeed, this has also been the approach taken by the GREET model in their modelling of automotive life cycles too (see for example Keoleian et al (2012) or Burnham et al (2006)).

Thus, the following general assumptions are made:

Firstly, it will be assumed that - unless otherwise known - the automotive industry will source it's primary raw materials in line with the national picture for that material. The country's largest supplier will be modelled - as it's the most likely case.

To illustrate this principle by an example: when considering steel used in a German made vehicle, it will be assumed that the steel is sourced along the lines of the national picture – unless there is evidence to make a different assumption (in this case, the automotive industry accounts for 26% of steel usage, second only to the construction industry which uses approx.. 33% of steel in Germany (Elsner *et al.*, 2019)) . Thus, the most likely source (with the largest supply percentage nationally) will be used. In the case of German steel, most iron ore supplied in 2018 was sourced from Brazil (at 51.7%) followed by South Africa (at 14.7%) and Canada at (12.5%) (Elsner *et al.*, 2019) and thus the calculations for this research will take Brazil as the source.

Secondly, figures are chosen to represent *typical* and *stable* supply chains as would typically occur in the absence of local conflicts or global pandemics (as may have occurred in recent years). For example, note that the data in the example above are the 2018 figures: while later figures are available, they may not be *typical* in the light of the COVID19 pandemic which may have impacted and skewed supply chains.

Note too that the above figures also predate the war in Ukraine and any international sanctions in place towards Russia are not reflected in these numbers. Thus – for example - in cases where Russia is the main supplier in 2018 (for example: coal to Germany) the *second* biggest supplier will be assumed for the current day scenario unless other more current information is available. In this example, it would be the USA (Elsner *et al.*, 2019).

The sections that follow summarise the supply chains appropriate to each of the raw materials considered in the model.

They:

- support the scenario being modelled in each material.
- serve as a guide for the reader to the various calculation sheets

More depth on each supply chain as well as the assumptions and figures relating to the transportation are documented in the actual calculation sheets which comprise Appendix C.

5.3.1. Steel Supply Chain

Steel is used extensively in automotive production making up significant parts of the motor vehicle. In most cases, the entire vehicle body and chassis are constructed from steel in sheet metal form, while other parts of the vehicle such as the engine transmission, air conditioning and brake systems are heavily dependent on steel as a material whether in forged, cast[71] or machined form (Burnham, A, Wang, M, Wu, 2006). In the case of the two vehicles modelled, it comprises over half of the vehicle's weight (excluding batteries) and can thus be considered to be the most significant material used.

The supply chain for steel described by Beresford et al. (2011) (supported by information from by Hua et al.. (2022) and Worldsteel.org (2019)) is used as a basis for the steel calculations. The supply chain derived from these publications is summarised in the paragraphs below.

The main components used to make steel are iron ore, metallic coal (or "coke") and scrap metal[72]. These are combined at a steel refinery to produce steel ingots which may be then further processed at a steel mill to produce steel sheet metal of an appropriate grade or steel bars, sections, or billets.

In the case of sheet metal this will then be made into steel body panels or similar at a press shop which are in turn supplied directly to the automotive assembly plant and made into a car body. Alternately, the steel bars, billets and sections are supplied to automotive part manufacturers who in turn supply their parts to component suppliers who produce assemblies and sub assembles which are supplied to automotive assembly plant to form part of the vehicle. Figure 5-2 shows these key phases graphically.

Note that the "steps" listed below correspond to steps labelled accordingly on the calculation sheets.

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[71] Including in the form of cast iron

[72] The proportions of these are documented on the calculations shown in Appendix C.

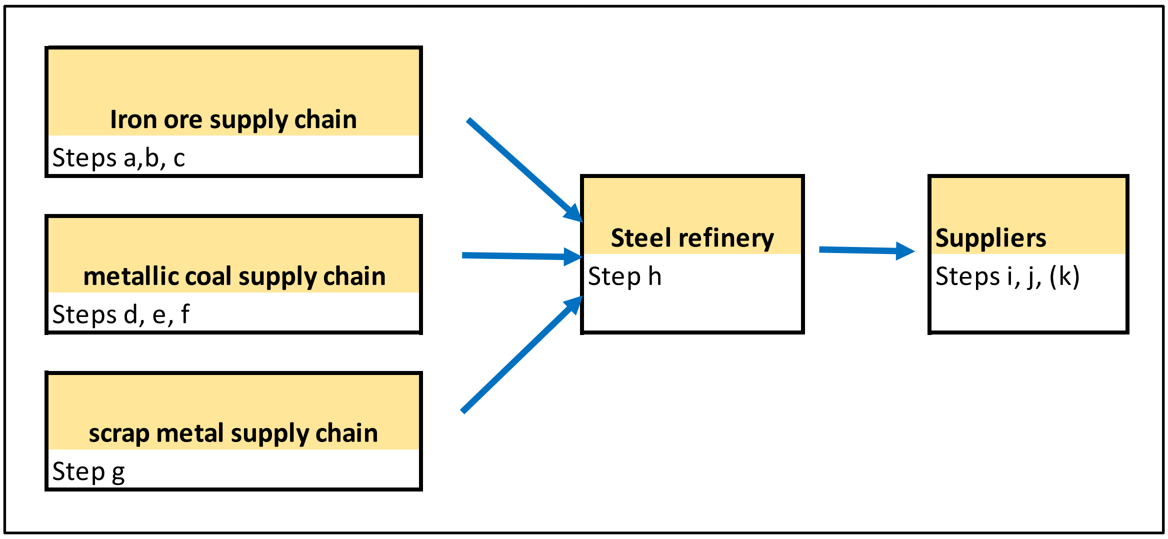

Figure 5-3: Steel Supply Chain

5.3.2. Aluminium Supply Chain

The use of aluminium has become increasingly widespread in vehicles as manufacturers endeavour to reduce the weight of their vehicles and in some cases entire vehicle bodies are constructed from aluminium for this reason. Although the vehicles modelled are not aluminium bodied, aluminium is still used extensively through the vehicle particularly in the engine, air conditioning and transmission systems (Burnham, A, Wang, M, Wu, 2006).

The supply chain for aluminium is widely documented[73] but for consistency, the steps described by Hua *et al.* (2019) [74] and Keoleian *et al.* (2012) are used as a basis for the calculations and is summarised in the following paragraphs.

Aluminium - as widely used - is comprised of "primary" aluminium (derived from mined raw materials) and "secondary" aluminium (derived from recycled scrap) (Aluminium Association, 2013) and thus two supply chains need to be considered.

For primary aluminium, the supply chain can be summarised as follows: Bauxite (the ore from which aluminium is eventually produced) is mined – and shipped to a refinery from which Aluminium Oxide (also known as "Alumina") is extracted – typically 2281 kg of bauxite per 1000kg Alumina is needed (Aluminium Association, 2013). The location of the refinery may be local to the mine to reduce transportation of bauxite or alternately closer to other

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[73] For example (Iqbal, 2017; Hulamin.com, 2021)

[74] For Consistency with the previous section and with the GREET database this publication by Gregory Keoleian is used again here and in the sections that follow too. Also cited in the "steel supply chain" paragraphs above, Gregory Keoleian is lead author of the ""Life Cycle Material Data Update for GREET Model" report upon which the data used for the model is based, suggesting a consistency of approach and assumptions.

input materials needed by the refinery, including fuel (International Amuminium Institute, 2018). This is then moved to a smelter where it is refined to produce aluminium metal (or “primary aluminium”), which is cast into ingots or billets (in the cast house – within the same facility (Aluminium Association, 2013)), ready for further processing. Of note at this stage is that the process consumes significant amounts of anode material (typically 428.6 kg anode material per 1000 kg aluminium produced (Aluminium Association, 2013)). This anode material is predominantly made from carbon based “coke” (or graphite) material – the transportation of which are thus also included in the calculations.

These billets are then alloyed with trace elements to produce aluminium of various grades and properties which are typically processed to form aluminium sheet, extrusions or billets of the desired grade. Secondary aluminium joins the supply chain here (Hua, Keoleian and Lewis, 2019). For this research, the IEA’s figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021) (IEA, 2022).

Finally, some parts are produced at a tier 1 supplier which are then shipped to the factory for assembly in a vehicle. Alternately other parts may also be used in assemblies and sub assembles which are then supplied to an automotive assembly plant to form part of the vehicle.

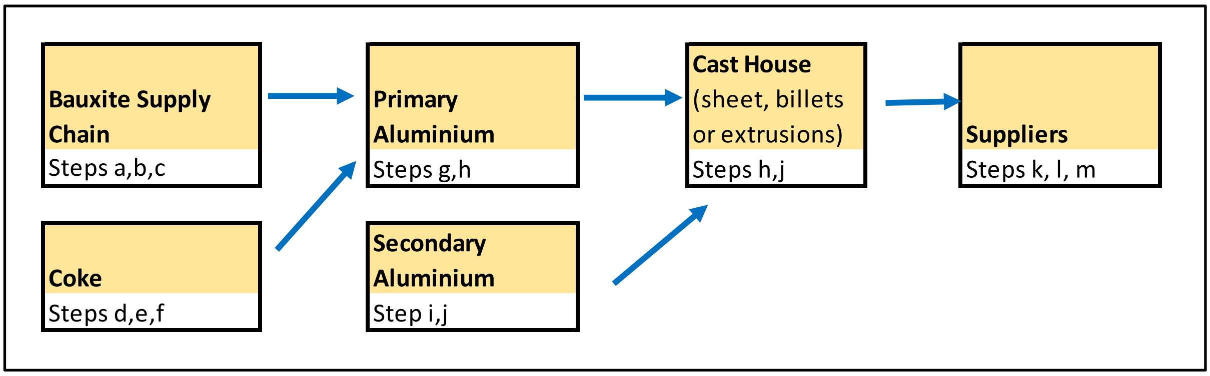

Figure 5-4: Aluminium Supply Chain

5.3.3. Copper supply chain

Used largely for copper wire in a vehicle (Keoleian *et al.*, 2012) and in electric motors (Argonne National Laboratory, 2021)[75] the importance of copper increases significantly in the case of EVs as it is the primary conductor of energy (in the form of electricity) for the vehicle’s powertrain (Copper Development Association Inc, 2023).

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[75] Not that the GREET model does not make a specific distinction between copper and brass, but groups them together. For consistency, this research will do the same.

The steps below summarise the manufacturing and supply chain steps for copper as documented by Keoleian et al. (2012) – supported by additional information from the International Copper Association's life cycle assessment published in 2018, cited below.

Copper ore is mined predominantly in "open pit" mines due to its relatively low ore concentration, typically spread over large areas. Once crushed (usually local to the mine), ore is then concentrated to a typical 30% copper[76]. Next, the copper goes through a smelting process to form a copper "matte" of 50-70% copper. The matte is then further refined to form "blister copper" of 98.5-99.5 purity. Lastly, the copper undergoes an electro-refining process to form "copper cathode" which is 99.99% pure copper. (International Copper Association, 2018).

The supply chain to Europe is a complex one without a single dominant source or form as with steel or aluminium. As with aluminium, secondary (or recycled from scrap) copper plays a key part of supply chain and in 2021 comprised 16.7% of globally refined copper production (International Copper Study Group, 2022). However, in Europe, this proportion is at 43% and this proportion is assumed for this research. Another 20% is supplied by European mines and a further 25% is imported as ore or concentrate (the main suppliers to Germany are Peru, Brazil and Chile). The remaining 12% is imported as purified metal (Kurlemann, 2022).

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[76] This follows the "pyrometallurgical" processing method which is applied to sulphide type copper ore which accounts for 80-90% of global copper production (Fthenakis, Wang and Kim, 2009). The alternative "hydrometallurgical" processing method is not considered in the GREET model, and thus for consistency is not considered in this research either.

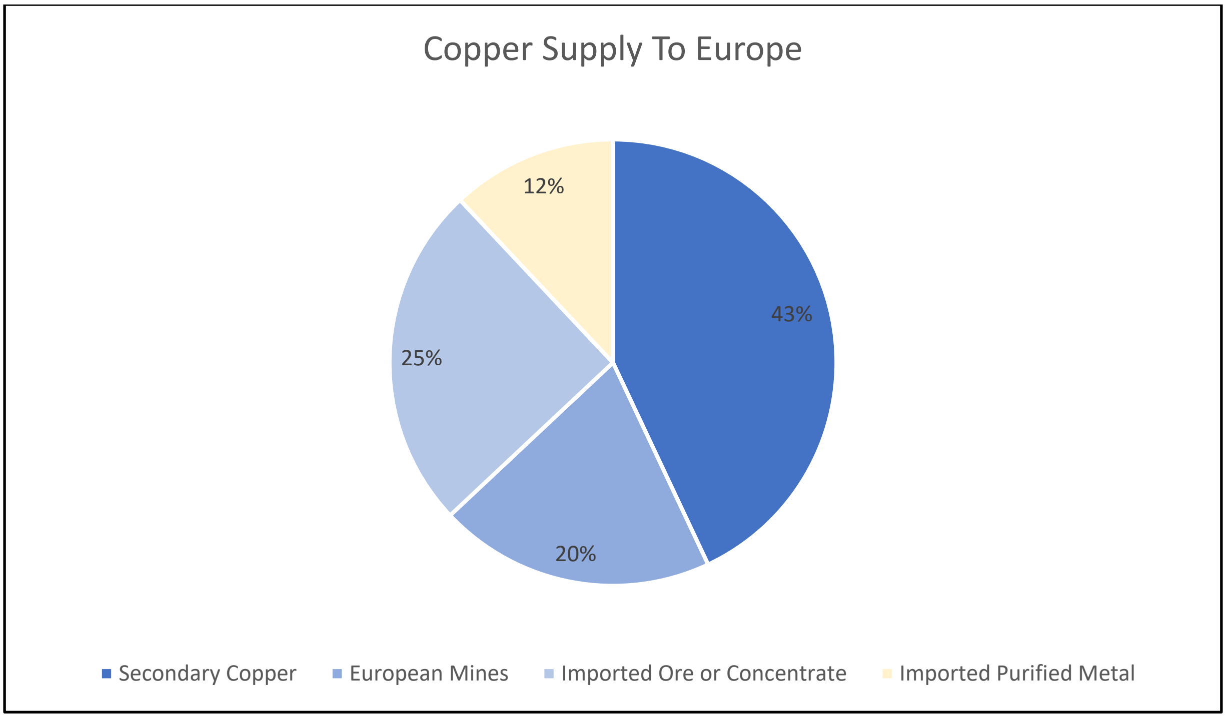

Figure 5-5: Copper supply to Europe – Data source: Kurlemann (2022).

This research will model the first three sources in their relative proportions which together comprise 88% of European copper supply - the remaining 12% of imported copper is not included as it is not feasible to model due to the lack of detailed data on imported copper.

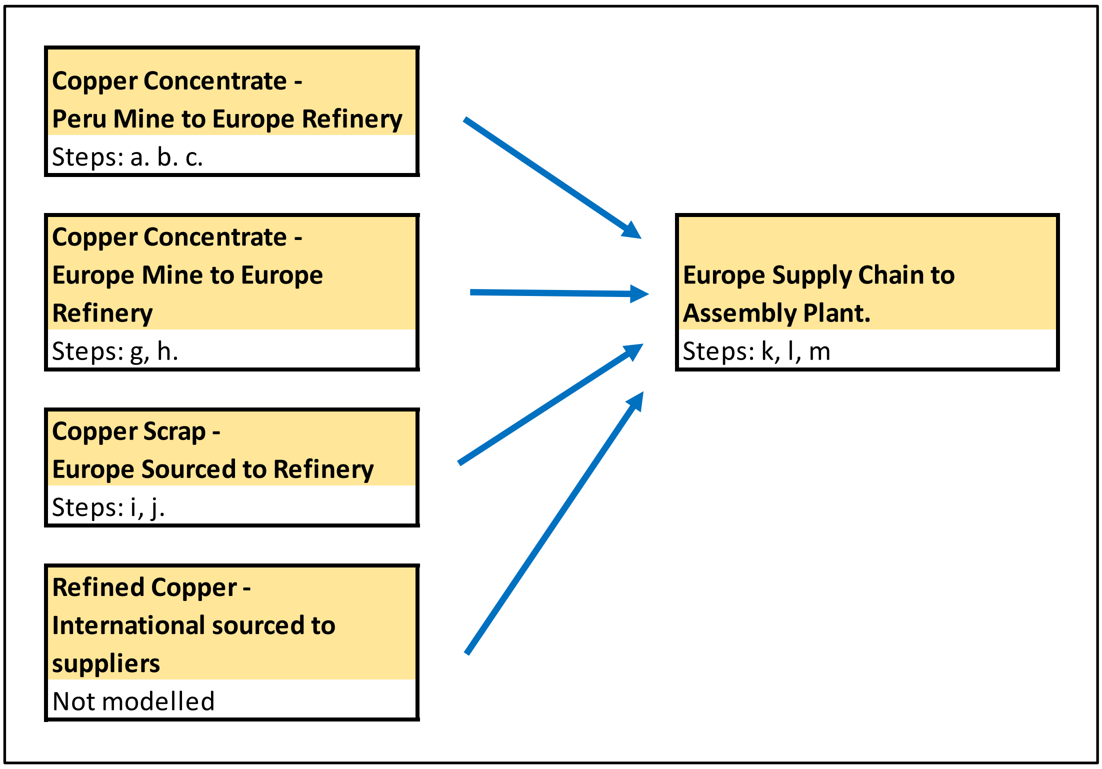

Figure 5-6: Copper supply chain

5.3.4. Plastics Supply chain

Plastics are used extensively in a vehicle both in the vehicle exterior (for bumpers, lights and other exterior hardware) as well as on the vehicle's interior (for trim, dashboard and seating). Moreover, plastics are extensively used in the electrical system as insulation and supporting structures. Lastly, they also comprise a significant proportion of engine parts by number if not by weight (Burnham, A, Wang, M, Wu, 2006).

While as many as 39 types of plastics may be used in a vehicle, one polymer, polypropylene accounts for the highest single plastic used at 44% (Ladhari *et al.*, 2021).

As it is not feasible to accurately model all 39 plastics, the model will focus on representing a *typical* polymer. The GREET dataset follows a similar approach and only accounts for the largest three key plastics used in automotive components (which in its analysis account for over half of plastics in a vehicle) (Burnham, A, Wang, M, Wu, 2006).

Unusually, the GREET data set does include detailed supply chain transportation figures for plastics - albeit for an American manufacturing scenario. While these values cannot be re-used for this European based analysis, it is notable that the energy of transportation is very similar in each case and within a +/- 10% range of polypropylene. (Keoleian *et al.*, 2012).

Therefore, for this analysis it is assumed that this similarity in transportation energy is also true in the European context and therefore the transportation emissions of polypropylene will be assumed to be representative of the other plastics also used in a vehicle, and modelled accordingly.

Plastics Europe – the association of plastics manufacturers which produce of over 90% of the polymers in Europe (Plastics Europe, 2023) – provides a comprehensive lifecycle analysis of polypropene which does include transportation emissions for the supply chain for raw and recycled materials used to make polypropylene - a figure of 0.0163 kg CO_2e per kg of polypropylene produced. (Fröhlich, Liebich and Volz, 2014).

With this figure being available from a credible source, it will therefore be used in the modelling for this research rendering a detailed supply chain model - as constructed for the other materials considered this far - unnecessary. Therefore the only remaining transportation to be modelled will be to the automotive component suppliers and assembly plants, shown in fig 5.6. below.

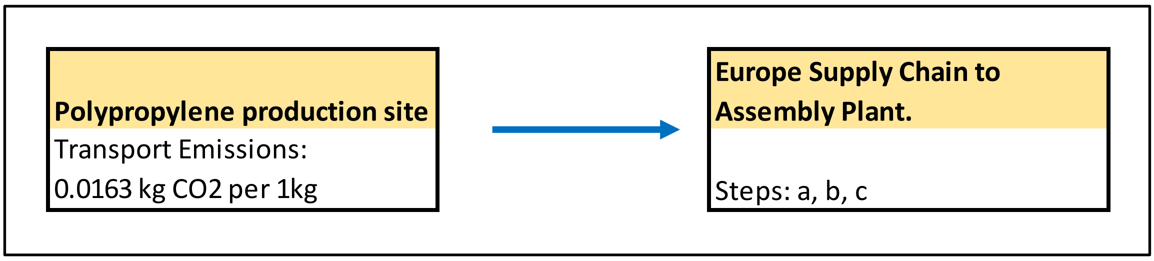

Figure 5-7: Plastics supply chain modelled.

5.3.5. Glass Supply Chain

Glass is used primarily for the windows and mirrors is a vehicle (Burnham, A, Wang, M, Wu, 2006). “Flat Glass” – as used in automotive applications – has a comparatively simple supply chain.

A glass manufacturing plant is fed with raw materials (the key materials are silica sand, soda ash and limestone (Westbroek *et al.*, 2021)) to produce large sheets of flat glass. These are then processed by a dedicated automotive glass plant to form windscreens and windows, ready to be fitted by automotive car plants (Glass for Europe, 2013).

Unlike many other materials considered thus far, Europe is able to supply the majority of its own raw materials – 90% of raw materials used in European glass are sourced within Europe (Glass for Europe, 2020). Indeed, Usbeck *et al.* (2011) document European sourcing for all raw materials in their LCA for European flat glass, possibly due to the very high purity levels required for flat glass, which typify European sand sources (Burkowicz, Galos and Guzik, 2020; Glassforeurope.com, 2020).

While glass is commonly recycled, (and European recycle rates are as high as 70%), this recycled glass is re-used in “container glass” (for example glass jars or bottles) and not “flat glass” which requires a much higher purity of raw materials (Westbroek *et al.*, 2021). Thus recycled glass does not form a significant proportion of flat glass’s raw materials[77] (Usbeck, Pflieger and Sun, 2011) and is therefore not accounted for in this modelling.

The supply chain can be represented as follows:

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[77] The LCA by Usbeck et el (2011) states a 4% contribution of recycled glass in flat glass, while Westbroek et el (2021) do not include it al all. To maintain consistency with the figures used for this modelling which are taken from Westbroek et al.’s analysis, recycled glass is not accounted for in this model.

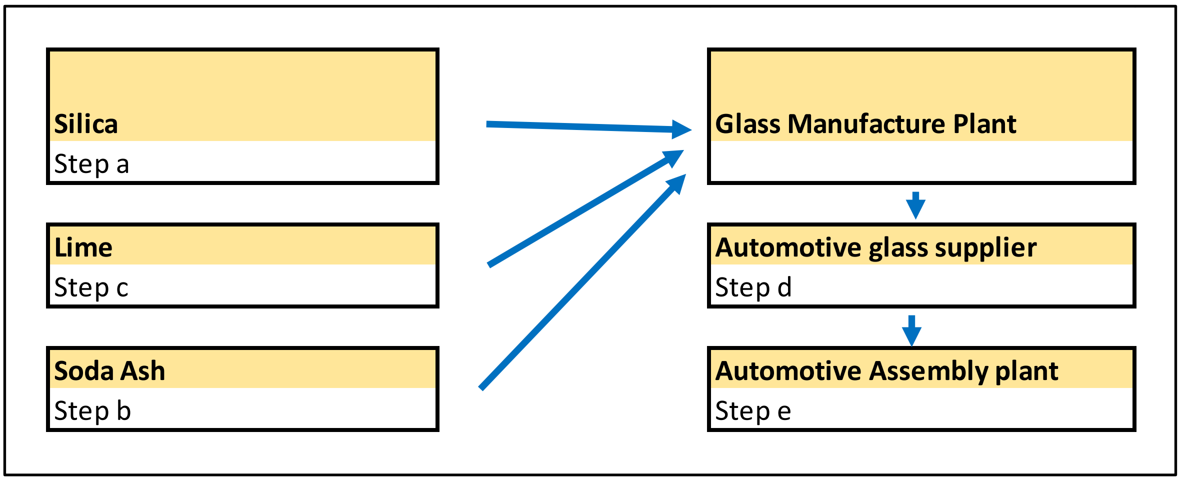

Figure 5-8: Automotive Glass Supply Chain

5.3.6. Glass fibre reinforced plastics

Glass fibre reinforced plastics (GFRP) are composite materials, consisting of a plastic resin which coats fibre glass strands (Burnham, A, Wang, M, Wu, 2006). This material is used across the vehicle, particularly where it's structural strength is valued, notably in car bumpers and as a potential lightweight replacement for components traditionally made from metals (Duan *et al.*, 2018) .

In its calculations and data, the GREET model simply treats GFRP as a fixed ratio mix of epoxy (a plastic resin) and automotive glass (calculated elsewhere already in the GREET model), noting the yield percentage which occurs at the GFRP manufacture stage (Burnham, A, Wang, M, Wu, 2006; Keoleian *et al.*, 2012).

This model will follow a corresponding strategy, and use the corresponding transport emissions for epoxy and for glass, noting the ratio of each used and percentage yield.

Table 5.4. Composition of GFRP, % by weight. Reproduced from Keoleian et al. (2012).

Material	Epoxy	Fibre	Tons of intermediate material needed for 1 ton of final reinforced plastic product
Glass fibre reinforced plastics	50.0%	50.0%	1.140

As in the plastics section above, the value for transportation CO_2 emissions for epoxy is taken from the comprehensive Plastics Europe LCA – a figure of 0.0277kgCO_2e/ kg epoxy resin[78] (Boustead, 2005).

The supply chain for GFRPs can be represented as follows:

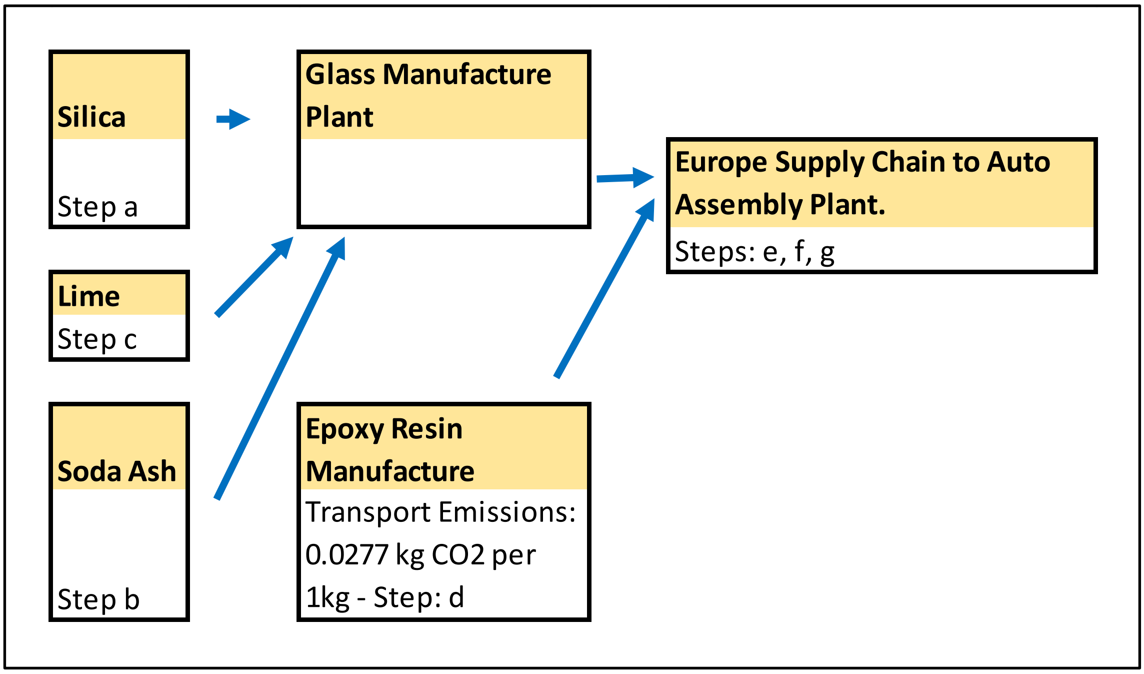

Figure 5-9: GFRP Supply Chain

5.3.7. Rubber

Rubber is used throughout the vehicle: used mainly in tyres, sealants and deadenders, it is also found in fluid hoses, in body trim and panels, in the vehicle transmission, suspension and in various seals and gaskets (Burnham, A, Wang, M, Wu, 2006).

The GREET model classifies all rubber parts as Styrene-butadiene rubber (SBR), which is the dominant rubber compound used in the automotive industry and is used to make tyres, gaskets, fan belts and other rubber parts (Burnham, A, Wang, M, Wu, 2006; TRP Polymer Solutions, 2023). This research will therefore focus on modelling SBR to align with the GREET data set.

Possibly due to its variety of uses, obtaining consistent data for transportation for SBR raw materials for Europe was not successful. However, the German tyre manufacturer

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[78] Boustead (2005) reports a value of 28 gCO2eq/kg in the main report, but the supporting data provided accompanying the report states a more precise value of 27.7gCO2 eq/ kg which is used in this modelling.

Continental performed an LCA in 1999, conducted by Kromer et al. (1999). The figures from this report were used for this analysis as its data pertains to the automotive context in Germany which is precisely the case studied in this model.

Notably, Kromer et al's LCA does specifically document transportation emissions (as in the case of plastics above) and thus given that this LCA would have had access to primary data (being performed by Continental AG themselves) its figures can be used in this research without the need to construct a supply chain model.

Kromer et al document that the transportation accounts for 1.247 kg CO_2 eq emissions per car tyre[79], weighing 6.5kg, or 0.192 kg CO_2 equivalent emissions per 1kg tyre[80]. While this LCA does include recycling of worn tyres, it specifically notes that it does not include transportation emissions of worn tyres to the recycling point. Therefore the above transportation figure can be considered as a "cradle to gate" figure which is consistent with this research scope and can therefore be used.

While several processes are available to use recycled rubber, automotive products tend to favour unrecycled rubber to ensure product quality, especially in tyres (Burnham, A, Wang, M, Wu, 2006). For this reason, recycled rubber is not considered part of the supply chain.

Note that because the emissions figure for rubber stated above is already a "cradle to gate" figure, corresponding supply chain modelling sheets were not built for rubber in the TCE model and consequently no supply chain diagram is required for this section. The TCE model instead has a single sheet where all rubber transportation emissions are calculated, and is presented in Appendix C with the other TCE model calculation sheets.

5.3.8. Battery specific materials

The GREET database separates the battery from the rest of the vehicle and calculates its emissions separately, and this modelling does the same for consistency. Note that supply

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[79] Section 4.1.2 of Continental's LCA states that transport accounts for 0.2% of a tyres CO_2 equivalent emissions. The LCA for the "carbon black / rayon" tyre states a total figure of 623.25 kg CO_2 e. Thus the transportation emissions portion of this is 0.02% of that figure: 1.247kg

[80] Note that tyres do contain a proportion of steel in them – typically 12% (US Tire Manufacturers Association, 2023). The figure for steel – as calculated on the steel calculations, Ref: ICE-01 - is 0.171 kg CO_2 equivalent – a difference of 0.02 kgCO_2 equivalent per kg. As these values are similar, Continentals figure of 0.192 kgCO_2 equivalent per kg will be assumed to be valid and typical for automotive rubber.

chains for materials used in a battery which have already been analysed in previous sections are not re-stated in this section[81], which focusses on battery unique materials.

Both EVs and ICE vehicles use batteries, albeit for different purposes. ICE batteries are used to propel the starter motor which starts the internal combustion whereas in EVs the batteries are used primarily for storing energy used to propel the electric drive system. In both cases, the batteries also supply current for electrical components in the vehicle (Burnham, A, Wang, M, Wu, 2006).

In the vehicles modelled, the ICE vehicle's battery is a "lead acid" (or Pb-Ac) type whereas in the case of the EV it is "lithium ion" (Li-ion) based. Note that in the case of the ICE battery, none of its unique materials comprised greater than 1% of the vehicles mass (thus falling below this modelling' s cutoff threshold) and therefore only battery materials already discussed above were modelled in this case. However, in the case of EV batteries several unique materials not documented above comprised greater than 1% of the vehicle mass and are therefore discussed below.

5.3.9 Li-ion batteries – an Introduction.

Considering that the batteries alone can comprise in the region of 20% of an EVs weight (Argonne National Laboratory, 2021), they form a significant subsystem of the vehicle and merit a brief introduction below before analysing their supply chains.

The specific Li-ion battery used in the EV modelled in this research is one based on $LiMn_2O_4$ chemistry (Dunn *et al.*, 2014). While a detailed description of how these batteries work is beyond the scope of this research, in general terms these batteries comprise of the following:

- the positive terminal or "cathode" which contains $LiMn_2O_4$ - also known as the "active material". The mass of the cathode has a key influence on how much energy a battery can store.
- the negative terminal or "anode" which is largely made of carbon graphite
- the "electrolyte" which connects the anode and cathode chemically and internally and allows the electricity to flow within the battery.
- a "binder" which is a polymer which provides structural support and connections within the battery

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[81] The supply chains outlined previously are however used when calculating those battery materials transportation emissions.

- The battery casing, typically made from plastics and aluminium whose function is structural.

The above is summarised from Dunn *et al* (2014).

The raw materials supply chains modelled in the TCE model follow the supply chain structure as described for EV batteries by Deng et al (2019) which follows the steps below unless otherwise documented[82]:

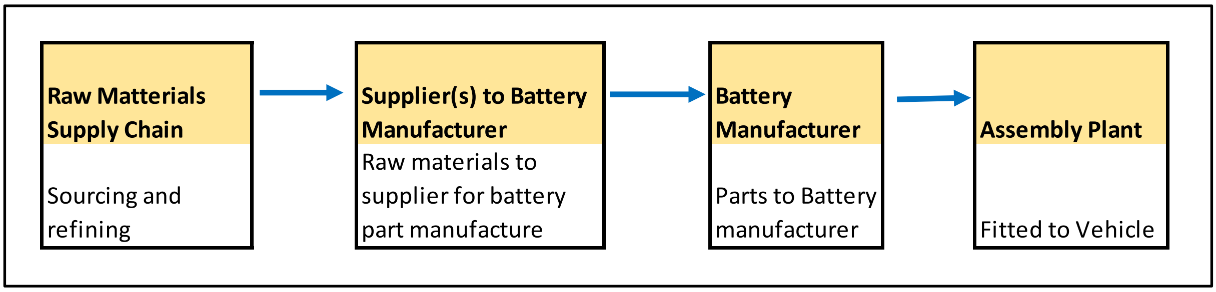

Figure 5-10: Typical Supply chains for EV Lion Batteries (redrawn from Deng et al (2019)).

This supply chain structure will be assumed, where the battery supplier receives components which will be assembled to form the battery. However, in cases where the raw materials are supplied directly to the battery manufacturer, there will be one fewer steps (with the second step not applicable).

The key supply chains for a Li-ion battery are summarised in the sections that follow. The GREET LCA by Dunn et al (2014) which focusses specifically on Automotive Lithium-Ion batteries is used. As with the previous calculations, materials which comprise <1% of the overall vehicle mass are not modelled.

5.3.10. Graphite

As noted above, graphite is the key component of the anode in an EV battery (Dunn *et al* 2014). They indicate that the graphite used in EV batteries is the same substance as found in aluminium manufacture and thus – like the GREET model data upon which the TCE model is based - the graphite supply chain for the batteries in this research will be the same as those used for aluminium, discussed previously above.

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[82] Deng et el (2019) do not include specifically note the step of transportation to an Automotive assembly plant and fitment to a vehicle, but logically a battery would need to be installed in a vehicle before it can be utilised.

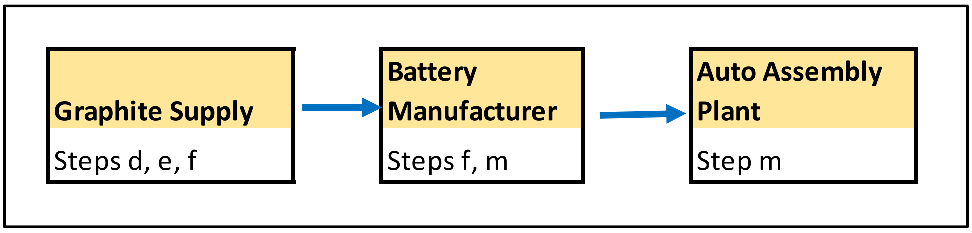

Figure 5-11: Graphite Supply Chain Modelled for EV batteries

5.3.11. Electrolytes

As documented above, the electrolyte in an EV battery forms the link between the anode and cathode (Dunn *et al.*, 2014).

The GREET model notes two electrolytes used in an EV battery, ethylene carbonate and dimethyl carbonate which are used in equal measure (Dunn *et al* 2014). Geographically, the supply of these electrolytes is dominated by Asian countries which account for 92% of global manufacture (China at 60%; Japan at 18% and Korea at 14%) (Olivetti *et al.*, 2017) – indeed a single manufacturer, Jiangxi Tinci Central Advanced Materials, in China produces 35% of global electrolyte ingredient materials.

Strong evidence of established supply chains in Europe was not found although there is evidence of emerging facilities being built[83] and electrolyte production is likely to increase as supply chains become more established for EV battery plants being built (Eddy, Pfeiffer and van de Staaij, 2019). However, given that European supply is (comparatively) in its infancy, for the purposes of this modelling it will be assumed that electrolyte is manufactured in China and shipped to a European battery manufacturing facility.

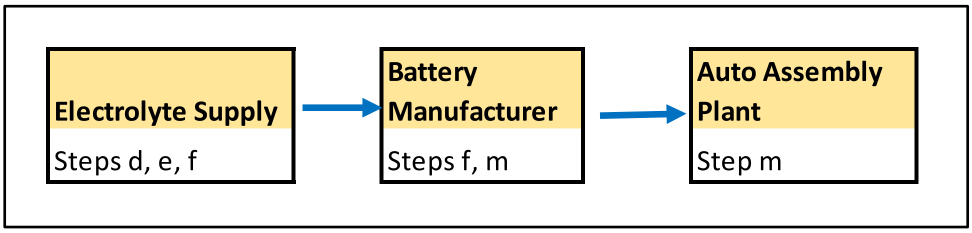

Figure 5-12: Electrolyte supply chain modelled for EV batteries

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[83] For example the Korean manufacturer building electrolyte plants in Hungary and Poland (Kim, 2020).

5.3.12. Cathode Supply Chain: Lithium Manganese Oxide ($LiMn_2O_4$) and Manganese Oxide (Mn_2O_3)

As noted above, the active material in the cathode is Lithium Manganese Oxide ($LiMn_2O_4$) which comprises 33% of the EV battery's mass in the GREET LCI used (Dunn *et al.*, 2014). The key raw materials for this active material are Lithium Carbonate (Li_2CO_3) and Manganese Oxide (Mn_2O_3) and they are considered together in this subsection.

Lithium Manganese Oxide ($LiMn_2O_4$) is a compound which depends on lithium mining operations. Australia, Chile and China mine approx. 90% of the world's lithium raw materials which can be mined from rock or extracted from brines (minerals dissolved in water found underground). Although Australia is the largest miner of lithium, accounting for almost half of global mining, it does not refine significant amounts of it (International Energy Agency, 2022), with China and Chile dominating refining with 58% and 29% respectively (Bunting *et al.*, 2023). The GREET data uses Chile as its raw materials source of $LiMn_2O_4$ and this research will do the same.

Chilean operations involve extraction from brine. The brine is pumped from wells, and after being concentrated, transported to a refinery. A key material used in the refinery process is Soda Ash (Na_2CO_3) and its supply chain is also therefore modelled[84]. The refinery produces Lithium Carbonate (Li_2CO_3) which in the GREET report is then transported to the USA for $LiMn_2O_4$ production at or near the battery production facility (Dunn *et al.*, 2014). However, in the case of this research, a European battery production is modelled.

In addition to Li_2CO_3, the GREET LCI records that Manganese – in the form of Manganese oxide (Mn_2O_3) - is another key ingredient for cathodes, which is assumed to be sourced and produced within the USA, and within 500 miles of an American battery manufacturing facility (Dunn *et al.*, 2014).

Again however, for European based battery production, the above Mn_2O_3 supply chain journeys need to be modelled accordingly.

Two likely supply chains are modelled in this case:

- Scenario 1: to reflect current supply chains where the Mn_2O_3 is supplied to Europe from China

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[84] Concentrate lithium Brine and Soda Ash comprise 97.5% of the raw materials weight delivered to the refinery. Lime, Hydrochloric acid, Organic Solvent, Sulphuric acid and alcohol are also used but as these together comprise approx. 2.5% of the materials weight delivered to the refinery (Dunn et al. 2014) and they are not modelled.

- Scenario 2: to reflect future potential European Mn_2O_3 material supply chains.

As Chile is the world's largest exporter of lithium carbonates[85] - it is assumed that Chile is the source of the lithium carbonates because – as Bunting et al (2023) note - there is currently no lithium mining available in Europe for EV battery application and even when currently planned projects for this are bought to fruition by 2030, only 25% of European demand would be met. Thus, importing Lithium raw materials remains most likely for the foreseeable future.

The two scenarios are described below:

5.3.12.a Scenario 1 – Mn_2O_3 supplied to Europe from China

As China currently dominates manganese refining (it refines over 93% of the world's manganese) (Bunting *et al.*, 2023) it has to be assumed that it is the most likely *current* source of Mn_2O_3 materials for European battery production.

In this case, South Africa – the worlds largest exporter of manganese ores[86] - is assumed to be the source of manganese.

Thus, this scenario models manganese raw materials supplied to China where they are refined and then supplied to Europe for battery manufacture.

This scenario will be the default figure in the results presented for this research, as it reflects the current situation.

5.3.12.b Scenario 2 – future potential European cathode material supply chains.

While China is currently the leading producer for manganese products for EV batteries and supplies most of current European demand - Bunting et al (2023) note that there is existing installed capacity in Belgium which currently processes this material for EV battery production.

Bunting et al (2023) also note that capacity for manganese mining operations is being expanded in the Czech Republic and Romania ramping up to full capacity in 2030, by which time these developments have potential to supply 45% of European demand[87]. As this

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[85] the form of lithium in the GREET data

[86] $1.59B USD out of South Africa's $2.9B USD exports (or 55%) were to China, making this a reasonable raw materials source of Manganese ore.

[87] A report by Transport & Environment (2023) - estimate this figure to be 46% by 2030

nears half of potential supply, the impact of a European supply of manganese products will be modelled in order to evaluate this alternative too.

In both scenarios, the supply chain can be represented as follows:

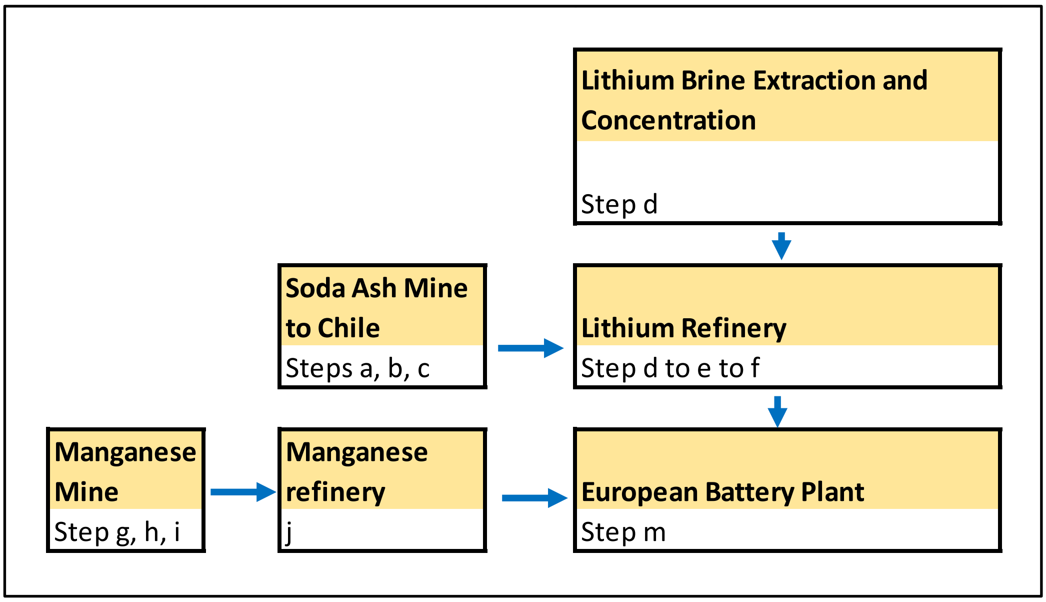

Figure 5-13: Cathode raw materials supply chains

The results of these two scenarios will be presented and discussed in the next chapters.

5.4. Summary

This chapter has made the case for vehicle production of both ICE and EVs in Germany as a representative case study with which to address the research questions and in line with the aims and objectives of this research. Having made this case, arguments have been made for the assumptions which underpin this location for vehicle manufacture.

With the assumptions in place the individual supply chains for all materials comprising more than 1% of the vehicle mass have been described and cross referenced to the model built. These supply chains have been modelled in significant detail in the TCE model and the individual calculation sheets are all included in Appendix C.

The modelling now complete, the next section – Chapter 6 presents the results from this modelling.

6. RESULTS

This chapter presents the results and key findings which arise from the modelling undertaken. The full output and detail of the modelling performed is included in Appendix C which documents the calculations of the carbon emissions generated for every subsystem by material, numbering 65 calculation sheets across 91 pages.

The results for ICE vehicles and EVs are listed below, alongside one another to allow for convenient comparison between the two different types of vehicle. They are arranged and listed in the same order as the GREET model data set used.

6.1. Results arranged by Vehicle Subsystem and Material

An individual calculation sheet has been made for the transportation carbon emissions for every subsystem and key component material. The results from each individual calculation sheet are consolidated and presented in the tables below. These are presented below by vehicle subsystem – a description of which is given with each set of results – to facilitate a more granular analysis and subsequent discussion in the next chapter.

All emissions units are in $kgCO_2e$ unless otherwise stated.

The reader will note cases below where no calculation result appears (and an “n/a” is shown). This may be due to one of two reasons:

- materials that were not modelled due to the cut off rules (discussed in section 4.8.) They are noted Appendix D, and the overall impact of applying these cutoff rules is discussed below.
- Where a material does not form part of a subsystem of one type of vehicle.

Lastly, note that the “Rubber” category is calculated on one sheet in Appendix C, labelled as “Rubber”.

6.1.1. Vehicle Body Subsystem - Cradle to Gate Transportation Emissions

The vehicle body consists not only of the primary vehicle structure made of pressed sheet metal (known as the “body in white”) but also components which attach to it such as vehicle bumpers, glass windshields and windows, exterior trim such as spoilers and nameplates, body sealers and acoustic deadeners as well as exterior lighting such as headlamps and tail light assemblies. It also includes interior parts of the vehicle such as the instrument panel, and interior trim, seats, air conditioning and interior electronics (Burnham, A, Wang, M, Wu, 2006). The cradle to gate transportation emissions arising from this subsystem are documented in Table 6.1. below.

Table 6.1. Vehicle Body Subsystem Cradle to Gate Transportation Emissions

Material	Calc REF	ICE Transportation emissions (kgCO$_2$e)	Calc REF	EV Transportation emissions (kgCO$_2$e)
Steel	ICE-01	86.39	EV-01	99.28
Wrought Aluminum	ICE-02	9.27	EV-02	10.65
Cast Aluminum	ICE-03	0.51	EV-03	0.59
Copper/Brass	ICE-04	4.90	EV-04	5.64
Glass Fiber-Reinforced Plastic	ICE-05	2.62	EV-05	3.02
Glass	ICE-06	2.69	EV-06	3.09
Average Plastic	ICE-07	62.65	EV-07	72.00
Rubber	Rubber	2.59	Rubber	2.98
	Total	171.63		197.24

6.1.2. Powertrain Subsystem - Cradle to Gate Transportation Emissions

The vehicle powertrain is made up of the subsystems which are required to propel the vehicle. They include - as applicable - the engine and it's supporting components, fuel storage, cooling, exhaust and supporting electrical systems (Burnham, A, Wang, M, Wu, 2006). Note that in the case of the EV, the electric motors which propel the vehicle are listed in a separate subsystem in the GREET model data set and not included in this subsystem but included in section 6.1.5. below.

The cradle to gate transportation emissions arising from this subsystem are documented in Table 6.2. that follows below.

Table 6.2. Powertrain Subsystem Cradle to Gate Transportation Emissions

Material	Calc REF	ICE Transportation emissions ($kgCO_2e$)	Calc REF	EV Transportation emissions ($kgCO_2e$)
Steel	ICE-10	38.55	EV-10	16.26
Wrought Aluminum	ICE-11	4.24		n/a
Cast Aluminum	ICE-12	20.21		n/a
Copper/Brass	ICE-13	5.06	EV-13	5.49
Glass Fiber-Reinforced Plastic	ICE-14	2.23		n/a
Average Plastic	ICE-15	15.92	EV-15	15.92
Rubber	Rubber	0.94		n/a
	Total	87.15		37.67

6.1.3. Transmission Subsystem - Cradle to Gate Transportation Emissions

The transmission subsystem consists of the gearbox(es) which connect the powertrain to the wheels, transferring the torque at different ratios and speeds as required. In the case of the EV, there may be multiple smaller gearboxes with one attached to each individual electric motor in the vehicle.

The cradle to gate transportation emissions arising from this subsystem are documented in Table 6.3. below.

Table 6.3. Transmission Subsystem Cradle to Gate Transportation Emissions.

Material	Calc REF	ICE Transportation emissions ($kgCO_2e$)	Calc REF	EV Transportation emissions ($kgCO_2e$)
Steel	ICE-19	11.15	EV-19	24.19
Copper		n/a	EV-20	6.22
Cast Iron	ICE-21	11.04		n/a
Wrought Aluminum	ICE-22	10.80	EV-22	7.69
Average Plastic	ICE-23	1.72	EV-23	0.07
Rubber	Rubber	0.87		n/a
	Total	35.58		38.17

6.1.4. Vehicle Chassis Subsystem - Cradle to Gate Transportation Emissions

The vehicle chassis subsystem can be thought of as the parts of the vehicle which connect the vehicle body to the powertrain, and in turn both of these subsystems to the road.

Connecting the powertrain to the vehicle body is a series of subframe assemblies which support powertrain components. Connecting both systems to the road are components such as the drive shafts and differentials, the suspension, wheels and braking system as well as the steering system and all of the electrical components which support these systems (Burnham, A, Wang, M, Wu, 2006).

The cradle to gate transportation emissions arising from this subsystem are documented in Table 6.4. below.

Table 6.4. Vehicle Chassis Subsystem Cradle to Gate Transportation Emissions

Material	Calc REF	ICE Transportation emissions ($kgCO_2e$)	Calc REF	EV Transportation emissions ($kgCO_2e$)
Steel	ICE-26	100.72	EV-26	115.75
Wrought Aluminum	ICE-27	2.18	EV-27	2.51
Cast Aluminum	ICE-28	27.89	EV-28	32.06
Copper/Brass	ICE-29	1.64	EV-29	1.89
Glass Fiber-Reinforced Plastic	ICE-31	0.23	EV-31	0.26
Average Plastic	ICE-32	3.26	EV-32	3.75
Rubber	Rubber	6.45	Rubber	7.41
	Total	142.38		163.63

6.1.5. EV Drive Subsystem - Cradle to Gate Transportation Emissions

Specific to EVs, this subsystem includes the electric motors which drive the wheels as well as supporting electrical and electronic components (Burnham, A, Wang, M, Wu, 2006).

The cradle to gate transportation emissions arising from this subsystem are documented in Table 6.5. below.

Table 6.5. EV Drive Subsystem Cradle to Gate Transportation Emissions.

Material	Calc REF	ICE Transportation emissions ($kgCO_2e$)	Calc REF	EV Transportation emissions ($kgCO_2e$)
Steel		n/a	EV-35	24.06
Cast Aluminum		n/a	EV-36	23.93
Copper/Brass		n/a	EV-37	15.24
	Total	n/a		63.23

6.1.6. EV Drive Control Subsystem - Cradle to Gate Transportation Emissions

Again specific to EVs, this subsystem consists of the electrical “power electronics” – the components which convert and control the electric power between the batteries and the electric motors which drive the wheels (Burnham, A, Wang, M, Wu, 2006).

The cradle to gate transportation emissions arising from this subsystem are documented in Table 6.6. below.

Table 6.6. EV Drive Control Subsystem Cradle to Gate Transportation Emissions

Material	Calc REF	ICE Transportation emissions ($kgCO_2e$)	Calc REF	EV Transportation emissions ($kgCO_2e$)
Steel		n/a	EV-38	2.10
Cast Aluminum		n/a	EV-39	19.69
Copper/Brass		n/a	EV-40	2.85
Rubber		n/a	Rubber	0.73
Average Plastic		n/a	EV-42	9.25
	Total	n/a		34.64

6.1.7. Battery Subsystem - Cradle to Gate Transportation Emissions

The vehicle battery stores and releases electrical energy and - as noted previously - the battery is considered separately in the GREET model data set, and this research follows suit. The reader will note the significantly higher emissions below for the EV battery which will be discussed in greater detail in the next chapter.

The cradle to gate transportation emissions arising from this subsystem are documented in Table 6.7. below.

Table 6.7. Battery Subsystems Cradle to Gate Transportation Emissions

Material	Calc REF	ICE Transportation emissions (kgCO$_2$e)	Calc REF	EV Transportation emissions (kgCO$_2$e)
Plastics	ICE-B-47	0.36	EV-B-47	4.49
Glass Fiber	ICE-B-48	0.14		n/a
Copper		n/a	EV-B-50	14.56
Wrought Al		n/a	EV-B-51	29.40
Graphite / carbon		n/a	EV-B-52	8.73
Electrolyte - EC - Ethylene carbonate		n/a	EV-B-53	4.91
Electrolyte - DMC - Dimethyl carbonate		n/a	EV-B-54	4.91
LiMn204		n/a	EV-B-55	148.85
Steel		n/a	EV-B-63	2.58
	Total	0.5		218.43

The total transportation CO$_2$e emissions (for all the subsystems above) are presented in section 6.2 below.

6.1.8. Impact of applying cut off Rules and "Other" Materials: Percentage vehicle weight modelled

Section 4.8. notes the cut off rules applied in this research which means that in some cases materials have not been modelled. In addition to this, in some cases the GREET data set does not specifically document certain materials describing them simply as "other" materials - and in this case the material is also not modelled. To note the impact of applying these cutoff rules and the "other" materials not modelled, an analysis has been done to evaluate this.

The results in sections 6.1.1 – 6.1.7 above document the materials that were modelled after applying the cutoff rules and excluding the "other" materials.

The materials *not* modelled are grouped as "undefined" materials and are documented in Appendix D.

As noted in Table 6.8. below, the above results represent 98.5% of the internal combustion vehicle's mass modelled and 97.8% of the EVs mass modelled.

Table 6.8. Share of undefined materials arising from applying cutoff rules.

	ICE Vehicle	EV
Total weight vehicle modelled (kg)	1438.4	2085.5
Total vehicle weight (kg)	1460.3	2133.3
% modelled	**98.5%**	**97.8%**
% vehicle not modelled: undefined material	**1.5%**	**2.2%**

These levels of “undefined material” are typical of an LCA and for reference, the levels of undefined material in the Volvo XC40 LCA (mentioned earlier in this document) are shown in table 6.9. below for comparison.

Table 6.9. Share of undefined material in Volvo XC 40 LCA (source Egeskog et al (2020))

Vehicle Model	Volvo XC40 ICE Vehicle	Volvo XC40 Recharge EV
Undefined material in Volvo XC40 LCA	**1.5%**	**2.0%**

In the light of this, any interpretation of the above results needs to take this uncertainty into account. Notwithstanding this, the impact of applying the cut off rules is considered as minor, in line with other LCA practice, and not having significant impact on the legitimacy of the overall results presented.

6.2. Analysis of results.

Having presented the separate results of the modelling above, key consolidated results are presented next which will form the basis of the discussion chapter which follows.

6.2.1. Total ICE and EV emissions compared.

One of the key objectives of this research – and one of the research questions - has been to compare the overall cradle to gate transportation emissions arising as a result of manufacturing internal combustion and EVs. Figure 6-1. below shows the total emissions for the two types of vehicle.

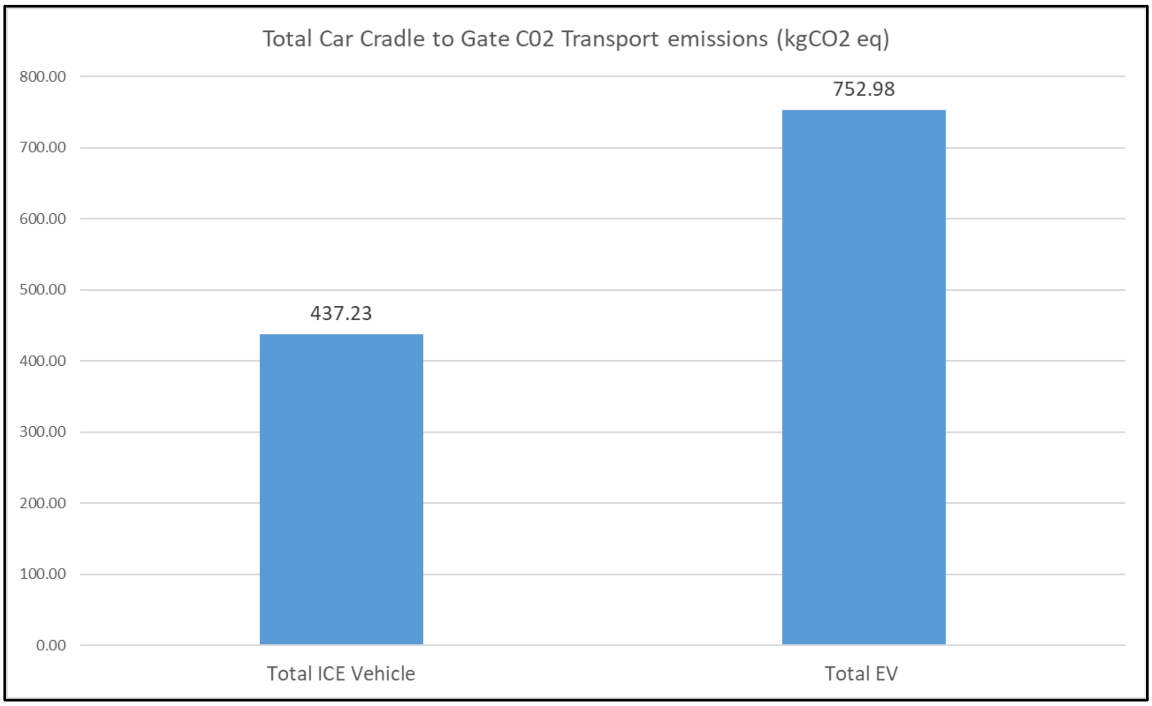

Figure 6-1: Total Cradle to Gate CO_2 Transport emissions compared

As can be clearly seen in this figure, EVs give rise to significantly more carbon emissions (72.2% more if calculated as a percentage) in the cradle to gate supply chain transportation activities in the case studies modelled. This will be discussed in significantly more detail in the next chapter.

6.2.2. Contribution of EV batteries to cradle to gate transportation emissions.

As noted in previous sections, the GREET model data set lists the vehicles batteries separately. This highlights the contribution that the EV battery makes to cradle to gate transport emissions, shown in figure 6-2 below.

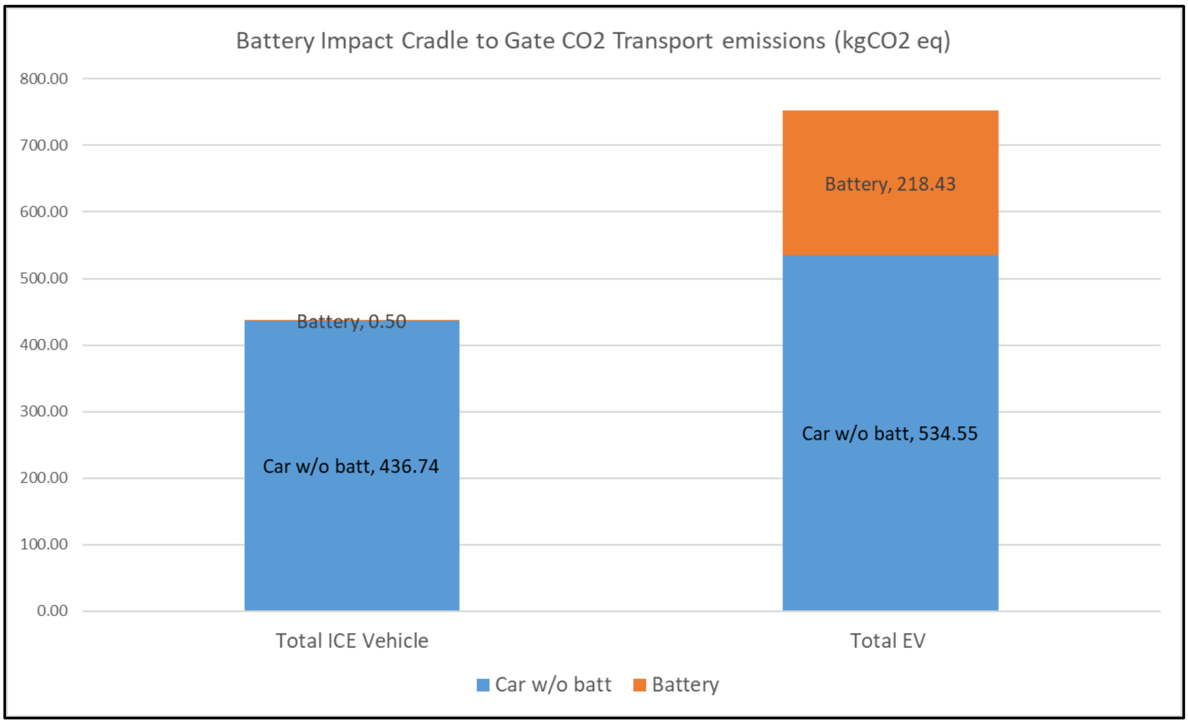

Figure 6-2: Impact of EV battery on transportation emissions.

As can be seen in this figure, the EV battery alone contributes a significant portion of the transportation carbon emissions.

However, even without the battery, the rest of the EV gives rise to notably more transportation carbon emissions than an ICE vehicle. This is because EV bodies need to be significantly stronger (thus requiring more material to build - see Martynyuk (2022) for a more comprehensive explanation) in order to carry the batteries of the EVs. Their weight may add up to 20% extra weight to a vehicle.

As above, these figures will be discussed in more detail in the next chapter.

6.2.3. Impact of Mn_2O_3 refining and sourcing location

As noted in section 5.3.12, two scenarios are modelled for sourcing Mn_2O_3 - a key raw material used to make the lithium-ion batteries in the GREET model data set. The two scenarios modelled are:

- the likely (current) scenario where Mn_2O_3 is sourced from China
- a potential (future) scenario where this is refined and sourced in Europe.

For comparison, the ICE vehicle is also shown in this chart, shown in figure 6-3. below.

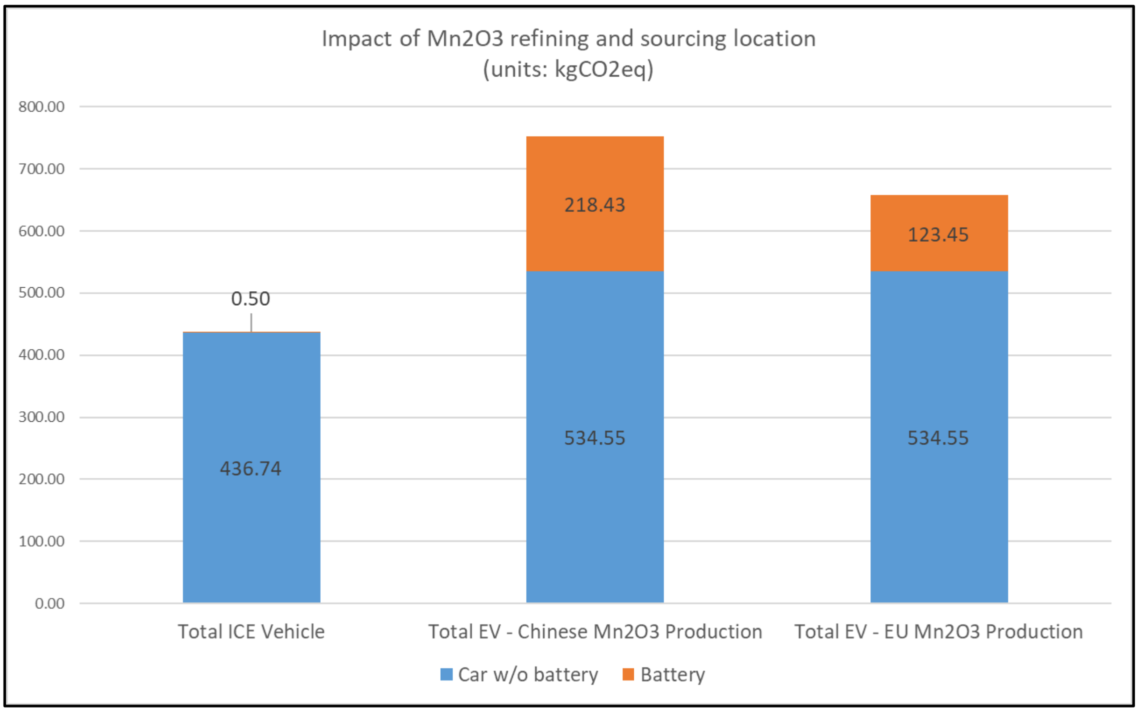

Figure 6-3: Impact of Mn_2O_3 refining and sourcing location on cradle to gate transportation carbon emissions.

Again, the significance of this will be discussed in the next chapter but the figure above clearly shows that sourcing this material from Europe presents a significant opportunity to reduce the transportation emissions for the battery and therefore the overall vehicle.

6.2.4. “Cradle to Gate” Transportation Emissions - By Material.

The analysis of “cradle to gate” transportation emissions has highlighted significant increases in carbon emissions generated by the transportation of certain materials, which will be discussed in the next section. The results below in Fig 6-4 documents these transportation emissions, grouped by material type.

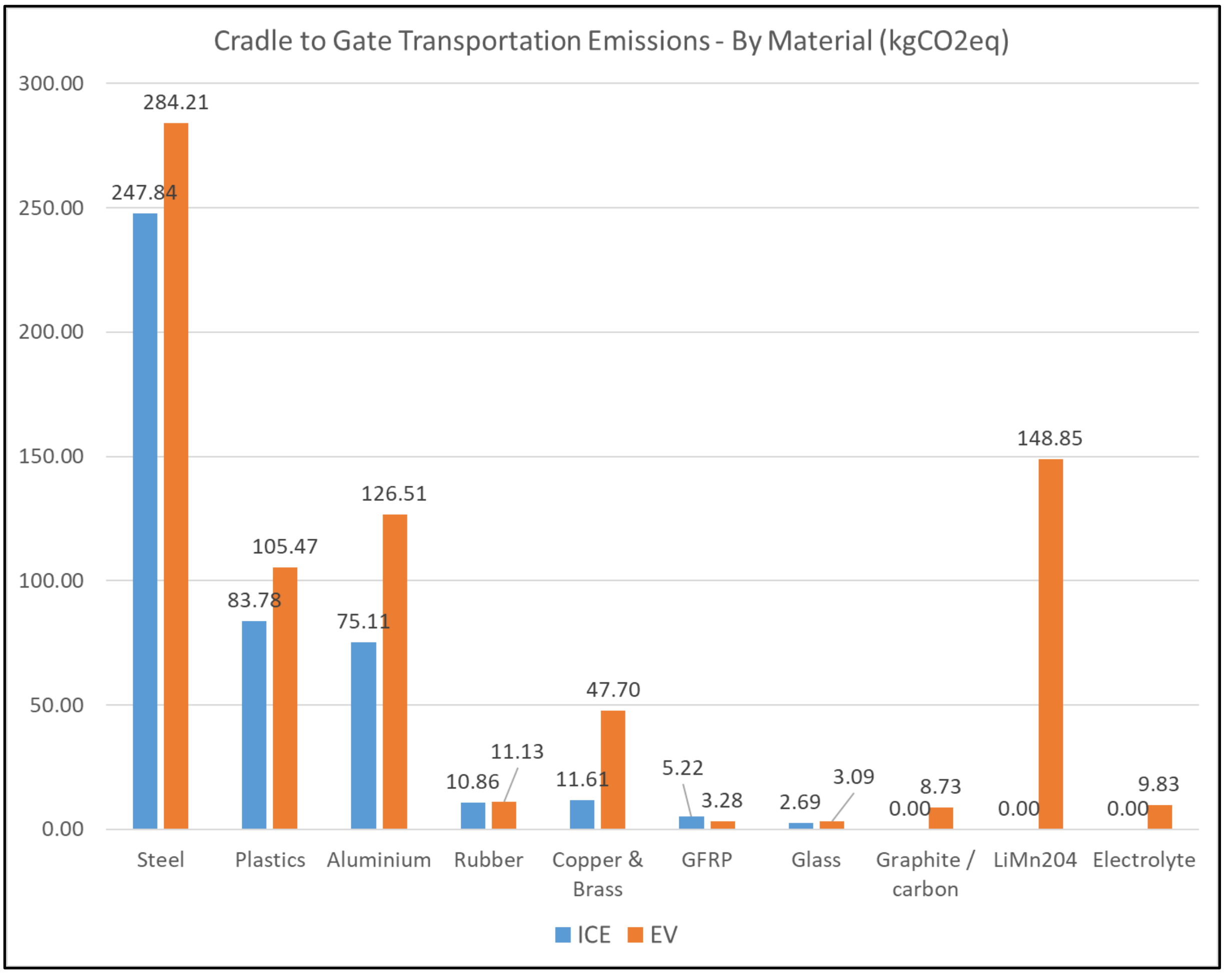

Figure 6-4: "Cradle to Gate" Transportation Emissions – by material type.

Besides the lithium elements of the batteries the above chart shows notable increases in copper and aluminium transportation emissions for EVs: above what would be expected in line with the increased weight of the vehicle.

6.2.5. Transportation carbon emissions arising from carbon / graphite content in the overall vehicle.

As noted in section 5.3.10, the carbon or graphite material used to manufacture lithium-ion batteries is the same substance as used in producing aluminium. However, when looking at the above chart in section 6.2.4., the transportation emissions associated with carbon graphite used in making aluminium (a key component of both internal combustion and EVs) is *included* in the aluminium figure, and thus difficult to compare.

Thus, to explore the impact of EV *batteries* on the carbon graphite supply chains' emissions, an analysis was done to *separately* document these emissions for comparison purposes.

The specific calculation is listed in Appendix C but the overall results are shown below in figure 6-5 below.

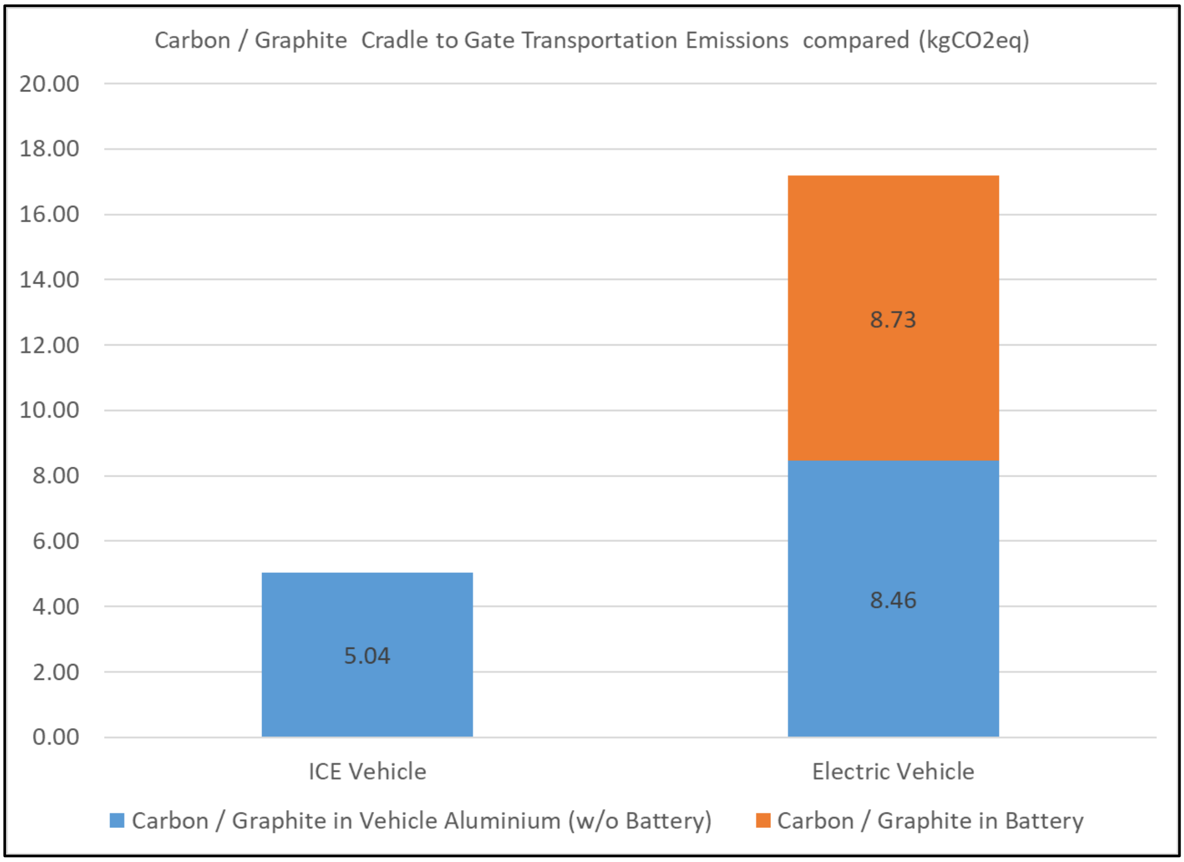

Figure 6-5: Carbon / Graphite "Cradle to Gate" Transportation Emissions compared (kgCO_2eq)

This figure clearly shows a significant increase in transportation emissions related to the carbon graphite material used in EV batteries which will be discussed further in the next chapter.

6.2.6. Impact of Supplier Distance to Automotive plant.

Section 5.2.3. describes how the model assumes a typical 1000 kilometre leg in the supply chain preceding the automotive manufacturer. This fits with the scenario where a German automotive plant would source its parts from across Europe.

Objective number 3 of this research's objectives states that it will evaluate factors contributing to cradle to gate carbon emissions, and the distance that goods are transported was identified as a key factor contributing to these emissions[88].

In order to evaluate the potential impact of supplier distance to the automotive plant, two further scenarios were modelled in addition to the default European sourcing scenario whose results are presented above. The two additional scenarios modelled are as follows:

- A *national* sourcing scenario where supplies are assumed to be within Germany and thus the longest journey in the supply chains preceding the automotive factory is an average 300 kilometres.
- A *local* sourcing scenario where in addition to assuming that suppliers in the supply chain are within Germany (as in the scenario above), this scenario also assumes *local suppliers* where tier 1 suppliers to the automotive plant are within an average 100 kilometre distance.

The results of these additional scenarios modelled are shown in figure 6-6.

Note that these two scenarios are chosen as they fall within the overall assumption noted in section 5.2.1 - that parts are sourced from Europe.

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[88] The other two factors that impact carbon emissions which would also align with the scope of Objective 3 are packing density and transportation mode, which combined determine the carbon emissions factor, as noted in section 4.3.1. These topics are however already the subject of considerable existing research (for example as discussed by McKinnon et el (2015)) and thus not discussed further in this research as further depth on these two areas would not significantly contribute to this research's novelty or original contribution to knowledge.

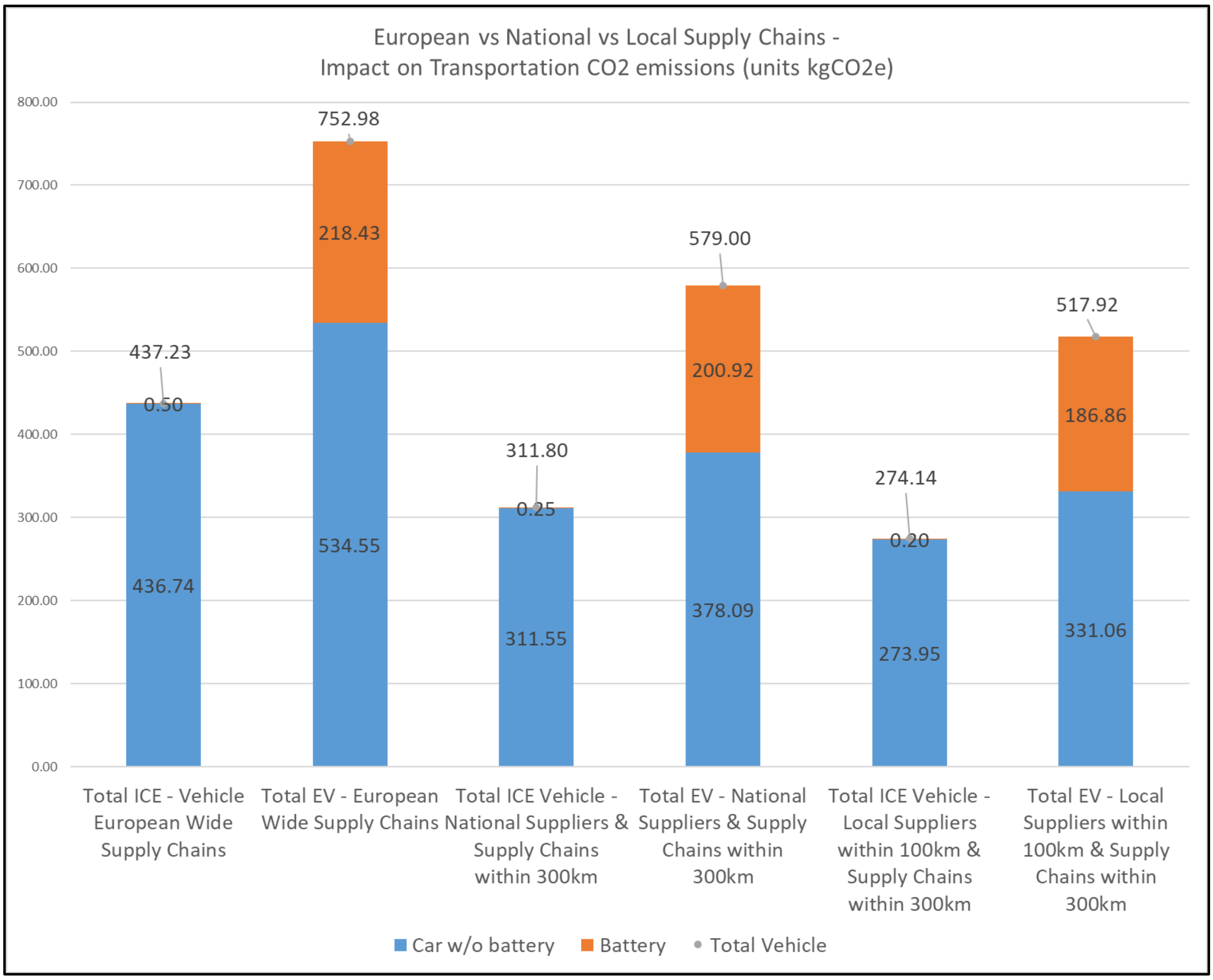

Figure 6-6: Transportation emissions from local, national and international supply chain scenarios.

As can be seen above, a local supply network, supported by national raw materials processing and supporting supply chains would deliver a significant reduction in transportation emissions and will be discussed in more detail in the next chapter.

6.3. Summary

This chapter has presented the results of the modelling and calculations which have been performed to satisfy the research aims, objectives and research questions. The first section of this chapter documented the output of each calculation - arranged by vehicle subsystem and material type and this was followed by analyses of these results which has provided key insights which arose from the modelling. The results presented in the chapter above provide the basis for the discussion chapter which follows.

7. DISCUSSION

Having presented the results in the previous chapter, this chapter will discuss the significance and impact of these results and insights gained from them.

To highlight the contribution to knowledge provided by this research, the chapter begins with sections revisiting and then addressing the research questions - underpinned by the results presented. Next, other insights and issues which arose from the results will be discussed. The chapter continues by confirming the contribution to knowledge that this research has provided and concludes with revisiting the original research objectives and confirming that these have been achieved.

7.1. Research Question 1 – EV and ICE supply chain transportation emissions

The first research question is stated again for the reader's convenience:

> "What is the relative impact of EV supply chains compared to ICE vehicle supply chains on transportation emissions when calculating "cradle to gate" automotive lifecycle analyses?"

The results documented in section 6.2.1. show clearly that for the scenario modelled, EVs have significantly more carbon emissions arising from cradle to gate transportation. As a percentage - compared to an ICE vehicle - the transportation emissions arising in EV supply chains are calculated to be 72.2% more than in the ICE vehicle modelled.

The results presented in the previous chapter therefore represent an original contribution to knowledge since no other author in the LCA literature to date has calculated, documented or compared the transportation emissions for ICE or EVs.

Two further significant implications arise:

- This suggests that the anticipated environmental benefits of EVs may be less than previously thought – this will be quantified in section 7.3.1 below.
- If the above carbon emissions figures are taken as a proxy to represent transportation activities and traffic (on the road, rail and sea ways) then this suggests that traffic due to automotive supply chains will increase significantly if society moves

> to EVs, which will have potential further knock on effects for infrastructure needed – which in turn will potentially give rise to further carbon emissions to create and maintain. Moreover, correspondingly more road, rail and sea *vehicles* will be needed for the increased automotive logistics activities which in turn give rise to further carbon emissions to manufacture these vehicles. However, the impact of these is beyond the scope of this research, but will be revisited in the future work chapter.

This addresses the first research question and provides a basis for several points of further discussion which will be detailed section 7.3. ff. However before moving to this discussion, research question 2 will be addressed.

7.2. Research Question 2 – the relative contribution of cradle to gate transport emissions.

The second research question was:

> "What is the relative contribution of supply chain transportation activities compared overall "cradle to gate" CO_2 emissions in automotive life cycle assessments?"

While the answer to Research Question 1 shows a significant increase in cradle to gate transportation carbon emissions arising from EVs compared to ICE vehicles, it does not address the *relative* impact of these carbon emissions compared to the rest of the vehicle life cycle which is the concern of the second research question. To address the second research question, the results from the TCE model needs to be presented as part of a *full* life cycle assessment - known to exclude transportation emissions - of a similar case study scenario.

However, as noted by Del Pero et al (2018) the total CO_2 emissions reported by different life cycle assessments are extremely varied, with some LCA's reporting figures *multiple times* the magnitude of others.   This is accounted for by a variety of different vehicles modelled, varying assumptions, energy mixes assumed, and geographical locations modelled. Thus, identifying a life cycle assessment of a scenario comparable to this research is essential if a meaningful answer to the second research question is to be found.

The next subsections discuss the choice of full life cycle assessment chosen to present alongside the results from this research in order to address Research Question 2.

7.2.1 The Choice of the Volvo XC40 LCA to compliment this research

After studying the results of several LCA's, one – the Volvo XC40 – was chosen which aligned closely with this research.

As noted previously in this document, the Swedish vehicle manufacturer Volvo performed a LCA comparing the life cycle carbon emissions of the ICE and electric versions of the XC40 model (Egeskog *et al.*, 2020).

The results from their study were found to provide a compatible point of reference for the other life cycle phases that fall outside the scope of this research (for example vehicle manufacturing, usage and end of life recycling) given that it is also based on a European manufactured vehicle (with the XC40 being manufactured in Ghent in Belgium (Volvo Newsroom, 2020)) with comparable distances involved and comparable energy mixes for other phases of the life cycle. Moreover the Volvo XC40 vehicles are very close to the vehicles in the GREET model data set in terms of weight (especially for the EV version), meaning that their results are likely to be comparable with the vehicles modelled in this research. This is shown in table 7.1. below.

Table 7.1. GREET Vehicle and Volvo XC40 Vehicle weights compared (data sources Argonne National Laboratory (2021) and Egeskog et al (2020))

Vehicle	Total ICE vehicle weight (kg)	Total EV weight (incl. battery) (kg)	EV w/o battery (kg)	EV Battery (kg)
GREET Vehicles modelled	1460	2133	1742	391
Volvo XC40	1690	2170	1820	350

Moreover, it was found that the emissions arising specifically from manufacturing emissions for a similar GREET ICE vehicle modelled by Argonne National Laboratory (Sullivan, Burnham and Wang, 2010) (in this case one weighing 1532kg) were a close match for the Volvo equivalent ICE version as shown in table 7.2. below. Although in this case the vehicle modelled by the GREET model was slightly heavier than the one modelled in this research, the proximity of the results suggests a comparable range of assumptions, and a comparable vehicle material composition which would be needed to reach such similar figures.

Table 7.2. Manufacturing Phase Emissions for a GREET modelled vehicle compared to the VOLVO XC40 (data sources Sullivan et al (2010) and Egeskog et al (2020))

Vehicle	Total ICE vehicle manufacturing emissions ($kgCO_2e$)
GREET Vehicle modelled (1532kg)	2013
Volvo XC40 ICE (1690kg)	2100

While an equivalent GREET LCA was not found for an EV, given that the two versions of the Volvo X40 are near identical other than their internal combustion and electric drivetrains - the similarity noted in table 7.2. above remains credible for parts of the EVs other than their drivetrains and thus still confirms a credible similarity between the two life cycle assessments in areas where they overlap.

Thus, on the basis of the above, the results of the Volvo XC40 LCA were chosen to compliment this research and used to put the results of this research into context to address the second research question.

7.2.2. The Cradle to Gate transportation emissions of a Volvo XC40.

Having chosen the Volvo XC40 as a compatible life cycle assessment, the TCE model was adjusted to make its results relevant to the Volvo XC40 as follows:

- The emissions from the last transportation leg – representing tier one suppliers - of each supply chain was removed (as the Volvo XC40 lifecycle assessment states that it *does* include transportation emissions from *tier one* suppliers).
- The vehicle weights of the TCE modelling were adjusted proportionally to those of the Volvo vehicle values – for both types of vehicle and for the EV battery

The Volvo XC40 LCA presents 3 scenarios, comparing the ICE emissions with 3 different electricity supply mixes[89] for the usage phase of the EV - and this is done up to a vehicle life time of 200,000 kilometres. It does not assume a new battery during this lifetime for the EV.

The three scenarios are shown below with the results of the TCE model[90] included (labelled “C2G Transportation” in each case):

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[89] the three electricity mixes presented will have different proportions of fossil fuel generated electricity producing different carbon emissions arising in the use face.

[90] the calculations for the results presented here are not included in the appendices but are available on request.

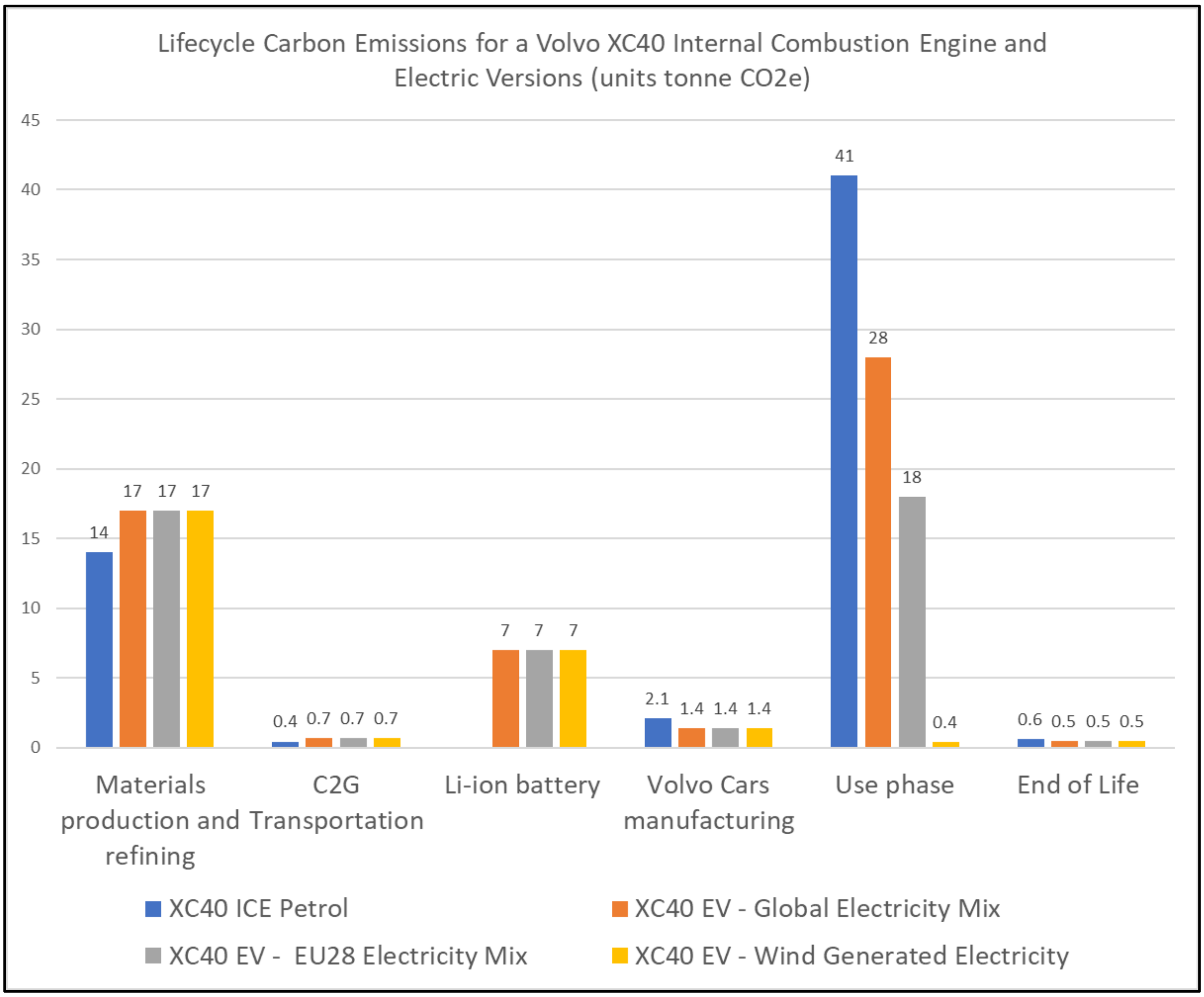

Figure 7-1: Lifecycle Carbon Emissions for a Volvo XC40 ICE and Electric Versions – Including Cradle to Gate Transportation (Volvo XC40 figures source: Egeskog el al (2020)).

As can be seen from Fig 7-1 above, transportation carbon emissions remain a relatively small proportion of carbon emissions relative to emissions arising in the usage phase.

Notwithstanding this, they become significant when compared with emissions arising from the vehicle manufacturing phase as well as the end of life phase which *are* frequently included in LCA.

Moreover when viewed as a proportion of emissions in the wind powered electricity scenario - they become a significant relative contribution. Figures 7-2 and 7-3 below compare the relative contribution of “cradle to gate” transportation emissions in the case of ICE vehicles and the wind power electricity scenario for the EV.

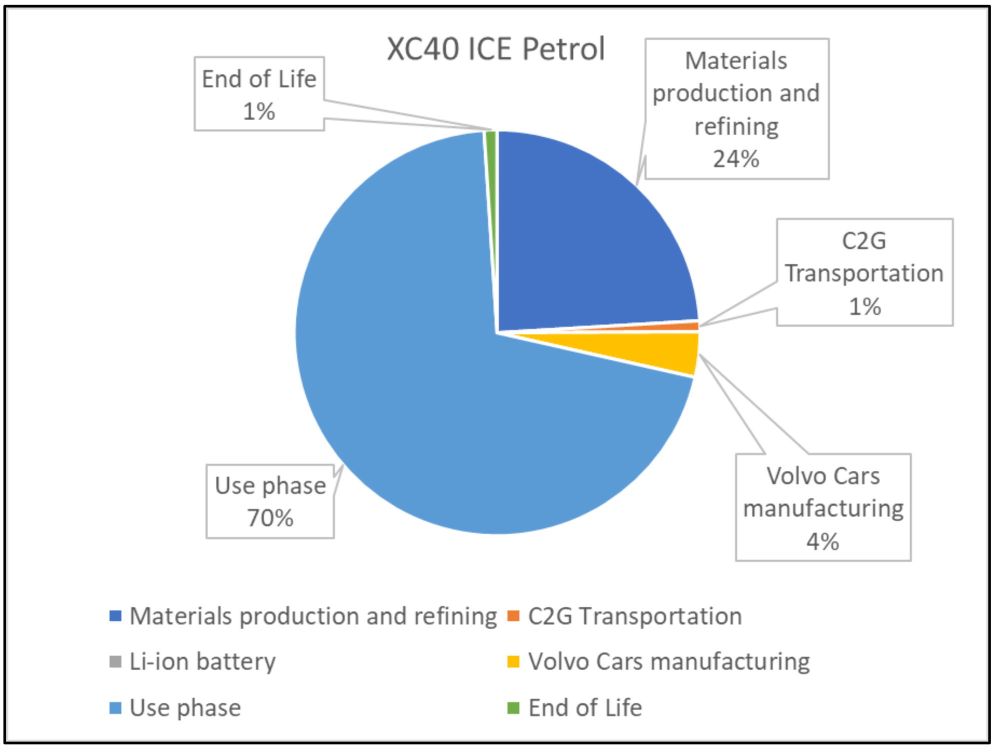

Figure 7-2: Relative contribution of different life cycle phases to overall life cycle carbon emissions - Volvo XC40 ICE.

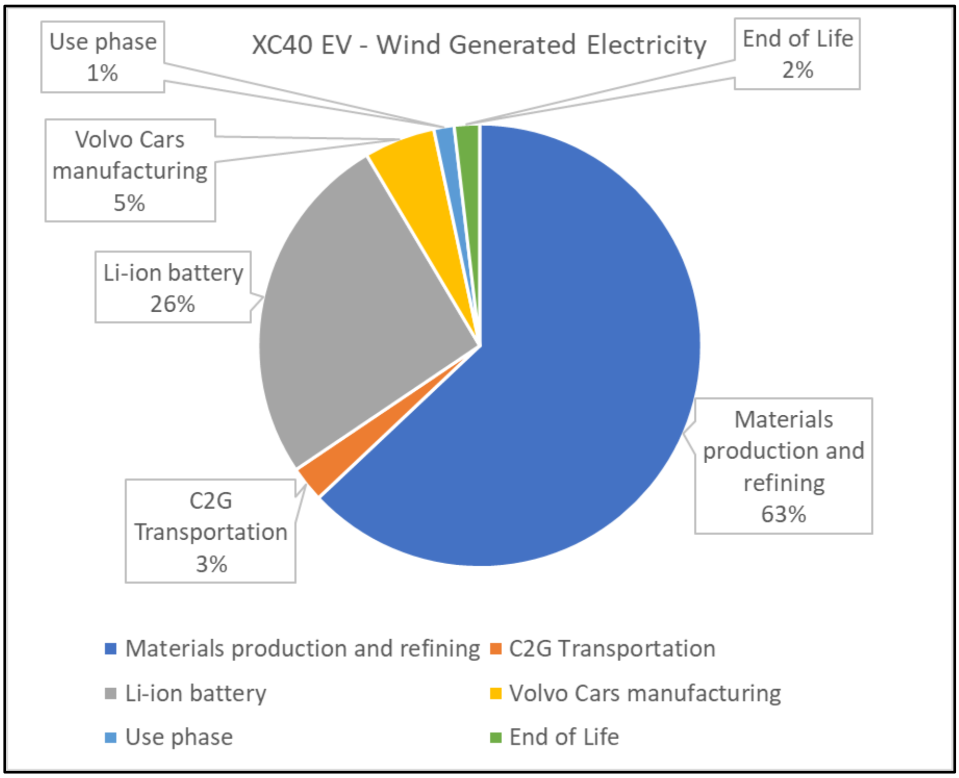

Figure 7-3: Relative contribution of different life cycle phases to overall life cycle carbon emissions – EV, wind generated electricity.

As can be seen from the two charts above, in a wind generated electricity driven “use” phase, emissions are reduced so much (to approx. 1% of overall emissions) that it becomes almost insignificant compared to the other life cycle phases. Thus, as a percentage of the remaining life cycle phases, the EV “cradle to gate” transportation emissions increases significantly compared to the ICE scenario.

7.2.3. Research Question 2 – Discussion

As introduced in section 1.2., transportation emissions are largely ignored in automotive lifecycle analyses even though - as a percentage of global emissions - transportation accounts for roughly a quarter of carbon emissions.

In answering the second research question, the *relative* contribution of transportation emissions can now be seen, and consequently the practice of omitting them in the literature can now be challenged or confirmed.

The difference in the profile and magnitude of life cycle carbon emissions occurring between electric and ICE vehicles merits a different answer in the case of each type of vehicle.

7.2.3.1 – ICE Vehicle Life Cycle Analyses

Figures 7-2 and 7-3 above show the relative contribution of cradle to gate transportation activities in ICE and EV vehicles’ life cycles. The solution to the apparent paradox identified in research Chapter 2[91] is that - in the case of ICEs - the significant majority of carbon emissions occur during the usage phase - *a transportation activity in and of itself* (although not contributing to the manufacture of that same vehicle).

Thus, viewed from a life cycle perspective in the case of an automobile, the contribution to global transportation emissions are *both* the emissions arising from the usage phase as well as the comparatively small transportation emissions that arise in the supply chains that provide the same vehicle.

In other words most of the life cycle emissions of a vehicle do in fact contribute to global transportation emissions: but the majority of these are in the *usage* phase of the vehicle. Viewing historical LCA on ICE vehicles from this perspective, may justify why transportation emissions in the cradle to gate phase are seen as insignificant or ignored. However, this is

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[91] i.e. that studies dealing with CO_2 emissions associated with manufacturing vehicles appear to omit the contribution arising from transportation activities, or consider them to be negligible, even though transportation carbon emissions account for approx.. one quarter of global emissions.

only credible for ICE vehicles which do have such a significant usage phase contribution to carbon emissions.

7.2.3.2. EVs - with low carbon energy sources – Life Cycle Analyses

In the case of EVs however, the cradle to gate transportation carbon emissions can no longer be ignored if the EV is powered by a low carbon electricity source such as wind generated electricity – as in the case of the Volvo XC40 LCA.

In this case, the supply chain transportation emissions approach 3% of the overall life cycle emissions: a figure which exceeds the “end of life” emissions[92] and which is significant when compared to emissions arising from actual vehicle manufacture and assembly - which represents 5% of the overall emissions.

Notwithstanding the above, when compared to the emissions arising from materials production and refining as well as manufacturing the battery, it is acknowledged that transportation emissions in the supply chain remain comparatively minor. Yet, if emissions such as “end of life” and vehicle manufacturing and assembly *are* typically accounted for in life cycle analyses then the cradle to gate transportation emissions which have been the topic of this research merit inclusion too in EV life cycle analyses.

7.2.4 Summary

To summarise the implications of the answer to research question 2 above: in the case of ICEs, the exclusion of transportation emissions may well be justified given the magnitude of carbon emissions arising in the usage cycle. However in the case of EVs, *where they are powered by low carbon electricity sources* - such as wind power - they do in fact merit inclusion in any LCA.

7.3. Further discussion and insights gained.

Having addressed the research questions above, the discussion will now turn to other insights and implications of this research.

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[92] which account for emissions arising in disposal and recycling of the vehicle.

7.3.1. The Volvo XC40 “break-even” results adjusted.

In the Volvo LCA it is noted that while the electric version of the XC40 causes considerably more carbon emissions in the cradle to gate phases, these are offset during the usage phase and a break-even point[93] (in km) has been identified in their LCA for the three different energy mix scenarios documented. This is shown below in figure 7-4.

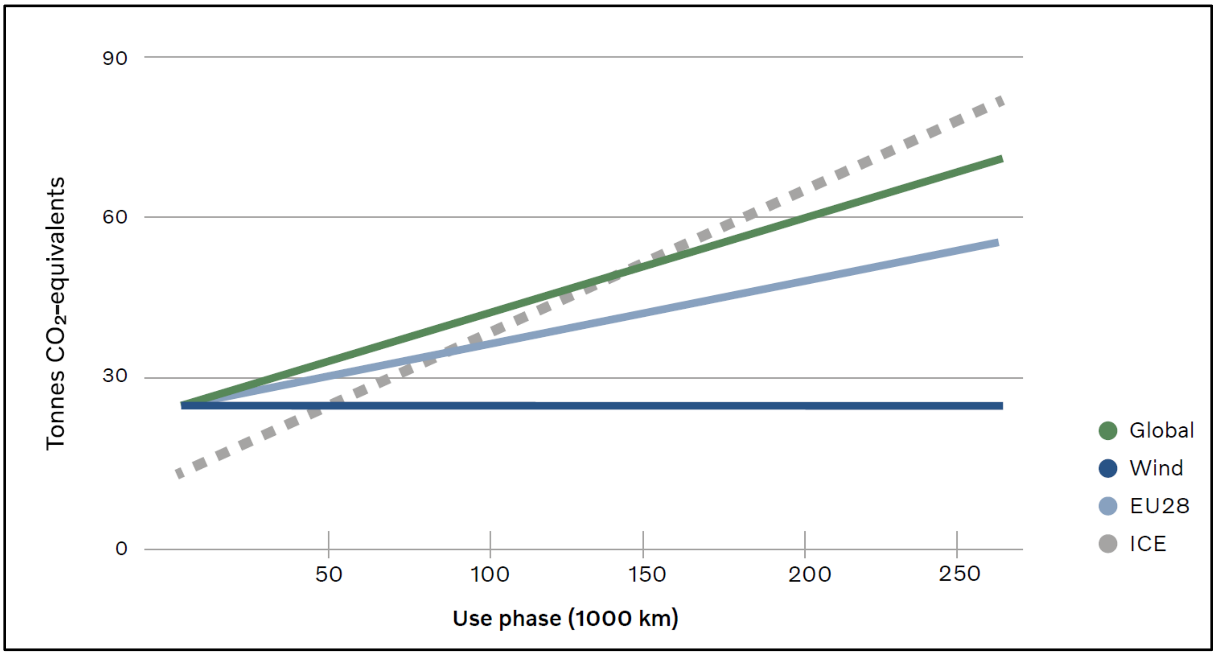

Figure 7-4: Distance break even points for different energy mixes for the Volvo XC40 (source Egeskog el al (2020)).

The results of the TCE modelling were added to the Volvo XC40 emissions, and the break even figures were recalculated – the results of which are as shown in table 7.3..

Table 7.3. Impact of including cradle to gate transport emissions on break even point.

	Break-even (km) Egeskog el al (2020)**.**	**Break-even with cradle to gate transportation emissions included (km)**[94]	**Difference (km)**

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[93] in this context, the “break even” point refers to the mileage at which the lifetime emissions of an electric vehicle become lower than an ICE vehicle.

[94] These figures are rounded to the nearest 100km, given that the Volvo figures are only given to the nearest 1000km

XC40 Recharge, Global Electricity Mix/XC40 ICE XC40 Recharge	146 000	149 300	3300
EU28 Electricity Mix/XC40 ICE XC40 Recharge	84 000	85 800	1800
Wind Electricity/XC40 ICE	47 000	48 000	1000

As can be seen above, the impact of including the transportation emissions is modest, and would delay the break-even point by a few weeks or months depending on the vehicle's mileage.

Viewing the break-even point in terms of time does provide an interesting perspective on how long it takes for the benefits of an EV to be realised. Fig 7-5 below plots the break-even point on a time perspective assuming an annual mileage of 10140km (or 6300 miles) per year (which is the pre-pandemic 2019 British average private vehicle mileage according to the UK Government (UK National Travel Survey, 2023) – which accounts for 98% of British vehicles).

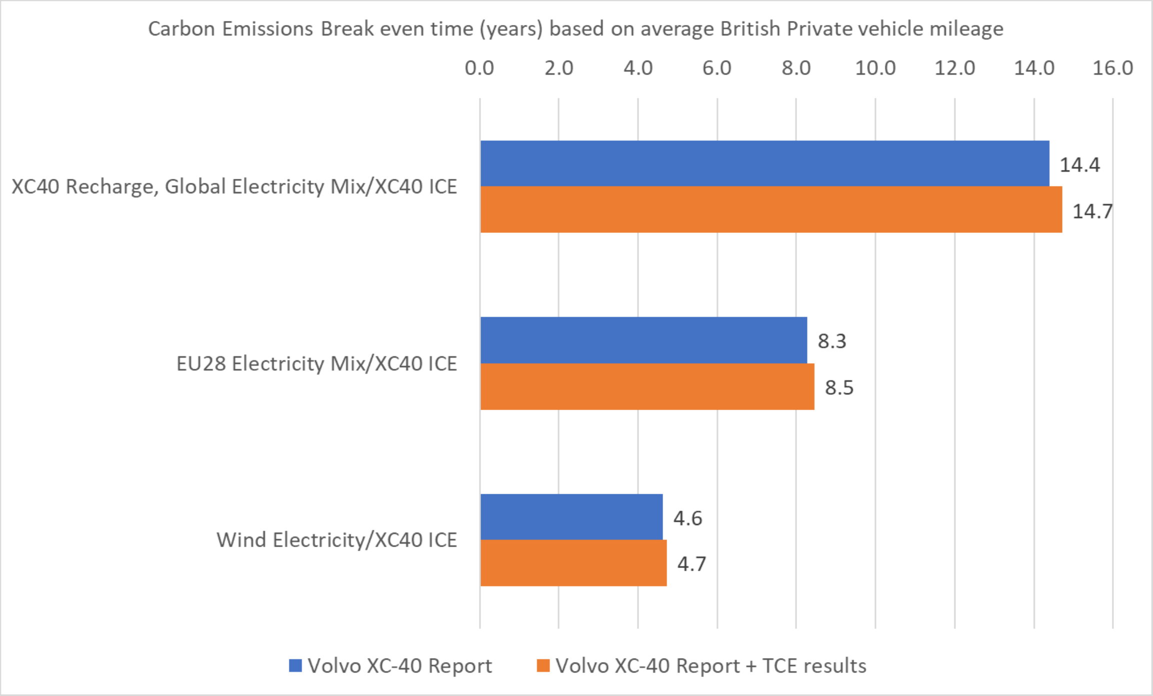

Figure 7-5: Volvo XC-40 carbon emissions break even time (years) based on average British private mileage.

However, as can be seen from the chart above, including the results from the TCE modelling does not significantly impact on the length of time which it takes for an EV to break even in terms of carbon emissions. For example - in the case of the European electricity mix, It would take 8.3 years before an EV starts to become better for the environment in terms of carbon emissions, based on Volvo's figures. However when transportation emissions are added to Volvo’s figures, this increases the time to 8.5 years. Compared to the 8.3 years taken to get to this point, the additional couple of months does not profoundly worsen the break even time, and is a comparatively minor increase to this break even time.

However, as can also be seen from the chart above, the break-even point for EVs can be *several years* in the case of the average British mileage. Exploring this topic further and its implications is however beyond the scope of this research and will not be pursued further in this document.

This concludes discussion relating directly to the Volvo XC40 case study and for the remainder of this document the original values modelled for this research will underlie the topics of discussion, unless stated otherwise.

7.3.2. The impact of the EV Battery and its supply chains

As presented in section 6.2.2., the EV battery accounts for a significant proportion of transportation emissions. While this might be expected due to the weight of the battery (accounting for approximately 18.4% of the vehicle weight) it is noted that the transportation emissions are a disproportionately higher figure of 29%. The reason for this is found in the shipping emissions of one of its key raw materials, MN_2O_3.

As discussed in Chapter 5, China currently is the main location of MN_2O_3 production and even though batteries may be produced in the European Union, this material is still currently sourced from China. The very high transportation emissions arising from this occur because the manganese raw material (in the form of ore) is first shipped to China from South Africa (by bulk carrier ship) and then - after refining - will be shipped to Europe for battery production. It is this last leg of marine shipping which especially contributes to the carbon emissions because once refined, it is unlikely that the refined material will be transported in a bulk carrier ship again.

Although bulk carrier ships are one of the largest type of ships available, they have a very high packing density and - per tonne - are one of the lowest-carbon means of transportation[95]. Thus when the manganese ore is transported to China, it will be done in a bulk carrier ship which has very low carbon emissions per tonne transported. However once the material has been refined it is more likely to be transported by means of a container ship and it is this leg of shipping - via container ship - which dominates the transportation carbon contribution of this material. While figure 7-6 is included in the appendices with the other results, it is enlarged and reproduced here (with the container ship leg of transportation highlighted in red) for the reader’s convenience to illustrate this point.

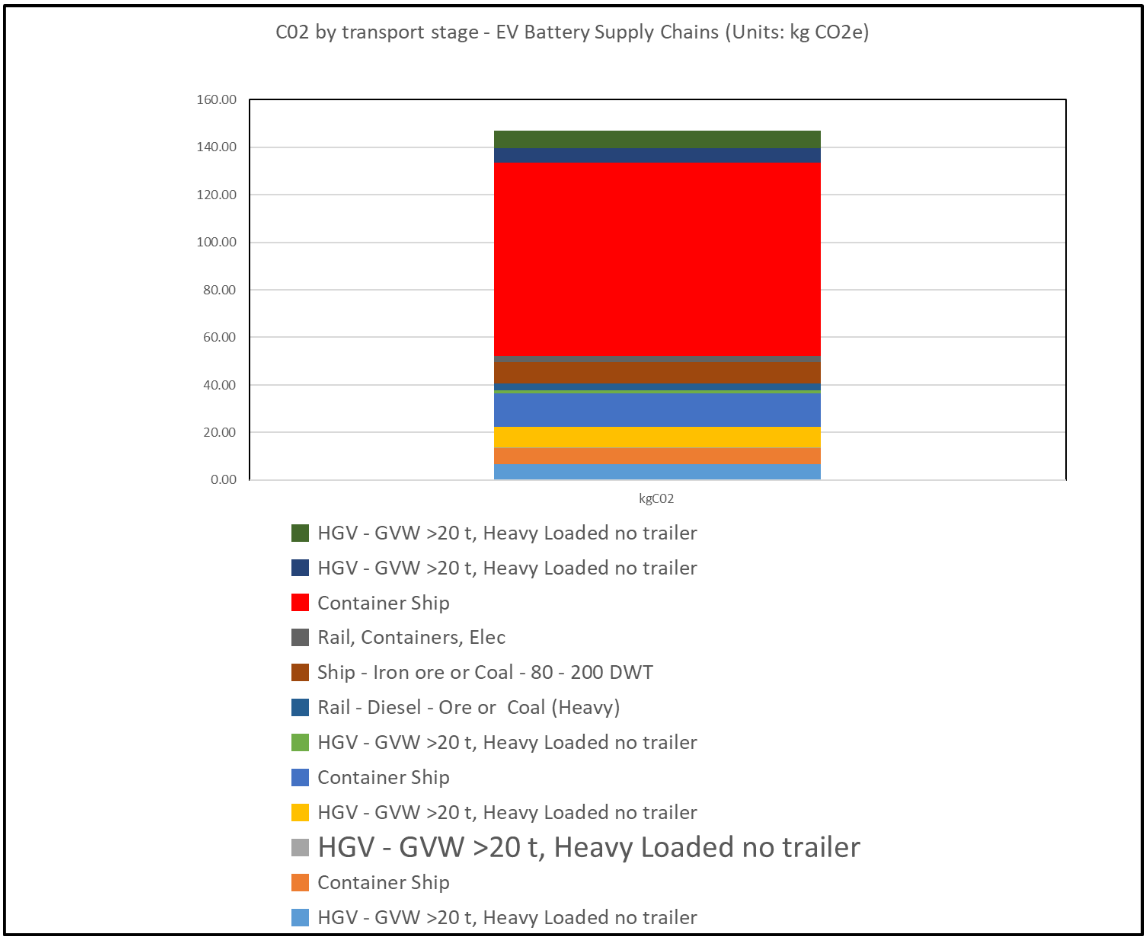

Figure 7-6: Transportation carbon emissions for EV batteries. Ref: calculation sheet EV-B-55China, Appendix C

As also noted in section 5.3.12, an alternative scenario was modelled whereby the MN_20_3 is refined in Europe – a likely future scenario in line with the European Union and other government body plans to expand EV battery production (and their supply chains) in Europe.

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[95] however this positive aspect of marine transport should not obscure the other significant environmental damage which it does on marine life, examples of which are discussed *inter alia* by the UK Maritime and Coastguard Agency (2017).

The effect of this on reducing transportation emissions will be significant because the "container ship" leg of the journey will no longer be necessary. Moreover in this scenario, instead of transporting manganese ore from South Africa, more locally available manganese ore from the Czech Republic can be supplied to a European refinery (the modelling done assumes that this will be to existing refining capacity located in Belgium). Once refined, the MN_20_3 can be transported to the battery factory by heavy goods vehicle (which would have also been the case if the material had been supplied from China as it would arrive from Rotterdam port and would need to reach the battery factory by the same mode of transport).

The effect of removing the container ship leg combined with local supply of manganese ore in the European context provides a dramatic reduction in carbon emissions by transportation for the whole vehicle as shown below in Figure 7-7.

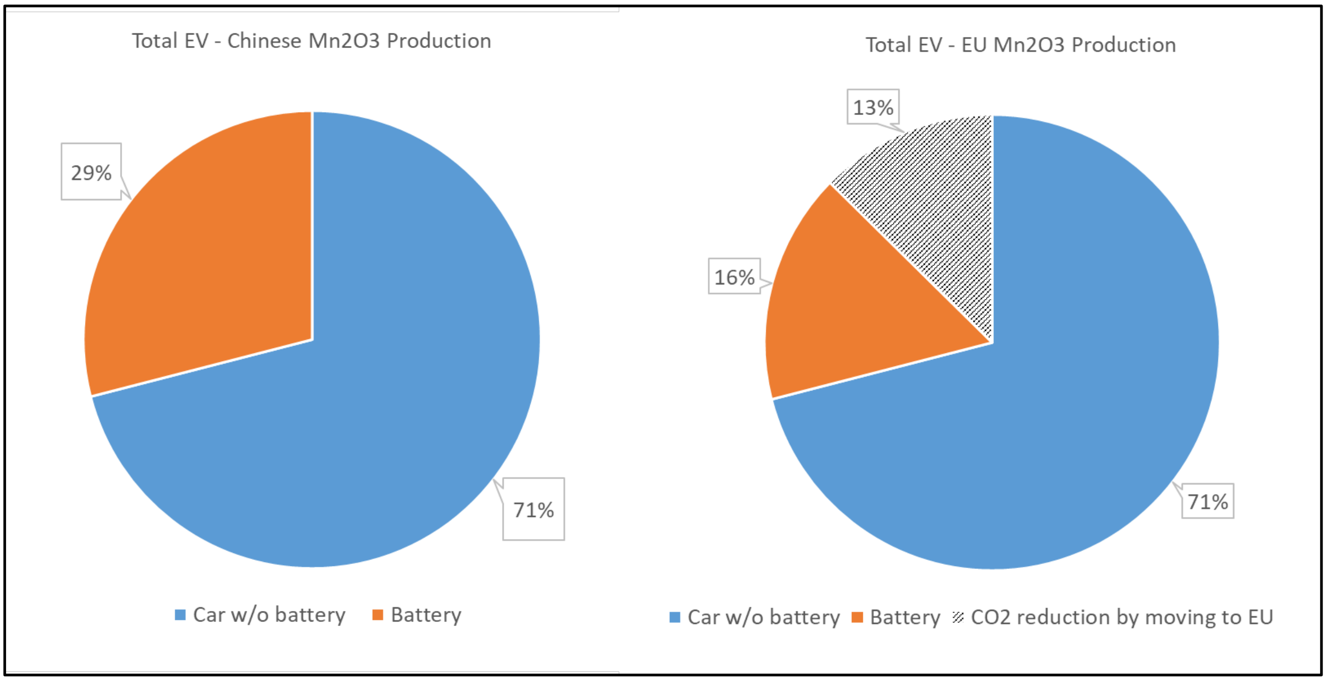

Figure 7-7: Reduction on transportation CO_2 emissions arising from MN_2O_3 production in Europe.

In this scenario, the battery accounts for 16% of the vehicle's transportation emissions - proportionately less than its weight compared to the rest of the vehicle. This is as would be expected given the relatively heavier weight of a battery which is a solid object allowing for high packing density in transportation thereby lowering the per tonne emissions, as minimal air is also shipped when transporting batteries (unlike for example rubber tyres which occupy a lot of space relative to their weight).

Thus, while the European Union and governments may be supporting battery production to ensure security of supply for the EV market which is seen as a political priority, pursuing this policy will have the positive effect of reducing transportation carbon emissions for the entire vehicle by as much as 13%.

This is one of the most significant opportunities to reduce transportation emissions in EVs using this battery technology made in Europe and should therefore remain a priority of the European governments.

This key finding of this study – while not anticipated in the course of answering the research questions – identifies a significant opportunity to reduce carbon emissions in battery supply chain transportation. It provides a novel contribution to knowledge which has arisen from taking a systems perspective in modelling transportation carbon emissions which provides a clear practical application with significant potential impact.

7.3.3 Impact on strategic raw materials for EVs

Section 6.2.4 presents the transportation carbon emissions linked with different materials. As noted previously, because of the significant weight of the battery, EVs need to be stronger structurally than an equivalent ICE vehicle and this accounts for the increased transportation emissions for structural materials (such as steel in particular which comprises the vehicle body).

However, there are several other materials whose transportation emissions are significantly higher than might be expected, beyond the proportional increase in weight of the vehicle.

Figure 6-4 above shows these numbers and will be discussed briefly in this section.

Notably more aluminium, copper and graphite is used in EVs and these increased supply chains are all reflected in the increased carbon emissions (the lithium supply chain also has significant emissions, but this has been discussed already in the previous subsection).

Firstly there is a significantly increased use of aluminium in EVs - accounted for by the structural role that aluminium plays in the EV batteries. As would be expected, significantly more copper is used in an EV as it is the primary means of conducting electrical energy from the batteries to the motors and is also used within the electric motors. Lastly there Is a significant increase in the carbon graphite used. As discussed in section 6.2.5 This carbon graphite material is used in both aluminium manufacture as well as the manufacture of EV batteries.

These results impact on areas in wider supply chains. While it is outside the remit of this research, brief comments will be made regarding these topics. The implications are twofold. Firstly as noted previously in this document - the European Union and European governments have prioritised EV manufacture and battery production and have sought to establish production and supply chains within Europe. Perhaps because of their novelty to EVs, the battery manufacture has received most attention. However as has been shown above, attention and support at a national and international level needs to be given to increase supply chain capacity specifically for aluminium, copper and graphite without which a significant rise in EV manufacture will be impeded.

Secondly, given the increased demand for these raw materials, there is a risk that the commodity prices for these specific raw materials may well increase if the demand for EVs places strain on these supply chains and their availability. This however is again outside the scope of this research but will be revisited in the "future work" chapter.

7.3.4 Impact of Supplier Distance to Automotive plant.

Section 6.2.6. Documents the results of modelling three different scenarios relating to supplier distance from the automotive vehicle plant. It demonstrates the tension between economic supply chain considerations and the consequential carbon emission results arising. As discussed by Harris et al (2011) manufacturers tend to make supplier choices based on economic considerations. As noted earlier in this document, as much as half of European automotive component manufacture occurs in Eastern Europe where a highly skilled workforce is found at a lower cost than in countries like Germany for example. Thus, many manufacturers will seek to gain a competitive advantage by sourcing automotive components from Eastern Europe. However, in doing so carbon emissions arising from transportation increase by over 30 %, compared to a local sourcing strategy (which may have been in place 20 or 30 years ago before Eastern Europe became a feasible manufacturing location).

Figure 7-8 below (compiled from the results presented in section 6.2.6.) shows the proportion of emissions which arise from a national and international sourcing strategy.

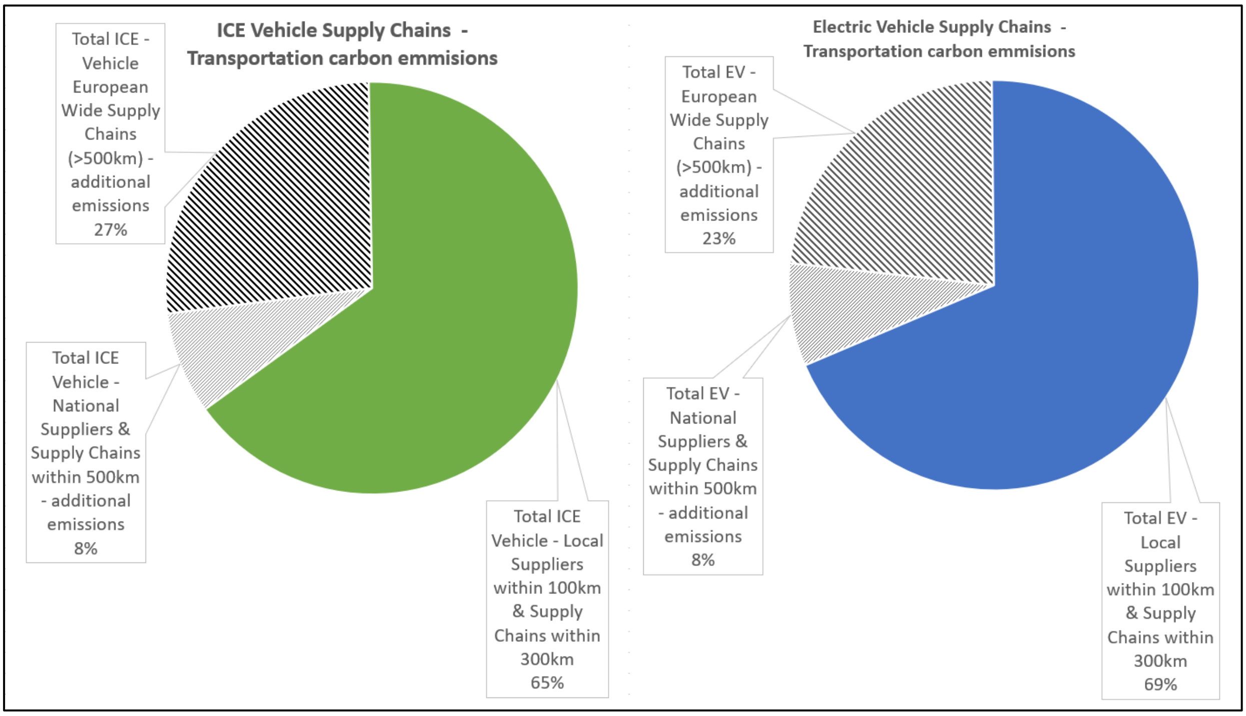

Figure 7-8: Impact of an international sourcing strategy on carbon emissions.

While raw materials have been shipped to Europe from around the world - and remain constant in all three scenarios – an international sourcing strategy results in a considerably higher level of carbon emissions compared to a potential local sourcing strategy or a national sourcing strategy. However, this also highlights the significant impact that the last leg of the supply chain contributes to the carbon emissions by transportation.

While it is unlikely that any vehicle manufacturer will move to a highly local sourcing strategy just to reduce transportation carbon emissions (due to the negative financial impact of doing so) there are other ways to reduce transportation emissions other than reducing distance (important though distance is).

The above is caused by the impact of the packing density of a product during the different supply phases. In the initial stages of the raw materials supply chains, raw materials such as iron ore are transported by bulk carriers, which have the lowest carbon emissions per tonne. However, during the very last legs of transportation, the product is typically transported by road vehicles which have much higher transportation emissions. Moreover, the parts have a much lower packing density because of the shape of the items being transported.

Thus, the key to reducing transportation emissions - if it is not feasible to bring suppliers closer to the automotive factory - is to focus on providing lower emissions in road transportation. This could be done in a number of ways which include:

- Lower carbon emissions heavy goods vehicles – perhaps in the form of electric heavy goods vehicles
- Ensuring that maximum packing density is maintained wherever possible.
- Optimising vehicle routing and utilisation.

However, these topics lie outside the remit of this research – and are extensive areas of research in and of themselves - but are nonetheless identified here as potential opportunities to reduce carbon emissions in supply chain transportation activities.

7.3.5. Summary

This concludes the topics of *further* discussion: the areas with the most impact and which were related to the aims of the research have been discussed here. However, other topics of relevance have also been identified and are discussed in the future work chapter as they do not specifically align with the objectives of this research or with addressing the research questions posed.

7.4. Discussion Conclusion

This chapter has discussed the results of this research to address the research questions posed as well as other areas of impact. Chapter 8 will discuss future work which arises from the modelling performed, both in terms of addressing limitations of the modelling done but also in exploring further potential research questions which have arisen in the course of the discussion and modelling performed.

8. CONCLUSION

Having discussed the modelling performed, and results achieved, the previous chapter provided clear and definitive solutions to the research questions posed within the context of the case study modelled. This chapter proceeds then to specifically identify the contributions to knowledge and to practice that then arise.

Following this, the limitations which apply to this research are considered. However, these also give rise to opportunities for further work which are described next.

The future work discussion that follows is divided into three sections. The first section will note opportunities to improve the results of the case study chosen to model. Next, opportunities will be identified to expand the validity of the research conducted. This is followed by a section considering opportunities noted which were outside the focus of this research but which nonetheless may present future opportunities to contribute to knowledge.

The aims, objectives and research questions are then reviewed, confirming their achievement, and the chapter closes with a few concluding remarks which will outline the immediate next steps which will be undertaken to further this research.

8.1. Contributions to knowledge, practice and theory.

The results of this research provide a number of original contributions to knowledge, some of which also have implications to existing practice, specifically in conducting LCAs. While the specific details are found in the previous chapter, the areas of contribution are summarised in the subsections below.

8.1.1. Calculation of cradle to gate carbon emissions for an ICE passenger vehicle

As noted in the literature review chapter, the automotive LCA literature is silent when it comes to any specific (or even estimated) figure of carbon emissions associated with cradle to gate supply chain transportation activities. While some studies may have alluded to energy usage for these activities, none presented an actual quantified figure, instead opting to consider it negligible, unfeasible to calculate, or simply not mentioning it at all. In this research a calculated quantifiable figure has been presented for these emissions.

8.1.2. Calculation of cradle to gate carbon emissions for an Electric passenger vehicle

While in the case of ICE vehicles (which have a much longer history of LCA) there were occasional mentions of energy usage for transportation activities in the LCA literature, in the comparatively new study of EVs not even a figure for energy was found in the recent literature. Thus, as in the case of ICE vehicles, a figure has been calculated for these emissions.

8.1.3. Comparison of cradle to gate transportation emissions between EVs and ICE vehicles.

This research has - for the first time[96] - presented a two case studies which actually allow for the robust comparison of the cradle to gate transportation emissions between an ICE vehicle and an EV. This research has shown that EV supply chain transportation activities contribute over 70% more carbon emissions then equivalent ICE vehicle supply chains.

8.1.4. Total cradle to gate carbon emissions for ICE and EV passenger vehicles.

While there has been considerable research comparing the whole life cycle carbon emissions between ICE and EVs, in the absence of any quantifiable figures for supply chain transportation activities, there is a level of uncertainty in these figures.

Thus, due to this research, the contribution of transportation activities can be incorporated into these full life cycle analyses, thereby presenting more accurate and representative figures for carbon emissions in each case. This in turn allows for more complete evaluations of the impact of EVs on the environment.

Moreover, having the transportation emissions shown alongside the other life cycle emissions allows decision makers to evaluate the relative contribution of transportation compared to the other phases of a vehicle’s life cycle, and thereby appropriately prioritise efforts to reduce carbon emissions.

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[96] Please see Footnote 1 which qualifies this assertion.

8.1.5. Justification not to include cradle to gate transportation carbon emissions for an ICE passenger vehicle – contribution to practice.

This research has shown that compared to the considerable carbon emissions generated during the usage phase of ICE vehicles, the supply chain transportation emissions may well be justifiably considered to be insignificant in comparison.

Thus, the implication is that historical lifecycle analyses which have ignored or not dealt with transportation carbon emissions - in the case of ICE vehicles – were probably justified in doing so, and that this omission did not significantly undermine their results and conclusions.

8.1.6. Imperative to include calculations of cradle to gate carbon emissions for an electric passenger vehicle – contribution to practice.

Where EVs are propelled by very low carbon electricity sources (such as wind power) the usage phase carbon emissions effectively approach zero.

In this case, this research has shown that as a proportion of the remaining life cycle carbon emissions, that transportation emissions during the cradle to gate supply chains exceed those of other life cycle phases which are frequently documented (such as end of life disposal).

While the contribution of transportation emissions remains modest compared to emissions associated with raw materials refining and battery production, if a lifecycle analysis claims to be comprehensive and compliant with the ISO standards, then the cradle to gate transport emissions merit discussion as a separate area of contribution as they can no longer be considered negligible.

8.1.7. Creation of the Transport Emissions Model

While the transport emissions model created for this research may not be a contribution to knowledge per se, it is an original contribution to practice and modelling in this area. No other modelling tool was found which is able to both account for multiple supply chains required to produce raw materials and components, as well as account for reducing weight of material transported as the material progressed through the supply chain journey (due to wastes and off cuts for example). In this respect the creation of the TCE model for this research has been an original and novel contribution to supply chain transportation emissions modelling and analysis.

8.1.8. A systems theory paradigm for evaluating transportation carbon emissions.

This research has developed and documented a theoretical paradigm – underpinned by Systems Theory - for evaluating transportation carbon emissions in supply chains. This approach ensures a comprehensive assessment of global transportation emissions, avoiding the risks of focusing on localised segments that may lead to incorrect conclusions. This can benefit practitioners, consultants, and academics conducting life cycle analyses in the automotive and other manufacturing industries as well as retail sectors.

8.2. Limitations of this research and modelling.

While the results discussed above are based on a robust calculation methodology, it is acknowledged that the absolute values of the results provided will contain a margin of error and uncertainty and are also limited in their application as constrained by the boundaries chosen within which to conduct this modelling.

The limitations of this research can be broadly divided into two categories: those inherent in the methodology chosen to model, and others which - given more time and resource - could be minimised. The first is identified in this subsection.

The key limitation of this modelling has already been discussed above in section 4.3., that the "usage based" approach to modelling - used in the absence of data pertaining to actual energy use in supply chains – inherently must be viewed as an *estimate* of emissions. Therefore, any results arising from such an analysis must be interpreted within this limitation.

Notwithstanding this, because the same approach has been taken for both types of vehicle modelled, any errors or uncertainties which arise because of this modelling approach will apply equally to both types of vehicle and thus discussions about the relative impact will remain a valid argument.

Turning to the other limitations which fall into the latter category mentioned above: these are now discussed in the subsection below as they form the basis of a number of opportunities to refine and improve the results of this research conducted thus far.

8.3. Future work: opportunities to improve the results of the case study modelled.

The previous subsection noted the key limitation of this research which is inherent in the usage based calculation model. Notwithstanding this, opportunities exist to improve the accuracy of the results achieved and this subsection will highlight opportunities for further work to improve the results of this modelling.

8.3.1. Data from automotive manufacturers and suppliers.

The biggest limitation to the accuracy of the modelling in this research has been the availability of data upon which to model the scenario chosen. As noted previously, attempts to obtain data from automotive suppliers met with limited success and thus other sources had to be used for this modelling. Thus the modelling undertaken for this research was based on the GREET model data set, and was taken as accurate at face value and modelled accordingly. Moreover, wherever possible the modelling was done in accordance with the assumptions of the GREET data set to ensure consistency and compatibility with their results.

An opportunity for further work in this area of research would be if more granular data could be obtained from an automotive manufacturer upon which to do this modelling. This would enable actual distances to be used for tier one suppliers, and a more granular modelling could be undertaken where data is available on specific parts (both from a distance to supplier point of view and also to confirm the materials composition of the components).

Data from an automotive manufacturer would potentially include who their suppliers are, and data from suppliers in the supply chains would also improve the accuracy of the modelling undertaken. For example, in this research, raw materials sourcing has been based upon the national picture and the most likely source of raw materials has been modelled. Access to suppliers further up the supply chain to obtain data on actual sourcing locations would again improve the accuracy of the results of this modelling.

Access to suppliers in the supply chain would also allow for more accurate modelling of actual material flows along the supply chain: again, this modelling has been based on typical waste figures in a supply chain but access to suppliers would improve the accuracy of these assumptions.

Note however that while having access to the data as discussed here would improve the accuracy of the results modelled, it would also significantly increase the time and resource required to undertake this modelling. The improvement in accuracy of results may not justify the time and resource required to do this.

Thus far, the modelling done in this research has been done at a subsystem level. However, if more granular data was obtained it would enable the modelling to be done at a component level - and there are potentially hundreds of components which comprise each subsystem. While the TCE model built is capable of handling this increased level of detail, it would potentially require a whole team of researchers to obtain results in a feasible time frame, and it is not anticipated that a dramatically different set of results would be obtained if this were done.

Notwithstanding the above, a potential “middle road” between modelling as described above based on more granular data and the modelling done in this research, may be to collaborate with an automotive manufacturer to improve the assumptions upon which the modelling in this research has been done. As noted previously, contact was made with Volvo to request the data upon which their XC40 LCA was conducted. While this was unfortunately declined interest was expressed in the results of this research. Thus, a potential next step may be to present the results of this research to the team at Volvo who conducted their LCA and to invite their feedback and comment on the assumptions made for this modelling. The benefit to Volvo would be an opportunity to apply this research to their own LCA.

8.3.2 Modelling excluded materials.

As noted in previous sections, a percentage of material was not modelled in the above results. This occurred when materials were excluded due to cut off rules applied and where the GREET data set described materials as “others”.

In addition to this, only the major constituent materials required to produce the raw materials were modelled. The supply chains of minor auxiliary materials which may have been used as part of the process to produce these raw materials (such as coolants, lubricants and other auxiliary consumables related to the machines which produce the raw materials) were not modelled. Similarly, minor trace elements (such as those used in metal alloys) or minor process materials and chemicals (for example used in purification of raw materials) were also not modelled.

Thus, an opportunity to improve the results of this modelling would be to revisit the supply chains modelled and incorporate minor constituent materials used to make the raw materials as well as auxiliary materials which formed part of the process.

Again however, the improvement in results may not justify the time and resource involved to revisit and incorporate these minor materials involved in the supply chains. It is anticipated that doing so may increase the transportation emissions slightly but would not materially impact the comparison between EVs and ICE vehicles nor the overall relative magnitude of transportation emissions.

8.3.3. Modelling “Cradle to Customer” or “Cradle to Gate” emissions.

As discussed in section 2.4., this research has focussed on “cradle to gate” emissions because of a lack of certainty that exists regarding the final destination of the manufactured vehicles and their “end of life” disposal and recycling.

However, if geographic data on customer locations is available, a "cradle to customer" or "cradle to grave" analysis becomes possible because the distances from the automotive plant to the customers would be known (and data-based assumptions on regional end of life practices can be made), allowing for the calculation of transportation emissions – which the model developed for this research is capable of doing.

Thus, a potential area of future work would be to endeavour to obtain information on customer locations, and model the full life cycle of the vehicles.

8.4. Future Work: Expansion and confirmation of this research

This research set out to evaluate the impact of EVs on transportation emissions in automotive supply chains and has provided robust and unambiguous results for the case of a vehicle manufactured in Germany. To the extent that this case study is a general representation of EVs the results would remain valid. Yet, to fully conclude that EVs do significantly increase these carbon emissions, the modelling would need to be repeated on other case studies before it can be fully confirmed. This subsection will explore other case studies which merit modelling to confirm these results.

8.4.1. Modelling other locations.

As noted in section 5.1. various locations were considered before Germany was chosen as a location to model for this research. To generalise the results of this research, three further locations are recommended to remove any location specific bias which may be inherent in Germany. The locations are as follows:

- **The USA.** The German case study was characterised by having the majority of raw materials imported to Europe as well as having a close proximity of suppliers to the automotive factory.

  In the USA two factors may differ. Firstly, the USA has a considerable availability of raw materials. If the raw materials are sourced in the USA and the results of that modelling echo the German case study, then this would further generalise the validity of the results (it is however acknowledged that the USA does import a significant proportion of its raw materials and it may be impossible to confirm if raw materials in the automotive context actually originated from the USA).

Secondly, the USA is also different in that its supplier network will be considerably more geographically dispersed than in Europe. Thus, if the data was available, an American scenario could be simulated. If it produced similar results, it would further generalise the validity of this research.

- **South Korea or Japan.** Both these countries share several characteristics with the German case study. They both enjoy a high concentration of automotive suppliers and therefore a similar geographical concentration and they also both rely highly on imported materials. However, both also have established local battery production facilities and much closer proximity to Chinese raw materials when needed. Simulating a case study in Japan or South Korea would clearly highlight the impact of localised battery manufacture.

- **China.** The German case study was characterised by significant dependence on imported materials. While China does import raw materials too, it has considerable refining and processing capacity which would then geographically shorten the supply chains to automotive suppliers - especially in the case of battery production. Modelling a case study in China would explore or mitigate the impact of the distances involved with transporting battery related materials and potentially enable further generalisation of the results of this research. However, it is likely that the geographic concentration of suppliers (compared to Europe) is less due to the larger size of China.

Because the increase in supply chain transportation emissions is closely linked to both the heavier weight of the vehicle and the lithium batteries used in EVs, it is anticipated that the above three case studies would in every case reveal higher supply chain transportation emissions in the case of the EV modelled. However, modelling vehicle production in the above contexts would mitigate any geographical influence which may have arisen in the present study.

8.4.2. Modelling other vehicles.

The modelling undertaken in this research has been applied to two comparable “conventional material” “passenger car” vehicles for which the GREET data set provides it's comprehensive information.

However several other vehicles are also available in the GREET data set which include “sport utility vehicles” as well as “pickup trucks”. If similar results were found when modelling these alternative types of vehicle it would further generalise the results beyond a passenger vehicle.

It is however anticipated that a similar pattern will again emerge across the different types of vehicle as was seen when scaling the results of this research to the Volvo XC40 compact sports utility vehicle. This is because EVs are characterised by their large and heavy batteries.

8.4.3. Other Battery Technologies

This modelling was based on the Mn_20_3 based lithium-ion batteries which are the type in the GREET data set. However other Li-ion battery technologies were noted during the course of this research (for example as discussed by Deng et al (2019)) and if data is available would merit further modelling to compare how the battery chemistry impacts the transportation emissions. For example, in this research it was noted that the manganese supply chain contributed disproportionately to the emissions and thus *other* types of lithium-ion battery technologies may produce lower supply chain transportation emissions.

Note however that other battery technologies may include elements such as cobalt (which did not form parts of the MN_20_3 technology batteries modelled) which in turn may introduce their own supply chain emissions.

Thus, further research on the impact of battery chemistry on supply chain transportation emissions presents an opportunity to further reinforce this research.

Notwithstanding the above, as in the previous subsections it is again anticipated that EVs will have higher transportation emissions because of the increased weight and the large battery needed for EVs.

8.5. Further work beyond the research questions.

This research has endeavoured to restrict its scope to areas which contribute to addressing the research questions and within the research objectives stated. However, in the course of this research, several opportunities for further but related research have been identified. The topics below are viewed as showing the potential for further original research.

8.5.1 Secondary CO_2 emissions arising from increased supply chain transportation.

As noted previously in this document, if transportation emissions are viewed as a proxy for transportation activities and traffic, then they point towards an increase in transportation activities caused by a societal move to EVs. This research has however restricted itself to carbon emissions generated by moving the freight, which arises from fuel burnt to do so. However, it has not considered that in order to move the increased freight, it logically follows that more transportation vehicles would potentially be needed and more infrastructure (for example roads or rail network) potentially required if the transportation traffic rises above current capacity. Thus, a further extension of this research would be to evaluate and calculate these emissions. Viewed from a systems perspective this means widening the boundaries of the analysis.

8.5.2. Synthetic carbon as an opportunity for carbon capture

As noted in section 6.2.5. the amount of carbon graphite used in an EV is significantly more than used in an ICE vehicle. During the course of this research, it was noted that “natural graphite” material is typically mined and refined for use in automotive applications. It is also widely used in steel production and other consumer contexts such as conventional batteries (Olivetti *et al.*, 2017).

While it is found abundantly in nature and since only approximately 2% of natural graphite is used for automotive batteries there is some strategic concern surrounding this material due to the geographical concentration of current supply being concentrated in China at over 65% of global production (Olivetti *et al.*, 2017).

This material can also be produced synthetically and used for automotive battery applications although it is more expensive (Olivetti *et al.*, 2017). Liang et al (2021) indicate that synthetic graphite can be made from CO_2. If this synthetic graphite described by Liang *et al* is suitable - or could be made suitable for use in an EV - it may be considered to be a form of carbon capture if CO_2 used for this could be potentially extracted from the atmosphere.

As this area of expertise is beyond the scope of this research, it is not known if this is feasible or financially viable. But if it were a possibility, it would ultimately mean that EVs could be a form of carbon capture and thus further contribute to the potentially positive impact from a life cycle point of view and is thus proposed here as a potential opportunity for further research.

8.5.3. Battery Heavy Goods Vehicles.

As noted previously in this document, heavy goods vehicles contribute disproportionately to carbon emissions given their very high emissions factors. To evaluate the magnitude of this, the TCE model calculated the proportion of transportation emissions that were generated by heavy goods vehicles in the cradle to gate transportation. The results are shown in figure 8-1. below.

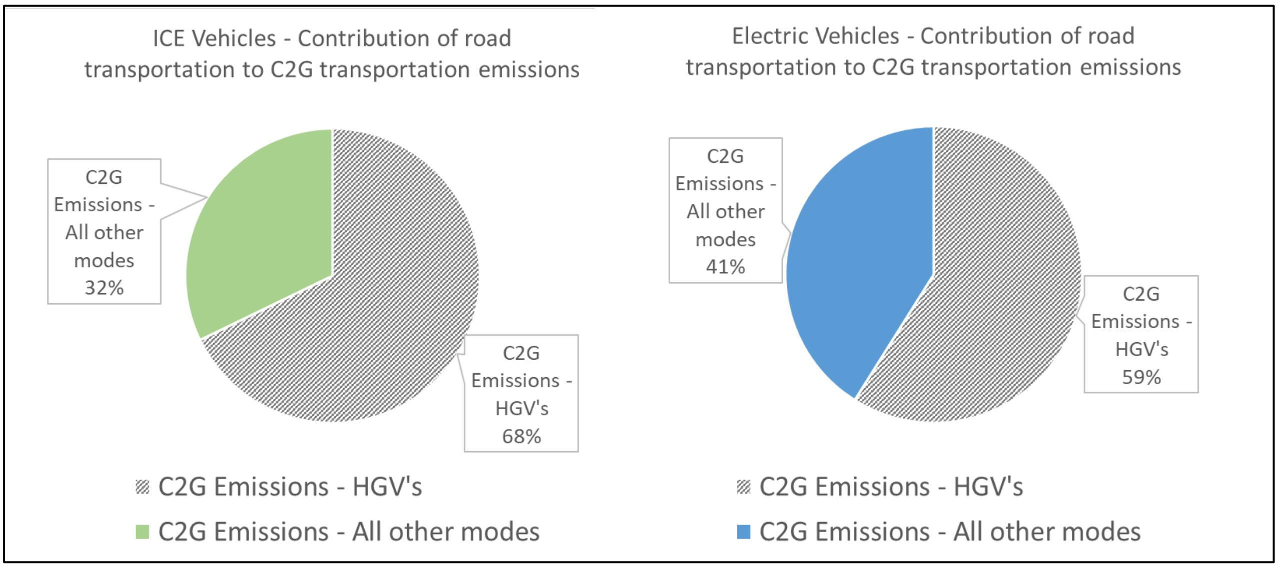

Figure 8-1: Contribution of HGV emissions to overall transport emissions in cradle to gate automotive supply chains.

As can be seen above, heavy goods vehicle road transportation generates most of the transportation carbon emissions in the case study modelled in this research[97].

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[97] as a proportion of emissions, heavy goods vehicles contribute more to ICE vehicle supply chains because EVs require batteries which - in this case study - had much of the materials supplied from China which required considerable sea transportation.

Thus, if there is a way to reduce or eliminate the transportation CO_2 emissions generated by ICE heavy goods vehicles, the grey areas of figure 8-1 above represent the proportion of carbon emissions that could be eliminated. Electrically powered heavy goods vehicles present an opportunity towards this potential reduction (Haugen *et al.*, 2021) and several manufacturers already offer battery electric heavy goods vehicles[98] and so this possibility is one which is has ready potential.

Note however that (as discussed elsewhere in this research) this opportunity is based upon a low carbon source of electric power such as wind and – as before - there would be a break-even point before the benefits of electrification would be realised. Nonetheless figure 8-1. does suggest the magnitude of the potential reduction in carbon emissions in automotive supply chain transportation emissions.

It is accepted however that the infrastructure does not always exist to support EVs and so the feasibility of this may be restricted to geographical sections of the supply chain where this infrastructure exists. However, given that the case study of this research is in Germany, much of the potential reduction implied above may be realised. This would also offset the impact of sourcing components from Eastern Europe as the transportation emissions would be potentially reduced (see previous discussion in section 7.3.4.).

While it is not anticipated that all of the road transportation emissions shown in figure 8-1 would be eliminated by electric heavy goods vehicles (given the increased CO_2 emissions which arise to manufacture them and the required infrastructure) further research into this area is proposed as a potential opportunity to reduce carbon emissions in transportation.

Moreover it is anticipated that the benefits of electric heavy goods vehicles would be transferable to any supply chain, regardless of the product. However, further research is merited to identify specific product sectors which would yield the most benefit.

8.5.4. Impact on supply chains of increased Copper, Carbon Graphite & Aluminium

As noted in section 6.2.4., EVs require significantly more copper, aluminium and carbon graphite compared to ICE vehicles. An initial literature search has shown that this impact has been noted by other researchers but given the infancy of general adoption of EVs, it is anticipated that the full impact of increased usage of these materials has not been fully researched and this area is likely to require further research.

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[98] See for example: DAF (2023), Scania (2023) or Volvo Trucks (2023)

8.5.5 “Cradle to Customer” transportation emissions

In this research the TCE model was used to calculate “cradle to gate” transportation emissions. However, if the data is available, the “gate to customer[99]” emissions can also be calculated with this model - the reason it was not done in this research was due to a lack of available data. If data from an automotive manufacturer was available which gave details of where their customers are located along with the number of vehicles being shipped to each destination, the TCE model can calculate the emissions arising from this last leg of transportation of the completed motor vehicle. This would then allow for a “cradle to customer” model of transportation emissions.

8.5.6. Transferability of the TCE model to other products.

The TCE model developed for this research has been used in an automotive case study. However its inputs are not specific to motor vehicles. This model can be used to calculate transportation emissions on any product where the material composition is known and sufficient information is available regarding supply chains to the manufacturing location.

In its current state, the model simulates transportation carbon emissions arising from manufacturing activities in Germany and without modification, its assumptions would remain valid for any products manufactured in North-West Europe.

However, the model has been designed to be completely flexible to adapt to local geographical considerations and wherever adequate data is available, the parameters of the model can be adjusted to simulate transport emissions arising from manufacture in a given location.

Thus, the model developed can be used when assessing the environmental impact of choosing potential manufacturing sites for a new product. Likewise, it enables designers to evaluate the transportation emissions associated with selecting different materials for a product in development.

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[99] in other words the transportation of finished vehicles from the factory to the customers who purchase and use these vehicles.

8.6. Research objectives reviewed

Having outlined the contribution of this research to knowledge and practice, and suggested opportunities for future work, the research objectives will be reviewed to confirm that they have been achieved. The sections that follow will review the aim and research questions.

The objectives of this research are re-stated here for the readers convenience:

1. To trace the "systems" concepts used in the life cycle analysis approach back to their origins in the systems theory literature, and outline systems thinking principles for this research.

This objective was achieved in the systems theory and literature review chapters. Through a historical review of systems theory, the key principles were identified and this in turn was shown to form the basis and language of key practices in the life cycle assessment approach. A set of systems principles was also derived from the discussion on systems theory and presented in Chapter 2[100]. These formed the foundation of the rest of this research.

2. To critically evaluate the extent to which emissions due to transportation activities are accounted for in the life cycle assessment literature for both EV and ICE vehicles.

In the literature review chapter, the life cycle assessment literature was thoroughly scrutinised, and it was found that the literature does not satisfactorily account for cradle to gate carbon emissions due to transportation activities thus identifying the contribution to knowledge of this research.

3. In order to build a model to evaluate and calculate carbon emissions arising in transportation, identify the main factors which influence the transportation energy usage across the automotive supply chain from "cradle to gate".

Using current practice in transportation carbon emissions studies and calculations, the factors which impact transportation emissions were identified and discussed in Chapter 4, which in turn formed the basis of the TCE model built for this research.

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[100] Which is expanded upon in appendix A

4. Taking these factors into account, develop a model for calculating transportation CO_2 emissions in automotive supply chain logistics.

As described in the methodology Chapter 4 a Transportation Carbon Emissions (TCE) model was developed for this research which allowed for a systems based approach to transportation modelling, capable of incorporating the whole “cradle to gate” journey.

5. Using the model built, evaluate EV supply chains’ CO_2 emissions arising in cradle to gate transportation activities, compared to traditional ICE.

As described in the methodology, results and discussion chapters, the TCE model successfully calculated these transportation emissions for both types of vehicle thereby addressing the research questions and providing original contributions to knowledge.

8.7. Research Questions reviewed.

To evaluate the extent to which the research questions have been addressed, they are reviewed in this subsection.

The research questions are stated again for the reader’s convenience:

Research Question 1:

“What is the relative impact of EV supply chains compared to ICE vehicle supply chains for transportation emissions when calculating “cradle to gate” automotive lifecycle analyses?”

As discussed in section 7.1., in the case study modelled in this research it was found that EV supply chains generate approximately 72.2% more carbon emissions in their cradle to gate transportation activities.

These results have been discussed at length elsewhere and it can thus be concluded that the first research question has been answered for the case study modelled.

Research Question 2:

“What is the relative contribution of supply chain transportation activities compared overall “cradle to gate” CO_2 emissions in automotive life cycle assessments?”

It was found that in the case of ICE vehicles, transportation emissions account for 1% of life cycle carbon emissions whereas in the case of an EV they account for as much as 3%[101].

This has relevance to the apparent omission in the automotive LCA literature: that transportation carbon emissions appear almost absent (even though transportation activities account for as much as a quarter of global carbon emissions).

The case study modelled demonstrated that in the case of ICE vehicles, the literature's silence on them was justified because compared to the carbon emissions generated during the usage stage, the contribution of transportation emissions during the manufacturing phases was relatively negligible.

However, in the case of EVs where carbon emissions in the usage stage are almost eliminated if a low carbon energy source is used, then the transportation carbon emissions do become a significant percentage of the life cycle emissions and therefore should be included and documented in LCA of EVs.

Again, this has been discussed at length previously in this document, but the above paragraphs note that the second research question and its implications have been addressed.

8.8. Research aim reviewed

In order to review the stated aim of this research, it is presented again for the readers convenience.

"To evaluate the impact of EVs' manufacturing supply chain "cradle to gate" CO_2 emissions arising in transportation, compared to traditional ICE vehicles. This is to be done via a systems theory based evaluation of automotive life cycle assessments to ensure that an equitable comparison is made."

As has been demonstrated in the discussion and results chapters before this, the impact of EVs manufacturing supply chain transportation activities has thoroughly been evaluated and this was done using a Systems Approach which was documented in chapter 2.

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[101] See Section 7.2.2 - Fig 7-2 and 7-3

8.9. Thesis of this research

The thesis of this research is that the "cradle to gate" transportation CO_2 emissions involved in producing electric passenger vehicles in Germany is significantly higher than the case of internal combustion engine vehicles.

This has been robustly shown to be the case, with electric vehicles giving rise to 72.2% higher CO_2 emissions than internal combustion engine vehicles in the case study that was modelled.

In addition to this contribution to knowledge, contributions to theory and to practice have also been made. A theoretical basis – underpinned by Systems Theory - for assessing transportation carbon emissions in supply chains has been developed and documented, thereby contributing to theory in this area. To LCA practice, this research has demonstrated that in the case of electric vehicles, transportation carbon emissions should not be ignored because they are of a magnitude comparable to other factors routinely included in LCA's (such as end of life disposal and recycling). Lastly, the "Transportation Carbon Emissions" model developed for this research also enables future work to be undertaken in this area.

Thus, the contributions to knowledge, practice and theory provided by this research are confirmed.

8.10. Final remarks

To summarise, the aims and objectives of this research have been achieved and clear results have been presented for the case study modelled. The research questions have been addressed, providing clear contributions to knowledge and the existing literature.

Thus, the immediate next steps following this research will be to disseminate the findings of this research. Several opportunities have been identified which include:

- Collaboration with an automaker to incorporate the findings of this research into their own LCA. Volvo may be the first choice given the extent to which their existing work has been incorporated into this research and given that contact has been made with their team already.
- Collaboration with the Argonne National Laboratories to supplement their data set with the findings of this research. Given that this research has been based on their data set, the findings correspond exactly to their assumptions about the vehicles although this research has been based on a European scenario. However, it is easily adapted to an American scenario if the resource is available. Given the

widespread use of the GREET data set, the impact of this will have significant reach in LCA research

- Publication of the results of this research in a peer reviewed journal. Beside the results of this research being a contribution to the literature, this research has identified an enhancement required in the practise of LCA of EVs.
  Publication in a peer reviewed journal would enable dissemination of this practice as well as typical results for the case study modelled which would allow researchers involved with LCA to benchmark the extent to which transportation emissions compare with other stages of the life cycle commonly modelled and in their own work.

  The Journal for Cleaner Production has been identified as a desirable publication vehicle given its historic publications in the area of lifecycle analysis and its widespread circulation.

This research set out to evaluate EV CO_2 emissions in their supply chains. A gap in the literature was noted specifically in the area of transportation carbon emissions and this research has filled this gap and documented an original contribution to knowledge.

While the emissions calculated in this research are modest compared to some of the other emissions which arise in the vehicle life cycle, this was not previously documented in the literature. Thus, the wider research conducted in this area can now with an increased level of confidence deal with the contribution of transportation carbon emissions and consequently to the overall life cycles of both electric and ICE vehicles. Immediate practical implications and recommendations to industry were identified with potential to reduce transportation carbon emissions. This research has also allowed for several areas of further work to be identified which in turn have potential to make further impact on transportation carbon emissions and provide contributions to knowledge.

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Appendix A – Systems Theory: a Historical Overview.

> *"The historical imagination is not greatly encouraged these days, yet it seems to me especially needed if we are to give perspective to contemporary changes"*
>
> (Vickers, 1983)

To appreciate what has become known as "systems theory" it us useful to trace its history and development over the last decades. The sections which follow trace key contributions to systems theory by selected leaders in the discipline who are generally acknowledged pioneers of this field.

This "historical" overview will be arranged by author and thereby also by theme. While the works of the authors mentioned below would run into several volumes, the brief paragraphs below are intended to précis (and acknowledge) the aspects of their works which have contributed to the approach taken in this research. Where possible, their later works are cited in order to gain the benefit of their hindsight on their many years of practice in systems thinking.

The omission of other prominent contributors to the discipline is not meant to imply that their contributions to systems theory is not important. Rather, the focus has been on key authors whose work has directed the "systems" approach taken in this research.

A.1. Ludwig von Bertalanffy's "General Systems Theory".

Ludwig von Bertalanffy is generally acknowledged to be the founder and creator of "General systems theory" – indeed he is credited with coining this term. He wrote at length to develop and provide the language and concepts of general systems theory and was one of the founding members of the "Society for general systems research". Although initially a biologist he later expanded his concepts and thinking, applying them to other areas (Ramage and Shipp, 2009; Adams and Hester, 2014). He worked at a number of universities in Europe and North America, and in 1972, he was nominated for the Nobel Prize in Physiology but died before the recipient of the award was decided upon (Lewis, 2015).

Upon reading Von Bertalanffy's work, the reader repeatedly meets with his promotion of the "new idea" or "new discipline" of "Systems theory" (Von Bertalanffy, 1968, 1972)[1]. His gravitation toward the concept of "systems" can be traced to his PhD studies in the early 1920's. While studying at the University of Vienna, his supervisor was Moritz Schlick – who was a founder member of the "Vienna Circle"[2] (Drack, Apfalter and Pouvreau, 2007). While he rejected some aspects of their views (notably their "reductionist" approach which argued that the way to understand phenomena is to break them down into ever smaller constituent parts and to "analyse them in terms of the properties of those isolated individual components" (Lewis 2015)), Von Bertalanffy was influenced by their goal of a "unified science" by which the various fields of study of the day could be understood, and towards which it was believed that they would naturally tend towards (Lewis 2015).

It was in the idea of "systems" that Von Bertalanffy posited that that this "unified science" could be found. He argued that "in the gamut of modern sciences and life new conceptualisations, new ideas and categories are required, and that these, in one way or another, are centred about the concept of "system" (Von Bertalanffy, 1968).

He thus proposed the discipline of "General Systems Theory", describing it as the "formulation and derivation of those principles which are valid for "systems" in general" (Von Bertalanffy 1968). In other words, he theorised that there would be "principles" which would apply to all systems, wherever they might be found. Checkland (1981) described Von Bertalanffy's vision as being "that there would arise as a result of work in different fields a high-level meta-theory of systems, mathematically expressed"[3] .

His concept of "systems" began in his early work as a biologist, where he viewed an organism as a "whole" or "system" (Von Bertalanffy, 1968) and developed the concept of an organism as an "open" system, with a clear boundary across which both matter and energy could cross (compared to a "closed" system across which only energy could cross), thereby drawing on thermodynamic principles which model thermodynamic reactions and systems in

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[1] It has been observed that his work can be repetitive. Checkland (1981) states that Von Bertalanffy's "thinking as reflected in his writings shows little development from the 1940's until his death in 1972" and he cites the comment by Lilienfeld (1978) who stated that his work was "rather repetitious and static and character". His 1968 publication, "General system theory: Foundations, development, applications" consists mostly of his previously published work, and is thus referenced here predominantly.

[2] The Vienna Circle was a group of early 20th century philosophers who sought to incorporate the then current mathematical and scientific advances into their discipline of philosophy (Sarkar, 1996).

[3] This assessment of the mathematical nature of Von Bertalanaffy's work is confirmed when reading his books and papers.

a similar way (Ramage & Shipp, 2009). He went on in later years to extend the concepts to other fields and science in general.

In its simplest "mathematical" form, he defined a system "as a set of elements standing in inter relations" whereby the relations between the elements influenced how they behave. Moreover, he argued – against the reductionist approach – that the correct way to understand the behaviour of an element, was in the context of a system. (Von Bertalanffy 1968). In this sentiment, he takes forward the historical "whole is greater than the sum of the parts" concept to that of a scientific approach rather than that of a purely philosophical notion. He argued that inadequate mathematical techniques of times past had been restricting the progress of this notion to a scientific method (Von Bertalanffy, 1972).

Applied to this research, it is not intended to use Von Bertalanffy's mathematical models and methods which he went on to develop[4]. Rather, he is acknowledged here as pioneering the idea of representing systems in computational models (albeit of their time). This idea is re-visited in section 4.2.2 by a later pioneer of systems modelling, Jay Forrester, who developed "System Dynamics", which is a potential modelling technique which could be used in this research.

In addition to this, the concepts and language of "systems", "boundaries" and "systems theory" endure to current usage (Adams & Hester 2014) – and are useful to this research when critiquing the wider literature, and in formulating the paradigm used in this research.

It should however be acknowledged that the existence of the above mentioned "principles" have not however always found agreement - even from other "systems theorists" (Checkland 1981). Indeed the influential systems author, Peter Checkland[5] stated that "the general theory envisaged by the founders has certainly not emerged" (referring to the founders of the "Society for general systems research"). Yet, other "systems thinkers" such as Jay Forrester[6] asserted that such principles do exist – albeit that our understanding of them may be incomplete (Forrester, 1994).

[4] They are however unfeasibly complex to use, and subsequent scholars (notably Forrester) have developed more suitable ways to calculate and model systems, and which can be done using modern software packages, discussed in section 4.2..

[5] Please See Appendix A for notes on Checkland's work.

[6] Please See Appendix A for notes on Forrester's work.

A2. Sir Geoffrey Vickers: "Relationships" are the system.

"Of what then do systems consist? They consist of relationships"

(Vickers, 1983)

During his long and varied professional career, Sir Geoffrey Vickers worked as a lawyer, advisor and manager: holding several senior roles in public office in the UK. His contributions to systems theory are however attributed to his thinking and reflection during his "retirement" (Ison, 2005). Checkland (1985) describes Vickers as "thinking long and hard about his experiences in order to "make sense", as he put it, of his professional life".

The tone and purpose of Vicker's work is different to some of his "systems theory" predecessors whose work and writings frequently espouse, introduce and promote this new discipline of "systems theory" (for example Bertalanffy (1968), Boulding (1956)), before going on to explain and expound their theories. Instead, Vickers work is more reflective and discusses the human systems he has experienced over his career, using systems theory to describe and understand them. He described the "essence" of systems thinking as being the "concept of form or order, sustained through time by a self-corrective process, that notices deviations from the standards which define order and responds with actions which sustains or restore it" (Vickers 1983)[7] . He saw human history and experience as being "systemic" in nature.

One of the key contributions that he is considered to have made is that he used his systems theory as an "epistemological" tool – a philosophical tool for understanding what we see in social, business and societal systems. Herein lies a different view of "Systems theory" compared with Von Bertalanffy's vision of universal, naturally occurring systems "principles" of systems. This became known as "soft" systems (in the context of social, business and societal systems for example[8]) as opposed to "hard" systems which focus on scientific reality and naturally occurring systems in biology and the sciences (Vickers, 1983; Brocklesby, 2007; Ramage and Shipp, 2009).

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[7] Vickers' final work, *Human systems are different* is referenced throughout this section. This work is considered to be the culmination of his earlier work (Caldwell, 1984) and is thus referenced in this section.

[8] This "soft" view of systems theory would prove influential on later systems thinkers, notably Peter Checkland, who would directly reference and quote Vickers' work when distinguishing between "hard" and "soft" systems in his work on soft systems methodologies (Checkland, 1985).

Vickers asserted that systems consist, fundamentally, of the “relationships” between the “entities” (or “elements” to use Von Bertalanffy’s terminology). He argued that the “entities” themselves might change, but as long as the “relationship” between the entities continues, the “form” of the system continues. Note that his definition has a “time” element incorporated – he argued that “systems are nets of relations which are sustained through time” (Vickers 1983).

Vickers illustrated his point with the following analogy: comparing the “form” of a system (for example in the context of an organisation) to a river – where “a river is the name we give to the form; not to the water which happens to constitute it at some moment in time”. In other words, the organisation is the “form”: even if the people or, materials within it change. He argued that the form – which like a river will seldom be absolutely unchanging - might be imposed by external factors, or by internal “directors or regulators” – or both. He proposed that the form is changed (or maintained) by regulation and this influences their stability. (Vickers 1983).

He argued too that such systems cannot be considered as a “whole” and independent from their surrounds – instead, he argued that “in so far as any open system acts as a whole in relation to its surrounds, it is useful to distinguish the internal relations which enable it to do so from the external relations which it thus sustains” (Vickers 1983). Thus, (to use the language of Von Bertalanffy), one therefore distinguishes these internal relations from external ones by means of a “boundary”. This consideration of “boundaries” was raised by a number of “systems thinkers” as being important (notably Churchman[9] (1971)). The topic of “boundaries” will be considered again in a later section.

Applied to this research, Vickers’ ideas have the following relevance: in the first place, systems theory can be used as a tool for understanding, and for addressing the research questions. Yet, a model of automotive supply chains will be used in addressing the research question – in the tradition of “hard” systems thinking. Thus, for this research, a “combined” approach will be used – the model to be developed (in the “hard systems” tradition) will also record the influence of the “soft” systems which impact the system modelled – for example government incentives to promote certain local industries. In this research, the “rivers” (to use Vickers’ terminology) which will be examined are automotive supply chains – the elements of which stand in interrelation with one another determined by the policies and

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[9] Churchman was an academic who is considered to have had great influence on his students who included notable “systems thinkers” authors such as Russell Ackoff and Werner Ulrich. (Ramage & Shipp 2009) – both of which will be mentioned in later sections.

decisions made by automotive companies (such as procurement or design decisions) or influenced by governments and regional political alliances.

A.3. Peter Checkland – “Soft” and “Hard” Systems.

Peter Checkland is noted for his development of “soft” systems thinking, culminating in the development of “Soft Systems Methodology” or SSM. Of interest for this research is his distinction between “hard” and “soft” systems (and associated definitions), which will be outlined next.

Before joining academia at the University of Lancaster in 1969, he had worked from 1954 at ICI fibres. Having worked as a manager at various levels, he found the “text book” management science of the day to be irrelevant to the actual problems he faced as a manager (Jackson, 2000). Upon joining Lancaster University, he began a programme of research “to see if systems ideas could help us to tackle the messy problems of “management”” (Checkland, 1999).

Systems engineering was already well developed, and used for example, for building large industrial systems (such as chemical works or telephone networks). He found that traditional systems engineering was inadequate to describe management problems with complex, social settings with various world views and values at play ((Jackson, 2000; Ramage and Shipp, 2009; Zexian and Xuhui, 2010).

He came to make a distinction between “hard systems” and “soft systems” where hard systems (such as those found in systems engineering and operations research) dealt with physical systems which could be modelled, and “soft systems” which dealt with how we understand the world – echoing Geoffrey Vickers’ ideas (as has been noted earlier) and developing them further (Checkland, 1985). Thus, his “SSM” emerged, as a managerial tool. In this methodology, SSM would not be used to exactly represent the world. Rather it was an epistemological tool used to find out about the world. This understanding could then be used to construct models of human activity systems which could “contribute to a debate about possible change” (Jackson, 2000).

A soft systems approach views “system models as models relevant to arguing about the world, not models of the world; this leads to 'learning' replacing 'optimizing' or 'satisficing'; this tradition talks the language of 'issues' and 'accommodations' rather than 'solutions'. (Checkland, 1985)

With regard to the relationship between hard systems and soft systems, Checkland argued that soft systems are the “general case” and that that hard systems were a “special case” or subset within soft systems. In a hard system, the system is one that can be “engineered” and where models can be made to represent it. Notably he describes the language of hard systems as systems with “problems” and “solutions”, compared with soft systems which have “issues” and “accommodations” (Checkland 1985).

It is not the intention of this research to use Checkland’s “SSM” methodology. Nonetheless, the “soft” systems aspect of Checkland’s work is important to the motivation of this research – namely the concern with the wider impact on the environment caused by transportation in Automotive supply chains. There may be no immediate impact of the pollution caused by automotive supply chain transportation on the functioning of that supply chain. Yet, the pollution which results impacts issues of environmental sustainability, and thus humanity – thereby making it a “soft” systems issue.

A.4. Russell Ackoff – A Systems approach to solving problems.

Russell Ackoff was a tireless proponent of the application systems theory, both in the areas of management as well as civil society and higher education. (Andrew, 2010; Wilson and Wilson, 2010). He spent much of his academic career at the University of Pennsylvania as a professor at its Wharton Business School and also consulted extensively to industry and businesses (Ramage & Shipp, 2009).

In his public lectures and other contexts he frequently cited (or paraphrased) Albert Einstein’s often quoted adage that:

“Without changing our pattern of thought, we will not be able to solve the problems we created with our current patterns of thought” [10]

(Allio, 2003; The Economist, 2009).

The solution then, to the “*problems*”, he argued, was a “systems thinking” approach. Like Von Bertalanffy before him he was an evangelist of systems theory and acknowledged Von Bertalanffy as pioneering systems theory (Allio, 2003) describing his contributions as the start of a “new cultural and technological age” which Ackoff would call the “systems age”(Ackoff, 1973; Kirby, 2003).

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[10] This version of the quote is taken from a transcript of an interview with Ackoff (Allio 2003). Einstein’s exact original wording is unclear but the most common version quoted (for example in The Economist (2009)) is: “we can't solve problems by using the same kind of thinking we used when we created them” .

Ackoff is considered to have been one of the founders of Operations Research (OR) as an academic discipline and (along with C. West Churchman) established the world's first "Operations Research group" at the Case Institute of Technology and was a co-author of the world's first textbook in Operations Research entitled "Introduction to operations research", published in 1957 (Ramage & Shipp, 2009). Of relevance to this research is that transportation modelling in supply chains and logistics is generally considered to fall within the subject area of "Operations research" (see for example Gonçalves (2020)).

Yet, despite his involvement in founding the OR discipline, he was later to move away from it towards systems theory as a more valid approach to addressing issues and problems. Kirby (2003) describes how from the start of his career, Ackoff had been concerned to widen the scope of OR beyond the "tactical problems of industry and commerce" to a wider the application of OR "to the alleviation of the human condition". He appears to have become frustrated with the narrow applications of OR as a discipline, and so moved to systems theory as a tool to understanding and addressing wider social issues and problems. In this respect we see echoes of Vickers: of Systems theory as being a tool for understanding the world, and – as Ackoff would develop it – into a tool for addressing problems.

Ackoff refined the definition of a system, stating that "A system is more than the sum of its parts; it is an indivisible whole. It loses its essential properties when it is taken apart. The elements of a system may themselves be systems, and every system may be part of a larger system" (Ackoff, 1973).

Ackoff also warned against the tendency to focus on (or attempt to improve on) individual elements of a system in the hope that it would necessarily improve the overall system performance[11] (Allio, 2003).

Instead, Ackoff argued, the overall system needs to be optimised rather than attempting to optimise individual (local) elements (Ackoff, 1999) - and thereby avoid optimising a solution for a local elements which may worsen the overall situation[12]. Improvement, as argued by Ulrich (2005) "is an eminently systemic concept, for unless it is defined with reference to the *entire* relevant system, *sub-optimisation will occur*" (italics added).

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[11] He used the analogy that taking the very best parts and components from the world's top automobiles and trying to put them together to form a "best" automobile would clearly not work very well – not least because they would not fit

[12] Goldratt et el (1992) echoed this concept (in is best-selling book "The Goal") by arguing that a series of local optimums does not constitute the optimum for the system.

Moreover, Ackoff argued that the “solution” (or the way to remove a “problem”) often lies outside the system (Brant, 2008) and attempting to solve a problem by trying to deal with individual elements inside a system was often fruitless and a mistake (Freeman, 2010). Ackoff argued that “that the best place to treat a problem is not necessarily where it appears” (Ackoff, 1999).

Applied to this research, Ackoff’s thinking demands and requires a “cradle to grave” approach that needs to be taken when considering the environmental impact of automotive supply chain transportation[13]. Any approach or analysis which only considers providing a “local optimum” or which focusses only on a small part of a system risks worsening the overall situation (the literature review chapter will begin by illustrating this principle).

A.5. Jay Forrester – System Dynamics and policies.

Jay Forrester started his career at the Massachusetts Institute of Technology (MIT) in 1939 in the area of electromechanical control research, before moving to MIT’s Sloan School of Management in the 1950’s. He is noted as being the founder of “Systems Dynamics” a computer modelling approach whereby industrial, management, civil and other systems can be simulated using “feedback” loops similar to those used in an engineering context to regulate mechanical systems[14]. The approaches he developed in the 1960’s remain the foundation of this approach to this day and which have been built upon by his successors at MIT’s System Dynamics group (Sterman, 2000; Ramage and Shipp, 2009).

“System dynamics” is concerned with “dynamic” systems as opposed to static systems which are not transient with time[15] (Forrester 1994). He also distinguished between “open” systems and “feedback” systems. In this context, “open” systems refer to systems where the inputs to the system – while affecting the outputs – are not influenced by the outputs i.e without a “feedback” loop. “Feedback” systems, on the other hand have feedback loops whereby the system inputs can be moderated or influenced by the outputs, in an effort to achieve some sort of predefined goal or condition (Forrester, 1968).

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[13] As is discussed in Section 2.4, this desirable “cradle to grave” approach unfortunately proved to be not possible for this research.

[14] He is also noted for his contribution to computer hardware as the inventor of “random-access magnetic-core memory” - the main type of computer memory in early computers (MIT, no date)

[15] Echoing Vickers’ concept of “relationships sustained through time” being central to thinking about systems.

Notwithstanding his “systems dynamics” approach for which he is noted, at this stage three of his reflections and viewpoints will be noted in the context of the current wider discussion of systems theory.

Firstly, he openly disagreed with Checkland’s distinction between “hard” and “soft” systems , whereby “soft” systems (which are seen not as actual systems but as representations of systems) are used merely as tools for understanding. Against this view, Forrester argued that “soft” system models can be actual representations of reality and that viewing “systems” as a mere representation of reality – a “construct for analysis” – most likely arises “from a lack of framework for analysis which is congruent with reality” . Forrester argued that his “Systems dynamics” approach does in fact offer principles which “do represent the actual nature of physical and social reality” – he does however acknowledge that these principles may be “incomplete” (Forrester, 1994). In this respect we see him echoing Von Bertalannfy’s ideas of universal “principles” which would apply to any system.

Secondly, note Forrester’s reflections on the output and usefulness of computational models when applied to corporate, social, governmental and other “human” systems. In the first place, Forrester argues that “system dynamics” is to be used for a purpose or goal of improving a system’s performance (Forrester, 1994). Yet, he reflects, once a satisfactory model had been established it simply confirmed what was observed in reality: that the “problems” faced by the system were predictably created by the system or more specifically, by the policies which govern the system (echoing Vickers concepts of “relationships” within a system). In fact, he points out that the very policies causing the “problem” may have been put in place for the specific purpose of solving the “problem”! (Forrester, 2013). He observes that due to the “nature of people”, those running the system usually resist changes to their “cherished” policies – even when these policies have been shown – computationally – to be causing the “problem”. Where this is the case, it represents a considerable limitation to the usefulness of such computational methods. The impact of this notion will be revisited in the discussion section of this document.

Thirdly, and following from this, he proposes that a further application of the modelling process is for the purpose of learning about a system. He argues that if the people running the system are themselves involved in the modelling process they will themselves learn about the system and thus be able to accept the conclusions drawn from the modelling (Forrester, 2007).

Forrester’s work is important to this research for the following reasons. Firstly, the “system dynamics” method of modelling he founded is a possible method to model automotive supply chains for this research – more detail on this will be documented in the methodology section to follow. Secondly, the model may highlight instances in the current literature where the policies implemented actually worsen the situation they are supposedly trying to alleviate. Thirdly, as predicted by Forrester significant insights to the research being done were gained by building a model to represent automotive supply chains.

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Appendix B Results: CO$_2$e Transportation emissions for ICE and EV

"Calc Ref" provides an index to each calculation sheet's reference number.
Reference numbers not used are in grey (occurs when a material weight is 0 or below calculation threshold, or calculated elsewhere)

Vehicle w/o battery			**(kgCO2e)**		**(kgCO2e)**
Subsystem:	**Material**	Calc REF	**ICE Transportation emissions (Calculated)**	Calc REF	**EV Transportation emissions (Calculated)**
Body	Steel	ICE-01	**86.39**	EV-01	**99.28**
Body	Wrought Aluminum	ICE-02	**9.27**	EV-02	**10.65**
Body	Cast Aluminum	ICE-03	**0.51**	EV-03	**0.59**
Body	Copper/Brass	ICE-04	**4.90**	EV-04	**5.64**
Body	Glass Fiber-Reinforced Plastic	ICE-05	**2.62**	EV-05	**3.02**
Body	Glass	ICE-06	**2.69**	EV-06	**3.09**
Body	Average Plastic	ICE-07	**62.65**	EV-07	**72.00**
Body	Rubber*	ICE-08	**2.59**	EV-08	**2.98**
Body	Others	ICE-09		EV-09	
Powertrain System	Steel	ICE-10	**38.55**	EV-10	**16.26**
Powertrain System	Wrought Aluminum	ICE-11	**4.24**	EV-11	
Powertrain System	Cast Aluminum	ICE-12	**20.21**	EV-12	
Powertrain System	Copper/Brass	ICE-13	**5.06**	EV-13	**5.49**
Powertrain System	Glass Fiber-Reinforced Plastic	ICE-14	**2.23**	EV-14	
Powertrain System	Average Plastic	ICE-15	**15.92**	EV-15	**15.92**
Powertrain System	Rubber*	ICE-16	**0.94**	EV-16	
Powertrain System	Platinum	ICE-17		EV-17	
Powertrain System	Others	ICE-18		EV-18	
Transmission System/Gearbox	Steel	ICE-19	**11.15**	EV-19	**24.19**
Transmission System/Gearbox	Copper	ICE-20		EV-20	**6.22**
Transmission System/Gearbox	Cast Iron	ICE-21	**11.04**	EV-21	
Transmission System/Gearbox	Wrought Aluminum	ICE-22	**10.80**	EV-22	**7.69**
Transmission System/Gearbox	Average Plastic	ICE-23	**1.72**	EV-23	**0.07**
Transmission System/Gearbox	Rubber*	ICE-24	**0.87**	EV-24	
Transmission System/Gearbox	Others	ICE-25		EV-25	
Chassis (w/o battery)	Steel	ICE-26	**100.72**	EV-26	**115.75**
Chassis (w/o battery)	Wrought Aluminum	ICE-27	**2.18**	EV-27	**2.51**
Chassis (w/o battery)	Cast Aluminum	ICE-28	**27.89**	EV-28	**32.06**
Chassis (w/o battery)	Copper/Brass	ICE-29	**1.64**	EV-29	**1.89**
Chassis (w/o battery)	Magnesium	ICE-30		EV-30	
Chassis (w/o battery)	Glass Fiber-Reinforced Plastic	ICE-31	**0.23**	EV-31	**0.26**
Chassis (w/o battery)	Average Plastic	ICE-32	**3.26**	EV-32	**3.75**
Chassis (w/o battery)	Rubber*	ICE-33	**38.62**	EV-33	**7.41**
Chassis (w/o battery)	Others	ICE-34		EV-34	
Traction Motor	Steel	ICE-35		EV-35	**24.06**
Traction Motor	Cast Aluminum	ICE-36		EV-36	**23.93**
Traction Motor	Copper/Brass	ICE-37		EV-37	**15.24**
Electronic Controller	Steel	ICE-38		EV-38	**2.10**
Electronic Controller	Cast Aluminum	ICE-39		EV-39	**19.69**
Electronic Controller	Copper/Brass	ICE-40		EV-40	**2.85**
Electronic Controller	Rubber*	ICE-41		EV-41	**0.73**
Electronic Controller	Average Plastic	ICE-42		EV-42	**9.25**
Electronic Controller	Others	ICE-43		EV-43	

*Rubber calcs - pls see "Rubber" Sheet for all rubber calcs

Battery results are overleaf

Battery			**(kgCO2e)**		**(kgCO2e)**
Subsystem:	**Material**	Calc REF	**ICE Transportation emissions (Calculated)**	Calc REF	**EV Transportation emissions (Calculated)**
Battery	Lead	ICE-B-44		EV-B-44	
Battery	Water	ICE-B-45		EV-B-45	
Battery	Sulphuric Acid	ICE-B-46		EV-B-46	
Battery	Plastics	ICE-B-47	0.36	EV-B-47**	**4.49**
Battery	Glass Fiber	ICE-B-48	0.14	EV-B-48	
Battery	Other	ICE-B-49		EV-B-49	
Battery	Copper	ICE-B-50		EV-B-50	**14.56**
Battery	Wrought Al	ICE-B-51		EV-B-51	**29.40**
Battery	Graphite / carbon	ICE-B-52		EV-B-52	**8.73**
Battery	Electrolyte - EC - Ethylene carbonate	ICE-B-53		EV-B-53	**4.91**
Battery	Electrolyte - DMC - Dimethyl carbonat	ICE-B-54		EV-B-54	**4.91**
Battery	LiMn204	ICE-B-55		EV-B-55	**148.85**
Battery	LiPF6	ICE-B-56		EV-B-56	
Battery	PP	ICE-B-57		**see EV-B-47**	
Battery	PE	ICE-B-58		**see EV-B-47**	
Battery	PET	ICE-B-59		**see EV-B-47**	
Battery	Binder	ICE-B-60		EV-B-60	
Battery	Thermal insulation	ICE-B-61		EV-B-61	
Battery	Electronic Parts	ICE-B-62		EV-B-62	
Battery	Steel	ICE-B-63		EV-B-63	**2.58**
Battery	Glycol	ICE-B-64		EV-B-64	

** Plastics are calculated together on EV-B-47

Appendix C

Calculation Sheets for ICE & EV Transportation Carbon Emissions

Table of Contents.

Index for Calculation Sheets:
CO2e Transportation emissions for ICE and EV

"Calc Ref" provides an index to each calculation sheet's reference number.
Reference numbers not used are in grey
(occurs when a material weight is 0, undefied, below calculation threshold, or calculated elsewhere)

Vehicle w/o battery

Subsystem:	**Material**	Calc REF	Calc REF
Body	Steel	ICE-01	EV-01
Body	Wrought Aluminum	ICE-02	EV-02
Body	Cast Aluminum	ICE-03	EV-03
Body	Copper/Brass	ICE-04	EV-04
Body	Glass Fiber-Reinforced Plastic	ICE-05	EV-05
Body	Glass	ICE-06	EV-06
Body	Average Plastic	ICE-07	EV-07
Body	Rubber*	ICE-08	EV-08
Body	Others	ICE-09	EV-09
Powertrain System	Steel	ICE-10	EV-10
Powertrain System	Wrought Aluminum	ICE-11	EV-11
Powertrain System	Cast Aluminum	ICE-12	EV-12
Powertrain System	Copper/Brass	ICE-13	EV-13
Powertrain System	Glass Fiber-Reinforced Plastic	ICE-14	EV-14
Powertrain System	Average Plastic	ICE-15	EV-15
Powertrain System	Rubber*	ICE-16	EV-16
Powertrain System	Platinum	ICE-17	EV-17
Powertrain System	Others	ICE-18	EV-18
Transmission System/Gearbox	Steel	ICE-19	EV-19
Transmission System/Gearbox	Copper	ICE-20	EV-20
Transmission System/Gearbox	Cast Iron	ICE-21	EV-21
Transmission System/Gearbox	Wrought Aluminum	ICE-22	EV-22
Transmission System/Gearbox	Average Plastic	ICE-23	EV-23
Transmission System/Gearbox	Rubber*	ICE-24	EV-24
Transmission System/Gearbox	Others	ICE-25	EV-25
Chassis (w/o battery)	Steel	ICE-26	EV-26
Chassis (w/o battery)	Wrought Aluminum	ICE-27	EV-27
Chassis (w/o battery)	Cast Aluminum	ICE-28	EV-28
Chassis (w/o battery)	Copper/Brass	ICE-29	EV-29
Chassis (w/o battery)	Magnesium	ICE-30	EV-30
Chassis (w/o battery)	Glass Fiber-Reinforced Plastic	ICE-31	EV-31
Chassis (w/o battery)	Average Plastic	ICE-32	EV-32
Chassis (w/o battery)	Rubber*	ICE-33	EV-33
Chassis (w/o battery)	Others	ICE-34	EV-34
Traction Motor	Steel	ICE-35	EV-35
Traction Motor	Cast Aluminum	ICE-36	EV-36
Traction Motor	Copper/Brass	ICE-37	EV-37
Electronic Controller	Steel	ICE-38	EV-38
Electronic Controller	Cast Aluminum	ICE-39	EV-39
Electronic Controller	Copper/Brass	ICE-40	EV-40
Electronic Controller	Rubber*	ICE-41	EV-41
Electronic Controller	Average Plastic	ICE-42	EV-42
Electronic Controller	Others	ICE-43	EV-43

*Rubber calcs - pls see "Rubber" Sheet for all rubber calcs

Battery results are overleaf

Battery

Subsystem:	**Material**	Calc REF	Calc REF
Battery	Lead	ICE-B-44	EV-B-44
Battery	Water	ICE-B-45	EV-B-45
Battery	Sulphuric Acid	ICE-B-46	EV-B-46
Battery	Plastics	ICE-B-47	EV-B-47**
Battery	Glass Fiber	ICE-B-48	EV-B-48
Battery	Other	ICE-B-49	EV-B-49
Battery	Copper	ICE-B-50	EV-B-50
Battery	Wrought Al	ICE-B-51	EV-B-51
Battery	Graphite / carbon	ICE-B-52	EV-B-52
Battery	Electrolyte - EC - Ethylene carbonate	ICE-B-53	EV-B-53
Battery	Electrolyte - DMC - Dimethyl carbonat	ICE-B-54	EV-B-54
Battery	LiMn204	ICE-B-55	EV-B-55C
Battery	LiPF6	ICE-B-56	EV-B-56
Battery	PP	ICE-B-57	**see EV-B-47**
Battery	PE	ICE-B-58	**see EV-B-47**
Battery	PET	ICE-B-59	**see EV-B-47**
Battery	Binder	ICE-B-60	EV-B-60
Battery	Thermal insulation	ICE-B-61	EV-B-61
Battery	Electronic Parts	ICE-B-62	EV-B-62
Battery	Steel	ICE-B-63	EV-B-63
Battery	Glycol	ICE-B-64	EV-B-64

** Plastics are calculated together on EV-B-47

Calculator for: EV-01 (Calculation Ref) *Blue values need to be entered.*

Body (Subsystem)

Steel (Material)

1. Enter Mass of Material:

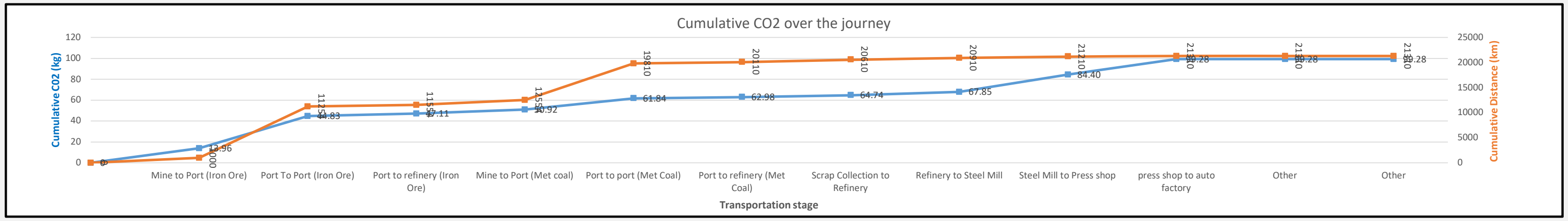
573.3 kg

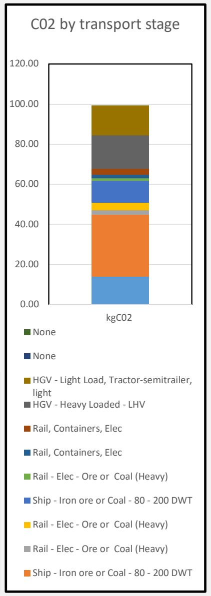
ANSWER

	Step	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist (km)	kgC02	Cum. C02 (kg)
	Ref - See Below			g/tkm		%	ton		km	0 0		
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.8362	National - 1000km	1000	1000	13.96	13.96
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.8362	Intercontinental: Brazil - Rotte	10254	11254	30.87	44.83
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.8362	National / Local - 300km	300	11554	2.28	47.11
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.4181	National - 1000km	1000	12554	3.80	50.92
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.4181	Intercontinental: New york - Ro	7256	19810	10.92	61.84
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.4181	National / Local - 300km	300	20110	1.14	62.98
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.2404	National - 500km	500	20610	1.75	64.74
h.	10, 13	**Refinery to Steel Mill**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.7108	National / Local - 300km	300	20910	3.11	67.85
i.	12, 13	**Steel Mill to Press shop**	HGV - Heavy Loaded - LHV	81.8	Sheet metal roll	94.9	0.6745	National / Local - 300km	300	21210	16.55	84.40
j.	10, 11	**press shop to auto factory**	HGV - Light Load, Tractor-semi	259.5	Pressed Panel	85	0.5733	Local 100 km	100	21310	14.88	99.28
k.		**Other**	None	0		100	0.5733	None, N/A, or see Alongside	0	21310	0.00	99.28
l.		Other	None	0		100	0.5733	None, N/A, or see Alongside	0	21310	0.00	99.28

m.

n.





References and Input Assumptions

	Input Assumptions	Inputs			Output crude steel	Ref / Citation
1.	Inputs for 1 tonne of steel	Iron ore	metallurgical coal	recyc steel		
	per tonne	**1.18**	**0.59**	**0.34**	**1.00**	(Worldsteel.org, 2019)
2	**Ore from Brazil (51.7 %of German Iron ore is from Brazil) (dist 8000km)**					(Elsner et al., 2019)
3	Distance from mining region to Ponta de Maderia - Approx 1000km (Capela et el 2019)					(Cepeda, Barros Kneipp and Caprace, 2019)
3	Ore from Ponta del Maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to Rotterdam				5537 Nautical miles =10254 km	(*Iron ore | Port of Rotterdam*, 2022) (Cepeda, Barros Kneipp and Caprace, 2019) (Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)
4	Scrap metal sourced from within Germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.					(Elsner et al., 2019)
5	Scrap metal transported dry freight containers					(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
6	Germany's biggest supplier of coal and coke is Russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA					(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)
7	Coking Coal provided from western USA deposits					(Trippi et al., 2021)
8	69% of coal in the USA is moved by rail, thus rail transportation is assumed					(*Freight Railroads & Coal | Association of American Railroads* , 2022)

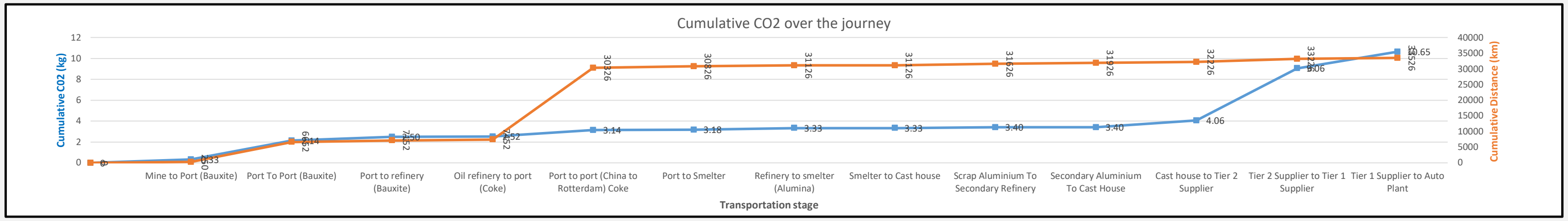
9	Transportation from USA to Europe is New York to Rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Journey of body panels as per Gaither & Frazier and Hua et el**	(Gaither, N. and Frazier, 2002) (Hua et al., 2022)
11	15% offcut scrap average in press shop	(Lore and Czechmeister, 2013) (Dallan, 2016)
12	Typically 80 percent of European steel is sourced from Europe. Thus local distances of up to 100 km are assumed.	(*European Steel in Figures 2020* , 2020)
13	Cold rolled steel as used in body panels has a loss factor of 1.054 i.e. 1/1.0154 = 94.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)

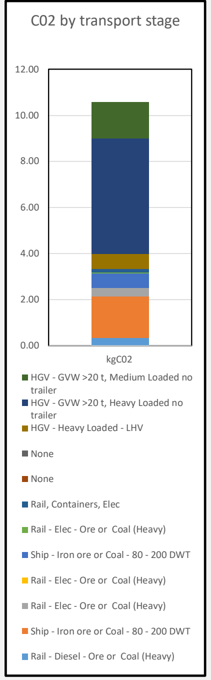
Calculator for: EV-02 (Calculation Ref) *Blue values need to be entered.*
Body (Subsystem)
Wrought Aluminum (Material)

1. Enter Mass of Material: 27.0 kg

ANSWER

Step	*Ref - See Below*	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.0785	None or N/A	250	250	0.33	0.33
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 2(	3.6	Bauxite	100	0.0785	Intercontinental: Guinea - Rott	6402	6652	1.81	2.14
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.0785	National - 500km	500	7152	0.36	2.50
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0076	National / Local - 300km	300	7452	0.02	2.52
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 2(	3.6	Coke	100	0.0076	None, N/A, or see Alongside	22874	30326	0.63	3.14
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0076	National - 500km	500	30826	0.03	3.18
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0344	National / Local - 300km	300	31126	0.15	3.33
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0178	None, N/A, or see Alongside	0	31126	0.00	3.33
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0100	National - 500km	500	31626	0.07	3.40
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0092	National / Local - 300km	300	31926	0.00	3.40
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	100	0.0270	National / Local - 300km	300	32226	0.66	4.06
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loadi	185.3	Parts	100	0.0270	National - 1000km	1000	33226	5.00	9.06
m.	7	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0270**	**National / Local - 300km**	**300**	33526	1.59	10.65
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

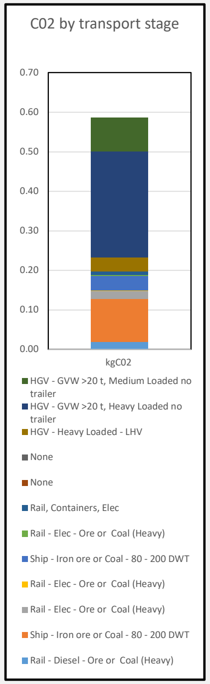
10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for hot rolled parts there is a loss factor of 3.5% whereas for cold rolled there is not. As it is not possible to know the proportion of hot rolled compared to cold rolled parts, and in the light of the relatively modest effect, this is not accounted for.	(Argonne GREET Vehicle Cycle Model, 2021)

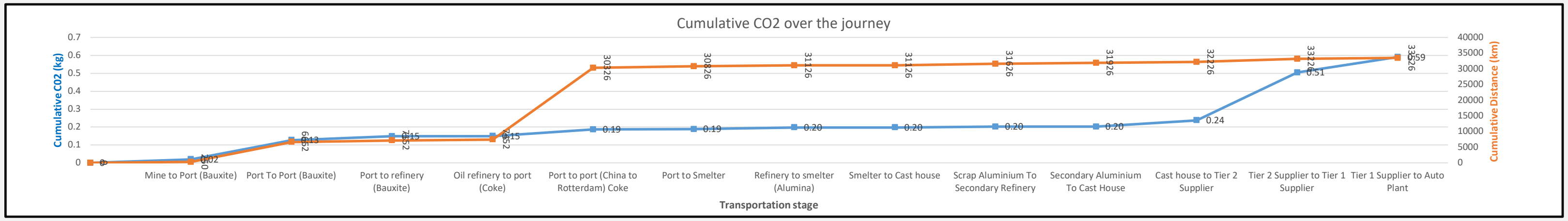
Calculator for: **EV-03** (Calculation Ref) *Blue values need to be entered.*
Body (Subsystem)
Cast Aluminum (Material)

1. Enter Mass of Material: 1.4 kg

ANSWER

Step	*Ref - See Below*	**Stage:**	2. Select Mode of transport	**Co2 factor CO2e (wtw) g/tkm**	3. Form	% of prev stage %	**Mass Transported ton**	4 Select Distance	or Enter Distance km	Cum. Dist. (km) 0 0	**kgC02**	**Cum. C02 (kg)**
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.0047	None or N/A	250	250	0.02	0.02
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.0047	Intercontinental: Guinea - Rott	6402	6652	0.11	0.13
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.0047	National - 500km	500	7152	0.02	0.15
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0005	National / Local - 300km	300	7452	0.00	0.15
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0005	None, N/A, or see Alongside	22874	30326	0.04	0.19
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0005	National - 500km	500	30826	0.00	0.19
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0020	National / Local - 300km	300	31126	0.01	0.20
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0011	None, N/A, or see Alongside	0	31126	0.00	0.20
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0006	National - 500km	500	31626	0.00	0.20
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0005	National / Local - 300km	300	31926	0.00	0.20
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	90.33	0.0014	National / Local - 300km	300	32226	0.04	0.24
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0014	National - 1000km	1000	33226	0.27	0.51
m.	**7**	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0014**	**National / Local - 300km**	**300**	33526	0.09	0.59
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

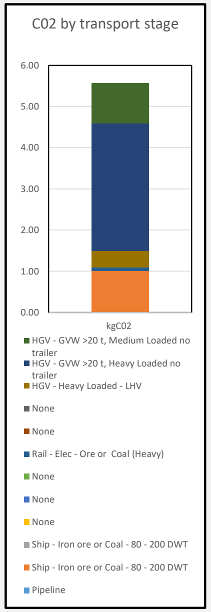
10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for cast aluminium parts, 1.107 kg aluminium needed to make a 1kg part	(Argonne GREET Vehicle Cycle Model, 2021)

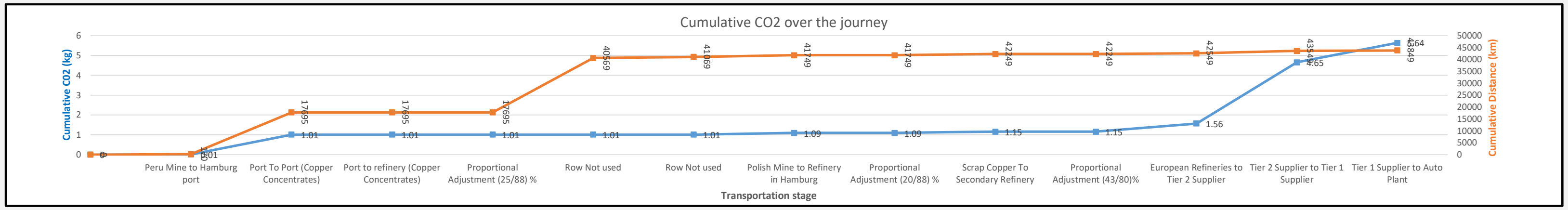
Calculator for: EV-04 (Calculation Ref) *Blue values need to be entered.*
Body (Subsystem)
Copper/Brass (Material)

1. Enter Mass of Material (kg): 16.7

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km) 0 0	kgC02	Cum. C02 (kg)
a.	1,2, 3	**Peru Mine to Hamburg port**	Pipeline	5	Copper Concentra	100	0.0158	Manual Entered Distance	170	170	0.01	0.01
b.	4	**Port To Port (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0158	Intercontinental: Manual Enter	17525	17695	1.00	1.01
c.	5	**Port to refinery (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0158	None, N/A, or see Alongside	0	17695	0.00	1.01
d.	9, 10	**Proportional Adjustment (25/88) %**	None	0	Copper Concentra	30	0.0047	None, N/A, or see Alongside	0	17695	0.00	1.01
e.		***Row Not used***	None	0	Coke	100	0.0016	None, N/A, or see Alongside	22874	40569	0.00	1.01
f.		***Row Not used***	None	0	Coke	100	0.0016	National - 500km	500	41069	0.00	1.01
g.	6	**Polish Mine to Refinery in Hamburg**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	100	0.0126	Manual Entered Distance	680	41749	0.08	1.09
h.	9, 10	**Proportional Adjustment (20/88) %**	None	0		30	0.0038	None, N/A, or see Alongside	0	41749	0.00	1.09
i.	7,8	**Scrap Copper To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Copper	100	0.0090	National - 500km	500	42249	0.07	1.15
j.	9	**Proportional Adjustment (43/80)%**	None	0		100	0.0090	None, N/A, or see Alongside	0	42249	0.00	1.15
k.		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0167	National / Local - 300km	300	42549	0.41	1.56
l.		**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0167	National - 1000km	1000	43549	3.09	4.65
m.		**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0167**	**National / Local - 300km**	**300**	43849	0.98	5.64
n.												





References and Input Assumptions

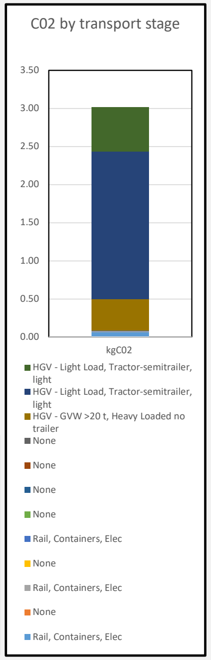
	Input Assumptions	Ref / Citation
1	Aurubis, Europe's largest copper producer is assumed to be the refiner and supplier at one of its facilities in Europe	(Kurlemann, 2022).
2	Chile, Peru and Brazil are the main suppliers of ore / concentrate to Germany. As Chile is the world's biggest supplier of copper this model will assume that it is supplied in Chile. Notwithstanding this, the shipping distance from Peru or Brazil is not dramatically different to Germany.	(Kurlemann, 2022) (International Copper Study Group, 2022)
3	Escodida, the world's largest copper mine is assumed to be the source. Concentrate is pumped 170km by pipeline to the port of Coloso	(www.mining-technology.com, 2020)
4	Copper concentrate is shipped in bulk for large quantities. The distance from Coloso to Hamburg is 9463 nm = 17525km	(Bulkcarrierguide.com, 2010) (ports.com, 2023)
5	Aurubus's Hamburg plant is near the port of Hamburg, and the concentrate is moved from the port to the plant via waterway. Thus for emissions purposes it will be assumed that this is part of the same sea journey. No additional distance therefore added	(Aurubis AG, 2021)
6	Poland is assumed to be the source of the ore, as its Europe's largest producer of ore after Russia. Transportation assumed to be by rail, 680km	(TheGlobalEconomy.com, 2018) (Google Maps, 2023)
7	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
8	Since 70% of copper in EU end of life products are recycled,, and given that Europe is a net exporter of scrap copper, it is assumed that the scrap copper is sourced from Europe	(euric-aisbl.eu, 2020)
9	These rows adjust the proportion of copper according to each source. 43% recycled, 20% European mines and 25% imported ore or concentrate - accounting for 88% of Europeal supply. The remaining 12% is not modelled as its source cannot be accurately determined. Thus the above proportions are adjusted accordingly: Recycled at 43/88 percent, European mines at 20/88% and imported iron or concentrate at 25/88%	(Kurlemann, 2022)
10	Based on 30% copper concentrate	

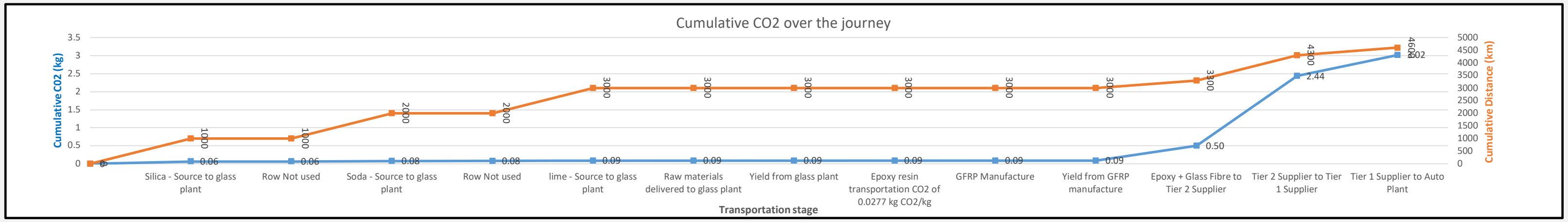
Calculator for: EV-05 (Calculation Ref) *Blue values need to be entered.*
Body (Subsystem)
GFRP (Material)

1. Enter Mass of Material:
7.5 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
										0		
										0		
a	2, 3, 4	**Silica - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0044	National - 1000km	1000	1000	0.06	0.06
		Row Not used	None	0		100		None, N/A, or see Alongside	0	1000	0.00	0.06
b	2,3, 5	**Soda - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0009	National - 1000km	1000	2000	0.01	0.08
		Row Not used	None	0		100		None, N/A, or see Alongside	0	2000	0.00	0.08
c	2,3, 6	**lime - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0006	National - 1000km	1000	3000	0.01	0.09
		Raw materials delivered to glass plant	None	0		100	0.0059	None, N/A, or see Alongside	0	3000	0.00	0.09
	1.	**Yield from glass plant**	None	0		72.25	0.0043	None, N/A, or see Alongside	0	3000	0.00	0.09
d		**Epoxy resin transportation CO2 of 0.0277 kg CO2/kg**	None	0			0.0043	None, N/A, or see Alongside	0	3000	0.00	0.09
		GFRP Manufacture	None	0			0.0085	None, N/A, or see Alongside	0	3000	0.00	0.09
d	7	**Yield from GFRP manufacture**	None	0		87.7193	0.0075	None, N/A, or see Alongside	0	3000	0.00	0.09
e		**Epoxy + Glass Fibre to Tier 2 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Bulk materials	100	0.0075	National / Local - 300km	300	3300	0.41	0.50
f	8	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0075	National - 1000km	1000	4300	1.94	2.44
g	**8**	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-sem**	**259.5**	**Parts**	**100**	**0.0075**	**National / Local - 300km**	**300**	4600	0.58	3.02





References and Input Assumptions

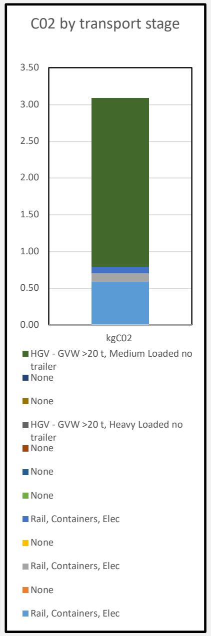
	Input Assumptions	Ref / Citation
1	Glass production at the melting stage has a yield of approx. 85%. A further reduction in yield for flat glass production is found, 85%. Total yield is therefore 85%*85%= 72.25%	Westbroek et el (2021)
2	Glass raw materials are sourced REGIONALLY in Europe.	(Glass for Europe, 2020)
3	glass comprises 75% silica sand, 15% soda ash and 10% lime.	Westbroek et el (2021)
4	Silica sand is typically transported by rail.	(Transportjournal.com, 2016; gbrailfreight.com, 2017)
5	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Cargohandbook.com, no date)
6	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Stork et al., 2014)
7	1.14 kg epoxy & glass fibre needed per 1kg GFRP. 1/1.14*100=87.7193	Keoleian et el (2012)
8	Due to low packing density of GFRP parts, it is assumed that the vehicles are "light" loaded	

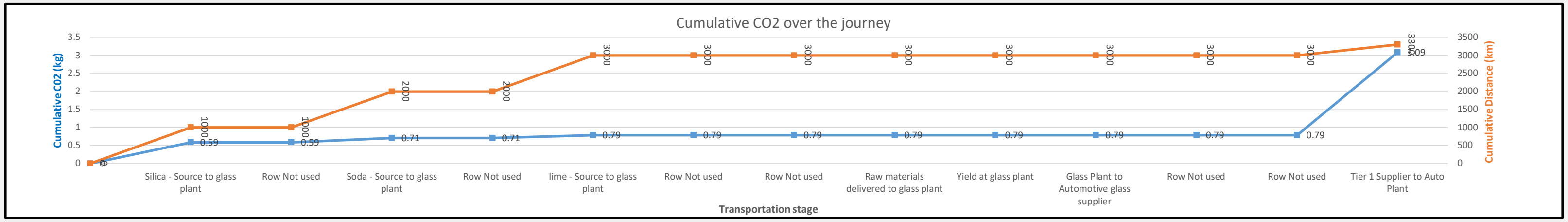
Calculator for: EV-06 (Calculation Ref) *Blue values need to be entered.*
Body (Subsystem)
Glass (Material)

1. Enter Mass of Material:
39.0 kg

ANSWER

		Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
Step	Ref - See Below			g/tkm		%	ton		km 0			
a	2, 3, 4	**Silica - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0405	National - 1000km	1000	1000	0.59	0.59
		Row Not used	None	0		100		None, N/A, or see Alongside	0	1000	0.00	0.59
b	2,3, 5	**Soda - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0081	National - 1000km	1000	2000	0.12	0.71
		Row Not used	None	0		100		None, N/A, or see Alongside	0	2000	0.00	0.71
c	2,3, 6	**lime - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0054	National - 1000km	1000	3000	0.08	0.79
		Row Not used	None	0		100	0.0540	None, N/A, or see Alongside	0	3000	0.00	0.79
		Row Not used	None	0		100	0.0540	None, N/A, or see Alongside	0	3000	0.00	0.79
		Raw materials delivered to glass plant	None	0		100	0.0540	None, N/A, or see Alongside	0	3000	0.00	0.79
	1.	**Yield at glass plant**	None	0		72.25	0.0390	None, N/A, or see Alongside	0	3000	0.00	0.79
d		**Glass Plant to Automotive glass supplier**	HGV - GVW >20 t, Heavy Load	185.3	Flat Glass	100	0.0390	None, N/A, or see Alongside	0	3000	0.00	0.79
		Row Not used	None	0		100	0.0390	None, N/A, or see Alongside	0	3000	0.00	0.79
		Row Not used	None	0		100	0.0390	None, N/A, or see Alongside	0	3000	0.00	0.79
e	7	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Glass parts**	**100**	**0.0390**	**National / Local - 300km**	**300**	3300	2.30	3.09





References and Input Assumptions

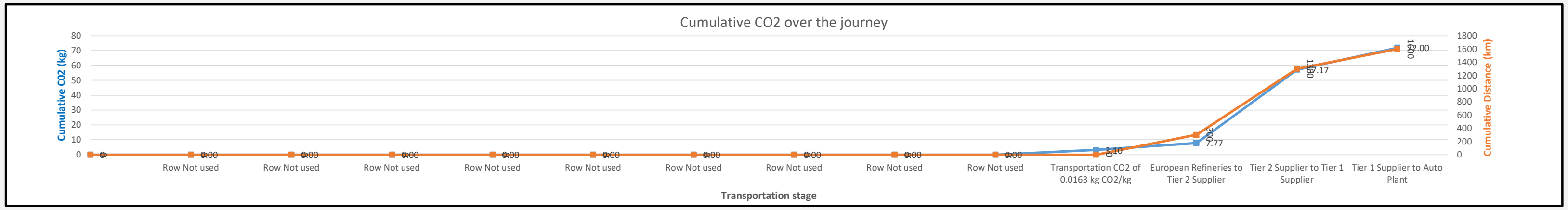
	Input Assumptions	Ref / Citation
1	Glass production at the melting stage has a yield of approx. 85%. A further reduction in yield for flat glass production is found, 85%. Total yield is therefore 85%*85%= 72.25%	Westbroek et el (2021)
2	Glass raw materials are sourced REGIONALLY in Europe.	(Glass for Europe, 2020)
3	glass comprises 75% silica sand, 15% soda ash and 10% lime.	Westbroek et el (2021)
4	Silica sand is typically transported by rail.	(Transportjournal.com, 2016; gbrailfreight.com, 2017)
5	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Cargohandbook.com, no date)
6	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Stork et al., 2014)
7	Glass For Europe indicates that there are 48 flat melting plants in Europe, and over 1000 companies processing and transforming flat glass. In the light of this it is reasonable to assume that the automotive glass can be supplied locally (within 300km) of a German vehicle plant.	

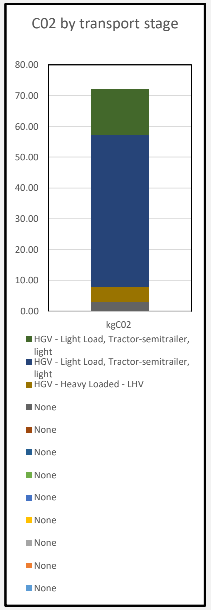
Calculator for: EV-07 (Calculation Ref) *Blue values need to be entered.*
Body (Subsystem)
Average Plastic (Material)

1. Enter Mass of Material: 190.4 kg

ANSWER

Step		Stage: *Ref - See Below*	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km) 0 0	kgC02	Cum. C02 (kg)
		Row Not used	None	0		100	0.1904	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.1904	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.1904	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.1904	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.1904	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.1904	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.1904	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.1904	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.1904	None, N/A, or see Alongside	0	0	0.00	0.00
	1.	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.1904	None, N/A, or see Alongside	0	0	3.10	3.10
a		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.1904	National / Local - 300km	300	300	4.67	7.77
b	2	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semit	259.5	Parts	100	0.1904	National - 1000km	1000	1300	49.40	57.17
c	2	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-semi**	**259.5**	**Assemblies**	**100**	**0.1904**	**National / Local - 300km**	**300**	1600	14.82	72.00





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

Calculator for: EV-10 (Calculation Ref) *Blue vlaues need to be entered.*

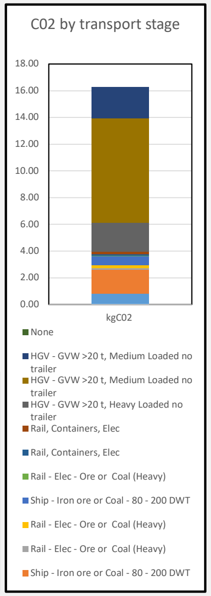
Powertrain System (Including BOP) (Subsystem)

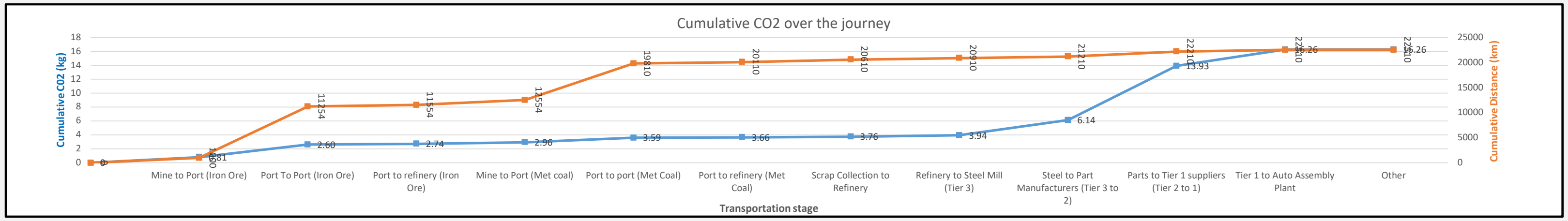
Steel (Material)

1. Enter Mass of Material: 39.6 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist (km)	kgC02	Cum. C02 (kg)
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.0486	National - 1000km	1000	1000	0.81	0.81
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.0486	Intercontinental: Brazil - Rotte	10254	11254	1.79	2.60
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.0486	National / Local - 300km	300	11554	0.13	2.74
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.0243	National - 1000km	1000	12554	0.22	2.96
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.0243	Intercontinental: New york - Ro	7256	19810	0.63	3.59
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.0243	National / Local - 300km	300	20110	0.07	3.66
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0140	National - 500km	500	20610	0.10	3.76
h.	10, 11	**Refinery to Steel Mill (Tier 3)**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.0413	National / Local - 300km	300	20910	0.18	3.94
i.	10,12	**Steel to Part Manufacturers (Tier 3 to 2)**	HGV - GVW >20 t, Heavy Loade	185.3	bar, lengths or s	95.9	0.0396	National / Local - 300km	300	21210	2.20	6.14
j.	10,13	**Parts to Tier 1 suppliers (Tier 2 to 1)**	HGV - GVW >20 t, Medium Loa	196.6	Parts	100	0.0396	National - 1000km	1000	22210	7.78	13.93
k.	10,11	**Tier 1 to Auto Assembly Plant**	HGV - GVW >20 t, Medium Loa	196.6	Components	100	0.0396	National / Local - 300km	300	22510	2.33	16.26
l.		Other	None	0		100	0.0396	None, N/A, or see Alongside	0	22510	0.00	16.26
m.												
n.												





Refernces and Input Assumptions

	Input Assumptions	Ref / Citation
1.	Inputs for 1 tonne of steel Inputs: Iron ore per tonne 1.18; metallurgical coal 0.59; recyc steel 0.34 Output crude steel: 1.00	(Worldsteel.org, 2019)
2	**Ore from Brazil (51.7 %of German Iron ore is from brazil) (dist 8000km)**	(Elsner et al., 2019)
3	Distance from mining region to ponta de maderia - Approx 1000km (Capela et el 2019)	(Cepeda, Barros Kneipp and Caprace, 2019)
3	Ore from Ponta del maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to rotterdam 5537 Nautical miles =10254 km	(Iron ore | Port of Rotterdam, 2022) (Cepeda, Barros Kneipp and Caprace, 2019) (Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)
4	Scrap metal sourced from within germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.	(Elsner et al., 2019)
5	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
6	Germany's biggerst supplier of coal and coke is russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA	(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)
7	Coking Coal provided from western USA deposits	(Trippi et al., 2021)
8	69% of coal in the usa is moved by rail, thus rail transporation is assumed	(*Freight Railroads & Coal | Association of American Railroads* , 2022)

9	Transporation from usa to europe is New yourk to rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Assumptions of Hua et el (2022) assumed to be transferrable to EU context, and also confirmed by Brown et el (2021)**	(Hua et al., 2022) (Brown et al., 2021)
11	Distances based on suppliers from across europe, including eastern europe as argued by Brown et.el (2021)	(Brown et al., 2021)
12	Rod and bar steel as used incar parts has a loss factor of 1.043 i.e. 1/1.043 = 95.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)
13	GREET model states a loss factor of 1.00 for machining or stamping operations. Other data to challenge this was not found.	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: EV-13 (Calculation Ref) *Blue values need to be entered.*

1. Enter Mass of Material (kg): 16.2

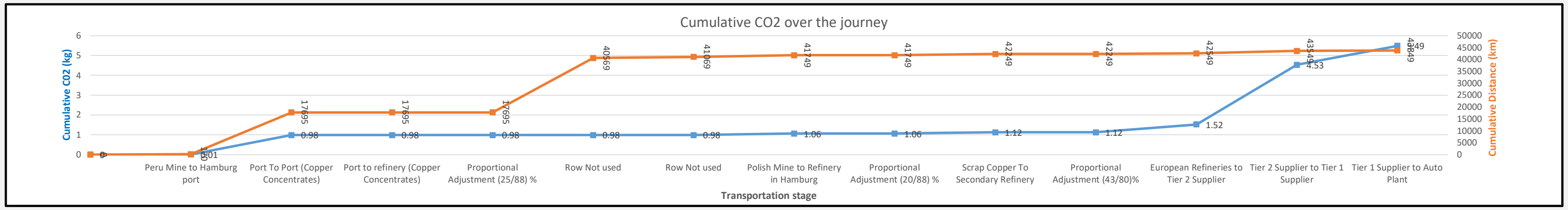
Powertrain System (Including BOP) (Subsystem)

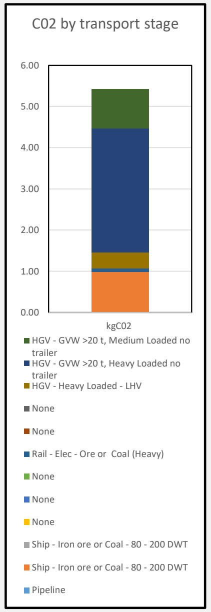
Copper/Brass (Material)

ANSWER

	Step Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a.	1,2, 3	**Peru Mine to Hamburg port**	Pipeline	5	Copper Concentra	100	0.0154	Manual Entered Distance	170	170	0.01	0.01
b.	4	**Port To Port (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0154	Intercontinental: Manual Enter	17525	17695	0.97	0.98
c.	5	**Port to refinery (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0154	None, N/A, or see Alongside	0	17695	0.00	0.98
d.	9, 10	**Proportional Adjustment (25/88) %**	None	0	Copper Concentra	30	0.0046	None, N/A, or see Alongside	0	17695	0.00	0.98
e.		***Row Not used***	None	0	Coke	100	0.0016	None, N/A, or see Alongside	22874	40569	0.00	0.98
f.		***Row Not used***	None	0	Coke	100	0.0016	National - 500km	500	41069	0.00	0.98
g.	6	**Polish Mine to Refinery in Hamburg**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	100	0.0123	Manual Entered Distance	680	41749	0.08	1.06
h.	9, 10	**Proportional Adjustment (20/88) %**	None	0		30	0.0037	None, N/A, or see Alongside	0	41749	0.00	1.06
i.	7,8	**Scrap Copper To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Copper	100	0.0087	National - 500km	500	42249	0.06	1.12
j.	9	**Proportional Adjustment (43/80)%**	None	0		100	0.0087	None, N/A, or see Alongside	0	42249	0.00	1.12
k.		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0162	National / Local - 300km	300	42549	0.40	1.52
l.		**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0162	National - 1000km	1000	43549	3.01	4.53
m.		**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0162**	**National / Local - 300km**	**300**	43849	0.96	5.49

n.





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Aurubis, Europe's largest copper producer is assumed to be the refiner and supplier at one of its facilities in Europe	(Kurlemann, 2022).
2	Chile, Peru and Brazil are the main suppliers of ore / concentrate to Germany. As Chile is the world's biggest supplier of copper this model will assume that it is supplied in Chile. Notwithstanding this, the shipping distance from Peru or Brazil is not dramatically differnt to Germany.	(Kurlemann, 2022) (International Copper Study Group, 2022)
3	Escodida, the world's largest copper mine is assumed to be the source. Concentrate is pumped 170km by pipeline to the port of Coloso	(www.mining-technology.com, 2020)
4	Copper concentrate is shipped in bulk for large quantiites. The distance from Coloso to Hamburg is 9463 nm = 17525km	(Bulkcarrierguide.com, 2010) (ports.com, 2023)
5	Aurubus's Hamburg plant is near the port of hamburg, and the concentrate is moved from the port to the plant via waterway. Thus for emissions purposes it will be assumed that this is part of the same sea journey. No addtiotnal distance therefore added	(Aurubis AG, 2021)
6	Poland is assumed to be the souirce of the ore, as its euope's largest producer of ore after Russia. Transporation assumed to be by rail, 680km	(TheGlobalEconomy.com, 2018) (Google Maps, 2023)
7	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
8	Since 70% of copper in EU end of life products are recycled,, and given that Europe is a net exporter of scrap copper, it is assumed that the scrap copper is sourced from europe	(euric-aisbl.eu, 2020)
9	These rows adjust the propotion of copper according to each source. 43% recycled, 20% european mines and 25% imported ore or concentrate - accounting for 88% of Europea supply. The remaining 12% is not modelled as its source cannot be accurately determined. Thus the above propotions are adjusted accordingly: Recycled at 43/88 percent, Eurpean mines at 20/88% and imported iron or concentrate at 25/88%	(Kurlemann, 2022)
10	Based on 30% copper concerate	

Calculator for: EV-15 (Calculation Ref) *Blue values need to be entered.*

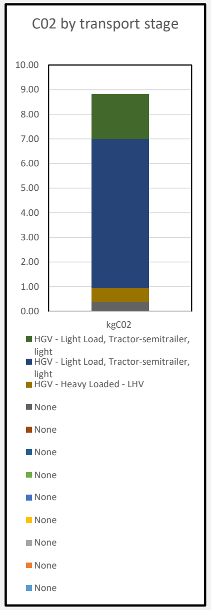
1. Enter Mass of Material: Powertrain System (Including BOP) (Subsystem)

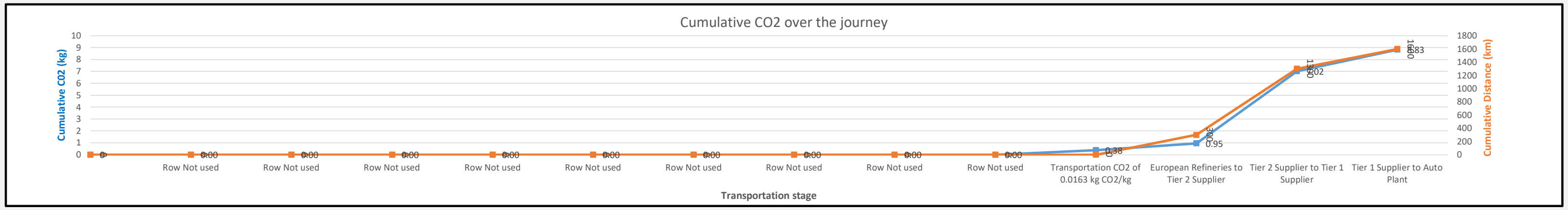
Average

23.4 kg Plastic (Material)

ANSWER

Step	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
Step	Ref - See Below		g/tkm		%	ton		km	0		
									0		
	Row Not used	None	0		100	0.0234	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0234	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0234	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0234	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0234	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0234	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0234	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0234	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0234	None, N/A, or see Alongside	0	0	0.00	0.00
1.	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.0234	None, N/A, or see Alongside	0	0	0.38	0.38
a	**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0234	National / Local - 300km	300	300	0.57	0.95
b	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0234	National - 1000km	1000	1300	6.06	7.02
c 2.	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-semi**	**259.5**	**Assemblies**	**100**	**0.0234**	**National / Local - 300km**	**300**	1600	1.82	8.83





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

Calculator for: EV-19 (Calculation Ref) *Blue vlaues need to be entered.*

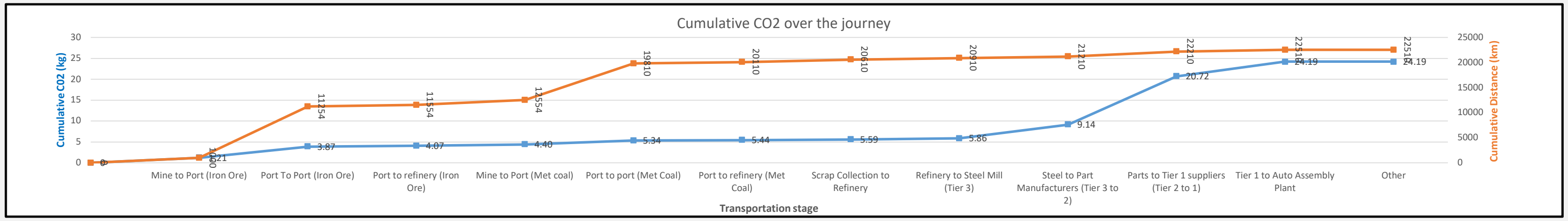
Transmission System/Gearbox (Subsystem)

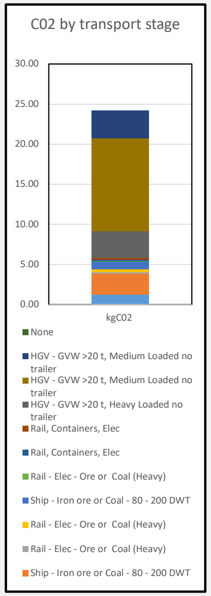
Steel (Material)

1. Enter Mass of Material:	
58.9	kg

ANSWER

	Step *Ref - See Below*	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist (km)	kgC02	Cum. C02 (kg)
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.0723	National - 1000km	1000	1000	1.21	1.21
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.0723	Intercontinental: Brazil - Rotter	10254	11254	2.67	3.87
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.0723	National / Local - 300km	300	11554	0.20	4.07
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.0361	National - 1000km	1000	12554	0.33	4.40
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.0361	Intercontinental: New york - Ro	7256	19810	0.94	5.34
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.0361	National / Local - 300km	300	20110	0.10	5.44
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0208	National - 500km	500	20610	0.15	5.59
h.	10, 11	**Refinery to Steel Mill (Tier 3)**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.0614	National / Local - 300km	300	20910	0.27	5.86
i.	10,12	**Steel to Part Manufacturers (Tier 3 to 2)**	HGV - GVW >20 t, Heavy Loade	185.3	bar, lengths or s	95.9	0.0589	National / Local - 300km	300	21210	3.27	9.14
j.	10,13	**Parts to Tier 1 suppliers (Tier 2 to 1)**	HGV - GVW >20 t, Medium Loa	196.6	Parts	100	0.0589	National - 1000km	1000	22210	11.58	20.72
k.	10,11	**Tier 1 to Auto Assembly Plant**	HGV - GVW >20 t, Medium Loa	196.6	Components	100	0.0589	National / Local - 300km	300	22510	3.47	24.19
l.		Other	None	0		100	0.0589	None, N/A, or see Alongside	0	22510	0.00	24.19
m.												
n.												





Refernces and Input Assumptions

<table>
<tr><th></th><th>Input Assumptions</th><th>Ref / Citation</th></tr>
<tr><td>1.</td><td>Inputs for 1 tonne of steel
<table>
<tr><td></td><td colspan="3">Inputs</td><td>Output crude steel</td></tr>
<tr><td></td><td>Iron ore</td><td>metallurgical coal</td><td>recyc steel</td><td></td></tr>
<tr><td>**per tonne**</td><td>**1.18**</td><td>**0.59**</td><td>**0.34**</td><td>**1.00**</td></tr>
</table></td><td>(Worldsteel.org, 2019)</td></tr>
<tr><td>2</td><td>**Ore from Brazil (51.7 %of German Iron ore is from brazil) (dist 8000km)**</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>3</td><td>Distance from mining region to ponta de maderia - Approx 1000km (Capela et el 2019)</td><td>(Cepeda, Barros Kneipp and Caprace, 2019)</td></tr>
<tr><td>3</td><td>Ore from Ponta del maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to rotterdam 5537 Nautical miles =10254 km</td><td>(Cepeda, Barros Kneipp and Caprace, 2019)
(Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)</td></tr>
<tr><td>4</td><td>Scrap metal sourced from within germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>5</td><td>Scrap metal transported dry freight containers</td><td>(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)</td></tr>
<tr><td>6</td><td>Germany's biggerst supplier of coal and coke is russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA</td><td>(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)</td></tr>
<tr><td>7</td><td>Coking Coal provided from western USA deposits</td><td>(Trippi et al., 2021)</td></tr>
<tr><td>8</td><td>69% of coal in the usa is moved by rail, thus rail transporation is assumed</td><td>(*Freight Railroads & Coal | Association of American Railroads* , 2022)</td></tr>
</table>

9	Transporation from usa to europe is New yourk to rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Assumptions of Hua et el (2022) assumed to be transferrable to EU context, and also confirmed by Brown et el (2021)**	(Hua et al., 2022) (Brown et al., 2021)
11	Distances based on suppliers from across europe, including eastern europe as argued by Brown et.el (2021)	(Brown et al., 2021)
12	Rod and bar steel as used incar parts has a loss factor of 1.043 i.e. 1/1.043 = 95.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)
13	GREET model states a loss factor of 1.00 for machining or stamping operations. Other data to challenge this was not found.	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: ICE-20 (Calculation Ref) *Blue values need to be entered.*

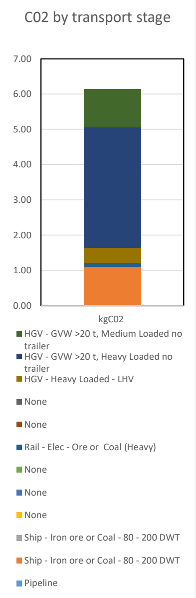
Transmission System/Gearbox (Subsystem)

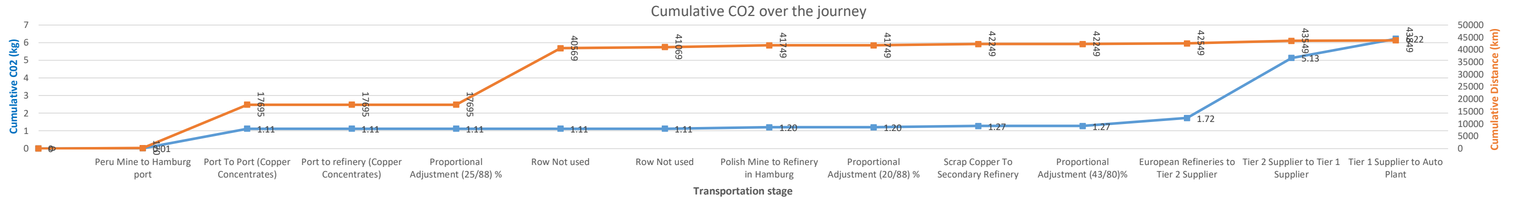
Copper/Brass (Material)

1. Enter Mass of Material (kg): 18.4

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (v g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	0 0 Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a.	1,2, 3	**Peru Mine to Hamburg port**	Pipeline	5	Copper Concentra	100	0.0174	Manual Entered Distance	170	170	0.01	0.01
b.	4	**Port To Port (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0174	Intercontinental: Manual Enter	17525	17695	1.10	1.11
c.	5	**Port to refinery (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0174	None, N/A, or see Alongside	0	17695	0.00	1.11
d.	9, 10	**Proportional Adjustment (25/88) %**	None	0	Copper Concentra	30	0.0052	None, N/A, or see Alongside	0	17695	0.00	1.11
e.		***Row Not used***	None	0	Coke	100	0.0018	None, N/A, or see Alongside	22874	40569	0.00	1.11
f.		***Row Not used***	None	0	Coke	100	0.0018	National - 500km	500	41069	0.00	1.11
g.	6	**Polish Mine to Refinery in Hamburg**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	100	0.0139	Manual Entered Distance	680	41749	0.09	1.20
h.	9, 10	**Proportional Adjustment (20/88) %**	None	0		30	0.0042	None, N/A, or see Alongside	0	41749	0.00	1.20
i.	7,8	**Scrap Copper To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Copper	100	0.0099	National - 500km	500	42249	0.07	1.27
j.	9	**Proportional Adjustment (43/80)%**	None	0		100	0.0099	None, N/A, or see Alongside	0	42249	0.00	1.27
k.		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0184	National / Local - 300km	300	42549	0.45	1.72
l.		**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0184	National - 1000km	1000	43549	3.41	5.13
m.		**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0184**	**National / Local - 300km**	**300**	43849	1.09	6.22
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Aurubis, Europe's largest copper producer is assumed to be the refiner and supplier at one of its facilities in Europe	(Kurlemann, 2022).
2	Chile, Peru and Brazil are the main suppliers of ore / concentrate to Germany. As Chile is the world's biggest supplier of copper this model will assume that it is supplied in Chile. Notwithstanding this, the shipping distance from Peru or Brazil is not dramatically differnt to Germany.	(Kurlemann, 2022) (International Copper Study Group, 2022)
3	Escodida, the world's largest copper mine is assumed to be the source. Concentrate is pumped 170km by pipeline to the port of Coloso	(www.mining-technology.com, 2020)
4	Copper concentrate is shipped in bulk for large quantiites. The distance from Coloso to Hamburg is 9463 nm = 17525km	(Bulkcarrierguide.com, 2010) (ports.com, 2023)
5	Aurubus's Hamburg plant is near the port of hamburg, and the concentrate is moved from the port to the plant via waterway. Thus for emissions purposes it will be assumed that this is part of the same sea journey. No addtiotnal distance therefore added	(Aurubis AG, 2021)
6	Poland is assumed to be the souirce of the ore, as its euope's largest producer of ore after Russia. Transporation assumed to be by rail, 680km	(TheGlobalEconomy.com, 2018) (Google Maps, 2023)
7	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
8	Since 70% of copper in EU end of life products are recycled,, and given that Europe is a net exporter of scrap copper, it is assumed that the scrap copper is sourced from europe	(euric-aisbl.eu, 2020)
9	These rows adjust the propotion of copper according to each source. 43% recycled, 20% european mines and 25% imported ore or concentrate - accounting for 88% of European supply. The remaining 12% is not modelled as its source cannot be accurately determined. Thus the above propotions are adjusted accordingly: Recycled at 43/88 percent, Eurpean mines at 20/88% and imported iron or concentrate at 25/88%	(Kurlemann, 2022)
10	Based on 30% copper concentrate	

Calculator for: EV-22 (Calculation Ref) *Blue values need to be entered.*

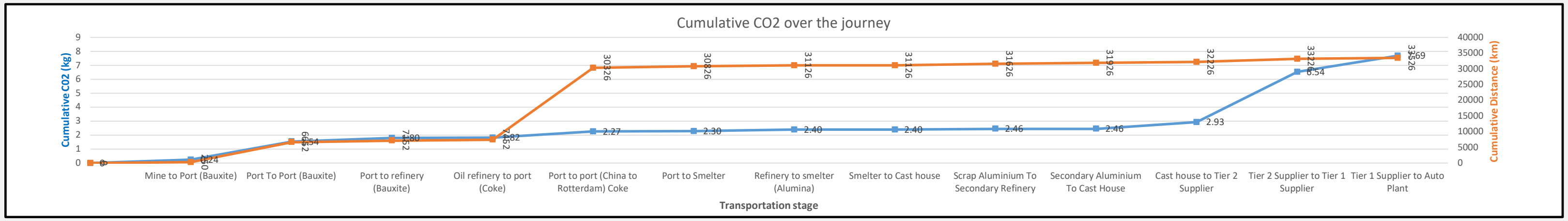
Transmission System/Gearbox (Subsystem)

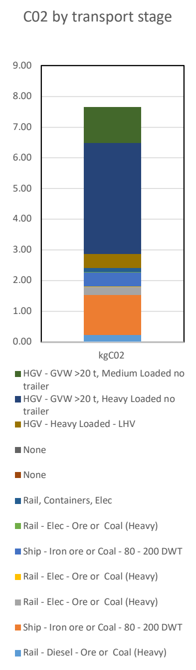
Wrought Aluminum (Material)

1. Enter Mass of Material: 19.5 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.0567	None or N/A	250	250	0.24	0.24
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.0567	Intercontinental: Guinea - Rott	6402	6652	1.31	1.54
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.0567	National - 500km	500	7152	0.26	1.80
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0055	National / Local - 300km	300	7452	0.02	1.82
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0055	None, N/A, or see Alongside	22874	30326	0.45	2.27
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0055	National - 500km	500	30826	0.03	2.30
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0249	National / Local - 300km	300	31126	0.11	2.40
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0128	None, N/A, or see Alongside	0	31126	0.00	2.40
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0072	National - 500km	500	31626	0.05	2.46
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0066	National / Local - 300km	300	31926	0.00	2.46
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	100	0.0195	National / Local - 300km	300	32226	0.48	2.93
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0195	National - 1000km	1000	33226	3.61	6.54
m.	**7**	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0195**	**National / Local - 300km**	**300**	33526	1.15	7.69
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

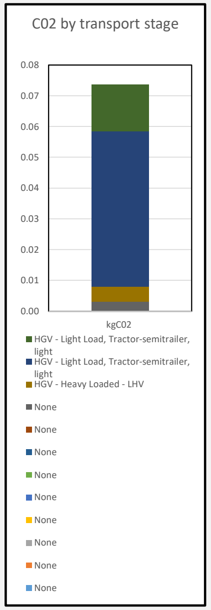
10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for hot rolled parts there is a loss factor of 3.5% whereas for cold rolled there is not. As it is not possible to know the proportion of hot rolled compared to cold rolled parts, and in the light of the relatively modest effect, this is not accounted for.	(Argonne GREET Vehicle Cycle Model, 2021)

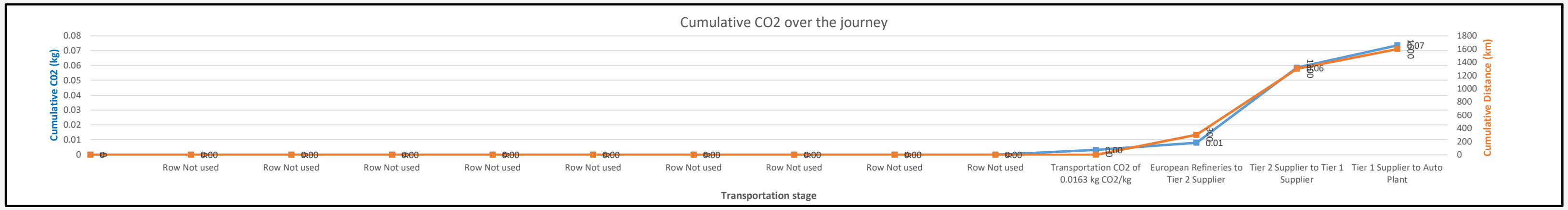
Calculator for: EV-23 (Calculation Ref) *Blue values need to be entered.*
Transmission System/Gearbox (Subsystem)
Average
Plastic (Material)

1. Enter Mass of Material: 0.2 kg

ANSWER

Step	Stage: *Ref - See Below*	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
	Row Not used	None	0		100	0.0002	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0002	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0002	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0002	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0002	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0002	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0002	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0002	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0002	None, N/A, or see Alongside	0	0	0.00	0.00
1.	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.0002	None, N/A, or see Alongside	0	0	0.00	0.00
a	**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0002	National / Local - 300km	300	300	0.00	0.01
b 2.	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semit	259.5	Parts	100	0.0002	National - 1000km	1000	1300	0.05	0.06
c 2.	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-semi**	**259.5**	**Assemblies**	**100**	**0.0002**	**National / Local - 300km**	**300**	1600	0.02	0.07





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

Calculator for: EV-26 (Calculation Ref) *Blue vlaues need to be entered.*
Chassis (w/o battery) (Subsystem)
Steel (Material)

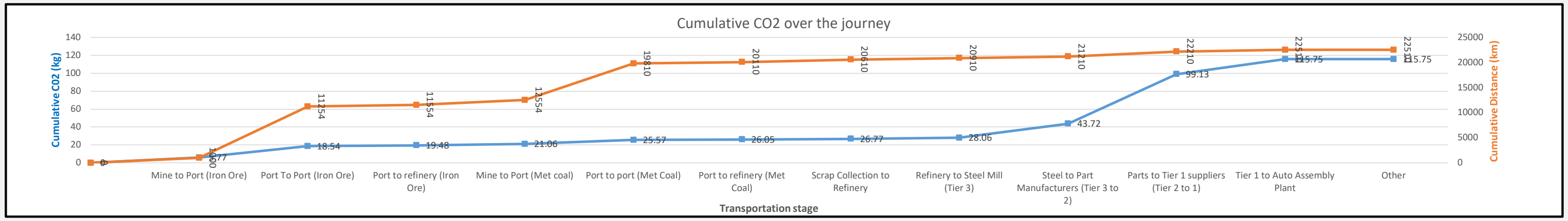
1. Enter Mass of Material: 281.8 kg

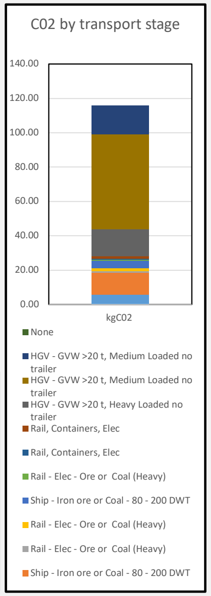
ANSWER

	Step Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist (km)	kgC02	Cum. C02 (kg)
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.3458	National - 1000km	1000	1000	5.77	5.77
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.3458	Intercontinental: Brazil - Rotter	10254	11254	12.76	18.54
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.3458	National / Local - 300km	300	11554	0.94	19.48
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.1729	National - 1000km	1000	12554	1.57	21.06
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.1729	Intercontinental: New york - Ro	7256	19810	4.52	25.57
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.1729	National / Local - 300km	300	20110	0.47	26.05
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0994	National - 500km	500	20610	0.73	26.77
h.	10, 11	**Refinery to Steel Mill (Tier 3)**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.2939	National / Local - 300km	300	20910	1.29	28.06
i.	10,12	**Steel to Part Manufacturers (Tier 3 to 2)**	HGV - GVW >20 t, Heavy Loade	185.3	bar, lengths or s	95.9	0.2818	National / Local - 300km	300	21210	15.67	43.72
j.	10,13	**Parts to Tier 1 suppliers (Tier 2 to 1)**	HGV - GVW >20 t, Medium Loa	196.6	Parts	100	0.2818	National - 1000km	1000	22210	55.40	99.13
k.	10,11	**Tier 1 to Auto Assembly Plant**	HGV - GVW >20 t, Medium Loa	196.6	Components	100	0.2818	National / Local - 300km	300	22510	16.62	115.75
l.		Other	None	0		100	0.2818	None, N/A, or see Alongside	0	22510	0.00	115.75

m.

n.





Refernces and Input Assumptions

	Input Assumptions	Ref / Citation
1.	Inputs for 1 tonne of steel	(Worldsteel.org, 2019)
2	**Ore from Brazil (51.7 %of German Iron ore is from brazil) (dist 8000km)**	(Elsner et al., 2019)
3	Distance from mining region to ponta de maderia - Approx 1000km (Capela et el 2019)	(Cepeda, Barros Kneipp and Caprace, 2019)
3	Ore from Ponta del maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to rotterdam 5537 Nautical miles =10254 km	(Iron ore | Port of Rotterdam, 2022) (Cepeda, Barros Kneipp and Caprace, 2019) (Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)
4	Scrap metal sourced from within germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.	(Elsner et al., 2019)
5	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
6	Germany's biggerst supplier of coal and coke is russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA	(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)
7	Coking Coal provided from western USA deposits	(Trippi et al., 2021)
8	69% of coal in the usa is moved by rail, thus rail transporation is assumed	(*Freight Railroads & Coal | Association of American Railroads* , 2022)

Inputs for 1 tonne of steel:

	Inputs			Output crude steel
	Iron ore	metallurgical coal	recyc steel	
per tonne	1.18	0.59	0.34	1.00

9	Transporation from usa to europe is New yourk to rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Assumptions of Hua et el (2022) assumed to be transferrable to EU context, and also confirmed by Brown et el (2021)**	(Hua et al., 2022) (Brown et al., 2021)
11	Distances based on suppliers from across europe, including eastern europe as argued by Brown et.el (2021)	(Brown et al., 2021)
12	Rod and bar steel as used incar parts has a loss factor of 1.043 i.e. 1/1.043 = 95.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)
13	GREET model states a loss factor of 1.00 for machining or stamping operations. Other data to challenge this was not found.	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: EV-27 (Calculation Ref) *Blue values need to be entered.*

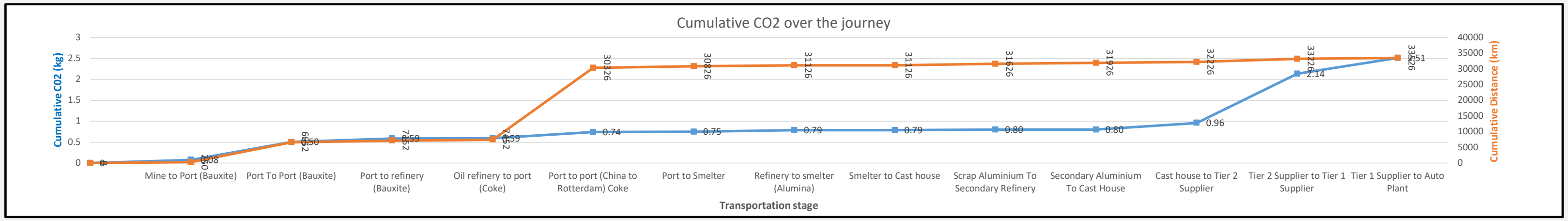
Chassis (w/o battery) (Subsystem)

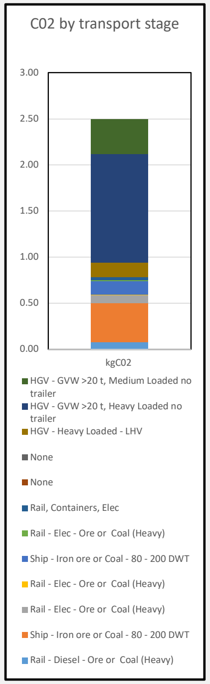
Wrought Aluminum (Material)

1. Enter Mass of Material: 6.4 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km) 0 0	kgC02	Cum. C02 (kg)
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.0185	None or N/A	250	250	0.08	0.08
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.0185	Intercontinental: Guinea - Rott	6402	6652	0.43	0.50
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.0185	National - 500km	500	7152	0.08	0.59
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0018	National / Local - 300km	300	7452	0.00	0.59
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0018	None, N/A, or see Alongside	22874	30326	0.15	0.74
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0018	National - 500km	500	30826	0.01	0.75
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0081	National / Local - 300km	300	31126	0.04	0.79
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0042	None, N/A, or see Alongside	0	31126	0.00	0.79
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0024	National - 500km	500	31626	0.02	0.80
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0022	National / Local - 300km	300	31926	0.00	0.80
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	100	0.0064	National / Local - 300km	300	32226	0.16	0.96
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0064	National - 1000km	1000	33226	1.18	2.14
m.	7	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0064**	**National / Local - 300km**	**300**	33526	0.37	2.51
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

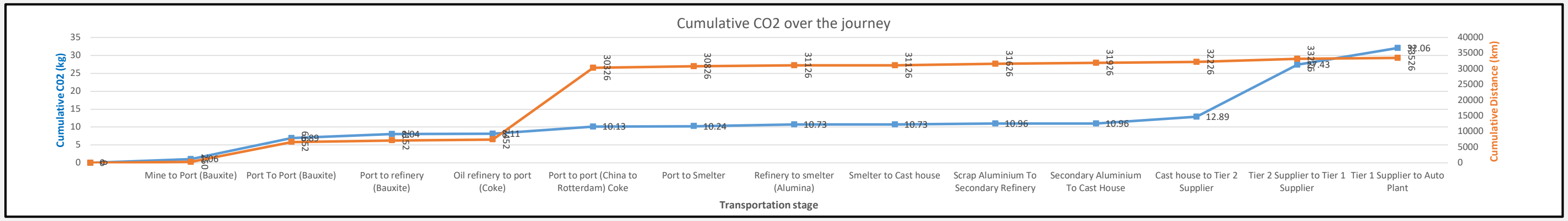
10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for hot rolled parts there is a loss factor of 3.5% whereas for cold rolled there is not. As it is not possible to know the proportion of hot rolled compared to cold rolled parts, and in the light of the relatively modest effect, this is not accounted for.	(Argonne GREET Vehicle Cycle Model, 2021)

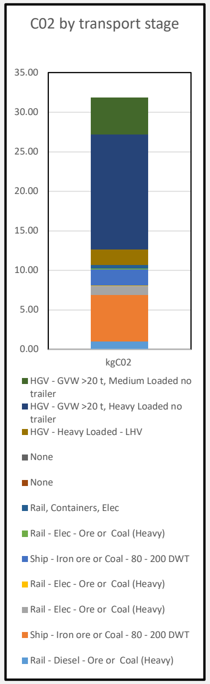
Calculator for: EV-28 (Calculation Ref) *Blue values need to be entered.*
Chassis (w/o battery) (Subsystem)
Cast Aluminum (Material)

1. Enter Mass of Material: 78.5 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.2530	None or N/A	250	250	1.06	1.06
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.2530	Intercontinental: Guinea - Rott	6402	6652	5.83	6.89
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.2530	National - 500km	500	7152	1.15	8.04
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0246	National / Local - 300km	300	7452	0.07	8.11
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0246	None, N/A, or see Alongside	22874	30326	2.02	10.13
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0246	National - 500km	500	30826	0.11	10.24
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.1109	National / Local - 300km	300	31126	0.49	10.73
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0573	None, N/A, or see Alongside	0	31126	0.00	10.73
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0322	National - 500km	500	31626	0.24	10.96
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0295	National / Local - 300km	300	31926	0.00	10.96
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	90.33	0.0785	National / Local - 300km	300	32226	1.93	12.89
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0785	National - 1000km	1000	33226	14.54	27.43
m.	7	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0785**	**National / Local - 300km**	**300**	33526	4.63	32.06
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for cast aluminium parts, 1.107 kg aluminium needed to make a 1kg part	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: **EV-29** (Calculation Ref) *Blue values need to be entered.*

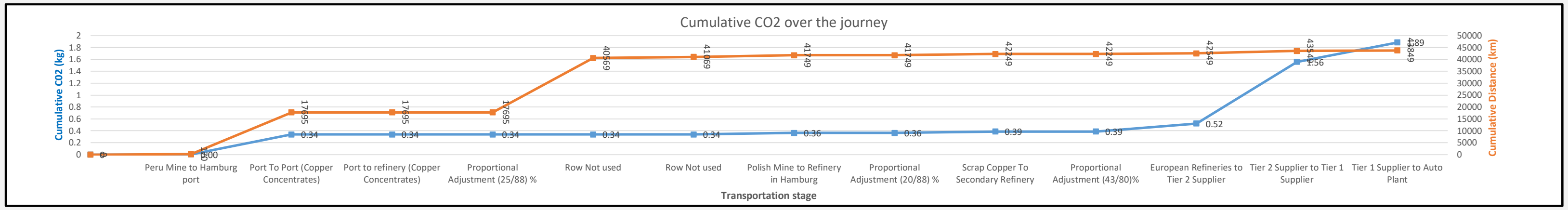
Chassis (w/o battery) (Subsystem)

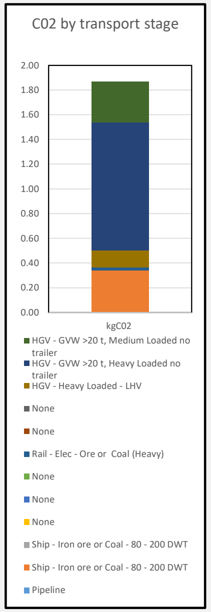
Copper/Brass (Material)

1. Enter Mass of Material (kg): 5.6

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km) 0	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0		
a.	1,2, 3	**Peru Mine to Hamburg port**	Pipeline	5	Copper Concentra	100	0.0053	Manual Entered Distance	170	170	0.00	0.00
b.	4	**Port To Port (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0053	Intercontinental: Manual Enter	17525	17695	0.33	0.34
c.	5	**Port to refinery (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0053	None, N/A, or see Alongside	0	17695	0.00	0.34
d.	9, 10	**Proportional Adjustment (25/88) %**	None	0	Copper Concentra	30	0.0016	None, N/A, or see Alongside	0	17695	0.00	0.34
e.		***Row Not used***	None	0	Coke	100	0.0005	None, N/A, or see Alongside	22874	40569	0.00	0.34
f.		***Row Not used***	None	0	Coke	100	0.0005	National - 500km	500	41069	0.00	0.34
g.	6	**Polish Mine to Refinery in Hamburg**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	100	0.0042	Manual Entered Distance	680	41749	0.03	0.36
h.	9, 10	**Proportional Adjustment (20/88) %**	None	0		30	0.0013	None, N/A, or see Alongside	0	41749	0.00	0.36
i.	7,8	**Scrap Copper To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Copper	100	0.0030	National - 500km	500	42249	0.02	0.39
j.	9	**Proportional Adjustment (43/80)%**	None	0		100	0.0030	None, N/A, or see Alongside	0	42249	0.00	0.39
k.		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0056	National / Local - 300km	300	42549	0.14	0.52
l.		**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0056	National - 1000km	1000	43549	1.03	1.56
m.		**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0056**	**National / Local - 300km**	**300**	43849	0.33	1.89
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Aurubis, Europe's largest copper producer is assumed to be the refiner and supplier at one of its facilities in Europe	(Kurlemann, 2022).
2	Chile, Peru and Brazil are the main suppliers of ore / concentrate to Germany. As Chile is the world's biggest supplier of copper this model will assume that it is supplied in Chile. Notwithstanding this, the shipping distance from Peru or Brazil is not dramatically differnt to Germany.	(Kurlemann, 2022) (International Copper Study Group, 2022)
3	Escodida, the world's largest copper mine is assumed to be the source. Concentrate is pumped 170km by pipeline to the port of Coloso	(www.mining-technology.com, 2020)
4	Copper concentrate is shipped in bulk for large quantiites. The distance from Coloso to Hamburg is 9463 nm = 17525km	(Bulkcarrierguide.com, 2010) (ports.com, 2023)
5	Aurubus's Hamburg plant is near the port of hamburg, and the concentrate is moved from the port to the plant via waterway. Thus for emissions purposes it will be assumed that this is part of the same sea journey. No addtiotnal distance therefore added	(Aurubis AG, 2021)
6	Poland is assumed to be the souirce of the ore, as its euope's largest producer of ore after Russia. Transporation assumed to be by rail, 680km	(TheGlobalEconomy.com, 2018) (Google Maps, 2023)
7	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
8	Since 70% of copper in EU end of life products are recycled,, and given that Europe is a net exporter of scrap copper, it is assumed that the scrap copper is sourced from europe	(euric-aisbl.eu, 2020)
9	These rows adjust the propotion of copper according to each source. 43% recycled, 20% european mines and 25% imported ore or concentrate - accounting for 88% of Europeal supply. The remaining 12% is not modelled as its source cannot be accurately determined. Thus the above propotions are adjusted accordingly: Recycled at 43/88 percent, Eurpean mines at 20/88% and imported iron or concentrate at 25/88%	(Kurlemann, 2022)
10	Based on 30% copper concentrate	

Calculator for: **EV-31** (Calculation Ref) *Blue values need to be entered.*

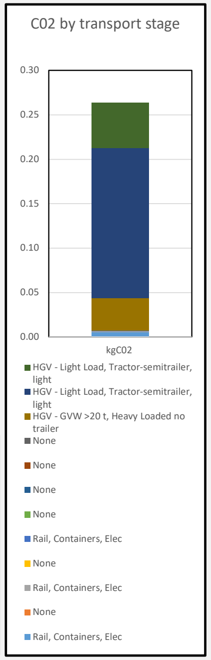
Chassis (w/o battery) (Subsystem)

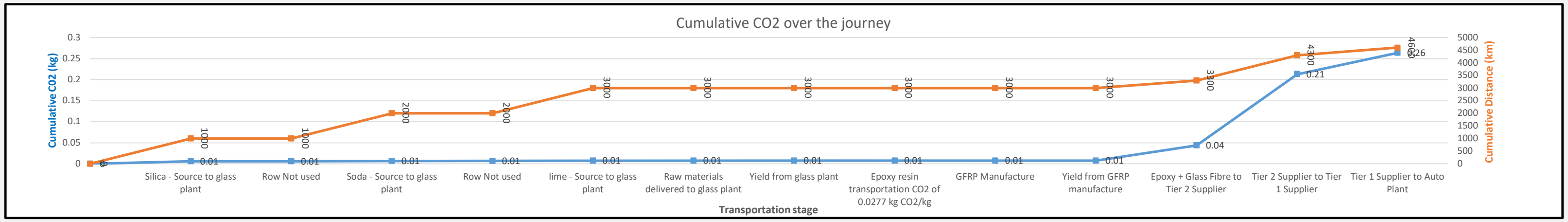
1. Enter Mass of Material: **0.7** kg

GFRP (Material)

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km) 0	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0		
a	2, 3, 4	**Silica - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0004	National - 1000km	1000	1000	0.01	0.01
		Row Not used	None	0		100		None, N/A, or see Alongside	0	1000	0.00	0.01
b	2,3, 5	**Soda - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0001	National - 1000km	1000	2000	0.00	0.01
		Row Not used	None	0		100		None, N/A, or see Alongside	0	2000	0.00	0.01
c	2,3, 6	**lime - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0001	National - 1000km	1000	3000	0.00	0.01
		Raw materials delivered to glass plant	None	0		100	0.0005	None, N/A, or see Alongside	0	3000	0.00	0.01
	1.	**Yield from glass plant**	None	0		72.25	0.0004	None, N/A, or see Alongside	0	3000	0.00	0.01
d		**Epoxy resin transportation CO2 of 0.0277 kg CO2/kg**	None	0			0.0004	None, N/A, or see Alongside	0	3000	0.00	0.01
		GFRP Manufacture	None	0			0.0007	None, N/A, or see Alongside	0	3000	0.00	0.01
d	7	**Yield from GFRP manufacture**	None	0		87.7193	0.0007	None, N/A, or see Alongside	0	3000	0.00	0.01
e		**Epoxy + Glass Fibre to Tier 2 Supplier**	HGV - GVW >20 t, Heavy Load	185.3	Bulk materials	100	0.0007	National / Local - 300km	300	3300	0.04	0.04
f	8	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0007	National - 1000km	1000	4300	0.17	0.21
g	8	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-sem**	**259.5**	**Parts**	**100**	**0.0007**	**National / Local - 300km**	**300**	4600	0.05	0.26





References and Input Assumptions

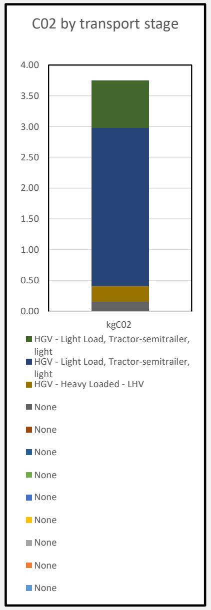
	Input Assumptions	Ref / Citation
1	Glass production at the melting stage has a yield of approx. 85%. A further reduction in yield for flat glass production is found, 85%. Total yield is therefore 85%*85%= 72.25%	Westbroek et el (2021)
2	Glass raw materials are sourced REGIONALLY in Europe.	(Glass for Europe, 2020)
3	glass comprises 75% silica sand, 15% soda ash and 10% lime.	Westbroek et el (2021)
4	Silica sand is typically transported by rail.	(Transportjournal.com, 2016; gbrailfreight.com, 2017)
5	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Cargohandbook.com, no date)
6	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Stork et al., 2014)
7	1.14 kg epoxy & glass fibre needed per 1kg GFRP. 1/1.14*100=87.7193	Keoleian et el (2012)
8	Due to low packing density of GFRP parts, it is assumed that the vehicles are "light" loaded	

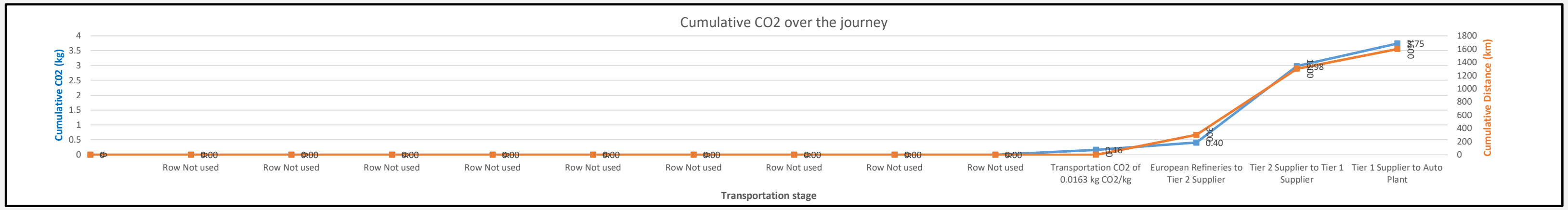
Calculator for: EV-32 (Calculation Ref) *Blue values need to be entered.*
Chassis (w/o battery) (Subsystem)
Average Plastic (Material)

1. Enter Mass of Material: 9.9 kg

ANSWER

Step	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
	Ref - See Below		g/tkm		%	ton		km	0		
	Row Not used	None	0		100	0.0099	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0099	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0099	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0099	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0099	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0099	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0099	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0099	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0099	None, N/A, or see Alongside	0	0	0.00	0.00
1.	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.0099	None, N/A, or see Alongside	0	0	0.16	0.16
a	**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0099	National / Local - 300km	300	300	0.24	0.40
b	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0099	National - 1000km	1000	1300	2.57	2.98
c	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-semi**	**259.5**	**Assemblies**	**100**	**0.0099**	**National / Local - 300km**	**300**	1600	0.77	3.75





References and Input Assumptions

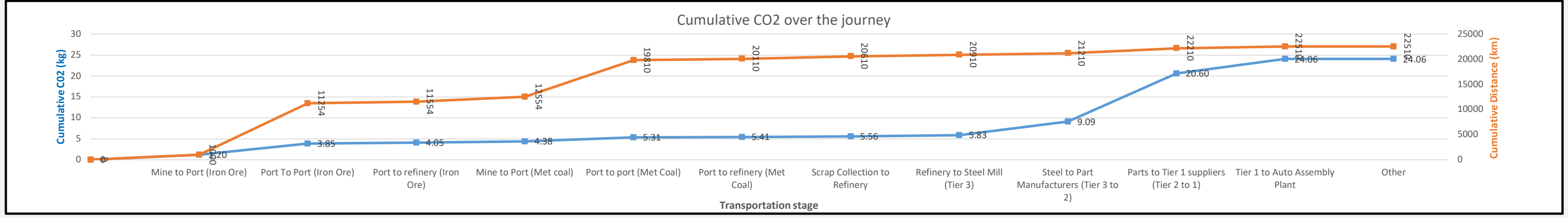
	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

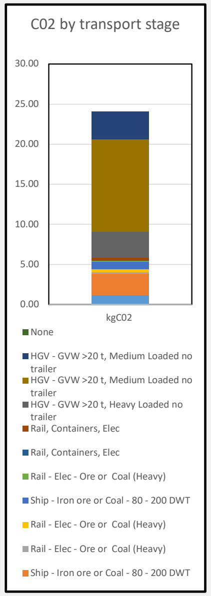
Calculator for: EV-35 (Calculation Ref) *Blue values need to be entered.*
Traction Motor (Subsystem)
Steel (Material)

1. Enter Mass of Material:
58.6 kg

ANSWER

	Step Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist (km)	kgC02	Cum. C02 (kg)
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.0719	National - 1000km	1000	1000	1.20	1.20
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.0719	Intercontinental: Brazil - Rotter	10254	11254	2.65	3.85
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.0719	National / Local - 300km	300	11554	0.20	4.05
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.0359	National - 1000km	1000	12554	0.33	4.38
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.0359	Intercontinental: New york - R	7256	19810	0.94	5.31
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.0359	National / Local - 300km	300	20110	0.10	5.41
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0207	National - 500km	500	20610	0.15	5.56
h.	10, 11	**Refinery to Steel Mill (Tier 3)**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.0611	National / Local - 300km	300	20910	0.27	5.83
i.	10,12	**Steel to Part Manufacturers (Tier 3 to 2)**	HGV - GVW >20 t, Heavy Loade	185.3	bar, lengths or s	95.9	0.0586	National / Local - 300km	300	21210	3.26	9.09
j.	10,13	**Parts to Tier 1 suppliers (Tier 2 to 1)**	HGV - GVW >20 t, Medium Loa	196.6	Parts	100	0.0586	National - 1000km	1000	22210	11.51	20.60
k.	10,11	**Tier 1 to Auto Assembly Plant**	HGV - GVW >20 t, Medium Loa	196.6	Components	100	0.0586	National / Local - 300km	300	22510	3.45	24.06
l.		Other	None	0		100	0.0586	None, N/A, or see Alongside	0	22510	0.00	24.06
m.												
n.												





References and Input Assumptions

<table>
<tr><th></th><th>Input Assumptions</th><th>Ref / Citation</th></tr>
<tr><td>1.</td><td>Inputs for 1 tonne of steel
<table>
<tr><td></td><td colspan="3">Inputs</td><td>Output crude steel</td></tr>
<tr><td></td><td>Iron ore</td><td>metallurgical coal</td><td>recyc steel</td><td></td></tr>
<tr><td>per tonne</td><td>1.18</td><td>0.59</td><td>0.34</td><td>1.00</td></tr>
</table></td><td>(Worldsteel.org, 2019)</td></tr>
<tr><td>2</td><td>Ore from Brazil (51.7 %of German Iron ore is from Brazil) (dist 8000km)</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>3</td><td>Distance from mining region to Ponta de Maderia - Approx 1000km (Capela et el 2019)</td><td>(Cepeda, Barros Kneipp and Caprace, 2019)</td></tr>
<tr><td>3</td><td>Ore from Ponta del Maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to Rotterdam 5537 Nautical miles =10254 km</td><td><i>(Iron ore | Port of Rotterdam, 2022)</i>
(Cepeda, Barros Kneipp and Caprace, 2019)
(Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)</td></tr>
<tr><td>4</td><td>Scrap metal sourced from within Germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>5</td><td>Scrap metal transported dry freight containers</td><td>(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)</td></tr>
<tr><td>6</td><td>Germany's biggest supplier of coal and coke is Russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA</td><td>(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)</td></tr>
<tr><td>7</td><td>Coking Coal provided from western USA deposits</td><td>(Trippi et al., 2021)</td></tr>
<tr><td>8</td><td>69% of coal in the USA is moved by rail, thus rail transportation is assumed</td><td>(<i>Freight Railroads & Coal | Association of American Railroads</i> , 2022)</td></tr>
</table>

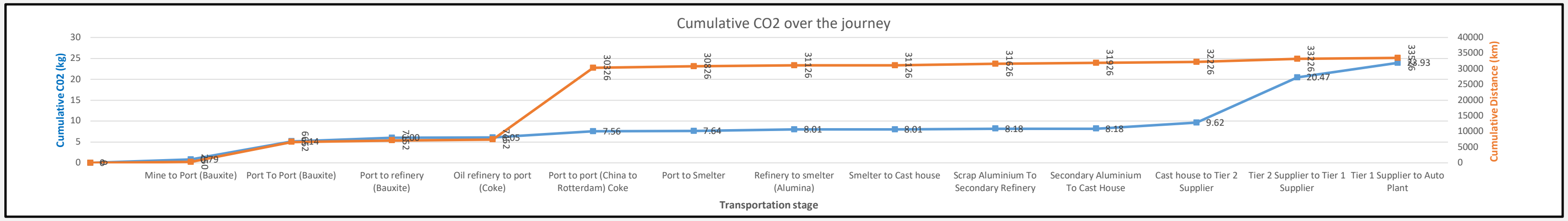
9	Transportation from USA to Europe is New York to Rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Assumptions of Hua et el (2022) assumed to be transferrable to EU context, and also confirmed by Brown et el (2021)**	(Hua et al., 2022) (Brown et al., 2021)
11	Distances based on suppliers from across Europe, including eastern Europe as argued by Brown et.el (2021)	(Brown et al., 2021)
12	Rod and bar steel as used in car parts has a loss factor of 1.043 i.e. 1/1.043 = 95.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)
13	GREET model states a loss factor of 1.00 for machining or stamping operations. Other data to challenge this was not found.	(Argonne GREET Vehicle Cycle Model, 2021)

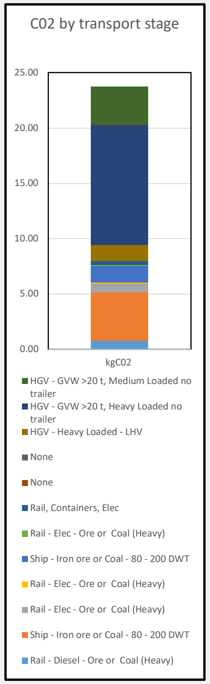
Calculator for: EV-36 (Calculation Ref) *Blue values need to be entered.*
Traction Motor (Subsystem)
Cast
Aluminum (Material)

1. Enter Mass of Material: 58.6 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.1889	None or N/A	250	250	0.79	0.79
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.1889	Intercontinental: Guinea - Rott	6402	6652	4.35	5.14
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.1889	National - 500km	500	7152	0.86	6.00
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0183	National / Local - 300km	300	7452	0.05	6.05
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0183	None, N/A, or see Alongside	22874	30326	1.51	7.56
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0183	National - 500km	500	30826	0.08	7.64
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0828	National / Local - 300km	300	31126	0.36	8.01
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0428	None, N/A, or see Alongside	0	31126	0.00	8.01
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0241	National - 500km	500	31626	0.18	8.18
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0220	National / Local - 300km	300	31926	0.00	8.18
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	90.33	0.0586	National / Local - 300km	300	32226	1.44	9.62
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0586	National - 1000km	1000	33226	10.85	20.47
m.	7	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0586**	**National / Local - 300km**	**300**	33526	3.45	23.93
n.												


Cumulative CO2 over the journey



References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for cast aluminium parts, 1.107 kg aluminium needed to make a 1kg part	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: EV-37 (Calculation Ref) *Blue values need to be entered.*

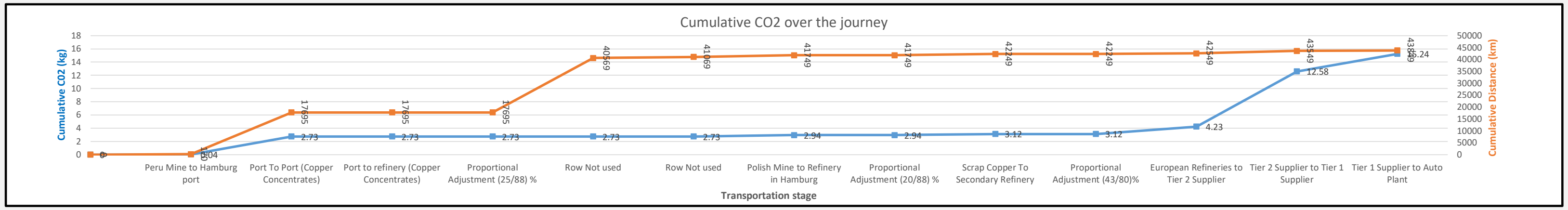
Traction Motor (Subsystem)

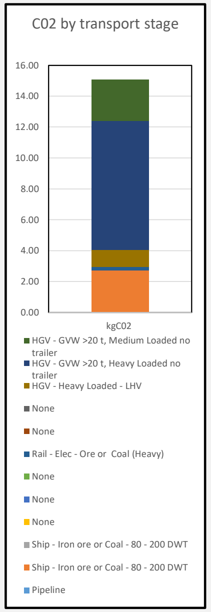
Copper/Brass (Material)

1. Enter Mass of Material (kg): 45.1

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
										0 0		
a.	1,2, 3	**Peru Mine to Hamburg port**	Pipeline	5	Copper Concentrа	100	0.0427	Manual Entered Distance	170	170	0.04	0.04
b.	4	**Port To Port (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentrа	100	0.0427	Intercontinental: Manual Enter	17525	17695	2.69	2.73
c.	5	**Port to refinery (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentrа	100	0.0427	None, N/A, or see Alongside	0	17695	0.00	2.73
d.	9, 10	**Proportional Adjustment (25/88) %**	None	0	Copper Concentrа	30	0.0128	None, N/A, or see Alongside	0	17695	0.00	2.73
e.		*Row Not used*	None	0	Coke	100	0.0044	None, N/A, or see Alongside	22874	40569	0.00	2.73
f.		*Row Not used*	None	0	Coke	100	0.0044	National - 500km	500	41069	0.00	2.73
g.	6	**Polish Mine to Refinery in Hamburg**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	100	0.0342	Manual Entered Distance	680	41749	0.21	2.94
h.	9, 10	**Proportional Adjustment (20/88) %**	None	0		30	0.0103	None, N/A, or see Alongside	0	41749	0.00	2.94
i.	7,8	**Scrap Copper To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Copper	100	0.0242	National - 500km	500	42249	0.18	3.12
j.	9	**Proportional Adjustment (43/80)%**	None	0		100	0.0242	None, N/A, or see Alongside	0	42249	0.00	3.12
k.		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0451	National / Local - 300km	300	42549	1.11	4.23
l.		**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0451	National - 1000km	1000	43549	8.36	12.58
m.		**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0451**	**National / Local - 300km**	**300**	43849	2.66	15.24
n.												





References and Input Assumptions

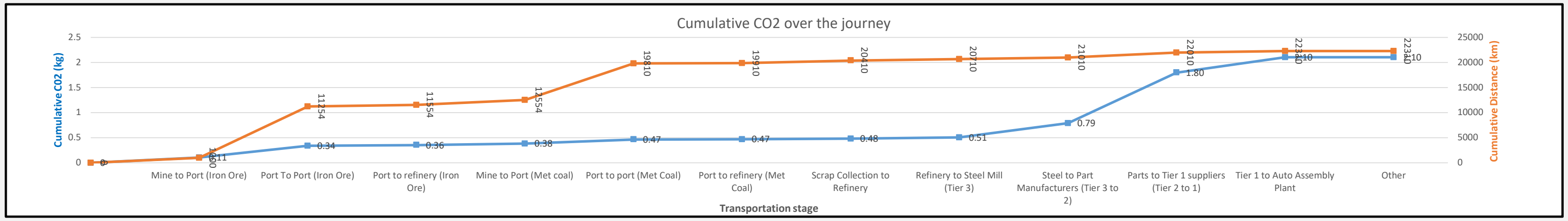
	Input Assumptions	Ref / Citation
1	Aurubis, Europe's largest copper producer is assumed to be the refiner and supplier at one of its facilities in Europe	(Kurlemann, 2022).
2	Chile, Peru and Brazil are the main suppliers of ore / concentrate to Germany. As Chile is the world's biggest supplier of copper this model will assume that it is supplied in Chile. Notwithstanding this, the shipping distance from Peru or Brazil is not dramatically different to Germany.	(Kurlemann, 2022) (International Copper Study Group, 2022)
3	Escodida, the world's largest copper mine is assumed to be the source. Concentrate is pumped 170km by pipeline to the port of Coloso	(www.mining-technology.com, 2020)
4	Copper concentrate is shipped in bulk for large quantities. The distance from Coloso to Hamburg is 9463 nm = 17525km	(Bulkcarrierguide.com, 2010) (ports.com, 2023)
5	Aurubus's Hamburg plant is near the port of Hamburg, and the concentrate is moved from the port to the plant via waterway. Thus for emissions purposes it will be assumed that this is part of the same sea journey. No additional distance therefore added	(Aurubis AG, 2021)
6	Poland is assumed to be the source of the ore, as its Europe's largest producer of ore after Russia. Transportation assumed to be by rail, 680km	(TheGlobalEconomy.com, 2018) (Google Maps, 2023)
7	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
8	Since 70% of copper in EU end of life products are recycled,, and given that Europe is a net exporter of scrap copper, it is assumed that the scrap copper is sourced from Europe	(euric-aisbl.eu, 2020)
9	These rows adjust the proportion of copper according to each source. 43% recycled, 20% European mines and 25% imported ore or concentrate - accounting for 88% of European supply. The remaining 12% is not modelled as its source cannot be accurately determined. Thus the above proportions are adjusted accordingly: Recycled at 43/88 percent, European mines at 20/88% and imported iron or concentrate at 25/88%	(Kurlemann, 2022)
10	Based on 30% copper concentrate	

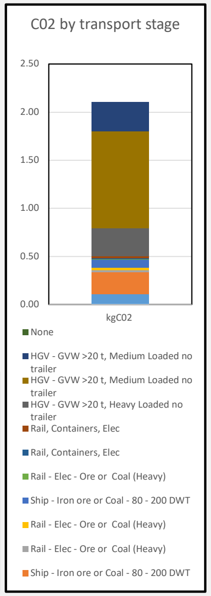
Calculator for: EV-38 (Calculation Ref) *Blue values need to be entered.*
Electronic Controller (Subsystem)
Steel (Material)

1. Enter Mass of Material:
5.1 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist (km)	kgC02	Cum. C02 (kg)
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.0063	National - 1000km	1000	1000	0.11	0.11
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.0063	Intercontinental: Brazil - Rotter	10254	11254	0.23	0.34
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.0063	National / Local - 300km	300	11554	0.02	0.36
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.0032	National - 1000km	1000	12554	0.03	0.38
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.0032	Intercontinental: New york - Ro	7256	19810	0.08	0.47
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.0032	Local 100 km	100	19910	0.00	0.47
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0018	National - 500km	500	20410	0.01	0.48
h.	10, 11	**Refinery to Steel Mill (Tier 3)**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.0054	National / Local - 300km	300	20710	0.02	0.51
i.	10,12	**Steel to Part Manufacturers (Tier 3 to 2)**	HGV - GVW >20 t, Heavy Loade	185.3	bar, lengths or s	95.9	0.0051	National / Local - 300km	300	21010	0.29	0.79
j.	10,13	**Parts to Tier 1 suppliers (Tier 2 to 1)**	HGV - GVW >20 t, Medium Loa	196.6	Parts	100	0.0051	National - 1000km	1000	22010	1.01	1.80
k.	10,11	**Tier 1 to Auto Assembly Plant**	HGV - GVW >20 t, Medium Loa	196.6	Components	100	0.0051	National / Local - 300km	300	22310	0.30	2.10
l.		Other	None	0		100	0.0051	None, N/A, or see Alongside	0	22310	0.00	2.10
m.												
n.												





References and Input Assumptions

	Inputs			Output crude steel
Inputs for 1 tonne of steel	Iron ore	metallurgical coal	recyc steel	
per tonne	**1.18**	**0.59**	**0.34**	**1.00**

	Input Assumptions	Ref / Citation
1.	Inputs for 1 tonne of steel	(Worldsteel.org, 2019)
2	**Ore from Brazil (51.7 %of German Iron ore is from Brazil) (dist 8000km)**	(Elsner et al., 2019)
3	Distance from mining region to Ponta de Maderia - Approx 1000km (Capela et el 2019)	(Cepeda, Barros Kneipp and Caprace, 2019)
3	Ore from Ponta del Maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to Rotterdam 5537 Nautical miles =10254 km	*(Iron ore | Port of Rotterdam, 2022)* (Cepeda, Barros Kneipp and Caprace, 2019) (Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)
4	Scrap metal sourced from within Germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.	(Elsner et al., 2019)
5	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
6	Germany's biggest supplier of coal and coke is Russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA	(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)
7	Coking Coal provided from western USA deposits	(Trippi et al., 2021)
8	69% of coal in the USA is moved by rail, thus rail transportation is assumed	(*Freight Railroads & Coal | Association of American Railroads* , 2022)

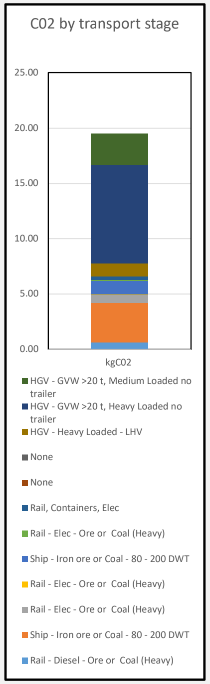
9	Transportation from USA to Europe is New York to Rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Assumptions of Hua et el (2022) assumed to be transferrable to EU context, and also confirmed by Brown et el (2021)**	(Hua et al., 2022) (Brown et al., 2021)
11	Distances based on suppliers from across Europe, including eastern Europe as argued by Brown et.el (2021)	(Brown et al., 2021)
12	Rod and bar steel as used in car parts has a loss factor of 1.043 i.e. 1/1.043 = 95.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)
13	GREET model states a loss factor of 1.00 for machining or stamping operations. Other data to challenge this was not found.	(Argonne GREET Vehicle Cycle Model, 2021)

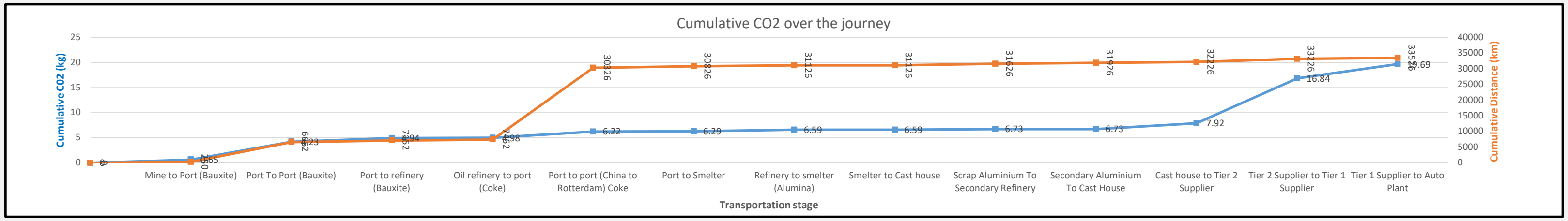
Calculator for: EV-39 (Calculation Ref) *Blue values need to be entered.*
Electronic Controller (Subsystem)
Cast Aluminum (Material)

1. Enter Mass of Material: 48.2 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km) 0 0	kgC02	Cum. C02 (kg)
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.1554	None or N/A	250	250	0.65	0.65
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.1554	Intercontinental: Guinea - Rott	6402	6652	3.58	4.23
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.1554	National - 500km	500	7152	0.71	4.94
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0151	National / Local - 300km	300	7452	0.04	4.98
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0151	None, N/A, or see Alongside	22874	30326	1.24	6.22
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0151	National - 500km	500	30826	0.07	6.29
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0681	National / Local - 300km	300	31126	0.30	6.59
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0352	None, N/A, or see Alongside	0	31126	0.00	6.59
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0198	National - 500km	500	31626	0.14	6.73
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0181	National / Local - 300km	300	31926	0.00	6.73
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	90.33	0.0482	National / Local - 300km	300	32226	1.18	7.92
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0482	National - 1000km	1000	33226	8.93	16.84
m.	**7**	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0482**	**National / Local - 300km**	**300**	33526	2.84	19.69





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted idark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted indark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for cast aluminium parts, 1.107 kg aluminium needed to make a 1kg part	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: **EV-40** (Calculation Ref) *Blue values need to be entered.*

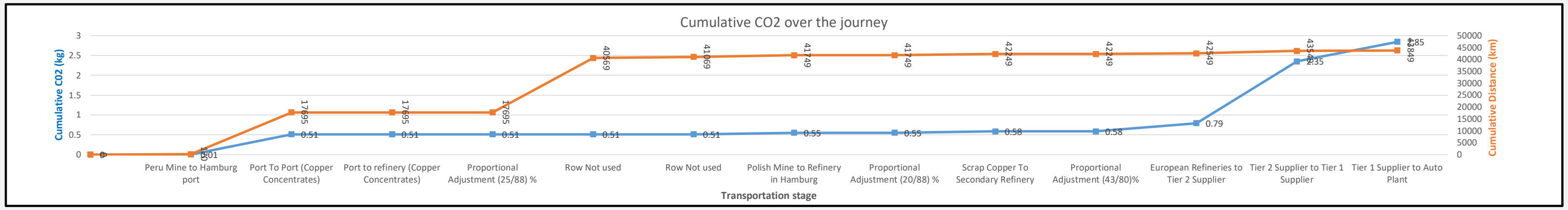
Electronic Controller (Subsystem)

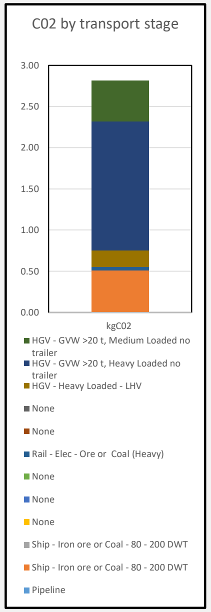
1. Enter Mass of Material (kg): **8.4**

Copper/Brass (Material)

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0		
a.	1,2, 3	**Peru Mine to Hamburg port**	Pipeline	5	Copper Concentra	100	0.0080	Manual Entered Distance	170	170	0.01	0.01
b.	4	**Port To Port (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0080	Intercontinental: Manual Enter	17525	17695	0.50	0.51
c.	5	**Port to refinery (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0080	None, N/A, or see Alongside	0	17695	0.00	0.51
d.	9, 10	**Proportional Adjustment (25/88) %**	None	0	Copper Concentra	30	0.0024	None, N/A, or see Alongside	0	17695	0.00	0.51
e.		***Row Not used***	None	0	Coke	100	0.0008	None, N/A, or see Alongside	22874	40569	0.00	0.51
f.		***Row Not used***	None	0	Coke	100	0.0008	National - 500km	500	41069	0.00	0.51
g.	6	**Polish Mine to Refinery in Hamburg**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	100	0.0064	Manual Entered Distance	680	41749	0.04	0.55
h.	9, 10	**Proportional Adjustment (20/88) %**	None	0		30	0.0019	None, N/A, or see Alongside	0	41749	0.00	0.55
i.	7,8	**Scrap Copper To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Copper	100	0.0045	National - 500km	500	42249	0.03	0.58
j.	9	**Proportional Adjustment (43/80)%**	None	0		100	0.0045	None, N/A, or see Alongside	0	42249	0.00	0.58
k.		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0084	National / Local - 300km	300	42549	0.21	0.79
l.		**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0084	National - 1000km	1000	43549	1.56	2.35
m.		**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0084**	**National / Local - 300km**	**300**	43849	0.50	2.85
n.												





References and Input Assumptions

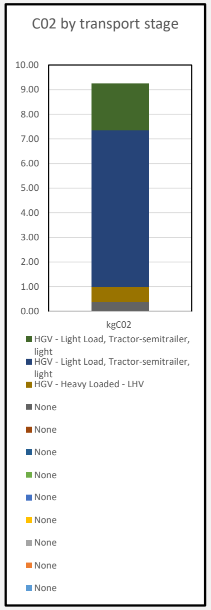
	Input Assumptions	Ref / Citation
1	Aurubis, Europe's largest copper producer is assumed to be the refiner and supplier at one of its facilities in Europe	(Kurlemann, 2022).
2	Chile, Peru and Brazil are the main suppliers of ore / concentrate to Germany. As Chile is the world's biggest supplier of copper this model will assume that it is supplied in Chile. Notwithstanding this, the shipping distance from Peru or Brazil is not dramatically different to Germany.	(Kurlemann, 2022) (International Copper Study Group, 2022)
3	Escodida, the world's largest copper mine is assumed to be the source. Concentrate is pumped 170km by pipeline to the port of Coloso	(www.mining-technology.com, 2020)
4	Copper concentrate is shipped in bulk for large quantities. The distance from Coloso to Hamburg is 9463 nm = 17525km	(Bulkcarrierguide.com, 2010) (ports.com, 2023)
5	Aurubus's Hamburg plant is near the port of Hamburg, and the concentrate is moved from the port to the plant via waterway. Thus for emissions purposes it will be assumed that this is part of the same sea journey. No additional distance therefore added	(Aurubis AG, 2021)
6	Poland is assumed to be the source of the ore, as its Europe's largest producer of ore after Russia. Transportation assumed to be by rail, 680km	(TheGlobalEconomy.com, 2018) (Google Maps, 2023)
7	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
8	Since 70% of copper in EU end of life products are recycled,, and given that Europe is a net exporter of scrap copper, it is assumed that the scrap copper is sourced from Europe	(euric-aisbl.eu, 2020)
9	These rows adjust the proportion of copper according to each source. 43% recycled, 20% European mines and 25% imported ore or concentrate - accounting for 88% of Europeal supply. The remaining 12% is not modelled as its source cannot be accurately determined. Thus the above proportions are adjusted accordingly: Recycled at 43/88 percent, European mines at 20/88% and imported iron or concentrate at 25/88%	(Kurlemann, 2022)
10	Based on 30% copper concentrate	

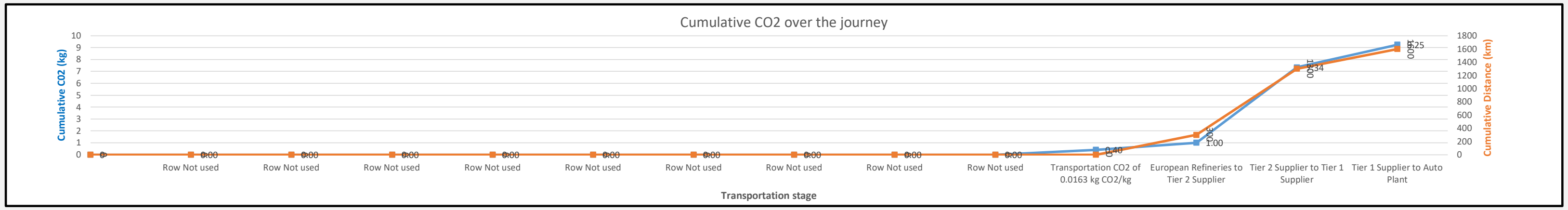
Calculator for: EV-42 (Calculation Ref) *Blue values need to be entered.*
Electronic Controller (Subsystem)
Average
Plastic (Material)

1. Enter Mass of Material: 24.5 kg

ANSWER

		Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km) 0	kgC02	Cum. C02 (kg)
	Step	*Ref - See Below*		g/tkm		%	ton		km	0		
		Row Not used	None	0		100	0.0245	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0245	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0245	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0245	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0245	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0245	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0245	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0245	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0245	None, N/A, or see Alongside	0	0	0.00	0.00
	1.	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.0245	None, N/A, or see Alongside	0	0	0.40	0.40
a		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0245	National / Local - 300km	300	300	0.60	1.00
b	2	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0245	National - 1000km	1000	1300	6.35	7.34
c	**2**	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-semi**	**259.5**	**Assemblies**	**100**	**0.0245**	**National / Local - 300km**	**300**	1600	1.90	9.25





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

Calculator for: EV-B-47 (Calculation Ref)

Battery (Subsystem)

Average Plastic (Material)

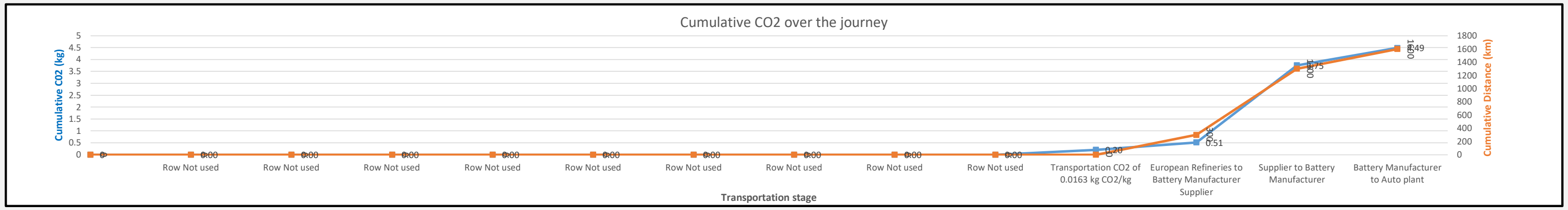
Blue values need to be entered.

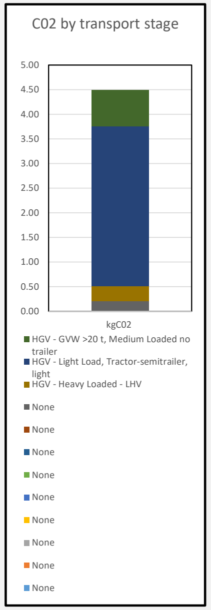
1. Enter Mass of Material:

Note 3 12.5 kg

ANSWER

	Step	Stage: *Ref - See Below*	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km) 0 0	kgC02	Cum. C02 (kg)
		Row Not used	None	0		100	0.0125	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0125	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0125	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0125	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0125	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0125	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0125	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0125	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0125	None, N/A, or see Alongside	0	0	0.00	0.00
	1, 2	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.0125	None, N/A, or see Alongside	0	0	0.20	0.20
a		**European Refineries to Battery Manufactur**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0125	National / Local - 300km	300	300	0.31	0.51
b	4	**Supplier to Battery Manufacturer**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0125	National - 1000km	1000	1300	3.24	3.75
c		**Battery Manufacturer to Auto plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0125**	**National / Local - 300km**	**300**	1600	0.74	4.49





References and Input Assumptions

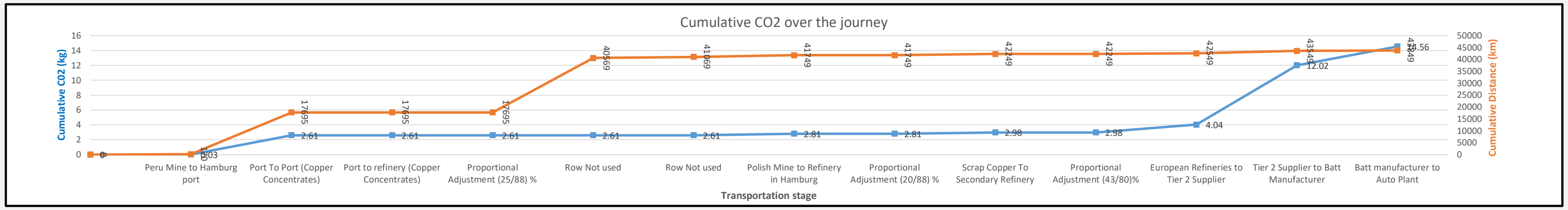
	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	As discussed in methodology, plastics are calculated based on the representative PP figures	
3	This figure is the sum of the weights of the 3 plastics listed in the EV battery	
4	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

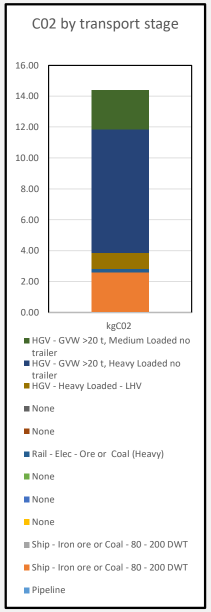
Calculator for: EV-B-50 (Calculation Ref) *Blue values need to be entered.*
Battery (Subsystem)
Copper/Brass (Material)

1. Enter Mass of Material (kg): 43.1

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km) 0 0	kgC02	Cum. C02 (kg)
a.	1,2, 3	**Peru Mine to Hamburg port**	Pipeline	5	Copper Concentrá	100	0.0408	Manual Entered Distance	170	170	0.03	0.03
b.	4	**Port To Port (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentrá	100	0.0408	Intercontinental: Manual Enter	17525	17695	2.57	2.61
c.	5	**Port to refinery (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentrá	100	0.0408	None, N/A, or see Alongside	0	17695	0.00	2.61
d.	9, 10	**Proportional Adjustment (25/88) %**	None	0	Copper Concentrá	30	0.0122	None, N/A, or see Alongside	0	17695	0.00	2.61
e.		*Row Not used*	None	0	Coke	100	0.0042	None, N/A, or see Alongside	22874	40569	0.00	2.61
f.		*Row Not used*	None	0	Coke	100	0.0042	National - 500km	500	41069	0.00	2.61
g.	6	**Polish Mine to Refinery in Hamburg**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	100	0.0326	Manual Entered Distance	680	41749	0.20	2.81
h.	9, 10	**Proportional Adjustment (20/88) %**	None	0		30	0.0098	None, N/A, or see Alongside	0	41749	0.00	2.81
i.	7,8	**Scrap Copper To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Copper	100	0.0232	National - 500km	500	42249	0.17	2.98
j.	9	**Proportional Adjustment (43/80)%**	None	0		100	0.0232	None, N/A, or see Alongside	0	42249	0.00	2.98
k.		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0431	National / Local - 300km	300	42549	1.06	4.04
l.		**Tier 2 Supplier to Batt Manufacturer**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0431	National - 1000km	1000	43549	7.98	12.02
m.		**Batt manufacturer to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0431**	**National / Local - 300km**	**300**	43849	2.54	14.56
n.												





References and Input Assumptions

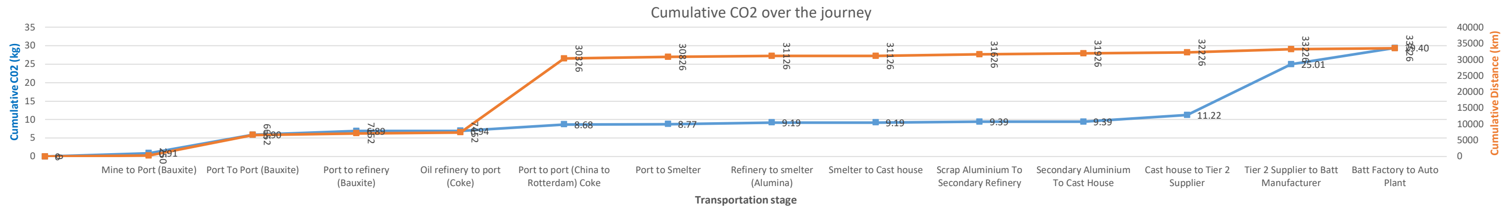
	Input Assumptions	Ref / Citation
1	Aurubis, Europe's largest copper producer is assumed to be the refiner and supplier at one of its facilities in Europe	(Kurlemann, 2022).
2	Chile, Peru and Brazil are the main suppliers of ore / concentrate to Germany. As Chile is the world's biggest supplier of copper this model will assume that it is supplied in Chile. Notwithstanding this, the shipping distance from Peru or Brazil is not dramatically different to Germany.	(Kurlemann, 2022) (International Copper Study Group, 2022)
3	Escodida, the world's largest copper mine is assumed to be the source. Concentrate is pumped 170km by pipeline to the port of Coloso	(www.mining-technology.com, 2020)
4	Copper concentrate is shipped in bulk for large quantities. The distance from Coloso to Hamburg is 9463 nm = 17525km	(Bulkcarrierguide.com, 2010) (ports.com, 2023)
5	Aurubus's Hamburg plant is near the port of Hamburg, and the concentrate is moved from the port to the plant via waterway. Thus for emissions purposes it will be assumed that this is part of the same sea journey. No additional distance therefore added	(Aurubis AG, 2021)
6	Poland is assumed to be the source of the ore, as its Europe's largest producer of ore after Russia. Transportation assumed to be by rail, 680km	(TheGlobalEconomy.com, 2018) (Google Maps, 2023)
7	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
8	Since 70% of copper in EU end of life products are recycled,, and given that Europe is a net exporter of scrap copper, it is assumed that the scrap copper is sourced from Europe	(euric-aisbl.eu, 2020)
9	These rows adjust the proportion of copper according to each source. 43% recycled, 20% European mines and 25% imported ore or concentrate - accounting for 88% of Europeal supply. The remaining 12% is not modelled as its source cannot be accurately determined. Thus the above proportions are adjusted accordingly: Recycled at 43/88 percent, European mines at 20/88% and imported iron or concentrate at 25/88%	(Kurlemann, 2022)
10	Based on 30% copper concentrate	

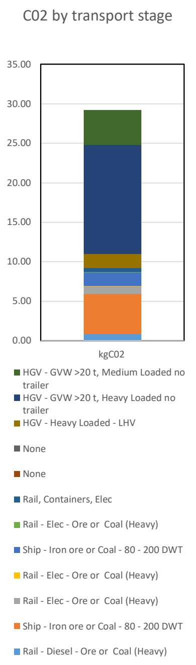
Calculator for: EV-B-51 (Calculation Ref) *Blue values need to be entered.*
Battery (Subsystem)
Wrought Aluminum (Material)

1. Enter Mass of Material: 74.4 kg

ANSWER

Step	*Ref - See Below*	**Stage:**	**2. Select Mode of transport**	**Co2 factor CO2e (wtw) g/tkm**	**3. Form**	**% of prev stage %**	**Mass Transported ton**	**4 Select Distance**	**or Enter Distance** 0 **km** 0	**Cum. Dist. (km)**	**kgC02**	**Cum. C02 (kg)**
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.2168	None or N/A	250	250	0.91	0.91
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 2(	3.6	Bauxite	100	0.2168	Intercontinental: Guinea - Rott	6402	6652	5.00	5.90
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.2168	National - 500km	500	7152	0.99	6.89
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0210	National / Local - 300km	300	7452	0.06	6.94
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 2(	3.6	Coke	100	0.0210	None, N/A, or see Alongside	22874	30326	1.73	8.68
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0210	National - 500km	500	30826	0.10	8.77
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0950	National / Local - 300km	300	31126	0.42	9.19
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0491	None, N/A, or see Alongside	0	31126	0.00	9.19
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0276	National - 500km	500	31626	0.20	9.39
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0253	National / Local - 300km	300	31926	0.00	9.39
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	100	0.0744	National / Local - 300km	300	32226	1.83	11.22
l.	7	**Tier 2 Supplier to Batt Manufacturer**	HGV - GVW >20 t, Heavy Load	185.3	Parts	100	0.0744	National - 1000km	1000	33226	13.79	25.01
m.	**7**	**Batt Factory to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0744**	**National / Local - 300km**	**300**	33526	4.39	29.40
n.												


Cumulative CO2 over the journey


C02 by transport stage

References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

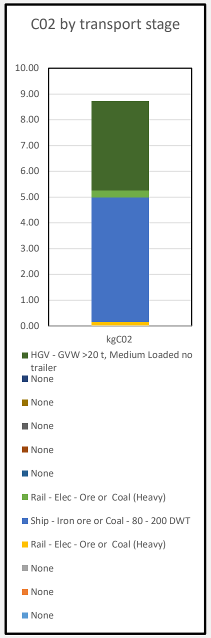
10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for hot rolled parts there is a loss factor of 3.5% whereas for cold rolled there is not. As it is not possible to know the proportion of hot rolled compared to cold rolled parts, and in the light of the relatively modest effect, this is not accounted for.	(Argonne GREET Vehicle Cycle Model, 2021)

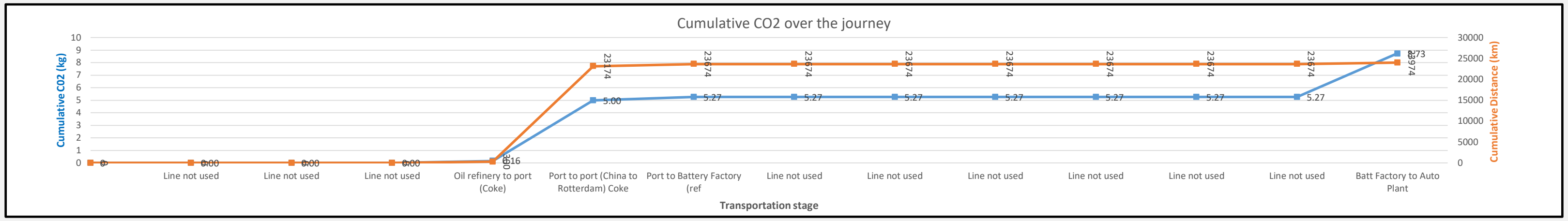
Calculator for: EV-B-52 (Calculation Ref) *Blue values need to be entered.*
Battery (Subsystem)
Graphite / carbon (Material)

1. Enter Mass of Material: 58.7 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
									0 0			
a.		Line not used	None	0	n/a	100	0.0000	None, N/A, or see Alongside	0	0	0.00	0.00
b.		Line not used	None	0	n/a	100	0.0000	None, N/A, or see Alongside	0	0	0.00	0.00
c.		Line not used	None	0	n/a	100		None, N/A, or see Alongside	0	0	0.00	0.00
d.	1, 2	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0587	National / Local - 300km	300	300	0.16	0.16
e.	3,4	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0587	None, N/A, or see Alongside	22874	23174	4.84	5.00
f.	5.	**Port to Battery Factory (ref**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0587	National - 500km	500	23674	0.27	5.27
g.		Line not used	None	0	n/a	100	0.0587	None, N/A, or see Alongside	0	23674	0.00	5.27
h.		Line not used	None	0	n/a	100.00	0.0587	None, N/A, or see Alongside	0	23674	0.00	5.27
i.		Line not used	None	0	n/a	100	0.0587	None, N/A, or see Alongside	0	23674	0.00	5.27
j.		Line not used	None	0	n/a	100.00	0.0587	None, N/A, or see Alongside	0	23674	0.00	5.27
k.		Line not used	None	0	n/a	100	0.0587	None, N/A, or see Alongside	0	23674	0.00	5.27
l.		Line not used	None	0	Parts	100	0.0587	None, N/A, or see Alongside	0	23674	0.00	5.27
m.	6, 7	**Batt Factory to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Batteries**	**100**	**0.0587**	**National / Local - 300km**	**300**	23974	3.46	8.73
n.												





References and Input Assumptions

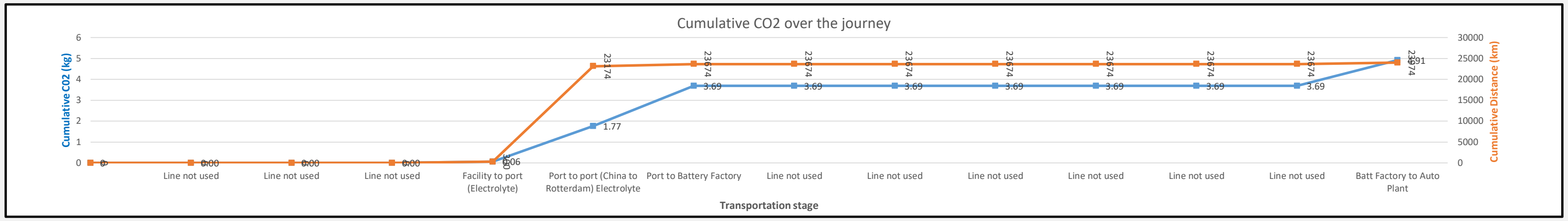
	Input Assumptions	Ref / Citation
1	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)(Bunting et al., 2023)
2	China is assumed to be the source of graphite as discussed on pg. 22 of the IEA's report on Global Supply chains of batteries, echoed by Djukanovic 2018	(Djukanovic, 2018) (International Energy Agency, 2022)(Bunting et al., 2023)
3	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
4	**Anodes are produced at Battery plant - thus coke raw materials assumed to be supplied directly to plant**	International Energy Agency, 2022
5	A European battery plant is assumed as argued in the methodology section	
6	The battery pack is completed either by at the battery plant or at the Auto maker. In either case the cells need to be transported from the battery manufacturer to the Auto plant.	International Energy Agency, 2022
7	EV batteries can be transported by road, rail or a combination. Thus Rushen's modal choice matrix is used as a guide, and which indicated road transportation is most likely, confirmed by trade publication UP.com.	(Automotive Logistics, 2021)(UP.com, 2023)

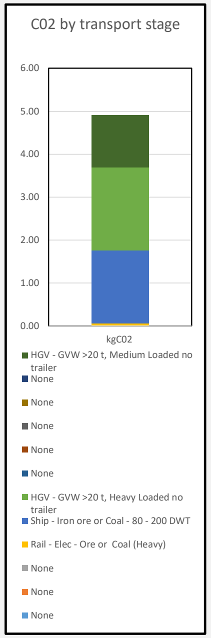
Calculator for: EV-B-53 (Calculation Ref) *Blue values need to be entered.*
Battery (Subsystem)
Electrolyte - EC - (Material)

1. Enter Mass of Material:
20.8 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0 0		
a.		Line not used	None	0	n/a	100	0.0000	None, N/A, or see Alongside	0	0	0.00	0.00
b.		Line not used	None	0	n/a	100	0.0000	None, N/A, or see Alongside	0	0	0.00	0.00
c.		Line not used	None	0	n/a	100		None, N/A, or see Alongside	0	0	0.00	0.00
d.	1	**Facility to port (Electrolyte)**	Rail - Elec - Ore or Coal (Heavy	9.1	Electrolyte	100	0.0208	National / Local - 300km	300	300	0.06	0.06
e.	2,3	**Port to port (China to Rotterdam) Electroly**	Ship - Iron ore or Coal - 80 - 20	3.6	Electrolyte	100	0.0208	None, N/A, or see Alongside	22874	23174	1.71	1.77
f.	4, 5	**Port to Battery Factory**	HGV - GVW >20 t, Heavy Loade	185.3	Electrolyte	100	0.0208	National - 500km	500	23674	1.92	3.69
g.		Line not used	None	0	n/a	100	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
h.		Line not used	None	0	n/a	100.00	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
i.		Line not used	None	0	n/a	100	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
j.		Line not used	None	0	n/a	100.00	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
k.		Line not used	None	0	n/a	100	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
l.		Line not used	None	0	Parts	100	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
m.	6,7	**Batt Factory to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Batteries**	**100**	**0.0208**	**National / Local - 300km**	**300**	23974	1.22	4.91
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	It is assumed that the electrolyte originates in Shandong Province, China, where several electrolyte manufacturers are based or have announced significant capacity expansions, including Shinghwa Advanced Material, Caijin New Materials, Shandong Chengyu, Shida Shenghua. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Shanghai Metals Market News, 2023)(takomabattery.com, 2022)(Google Maps, 2023)
2	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
3	**Electrolyte is part of the battery cell assembly, and would be supplied to the battery manufacturing plant**	International Energy Agency, 2022
4	A European battery plant is assumed as argued in the methodology section	
5	Rushden's modal choice matrix discussed in the Methodology chapter is used to guide this choice of transportation along with trade publications that discuss.	(UP.com, 2023)
6	The battery pack is completed either by at the battery plant or at the Auto maker. In either case the cells need to be transported from the battery manufacturer to the Auto plant.	International Energy Agency, 2022
7	EV batteries can be transported by road, rail or a combination. Thus Rushen's modal choice matrix is used as a guide, and which indicated road transportation is most likely.	(Automotive Logistics, 2021)

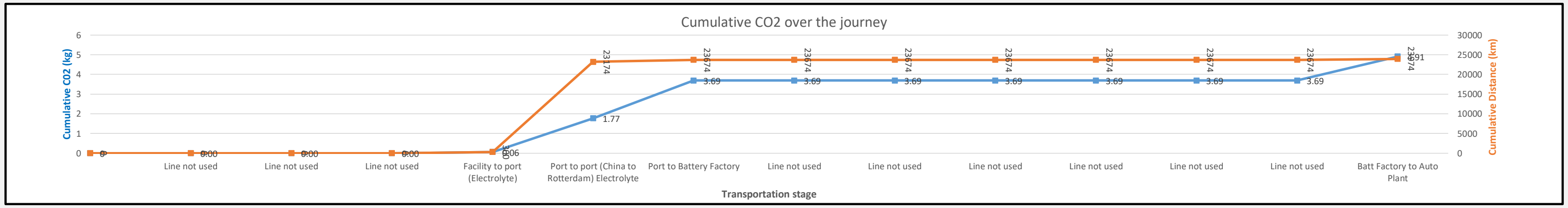
Calculator for: EV-B-54 (Calculation Ref) *Blue values need to be entered.*
Battery (Subsystem)
20.75740864 (Material)

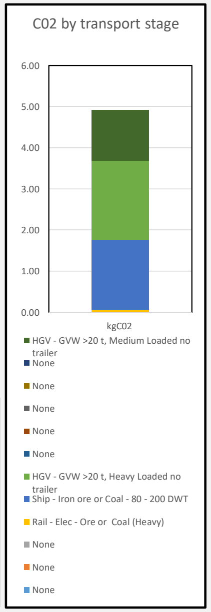
1. Enter Mass of Material:
20.8 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km) 0	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0		
a.		Line not used	None	0	n/a	100	0.0000	None, N/A, or see Alongside	0	0	0.00	0.00
b.		Line not used	None	0	n/a	100	0.0000	None, N/A, or see Alongside	0	0	0.00	0.00
c.		Line not used	None	0	n/a	100		None, N/A, or see Alongside	0	0	0.00	0.00
d.	1	**Facility to port (Electrolyte)**	Rail - Elec - Ore or Coal (Heavy)	9.1	Electrolyte	100	0.0208	National / Local - 300km	300	300	0.06	0.06
e.	2,3	**Port to port (China to Rotterdam) Electrolyt**	Ship - Iron ore or Coal - 80 - 20(	3.6	Electrolyte	100	0.0208	None, N/A, or see Alongside	22874	23174	1.71	1.77
f.	4, 5	**Port to Battery Factory**	HGV - GVW >20 t, Heavy Loade	185.3	Electrolyte	100	0.0208	National - 500km	500	23674	1.92	3.69
g.		Line not used	None	0	n/a	100	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
h.		Line not used	None	0	n/a	100.00	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
i.		Line not used	None	0	n/a	100	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
j.		Line not used	None	0	n/a	100.00	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
k.		Line not used	None	0	n/a	100	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
l.		Line not used	None	0	Parts	100	0.0208	None, N/A, or see Alongside	0	23674	0.00	3.69
m.	6,7	**Batt Factory to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Batteries**	**100**	**0.0208**	**National / Local - 300km**	**300**	23974	1.22	4.91

n.





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	It is assumed that the electrolyte originates in Shandong Province, China, where several electrolyte manufacturers are based or have announced significant capacity expansions, including Shinghwa Advanced Material, Caijin New Materials, Shandong Chengyu, Shida Shenghua. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Shanghai Metals Market News, 2023)(takomabattery.com, 2022)(Google Maps, 2023)
2	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
3	**Electrolyte is part of the battery cell assembly, and would be supplied to the battery manufacturing plant**	International Energy Agency, 2022
4	A European battery plant is assumed as argued in the methodology section	
5	Rushden's modal choice matrix discussed in the Methodology chapter is used to guide this choice of transportation, as well as trade publication: UP.com.	(UP.com, 2023)
6	The battery pack is completed either by at the battery plant or at the Auto maker. In either case the cells need to be transported from the battery manufacturer to the Auto plant.	International Energy Agency, 2022
7	EV batteries can be transported by road, rail or a combination. Thus Rushen's modal choice matrix is used as a guide, and which indicated road transportation is most likely confirmed by UP.com.	(Automotive Logistics, 2021)

Calculator for: EV-B-55 C (Calculation Ref)
Battery (Subsystem)
LiMn204 (Material)

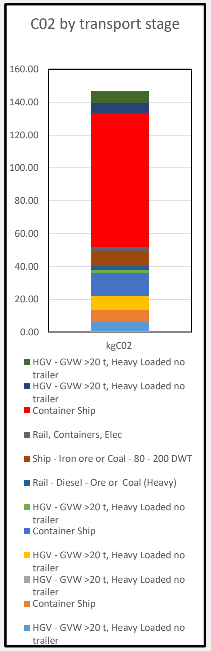
Blue values need to be entered.

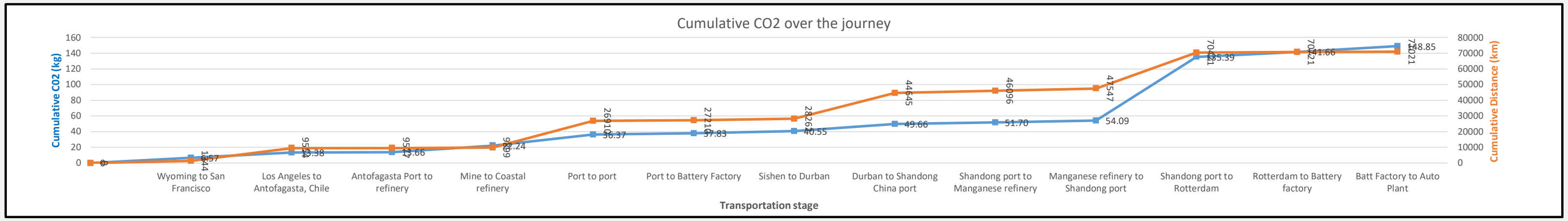
Note: MN_2O_3 - China Sourced

1. Enter Mass of Material: 129.2 kg

ANSWER

	Step	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
	Ref - See Below			g/tkm		%	ton		km	0 0		
a.	1.	**Wyoming to San Francisco**	HGV - GVW >20 t, Heavy Load	185.3	Soda Ash	100	0.0264	None, N/A, or see Alongside	1344	1344	6.57	6.57
b.	2.	**Los Angeles to Antofagasta, Chile**	Container Ship	31.5	Soda Ash	100	0.0264	None, N/A, or see Alongside	8210	9554	6.82	13.38
c.	3.	**Antofagasta Port to refinery**	HGV - GVW >20 t, Heavy Load	185.3	Soda Ash	248	0.0654	None, N/A, or see Alongside	23	9577	0.28	13.66
d.	4	**Mine to Coastal refinery**	HGV - GVW >20 t, Heavy Load	185.3	Brine to refinery	545	0.1437	National / Local - 300km	322	9899	8.57	22.24
e.	5.	**Port to port**	Container Ship	31.5	Li2CO3	100	0.0264	None, N/A, or see Alongside	17011	26910	14.13	36.37
f.	5. 13	**Port to Battery Factory**	HGV - GVW >20 t, Heavy Load	185.3	Li2CO3	100	0.0264	National / Local - 300km	300	27210	1.47	37.83
g.	8,9	**Sishen to Durban**	Rail - Diesel - Ore or Coal (Hea	16.7	Mn Ore	100	0.1546	None, N/A, or see Alongside	1052	28262	2.72	40.55
h.	10	**Durban to Shandong China port**	Ship - Iron ore or Coal - 80 - 20	3.6	Mn Ore	100.00	0.1546	None, N/A, or see Alongside	16383	44645	9.12	49.66
i.	10	**Shandong port to Manganese refinery**	Rail - Elec - Ore or Coal (Heavy	9.1	Mn Ore	100	0.1546	National / Local - 300km	1451	46096	2.04	51.70
j.		**Manganese refinery to Shandong port**	Rail, Containers, Elec	14.6	MN2O3	73.00	0.1128	National / Local - 300km	1451	47547	2.39	54.09
k.	11, 12	**Shandong port to Rotterdam**	Container Ship	31.5	MN2O3	100	0.1128	None, N/A, or see Alongside	22874	70421	81.30	135.39
l.		**Rotterdam to Battery factory**	HGV - GVW >20 t, Heavy Load	185.3	MN2O3	100	0.1128	National / Local - 300km	300	70721	6.27	141.66
m.	**6, 7,12, 13**	**Batt Factory to Auto Plant**	**HGV - GVW >20 t, Heavy Load**	**185.3**	**Batteries**	**100**	**0.1292**	**National / Local - 300km**	**300**	71021	7.18	148.85
n.												


C02 by transport stage


Cumulative CO2 over the journey

References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Soda Ash originates in Wyoming, USA & transported to Los Angeles Port. GREET states that road transport for soda ash is 850 miles (including transport from Antofagasta port to refiner which is 15 miles (see ref 3 below). Thus USA distance is 835 miles = 1344 km	Dunn et al, 2014
2	Nautical distance as per GREET, 4433 nautical miles = 8210km	Dunn et al, 2014
3	23km from Antofagasta port to refinery Albemarle, Antofagasta, Chile. The Greet report states that 2.48 ton soda ash is needed per ton LiCO3 produced at the refinery	maps.google.com, 2023, Dunn et el 2014
4	200 miles from mine to refinery, by road = 322km. 5.45 tons of concentrated brine are needed per ton of LiCO3 produced at the refinery	Dunn et al, 2014
5	A European battery plant is assumed as argued in the methodology section which would likely move through Rotterdam. Which is 9185 nautical miles = 17011 km	ports.com 2023
6	The battery pack is completed either by at the battery plant or at the Auto maker. In either case the cells need to be transported from the battery manufacturer to the Auto plant.	International Energy Agency, 2022
7	EV batteries can be transported by road, rail or a combination. Thus Rushen's modal choice matrix is used as a guide, and which indicated road transportation is most likely, confirmed by trade publication UP.com.	(Automotive Logistics, 2021)(UP.com, 2023)
8	South Africa, the worlds largest exporter of manganese ore is assumed to be the source	(Bunting et al., 2023)
9	Manganese is mined in the Kalahari desert in she Sishen area, with rail links to Saldanha, Port Elizabeth and Durban ports. Assuming the export is to China, Durban being on South Africa's eastern coast is the most likely port, a distance of 1052km.	(Jupitermines.com, 2023)(maps.google.com 2023)

10	The worlds largest supplier of Manganese, Ningxia Tianyuan Manganese Industry, which has a global market share of approx. 40% is assumed to be the supplier and refiner. Qingdao, Shandong port is assumed to be the port used, as it is one of the closer major ports to Ningxia. Durban to Qingdao is 8846 nm = 16383km Qingdao to Ninxia is 1451km	ports.com 2023, Ningxia Tianyuan Manganese Industry Group, 2023, Bunting et al 2023
11	A European battery plant is assumed as argued in the methodology section which would likely move through Rotterdam	
12	A European Manganese refinery is assumed as argued in the methodology section which would likely move through Rotterdam. Qingdao to Rotterdam is 22874km	ports.com
13	The Greet data indicate that 1 tonne of LiMn2O4 requires 0.873 tonnes of Mn2O3 and 0.204 tonnes of Li2CO3. The yield from 1 tonne Manganese ore is 0.73 tonnes Mn2O3	

Calculator for: EV-B-55 E (Calculation Ref) *Blue values need to be entered.*
Battery (Subsystem)

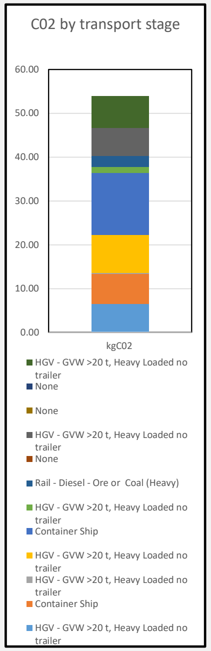
1. Enter Mass of Material:
129.2 kg

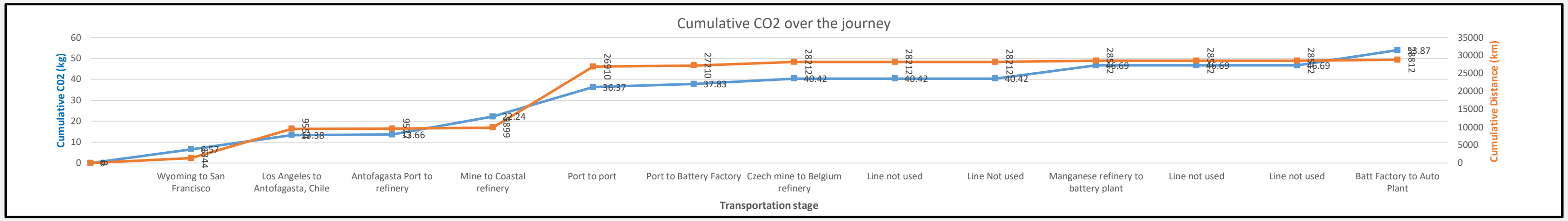
LiMn204 (Material)

Note: MN_2O_3 - Europe Sourced

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0 0		
a.	1.	**Wyoming to San Francisco**	HGV - GVW >20 t, Heavy Loade	185.3	Soda Ash	100	0.0264	None, N/A, or see Alongside	1344	1344	6.57	6.57
b.	2.	**Los Angeles to Antofagasta, Chile**	Container Ship	31.5	Soda Ash	100	0.0264	None, N/A, or see Alongside	8210	9554	6.82	13.38
c.	3.	**Antofagasta Port to refinery**	HGV - GVW >20 t, Heavy Loade	185.3	Soda Ash	248	0.0654	None, N/A, or see Alongside	23	9577	0.28	13.66
d.	4	**Mine to Coastal refinery**	HGV - GVW >20 t, Heavy Loade	185.3	Brine to refinery	545	0.1437	National / Local - 300km	322	9899	8.57	22.24
e.	5.	**Port to port**	Container Ship	31.5	Li2CO3	100	0.0264	None, N/A, or see Alongside	17011	26910	14.13	36.37
f.	5. 13	**Port to Battery Factory**	HGV - GVW >20 t, Heavy Loade	185.3	Li2CO3	100	0.0264	National / Local - 300km	300	27210	1.47	37.83
g.	8,9	**Czech mine to Belgium refinery**	Rail - Diesel - Ore or Coal (Hea	16.7	Mn Ore	100	0.1546	None, N/A, or see Alongside	1002	28212	2.59	40.42
h.	10	Line not used	None	0		100.00	0.1546	None, N/A, or see Alongside	0	28212	0.00	40.42
i.		Line Not used	None	0		100	0.1546	None, N/A, or see Alongside	0	28212	0.00	40.42
j.	11, 13	**Manganese refinery to battery plant**	HGV - GVW >20 t, Heavy Loade	185.3	MN2O3	73.00	0.1128	National / Local - 300km	300	28512	6.27	46.69
k.		Line not used	None	0	n/a	100	0.1292	None, N/A, or see Alongside	0	28512	0.00	46.69
l.		Line not used	None	0	Parts	100	0.1292	None, N/A, or see Alongside	0	28512	0.00	46.69
m.	**6, 7,12, 13**	**Batt Factory to Auto Plant**	**HGV - GVW >20 t, Heavy Load**	**185.3**	**Batteries**	**100**	**0.1292**	**National / Local - 300km**	**300**	28812	7.18	53.87
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Soda Ash originates in Wyoming, USA & transported to Los Angeles Port. GREET states that road transport for soda ash is 850 miles (including transport from Antofagasta port to refiner which is 15 miles (see ref 3 below). Thus USA distance is 835 miles = 1344 km	Dunn et al, 2014
2	Nautical distance as per GREET, 4433 nautical miles = 8210km	Dunn et al, 2014
3	23km from Anotfagasta port to refinery Albemarle, Antofagasta, Chile. The Greet report states that 2.48 ton soda ash is needed per ton LiCO3 produced at the refinery	maps.google.com, 2023, Dunn et el 2014
4	200 miles from mine to refinery, by road = 322km. 5.45 tons of concentrated brine are needed per ton of LiCO3 produced at the refinery	Dunn et el, 2014
5	A european battery plant is assumed as argued in the methodology section which would likely move through rotterdam. Which is 9185 nautical miles = 17011 km	ports.com 2023
6	The battery pack is completed either by at the battery plant or at the Auto maker. In either case the cells need to be transported from the battery manufacturer to the Auto plant.	International Energy Agency, 2022
7	EV batteries can be trasported by road, rail or a combination. Thus Rushen's modal choice matrix is used as a guide, and which indicated road transporation is most likely, confirmed by trade publication UP.com.	(Automotive Logistics, 2021)(UP.com, 2023)
8	South Africa, the worlds largest exporter of manganese ore is assumed to be the source	(Bunting et al., 2023)
9	The Chvaletice manganese project near prague is assumed to be the source of manganese. Distance from Chvaletice to Belgium is 1002km	(Euro Manganese Inc, 2023)(maps.google.com 2023)

10	Line not used	
11	A european battery plant is assumed as argued in the methodology section which would likely move through Rotterdam	
12	A european Manganese refinery is assumed as argued in the methodology section which would likely move through Rotterdam	
13	The Greet data indicate that 1 tonne of LiMn2O4 requires 0.873 tonnes of Mn2O3 and 0.204 tonnes of Li2CO3. The yield from 1 tonne Manganese ore is 0.73 tonnes Mn2O3	

Calculator for: **EV-B-63** (Calculation Ref) *Blue vlaues need to be entered.*

1. Enter Mass of Material: **Powertrain System (Including BOP)** (Subsystem)

5.5 kg **Steel** (Material)

ANSWER

		Stage:	**2. Select Mode of transport**	**Co2 factor CO2e (wtw)**	**3. Form**	**% of prev stage**	**Mass Transported**	**4 Select Distance**	**or Enter Distance**	**Cum. Dist (km)** 0	**kgC02**	**Cum. C02 (kg)**
Step	***Ref - See Below***			**g/tkm**		**%**	**ton**		**km**	0		
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.0067	National - 1000km	1000	1000	0.11	0.11
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.0067	Intercontinental: Brazil - Rotter	10254	11254	0.25	0.36
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.0067	National / Local - 300km	300	11554	0.02	0.38
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.0034	National - 1000km	1000	12554	0.03	0.41
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.0034	Intercontinental: New york - R	7256	19810	0.09	0.50
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.0034	National / Local - 300km	300	20110	0.01	0.51
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0019	National - 500km	500	20610	0.01	0.52
h.	10, 11	**Refinery to Steel Mill (Tier 3)**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.0057	National / Local - 300km	300	20910	0.03	0.55
i.	10,12	**Steel to Part Manufacturers (Tier 3 to 2)**	HGV - GVW >20 t, Heavy Load	185.3	bar, lengths or s	95.9	0.0055	National / Local - 300km	300	21210	0.30	0.85
j.	10,13	**Parts to Tier 1 suppliers (Tier 2 to 1)**	HGV - GVW >20 t, Medium Loa	196.6	Parts	100	0.0055	National - 1000km	1000	22210	1.08	1.93
k.	10,11	**Tier 1 to Auto Assembly Plant**	HGV - GVW >20 t, Medium Loa	196.6	Components	100	0.0055	National / Local - 300km	300	22510	0.32	2.25
I.		**Batery Plant to Auto Assy plant**	HGV - GVW >20 t, Medium Loa	196.6	Batteries	100	0.0055	National / Local - 300km	300	22810	0.32	2.58

m.

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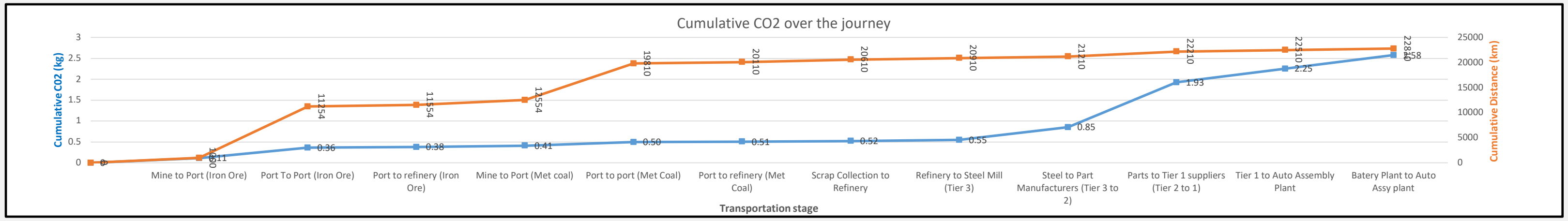

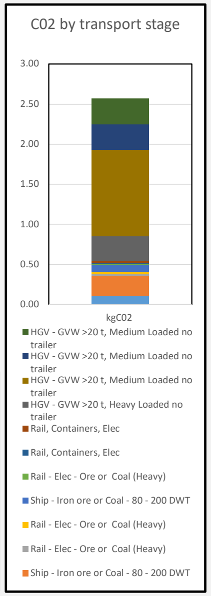

Refernces and Input Assumptions

<table>
<tr><th></th><th>Input Assumptions</th><th>Ref / Citation</th></tr>
<tr><td>1.</td><td>Inputs for 1 tonne of steel
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<tr><td></td><td colspan="3">Inputs</td><td>Output crude steel</td></tr>
<tr><td></td><td>Iron ore</td><td>mettalurigal coal coal</td><td>recyc steel</td><td></td></tr>
<tr><td>per tonne</td><td>1.18</td><td>0.59</td><td>0.34</td><td>1.00</td></tr>
</table></td><td>(Worldsteel.org, 2019)</td></tr>
<tr><td>2</td><td>Ore from Brazil (51.7 %of German Iron ore is from brazil) (dist 8000km)</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>3</td><td>Distance from mining region to ponta de maderia - Approx 1000km (Capela et el 2019)</td><td>(Cepeda, Barros Kneipp and Caprace, 2019)</td></tr>
<tr><td>3</td><td>Ore from Ponta del maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to rotterdam   5537 Nautical miles   =10254 km</td><td>(Iron ore | Port of Rotterdam, 2022)
(Cepeda, Barros Kneipp and Caprace, 2019)
(Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)</td></tr>
<tr><td>4</td><td>Scrap metal sourced from within germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km).   Thus a typical average distance of 500 km is assumed.</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>5</td><td>Scrap metal transported dry freight containers</td><td>(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)</td></tr>
<tr><td>6</td><td>Germany's biggest supplier of coal and coke is Russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA</td><td>(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)</td></tr>
<tr><td>7</td><td>Coking Coal provided from western USA deposits</td><td>(Trippi et al., 2021)</td></tr>
<tr><td>8</td><td>69% of coal in the usa is moved by rail, thus rail transporation is assumed</td><td>(<i>Freight Railroads & Coal | Association of American Railroads</i> , 2022)</td></tr>
</table>

9	Transporation from usa to europe is New yourk to rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Assumptions of Hua et el (2022) assumed to be transferrable to EU context, and also confirmed by Brown et el (2021)**	(Hua et al., 2022) (Brown et al., 2021)
11	Distances based on suppliers from across europe, including eastern europe as argued by Brown et.el (2021)	(Brown et al., 2021)
12	Rod and bar steel as used incar parts has a loss factor of 1.043 i.e. 1/1.043 = 95.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)
13	GREET model states a loss factor of 1.00 for machining or stamping operations. Other data to challenge this was not found.	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: ICE-01 (Calculation Ref) *Blue values need to be entered.*
Body (Subsystem)
Steel (Material)

1. Enter Mass of Material: 498.9 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.7276	National - 1000km	1000	1000	12.15	12.15
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.7276	Intercontinental: Brazil - Rotter	10254	11254	26.86	39.01
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.7276	National / Local - 300km	300	11554	1.99	41.00
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.3638	National - 1000km	1000	12554	3.31	44.31
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.3638	Intercontinental: New York - R	7256	19810	9.50	53.81
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	.59t per ton	0.3638	National / Local - 300km	300	20110	0.99	54.80
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.2092	National - 500km	500	20610	1.53	56.33
h.	10, 13	**Refinery to Steel Mill**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.6185	National / Local - 300km	300	20910	2.71	59.04
i.	12, 13	**Steel Mill to Press shop**	HGV - Heavy Loaded - LHV	81.8	Sheet metal roll	94.9	0.5869	National / Local - 300km	300	21210	14.40	73.44
j.	10, 11	**press shop to auto factory**	HGV - Light Load, Tractor-semi	259.5	Pressed Panel	85	0.4989	Local 100 km	100	21310	12.95	86.39
k.		**Other**	None	0		100	0.4989	None, N/A, or see Alongside	0	21310	0.00	86.39
l.		Other	None	0		100	0.4989	None, N/A, or see Alongside	0	21310	0.00	86.39

m.
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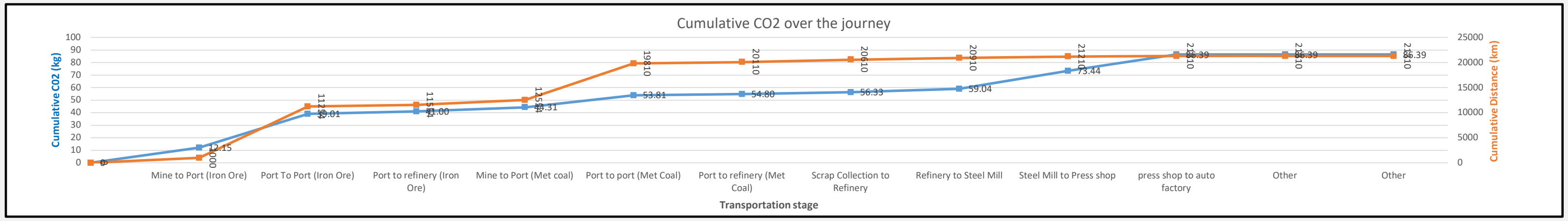

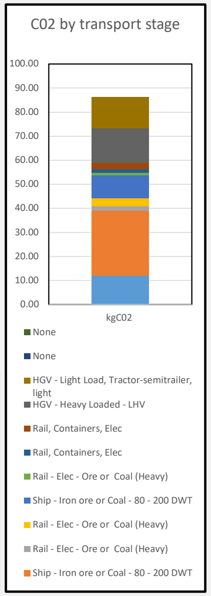

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<tr><td>5</td><td>Scrap metal transported dry freight containers</td><td>(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)</td></tr>
<tr><td>6</td><td>Germany's biggest supplier of coal and coke is Russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA</td><td>(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)</td></tr>
<tr><td>7</td><td>Coking Coal provided from western USA deposits</td><td>(Trippi et al., 2021)</td></tr>
<tr><td>8</td><td>69% of coal in the USA is moved by rail, thus rail transportation is assumed</td><td>(*Freight Railroads & Coal | Association of American Railroads* , 2022)</td></tr>
</table>

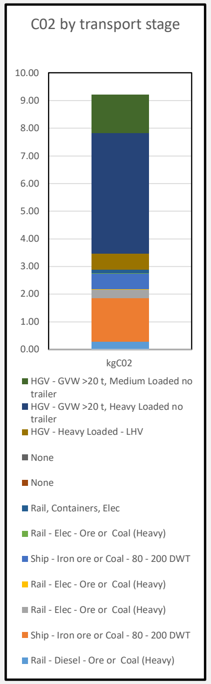
9	Transportation from USA to Europe is New York to Rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Journey of body panels as per Gaither & frazer and Hua et el**	(Gaither, N. and Frazier, 2002) (Hua et al., 2022)
11	15% offcut scrap average in press shop.. Press shops tend to be close to or within the Automotive factory as pressed parts are expensive to transport by weight and very prone to damage, requiring substantial packaging	(Lore and Czechmeister, 2013) (Dallan, 2016)
12	Typically 80 percent of European steel is sourced from Europe. Thus local distances of up to 300 km are assumed. Steel rolls are extremely heavy and typically transported on a long heavy vehicle.	(*European Steel in Figures 2020* , 2020) (DBcargo.com, 2023)
13	Cold rolled steel as used in body panels has a loss factor of 1.054 i.e. 1/1.0154 = 94.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)

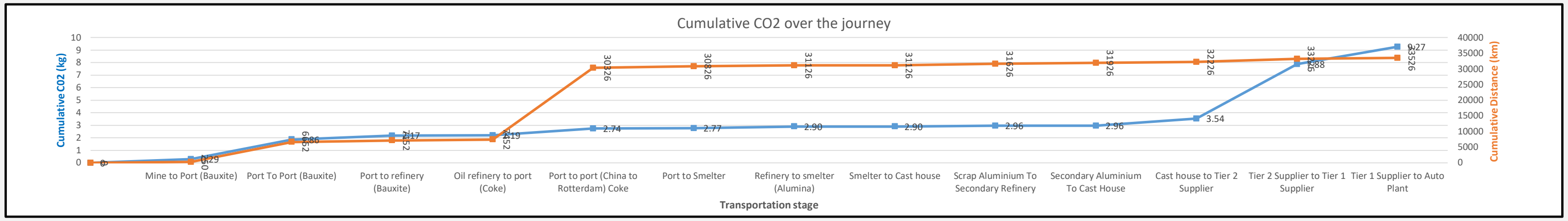
Calculator for: ICE-02 (Calculation Ref) *Blue values need to be entered.*
Body (Subsystem)
Wrought Aluminum (Material)

1. Enter Mass of Material:
23.5 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km) 0	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0		
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.0683	None or N/A	250	250	0.29	0.29
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 2(	3.6	Bauxite	100	0.0683	Intercontinental: Guinea - Rott	6402	6652	1.58	1.86
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.0683	National - 500km	500	7152	0.31	2.17
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0066	National / Local - 300km	300	7452	0.02	2.19
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 2(	3.6	Coke	100	0.0066	None, N/A, or see Alongside	22874	30326	0.55	2.74
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0066	National - 500km	500	30826	0.03	2.77
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0300	National / Local - 300km	300	31126	0.13	2.90
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0155	None, N/A, or see Alongside	0	31126	0.00	2.90
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0087	National - 500km	500	31626	0.06	2.96
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0080	National / Local - 300km	300	31926	0.00	2.96
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	100	0.0235	National / Local - 300km	300	32226	0.58	3.54
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loadı	185.3	Parts	100	0.0235	National - 1000km	1000	33226	4.35	7.88
m.	**7**	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0235**	**National / Local - 300km**	**300**	33526	1.38	9.27
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for hot rolled parts there is a loss factor of 3.5% whereas for cold rolled there is not. As it is not possible to know the proportion of hot rolled compared to cold rolled parts, and in the light of the relatively modest effect, this is not accounted for.	(Argonne GREET Vehicle Cycle Model, 2021)

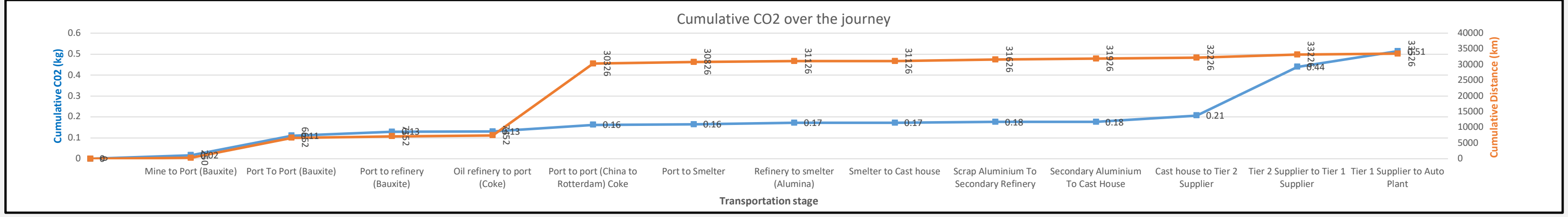
Calculator for: **ICE-03** (Calculation Ref) **Body** (Subsystem) **Cast Aluminum** (Material)

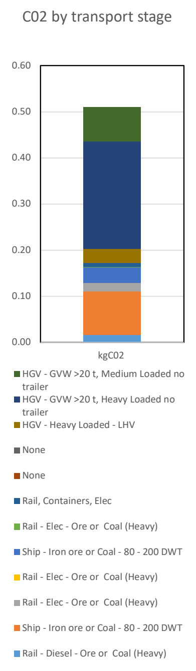
Blue values need to be entered.

1. Enter Mass of Material: **1.3** kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0 0		
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.0041	None or N/A	250	250	0.02	0.02
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.0041	Intercontinental: Guinea - Rott	6402	6652	0.09	0.11
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.0041	National - 500km	500	7152	0.02	0.13
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0004	National / Local - 300km	300	7452	0.00	0.13
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0004	None, N/A, or see Alongside	22874	30326	0.03	0.16
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0004	National - 500km	500	30826	0.00	0.16
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0018	National / Local - 300km	300	31126	0.01	0.17
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0009	None, N/A, or see Alongside	0	31126	0.00	0.17
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0005	National - 500km	500	31626	0.00	0.18
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0005	National / Local - 300km	300	31926	0.00	0.18
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	90.33	0.0013	National / Local - 300km	300	32226	0.03	0.21
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0013	National - 1000km	1000	33226	0.23	0.44
m.	**7**	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0013**	**National / Local - 300km**	**300**	33526	0.07	0.51
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for cast aluminium parts, 1.107 kg aluminium needed to make a 1kg part	(Argonne GREET Vehicle Cycle Model, 2021)

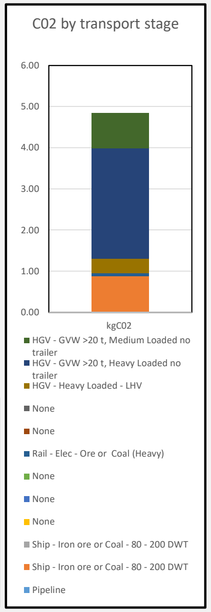
Calculator for: ICE-04 (Calculation Ref) *Blue values need to be entered.*
Body (Subsystem)

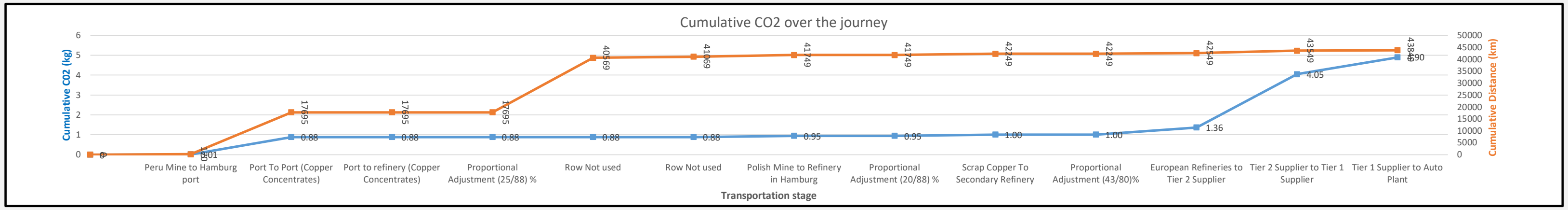
Copper/Brass (Material)

1. Enter Mass of Material (kg):
14.51

ANSWER

	Step	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
	Ref - See Below			g/tkm		%	ton		km	0 0		
a.	1,2, 3	**Peru Mine to Hamburg port**	Pipeline	5	Copper Concentra	100	0.0137	Manual Entered Distance	170	170	0.01	0.01
b.	4	**Port To Port (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0137	Intercontinental: Manual Enter	17525	17695	0.87	0.88
c.	5	**Port to refinery (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0137	None, N/A, or see Alongside	0	17695	0.00	0.88
d.	9, 10	**Proportional Adjustment (25/88) %**	None	0	Copper Concentra	30	0.0041	None, N/A, or see Alongside	0	17695	0.00	0.88
e.		***Row Not used***	None	0	Coke	100	0.0014	None, N/A, or see Alongside	22874	40569	0.00	0.88
f.		***Row Not used***	None	0	Coke	100	0.0014	National - 500km	500	41069	0.00	0.88
g.	6	**Polish Mine to Refinery in Hamburg**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	100	0.0110	Manual Entered Distance	680	41749	0.07	0.95
h.	9, 10	**Proportional Adjustment (20/88) %**	None	0		30	0.0033	None, N/A, or see Alongside	0	41749	0.00	0.95
i.	7,8	**Scrap Copper To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Copper	100	0.0078	National - 500km	500	42249	0.06	1.00
j.	9	**Proportional Adjustment (43/80)%**	None	0		100	0.0078	None, N/A, or see Alongside	0	42249	0.00	1.00
k.		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0145	National / Local - 300km	300	42549	0.36	1.36
l.		**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0145	National - 1000km	1000	43549	2.69	4.05
m.		**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0145**	**National / Local - 300km**	**300**	43849	0.86	4.90
n.												


C02 by transport stage


Cumulative CO2 over the journey

References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Aurubis, Europe's largest copper producer is assumed to be the refiner and supplier at one of its facilities in Europe	(Kurlemann, 2022).
2	Chile, Peru and Brazil are the main suppliers of ore / concentrate to Germany. As Chile is the world's biggest supplier of copper this model will assume that it is supplied in Chile. Notwithstanding this, the shipping distance from Peru or Brazil is not dramatically different to Germany.	(Kurlemann, 2022) (International Copper Study Group, 2022)
3	Escodida, the world's largest copper mine is assumed to be the source. Concentrate is pumped 170km by pipeline to the port of Coloso	(www.mining-technology.com, 2020)
4	Copper concentrate is shipped in bulk for large quantities. The distance from Coloso to Hamburg is 9463 nm = 17525km	(Bulkcarrierguide.com, 2010) (ports.com, 2023)
5	Aurubus's Hamburg plant is near the port of Hamburg, and the concentrate is moved from the port to the plant via waterway. Thus for emissions purposes it will be assumed that this is part of the same sea journey. No additional distance therefore added	(Aurubis AG, 2021)
6	Poland is assumed to be the source of the ore, as its Europe's largest producer of ore after Russia. Transportation assumed to be by rail, 680km	(TheGlobalEconomy.com, 2018) (Google Maps, 2023)
7	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
8	Since 70% of copper in EU end of life products are recycled,, and given that Europe is a net exporter of scrap copper, it is assumed that the scrap copper is sourced from Europe	(euric-aisbl.eu, 2020)
9	These rows adjust the proportion of copper according to each source. 43% recycled, 20% European mines and 25% imported ore or concentrate - accounting for 88% of European supply. The remaining 12% is not modelled as its source cannot be accurately determined. Thus the above proportions are adjusted accordingly: Recycled at 43/88 percent, European mines at 20/88% and imported iron or concentrate at 25/88%	(Kurlemann, 2022)
10	Based on 30% copper concentrate	

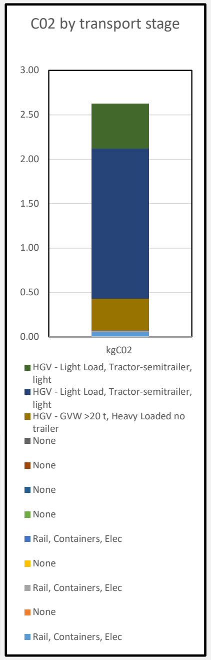
Calculator for: ICE-05 (Calculation Ref)
Body (Subsystem)
GFRP (Material)

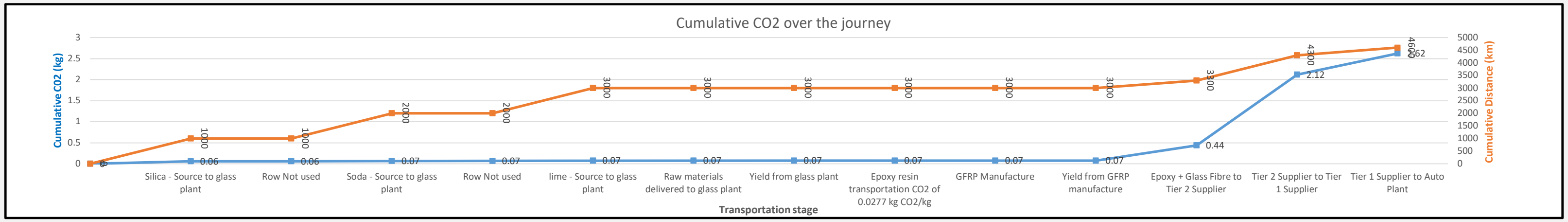
Blue values need to be entered.

1. Enter Mass of Material: 6.5 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
									0			
									0			
a	2, 3, 4	**Silica - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0038	National - 1000km	1000	1000	0.06	0.06
		Row Not used	None	0		100		None, N/A, or see Alongside	0	1000	0.00	0.06
b	2,3, 5	**Soda - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0008	National - 1000km	1000	2000	0.01	0.07
		Row Not used	None	0		100		None, N/A, or see Alongside	0	2000	0.00	0.07
c	2,3, 6	**lime - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0005	National - 1000km	1000	3000	0.01	0.07
		Raw materials delivered to glass plant	None	0		100	0.0051	None, N/A, or see Alongside	0	3000	0.00	0.07
	1.	**Yield from glass plant**	None	0		72.25	0.0037	None, N/A, or see Alongside	0	3000	0.00	0.07
d		**Epoxy resin transportation CO2 of 0.0277 kg CO2/kg**	None	0			0.0037	None, N/A, or see Alongside	0	3000	0.00	0.07
		GFRP Manufacture	None	0			0.0074	None, N/A, or see Alongside	0	3000	0.00	0.07
d	7	**Yield from GFRP manufacture**	None	0		87.7193	0.0065	None, N/A, or see Alongside	0	3000	0.00	0.07
e		**Epoxy + Glass Fibre to Tier 2 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Bulk materials	100	0.0065	National / Local - 300km	300	3300	0.36	0.44
f	8	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0065	National - 1000km	1000	4300	1.68	2.12
g	8	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-sem**	**259.5**	**Parts**	**100**	**0.0065**	**National / Local - 300km**	**300**	4600	0.51	2.62





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Glass production at the melting stage has a yield of approx. 85%. A further reduction in yield for flat glass production is found, 85%. Total yield is therefore 85%*85%= 72.25%	Westbroek et el (2021)
2	Glass raw materials are sourced REGIONALLY in Europe.	(Glass for Europe, 2020)
3	glass comprises 75% silica sand, 15% soda ash and 10% lime.	Westbroek et el (2021)
4	Silica sand is typically transported by rail.	(Transportjournal.com, 2016; gbrailfreight.com, 2017)
5	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Cargohandbook.com, no date)
6	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Stork et al., 2014)
7	1.14 kg epoxy & glass fibre needed per 1kg GFRP. 1/1.14*100=87.7193	Keoleian et el (2012)
8	Due to low packing density of GFRP parts, it is assumed that the vehicles are "light" loaded	

Calculator for: **ICE-06** (Calculation Ref) *Blue values need to be entered.*

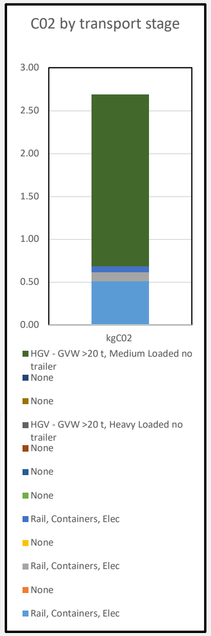
Body (Subsystem)

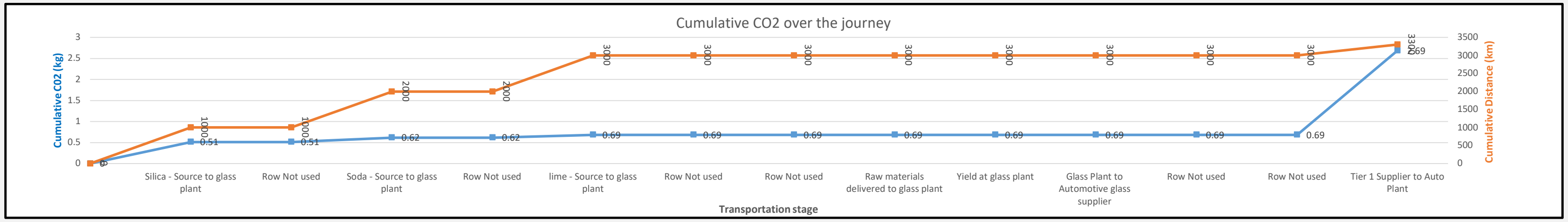
Glass (Material)

1. Enter Mass of Material: 33.9 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a	2, 3, 4	**Silica - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0352	National - 1000km	1000	1000	0.51	0.51
		Row Not used	None	0		100		None, N/A, or see Alongside	0	1000	0.00	0.51
b	2,3, 5	**Soda - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0070	National - 1000km	1000	2000	0.10	0.62
		Row Not used	None	0		100		None, N/A, or see Alongside	0	2000	0.00	0.62
c	2,3, 6	**lime - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0047	National - 1000km	1000	3000	0.07	0.69
		Row Not used	None	0		100	0.0470	None, N/A, or see Alongside	0	3000	0.00	0.69
		Row Not used	None	0		100	0.0470	None, N/A, or see Alongside	0	3000	0.00	0.69
		Raw materials delivered to glass plant	None	0		100	0.0470	None, N/A, or see Alongside	0	3000	0.00	0.69
	1.	**Yield at glass plant**	None	0		72.25	0.0339	None, N/A, or see Alongside	0	3000	0.00	0.69
d		**Glass Plant to Automotive glass supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Flat Glass	100	0.0339	None, N/A, or see Alongside	0	3000	0.00	0.69
		Row Not used	None	0		100	0.0339	None, N/A, or see Alongside	0	3000	0.00	0.69
		Row Not used	None	0		100	0.0339	None, N/A, or see Alongside	0	3000	0.00	0.69
e	7	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Glass parts**	**100**	**0.0339**	**National / Local - 300km**	**300**	3300	2.00	2.69





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Glass production at the melting stage has a yield of approx. 85%. A further reduction in yield for flat glass production is found, 85%. Total yield is therefore 85%*85%= 72.25%	Westbroek et el (2021)
2	Glass raw materials are sourced REGIONALLY in Europe.	(Glass for Europe, 2020)
3	glass comprises 75% silica sand, 15% soda ash and 10% lime.	Westbroek et el (2021)
4	Silica sand is typically transported by rail.	(Transportjournal.com, 2016; gbrailfreight.com, 2017)
5	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Cargohandbook.com, no date)
6	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Stork et al., 2014)
7	Glass For Europe indicates that there are 48 flat melting plants in Europe, and over 1000 companies processing and transforming flat glass. In the light of this it is reasonable to assume that the automotive glass can be supplied locally (within 300km) of a German vehicle plant.	(Glass for Europe, 2020)

Calculator for: ICE-07 (Calculation Ref) *Blue values need to be entered.*

Body (Subsystem)

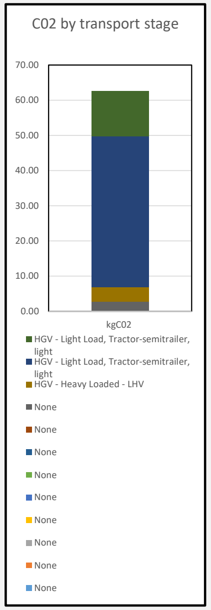
Average Plastic (Material)

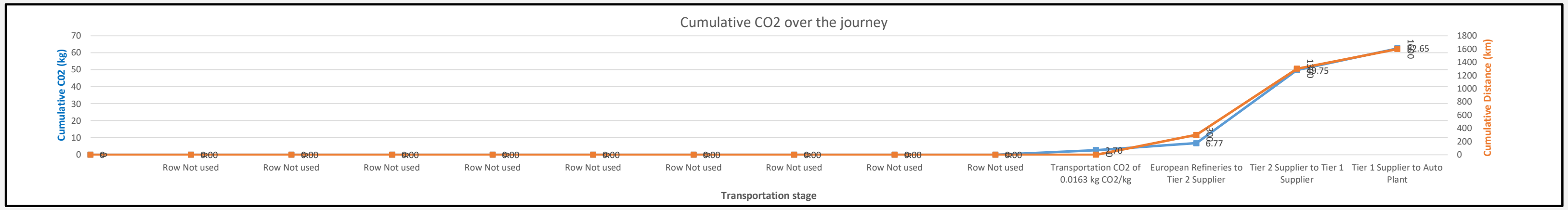
1. Enter Mass of Material:

165.6 kg

ANSWER

Step	Stage: *Ref - See Below*	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
	Row Not used	None	0		100	0.1656	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.1656	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.1656	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.1656	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.1656	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.1656	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.1656	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.1656	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.1656	None, N/A, or see Alongside	0	0	0.00	0.00
1.	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.1656	None, N/A, or see Alongside	0	0	2.70	2.70
a	**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.1656	National / Local - 300km	300	300	4.06	6.77
b 2	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.1656	National - 1000km	1000	1300	42.99	49.75
c **2**	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-semi**	**259.5**	**Assemblies**	**100**	**0.1656**	**National / Local - 300km**	**300**	1600	12.90	62.65





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

Calculator for: ICE-10 (Calculation Ref) *Blue vlaues need to be entered.*

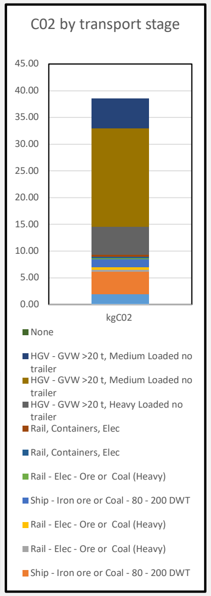
Powertrain System (Including BOP) (Subsystem)

Steel (Material)

1. Enter Mass of Material: 93.8 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist (km)	kgC02	Cum. C02 (kg)
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.1152	National - 1000km	1000	1000	1.92	1.92
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.1152	Intercontinental: Brazil - Rotter	10254	11254	4.25	6.17
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.1152	National / Local - 300km	300	11554	0.31	6.49
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.0576	National - 1000km	1000	12554	0.52	7.01
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.0576	Intercontinental: New york - Ro	7256	19810	1.50	8.52
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.0576	National / Local - 300km	300	20110	0.16	8.67
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0331	National - 500km	500	20610	0.24	8.92
h.	10, 11	**Refinery to Steel Mill (Tier 3)**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.0979	National / Local - 300km	300	20910	0.43	9.34
i.	10,12	**Steel to Part Manufacturers (Tier 3 to 2)**	HGV - GVW >20 t, Heavy Loade	185.3	bar, lengths or s	95.9	0.0938	National / Local - 300km	300	21210	5.22	14.56
j.	10,13	**Parts to Tier 1 suppliers (Tier 2 to 1)**	HGV - GVW >20 t, Medium Loa	196.6	Parts	100	0.0938	National - 1000km	1000	22210	18.45	33.01
k.	10,11	**Tier 1 to Auto Assembly Plant**	HGV - GVW >20 t, Medium Loa	196.6	Components	100	0.0938	National / Local - 300km	300	22510	5.54	38.55
l.		Other	None	0		100	0.0938	None, N/A, or see Alongside	0	22510	0.00	38.55



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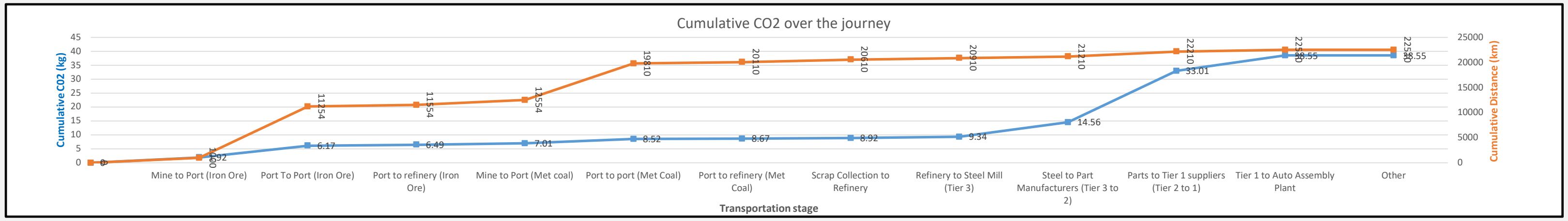


Refernces and Input Assumptions

	Input Assumptions	Ref / Citation
1.	Inputs for 1 tonne of steel — Inputs: Iron ore, metallurgical coal, recyc steel; Output crude steel	(Worldsteel.org, 2019)
2	**Ore from Brazil (51.7 %of German Iron ore is from brazil) (dist 8000km)**	(Elsner et al., 2019)
3	Distance from mining region to ponta de maderia - Approx 1000km (Capela et el 2019)	(Cepeda, Barros Kneipp and Caprace, 2019)
3	Ore from Ponta del maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to rotterdam 5537 Nautical miles =10254 km	*(Iron ore | Port of Rotterdam, 2022)* (Cepeda, Barros Kneipp and Caprace, 2019) (Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)
4	Scrap metal sourced from within germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.	(Elsner et al., 2019)
5	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
6	Germany's biggerst supplier of coal and coke is russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA	(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)
7	Coking Coal provided from western USA deposits	(Trippi et al., 2021)
8	69% of coal in the usa is moved by rail, thus rail transporation is assumed	(*Freight Railroads & Coal | Association of American Railroads* , 2022)

Inputs for 1 tonne of steel:

	Inputs			Output crude steel
	Iron ore	metallurgical coal	recyc steel	
per tonne	**1.18**	**0.59**	**0.34**	**1.00**

9	Transporation from usa to europe is New yourk to rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Assumptions of Hua et el (2022) assumed to be transferrable to EU context, and also confirmed by Brown et el (2021)**	(Hua et al., 2022) (Brown et al., 2021)
11	Distances based on suppliers from across europe, including eastern europe as argued by Brown et.el (2021)	(Brown et al., 2021)
12	Rod and bar steel as used incar parts has a loss factor of 1.043 i.e. 1/1.043 = 95.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)
13	GREET model states a loss factor of 1.00 for machining or stamping operations. Other data to challenge this was not found.	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: ICE-11 (Calculation Ref) *Blue values need to be entered.*

Powertrain System (Including BOP) (Subsystem)

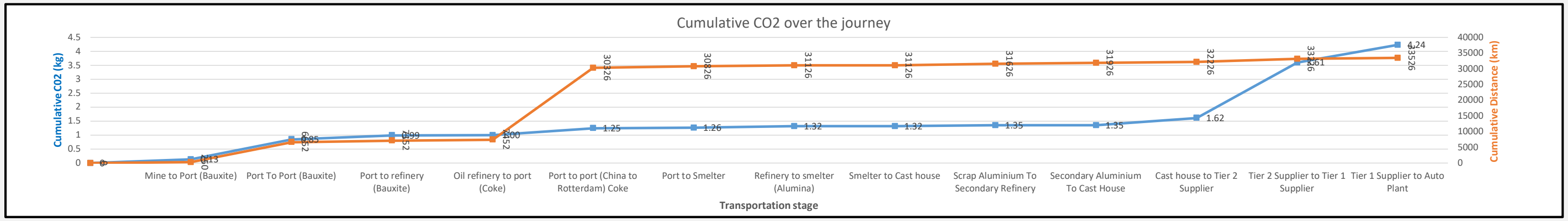
Wrought Aluminum (Material)

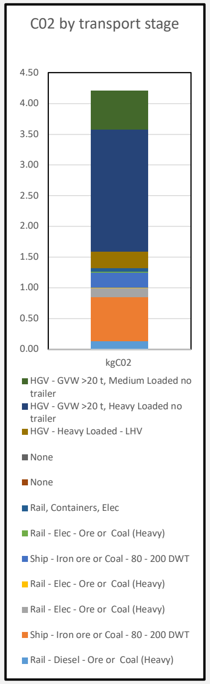
1. Enter Mass of Material: 10.7 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km) 0	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0		
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.0313	None or N/A	250	250	0.13	0.13
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.0313	Intercontinental: Guinea - Rott	6402	6652	0.72	0.85
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.0313	National - 500km	500	7152	0.14	0.99
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0030	National / Local - 300km	300	7452	0.01	1.00
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0030	None, N/A, or see Alongside	22874	30326	0.25	1.25
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0030	National - 500km	500	30826	0.01	1.26
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0137	National / Local - 300km	300	31126	0.06	1.32
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0071	None, N/A, or see Alongside	0	31126	0.00	1.32
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0040	National - 500km	500	31626	0.03	1.35
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0036	National / Local - 300km	300	31926	0.00	1.35
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	100	0.0107	National / Local - 300km	300	32226	0.26	1.62
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0107	National - 1000km	1000	33226	1.99	3.61
m.	**7**	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0107**	**National / Local - 300km**	**300**	33526	0.63	4.24

n.


Cumulative CO2 over the journey


C02 by transport stage

References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for hot rolled parts there is a loss factor of 3.5% whereas for cold rolled there is not. As it is not possible to know the proportion of hot rolled compared to cold rolled parts, and in the light of the relatively modest effect, this is not accounted for.	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: ICE-12 (Calculation Ref) *Blue values need to be entered.*

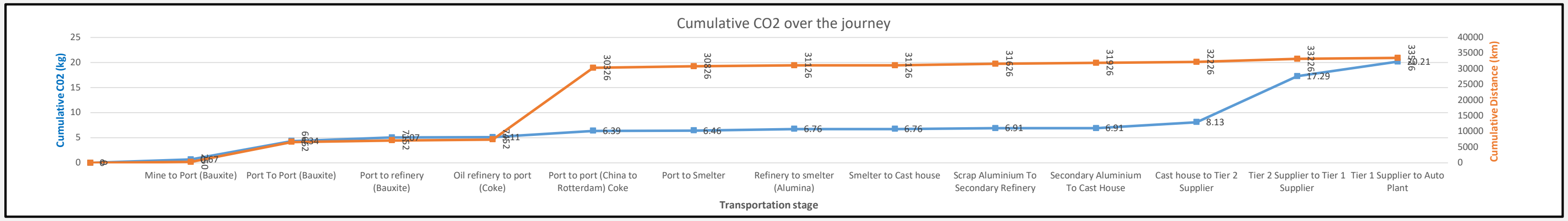
1. Enter Mass of Material: 49.5 kg

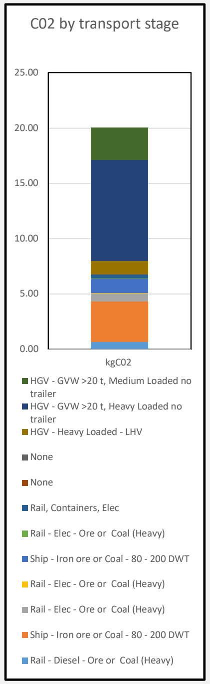
Powertrain System (Including BOP) (Subsystem)

Cast Aluminum (Material)

ANSWER

	Step Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.1595	None or N/A	250	250	0.67	0.67
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.1595	Intercontinental: Guinea - Rott	6402	6652	3.68	4.34
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.1595	National - 500km	500	7152	0.73	5.07
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0155	National / Local - 300km	300	7452	0.04	5.11
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0155	None, N/A, or see Alongside	22874	30326	1.28	6.39
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0155	National - 500km	500	30826	0.07	6.46
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0699	National / Local - 300km	300	31126	0.31	6.76
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0361	None, N/A, or see Alongside	0	31126	0.00	6.76
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0203	National - 500km	500	31626	0.15	6.91
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0186	National / Local - 300km	300	31926	0.00	6.91
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	90.33	0.0495	National / Local - 300km	300	32226	1.21	8.13
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0495	National - 1000km	1000	33226	9.17	17.29
m.	**7**	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0495**	**National / Local - 300km**	**300**	33526	2.92	20.21
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for cast aluminium parts, 1.107 kg aluminium needed to make a 1kg part	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: ICE-13 (Calculation Ref) *Blue values need to be entered.*

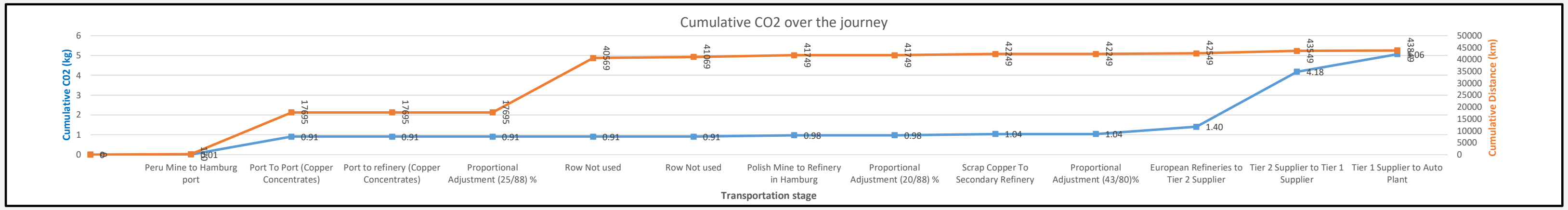
Powertrain System (Including BOP) (Subsystem)

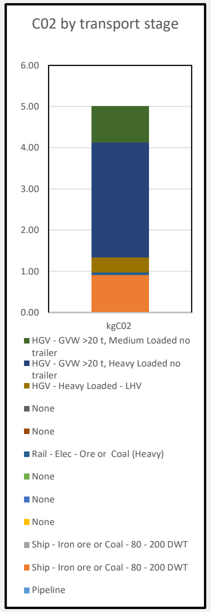
Copper/Brass (Material)

1. Enter Mass of Material (kg): 14.98

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a.	1,2, 3	**Peru Mine to Hamburg port**	Pipeline	5	Copper Concentra	100	0.0142	Manual Entered Distance	170	170	0.01	0.01
b.	4	**Port To Port (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0142	Intercontinental: Manual Enter	17525	17695	0.90	0.91
c.	5	**Port to refinery (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentra	100	0.0142	None, N/A, or see Alongside	0	17695	0.00	0.91
d.	9, 10	**Proportional Adjustment (25/88) %**	None	0	Copper Concentra	30	0.0043	None, N/A, or see Alongside	0	17695	0.00	0.91
e.		***Row Not used***	None	0	Coke	100	0.0015	None, N/A, or see Alongside	22874	40569	0.00	0.91
f.		***Row Not used***	None	0	Coke	100	0.0015	National - 500km	500	41069	0.00	0.91
g.	6	**Polish Mine to Refinery in Hamburg**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	100	0.0114	Manual Entered Distance	680	41749	0.07	0.98
h.	9, 10	**Proportional Adjustment (20/88) %**	None	0		30	0.0034	None, N/A, or see Alongside	0	41749	0.00	0.98
i.	7,8	**Scrap Copper To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Copper	100	0.0081	National - 500km	500	42249	0.06	1.04
j.	9	**Proportional Adjustment (43/80)%**	None	0		100	0.0081	None, N/A, or see Alongside	0	42249	0.00	1.04
k.		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0150	National / Local - 300km	300	42549	0.37	1.40
l.		**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0150	National - 1000km	1000	43549	2.78	4.18
m.		**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0150**	**National / Local - 300km**	**300**	43849	0.88	5.06
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Aurubis, Europe's largest copper producer is assumed to be the refiner and supplier at one of its facilities in Europe	(Kurlemann, 2022).
2	Chile, Peru and Brazil are the main suppliers of ore / concentrate to Germany. As Chile is the world's biggest supplier of copper this model will assume that it is supplied in Chile. Notwithstanding this, the shipping distance from Peru or Brazil is not dramatically differnt to Germany.	(Kurlemann, 2022) (International Copper Study Group, 2022)
3	Escodida, the world's largest copper mine is assumed to be the source. Concentrate is pumped 170km by pipeline to the port of Coloso	(www.mining-technology.com, 2020)
4	Copper concentrate is shipped in bulk for large quantiites. The distance from Coloso to Hamburg is 9463 nm = 17525km	(Bulkcarrierguide.com, 2010) (ports.com, 2023)
5	Aurubus's Hamburg plant is near the port of hamburg, and the concentrate is moved from the port to the plant via waterway. Thus for emissions purposes it will be assumed that this is part of the same sea journey. No addtiotnal distance therefore added	(Aurubis AG, 2021)
6	Poland is assumed to be the souirce of the ore, as its euope's largest producer of ore after Russia. Transporation assumed to be by rail, 680km	(TheGlobalEconomy.com, 2018) (Google Maps, 2023)
7	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
8	Since 70% of copper in EU end of life products are recycled,, and given that Europe is a net exporter of scrap copper, it is assumed that the scrap copper is sourced from europe	(euric-aisbl.eu, 2020)
9	These rows adjust the propotion of copper according to each source. 43% recycled, 20% european mines and 25% imported ore or concentrate - accounting for 88% of Europeal supply. The remaining 12% is not modelled as its source cannot be accurately determined. Thus the above propotions are adjusted accordingly: Recycled at 43/88 percent, Eurpean mines at 20/88% and imported iron or concentrate at 25/88%	(Kurlemann, 2022)
10	Based on 30% copper concerate	

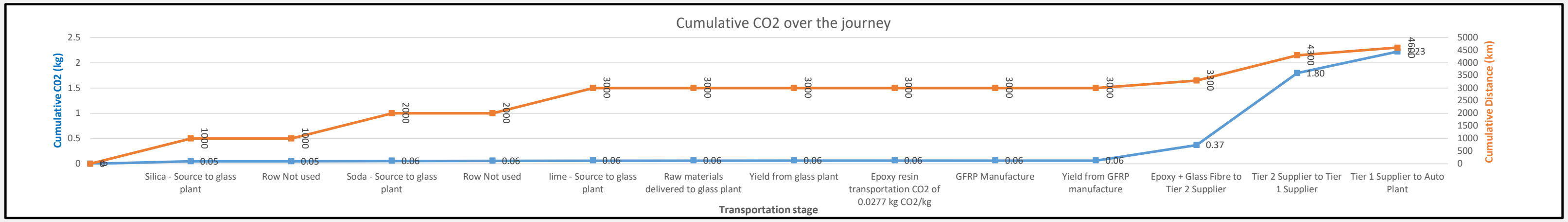
Calculator for: ICE-14 (Calculation Ref) *Blue values need to be entered.*

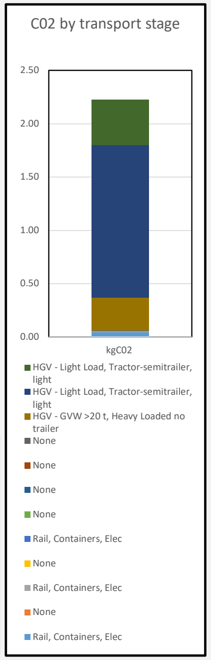
1. Enter Mass of Material: Powertrain System (Including BOP) (Subsystem)

5.5 kg GFRP (Material)

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km) 0	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0		
a	2, 3, 4	**Silica - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0033	National - 1000km	1000	1000	0.05	0.05
		Row Not used	None	0		100		None, N/A, or see Alongside	0	1000	0.00	0.05
b	2,3, 5	**Soda - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0007	National - 1000km	1000	2000	0.01	0.06
		Row Not used	None	0		100		None, N/A, or see Alongside	0	2000	0.00	0.06
c	2,3, 6	**lime - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0004	National - 1000km	1000	3000	0.01	0.06
		Raw materials delivered to glass plant	None	0		100	0.0043	None, N/A, or see Alongside	0	3000	0.00	0.06
	1.	**Yield from glass plant**	None	0		72.25	0.0031	None, N/A, or see Alongside	0	3000	0.00	0.06
d		**Epoxy resin transportation CO2 of 0.0277 kg CO2/kg**	None	0			0.0031	None, N/A, or see Alongside	0	3000	0.00	0.06
		GFRP Manufacture	None	0			0.0063	None, N/A, or see Alongside	0	3000	0.00	0.06
d	7	**Yield from GFRP manufacture**	None	0		87.7193	0.0055	None, N/A, or see Alongside	0	3000	0.00	0.06
e		**Epoxy + Glass Fibre to Tier 2 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Bulk materials	100	0.0055	National / Local - 300km	300	3300	0.31	0.37
f	8	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0055	National - 1000km	1000	4300	1.43	1.80
g	**8**	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-sem**	**259.5**	**Parts**	**100**	**0.0055**	**National / Local - 300km**	**300**	4600	0.43	2.23





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Glass production at the melting stage has a yield of approx. 85%. A further reduction in yield for flat glass production is found, 85%. Total yield is therefore 85%*85%= 72.25%	Westbroek et el (2021)
2	Glass raw materials are sourced REGIONALLY in Europe.	(Glass for Europe, 2020)
3	glass comprises 75% silica sand, 15% soda ash and 10% lime.	Westbroek et el (2021)
4	Silica sand is typically transported by rail.	(Transportjournal.com, 2016; gbrailfreight.com, 2017)
5	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Cargohandbook.com, no date)
6	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Stork et al., 2014)
7	1.14 kg epoxy & glass fibre needed per 1kg GFRP. 1/1.14*100=87.7193	Keoleian et el (2012)
8	Due to low packing density of GFRP parts, it is assumed that the vehicles are "light" loaded	

Calculator for: ICE-15 (Calculation Ref) *Blue values need to be entered.*

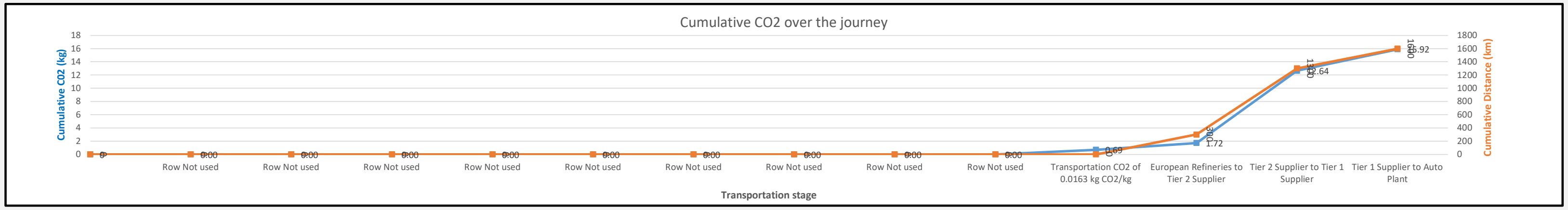
Powertrain System (Including BOP) (Subsystem)

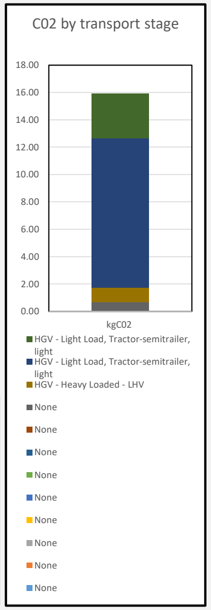
Average Plastic (Material)

1. Enter Mass of Material: 42.1 kg

ANSWER

Step	Stage: *Ref - See Below*	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
	Row Not used	None	0		100	0.0421	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0421	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0421	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0421	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0421	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0421	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0421	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0421	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0421	None, N/A, or see Alongside	0	0	0.00	0.00
1.	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.0421	None, N/A, or see Alongside	0	0	0.69	0.69
a	**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0421	National / Local - 300km	300	300	1.03	1.72
b	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0421	National - 1000km	1000	1300	10.92	12.64
c 2.	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-semi**	**259.5**	**Assemblies**	**100**	**0.0421**	**National / Local - 300km**	**300**	1600	3.28	15.92





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

Calculator for: ICE-19 (Calculation Ref)

Transmission System/Gearbox (Subsystem)

Steel (Material)

Blue vlaues need to be entered.

1. Enter Mass of Material: 27.3 kg

ANSWER

	Step	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist (km) 0	kgC02	Cum. C02 (kg)
	Ref - See Below			g/tkm		%	ton		km	0		
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.0335	National - 1000km	1000	1000	0.56	0.56
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.0335	Intercontinental: Brazil - Rotter	10254	11254	1.24	1.80
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.0335	National / Local - 300km	300	11554	0.09	1.89
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.0168	National - 1000km	1000	12554	0.15	2.04
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.0168	Intercontinental: New york - Ro	7256	19810	0.44	2.48
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.0168	National / Local - 300km	300	20110	0.05	2.53
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0096	National - 500km	500	20610	0.07	2.60
h.	10, 11	**Refinery to Steel Mill (Tier 3)**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.0285	Local 100 km	100	20710	0.04	2.64
i.	10,12	**Steel to Part Manufacturers (Tier 3 to 2)**	HGV - GVW >20 t, Heavy Loade	185.3	bar, lengths or s	95.9	0.0273	National / Local - 300km	300	21010	1.52	4.16
j.	10,13	**Parts to Tier 1 suppliers (Tier 2 to 1)**	HGV - GVW >20 t, Medium Loa	196.6	Parts	100	0.0273	National - 1000km	1000	22010	5.37	9.53
k.	10,11	**Tier 1 to Auto Assembly Plant**	HGV - GVW >20 t, Medium Loa	196.6	Components	100	0.0273	National / Local - 300km	300	22310	1.61	11.15
l.		Other	None	0		100	0.0273	None, N/A, or see Alongside	0	22310	0.00	11.15

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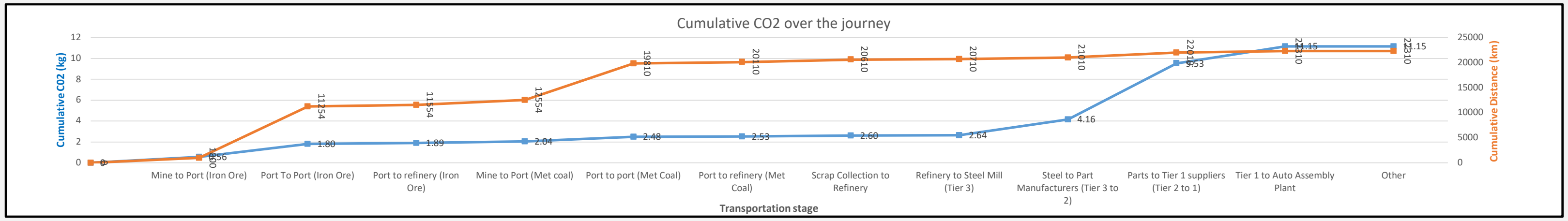

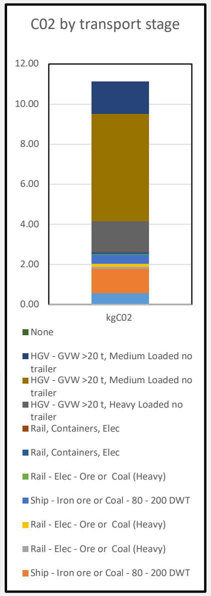

Refernces and Input Assumptions

<table>
<tr><td></td><td>Input Assumptions</td><td>Ref / Citation</td></tr>
<tr><td>1.</td><td>Inputs for 1 tonne of steel
<table>
<tr><td></td><td colspan="3">Inputs</td><td>Output crude steel</td></tr>
<tr><td></td><td>Iron ore</td><td>metallurgical coal</td><td>recyc steel</td><td></td></tr>
<tr><td>per tonne</td><td>1.18</td><td>0.59</td><td>0.34</td><td>1.00</td></tr>
</table></td><td>(Worldsteel.org, 2019)</td></tr>
<tr><td>2</td><td>Ore from Brazil (51.7 %of German Iron ore is from brazil) (dist 8000km)</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>3</td><td>Distance from mining region to ponta de maderia - Approx 1000km (Capela et el 2019)</td><td>(Cepeda, Barros Kneipp and Caprace, 2019)</td></tr>
<tr><td>3</td><td>Ore from Ponta del maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to rotterdam 5537 Nautical miles =10254 km</td><td><i>(Iron ore | Port of Rotterdam</i>, 2022)
(Cepeda, Barros Kneipp and Caprace, 2019)
(Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)</td></tr>
<tr><td>4</td><td>Scrap metal sourced from within germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>5</td><td>Scrap metal transported dry freight containers</td><td>(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)</td></tr>
<tr><td>6</td><td>Germany's biggerst supplier of coal and coke is russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA</td><td>(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)</td></tr>
<tr><td>7</td><td>Coking Coal provided from western USA deposits</td><td>(Trippi et al., 2021)</td></tr>
<tr><td>8</td><td>69% of coal in the usa is moved by rail, thus rail transporation is assumed</td><td>(<i>Freight Railroads & Coal | Association of American Railroads</i> , 2022)</td></tr>
</table>

9	Transporation from usa to europe is New yourk to rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Assumptions of Hua et el (2022) assumed to be transferrable to EU context, and also confirmed by Brown et el (2021)**	(Hua et al., 2022) (Brown et al., 2021)
11	Distances based on suppliers from across europe, including eastern europe as argued by Brown et.el (2021)	(Brown et al., 2021)
12	Rod and bar steel as used incar parts has a loss factor of 1.043 i.e. 1/1.043 = 95.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)
13	GREET model states a loss factor of 1.00 for machining or stamping operations. Other data to challenge this was not found.	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: ICE-21 (Calculation Ref) *Blue vlaues need to be entered.*

Transmission System/Gearbox (Subsystem)

Cast Iron (Material)

1. Enter Mass of Material:
27.3 kg

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist (km)	ANSWER kgC02	Cum. C02 (kg)
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.0322	National - 1000km	1000	1000	0.54	0.54
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.0322	Intercontinental: Brazil - Rotter	10254	11254	1.19	1.72
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.0322	National / Local - 300km	300	11554	0.09	1.81
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.0161	National - 1000km	1000	12554	0.15	1.96
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.0161	Intercontinental: New york - Ro	7256	19810	0.42	2.38
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.0161	National / Local - 300km	300	20110	0.04	2.42
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0092	National - 500km	500	20610	0.07	2.49
h.	10, 11	**Refinery to Steel Mill (Tier 3)**	Rail, Containers, Elec	14.6	Iron Ingots	100	0.0273	Local 100 km	100	20710	0.04	2.53
i.	12	**Steel to Part Manufacturers (Tier 3 to 2)**	HGV - GVW >20 t, Heavy Loade	185.3	Iron Ingots	100.0	0.0273	National / Local - 300km	300	21010	1.52	4.05
j.	10	**Parts to Tier 1 suppliers (Tier 2 to 1)**	HGV - GVW >20 t, Medium Loa	196.6	Parts	100	0.0273	National - 1000km	1000	22010	5.37	9.42
k.	10,11	**Tier 1 to Auto Assembly Plant**	HGV - GVW >20 t, Medium Loa	196.6	Components	100	0.0273	National / Local - 300km	300	22310	1.61	11.04
l.		Other	None	0		100	0.0273	None, N/A, or see Alongside	0	22310	0.00	11.04

m.

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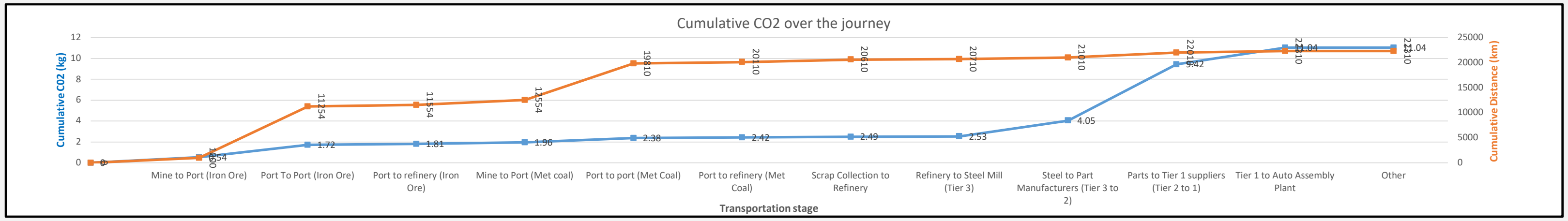
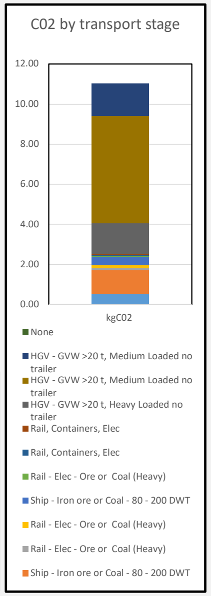




Refernces and Input Assumptions

	Input Assumptions	Ref / Citation
1.	Inputs for 1 tonne of steel (see table below)	(Worldsteel.org, 2019)
2	**Ore from Brazil (51.7 %of German Iron ore is from brazil) (dist 8000km)**	(Elsner et al., 2019)
3	Distance from mining region to ponta de maderia - Approx 1000km (Capela et el 2019)	(Cepeda, Barros Kneipp and Caprace, 2019)
3	Ore from Ponta del maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to rotterdam 5537 Nautical miles =10254 km	*(Iron ore | Port of Rotterdam, 2022)* (Cepeda, Barros Kneipp and Caprace, 2019) (Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)
4	Scrap metal sourced from within germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.	(Elsner et al., 2019)
5	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
6	Germany's biggerst supplier of coal and coke is russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA	(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)
7	Coking Coal provided from western USA deposits	(Trippi et al., 2021)
8	69% of coal in the usa is moved by rail, thus rail transporation is assumed	(*Freight Railroads & Coal | Association of American Railroads* , 2022)

Inputs for 1 tonne of steel	Inputs			Output crude steel
	Iron ore	metallurgical coal	recyc steel	
per tonne	**1.18**	**0.59**	**0.34**	**1.00**

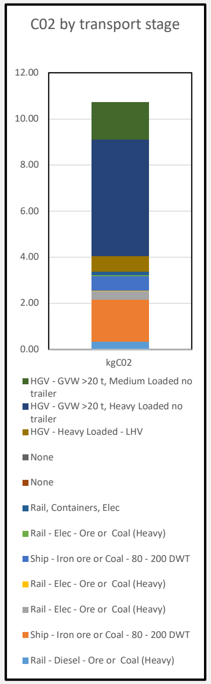
9	Transporation from usa to europe is New yourk to rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Assumptions of Hua et el (2022) assumed to be transferrable to EU context, and also confirmed by Brown et el (2021)**	(Hua et al., 2022) (Brown et al., 2021)
11	Distances based on suppliers from across europe, including eastern europe as argued by Brown et.el (2021)	(Brown et al., 2021)
12	loss factor assumed tio be zero in the case of cast iron because machining needed will be minimal. Greet 2 data does not state a loss factor for cast oron	(Diecasting.com, 2018)

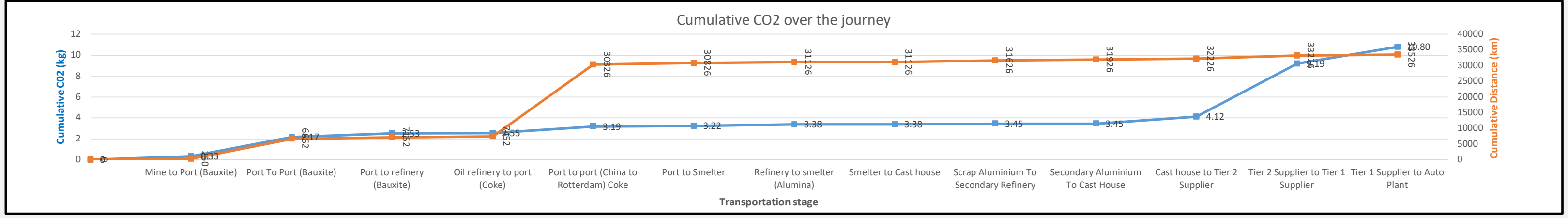
Calculator for: ICE-22 (Calculation Ref) *Blue values need to be entered.*
Transmission System/Gearbox (Subsystem)
Wrought Aluminum (Material)

1. Enter Mass of Material: 27.3 kg

ANSWER

		Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km) 0	kgC02	Cum. C02 (kg)
Step	*Ref - See Below*			g/tkm		%	ton		km	0		
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.0796	None or N/A	250	250	0.33	0.33
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.0796	Intercontinental: Guinea - Rott	6402	6652	1.84	2.17
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.0796	National - 500km	500	7152	0.36	2.53
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0077	National / Local - 300km	300	7452	0.02	2.55
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0077	None, N/A, or see Alongside	22874	30326	0.64	3.19
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0077	National - 500km	500	30826	0.04	3.22
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0349	National / Local - 300km	300	31126	0.15	3.38
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0180	None, N/A, or see Alongside	0	31126	0.00	3.38
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0101	National - 500km	500	31626	0.07	3.45
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0093	National / Local - 300km	300	31926	0.00	3.45
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	100	0.0273	National / Local - 300km	300	32226	0.67	4.12
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0273	National - 1000km	1000	33226	5.07	9.19
m.	**7**	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0273**	**National / Local - 300km**	**300**	33526	1.61	10.80
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for hot rolled parts there is a loss factor of 3.5% whereas for cold rolled there is not. As it is not possible to know the proportion of hot rolled compared to cold rolled parts, and in the light of the relatively modest effect, this is not accounted for.	(Argonne GREET Vehicle Cycle Model, 2021)

Calculator for: ICE-23 (Calculation Ref) *Blue values need to be entered.*

1. Enter Mass of Material: 4.6 kg

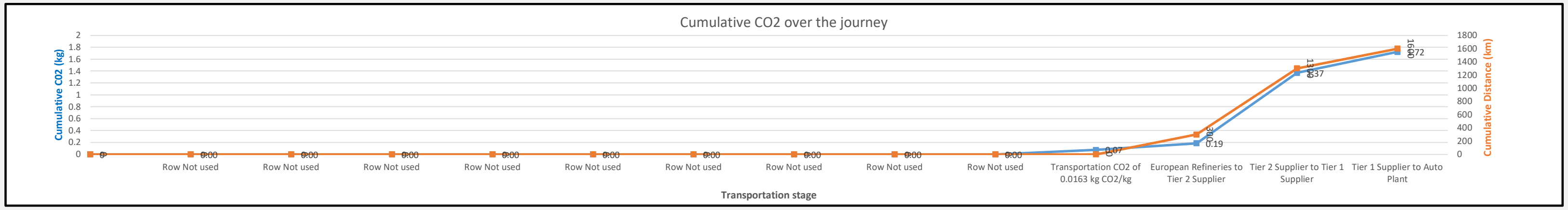
Transmission System/Gearbox (Subsystem)

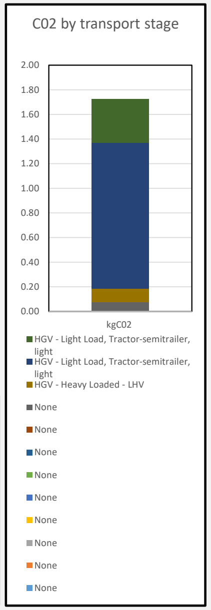
Average

Plastic (Material)

ANSWER

										Cum. Dist. (km)	kgC02	Cum. C02 (kg)
		Stage:	2. Select Mode of transport	**Co2 factor CO2e (wtw)**	3. Form	% of prev stage	**Mass Transported**	4 Select Distance	or Enter Distance	0		
Step		*Ref - See Below*		**g/tkm**		%	**ton**		km	0		
		Row Not used	None	0		100	0.0046	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0046	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0046	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0046	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0046	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0046	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0046	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0046	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0046	None, N/A, or see Alongside	0	0	0.00	0.00
	1.	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.0046	None, N/A, or see Alongside	0	0	0.07	0.07
a		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0046	National / Local - 300km	300	300	0.11	0.19
b	2.	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0046	National - 1000km	1000	1300	1.18	1.37
c	2.	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-semi**	**259.5**	**Assemblies**	**100**	**0.0046**	**National / Local - 300km**	**300**	1600	0.35	1.72





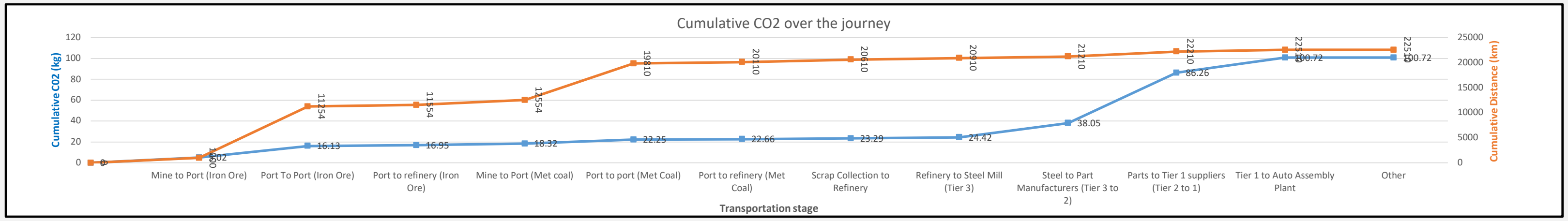
References and Input Assumptions

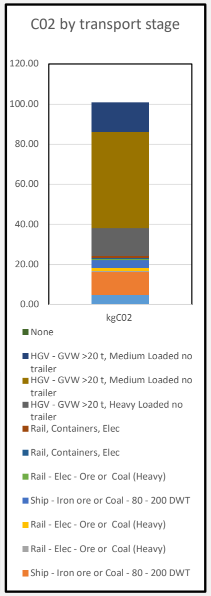
	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

Calculator for: ICE-26 (Calculation Ref) *Blue vlaues need to be entered.*
Chassis (w/o battery) (Subsystem)
Steel (Material)

1. Enter Mass of Material: 245.2 kg

											ANSWER	
										Cum. Dist (km)	**kgC02**	**Cum. C02 (kg)**
		Stage:	2. Select Mode of transport	**Co2 factor CO2e (wtw)**	3. Form	% of prev stage	**Mass Transported**	4 Select Distance	or Enter Distance 0			
	Step *Ref - See Below*			**g/tkm**		%	**ton**		km 0			
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.3009	National - 1000km	1000	1000	5.02	5.02
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.3009	Intercontinental: Brazil - Rotte	10254	11254	11.11	16.13
c.	3.	**Port to refinery (Iron Ore)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	1.18t per ton	0.3009	National / Local - 300km	300	11554	0.82	16.95
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.1504	National - 1000km	1000	12554	1.37	18.32
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.1504	Intercontinental: New york - R	7256	19810	3.93	22.25
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	.59t per ton	0.1504	National / Local - 300km	300	20110	0.41	22.66
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0865	National - 500km	500	20610	0.63	23.29
h.	10, 11	**Refinery to Steel Mill (Tier 3)**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.2558	National / Local - 300km	300	20910	1.12	24.42
i.	10,12	**Steel to Part Manufacturers (Tier 3 to 2)**	HGV - GVW >20 t, Heavy Loade	185.3	bar, lengths or s	95.9	0.2452	National / Local - 300km	300	21210	13.63	38.05
j.	10,13	**Parts to Tier 1 suppliers (Tier 2 to 1)**	HGV - GVW >20 t, Medium Loa	196.6	Parts	100	0.2452	National - 1000km	1000	22210	48.21	86.26
k.	10,11	**Tier 1 to Auto Assembly Plant**	HGV - GVW >20 t, Medium Loa	196.6	Components	100	0.2452	National / Local - 300km	300	22510	14.46	100.72
l.		Other	None	0		100	0.2452	None, N/A, or see Alongside	0	22510	0.00	100.72
m.												
n.												





Refernces and Input Assumptions

<table>
<tr><td></td><td>Input Assumptions</td><td>Ref / Citation</td></tr>
<tr><td>1.</td><td>Inputs for 1 tonne of steel
<table>
<tr><td></td><td>Inputs</td><td></td><td></td><td>Output crude steel</td></tr>
<tr><td></td><td>Iron ore</td><td>metallurgical coal</td><td>recyc steel</td><td></td></tr>
<tr><td>per tonne</td><td>1.18</td><td>0.59</td><td>0.34</td><td>1.00</td></tr>
</table></td><td>(Worldsteel.org, 2019)</td></tr>
<tr><td>2</td><td>Ore from Brazil (51.7 %of German Iron ore is from brazil) (dist 8000km)</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>3</td><td>Distance from mining region to ponta de maderia - Approx 1000km (Capela et el 2019)</td><td>(Cepeda, Barros Kneipp and Caprace, 2019)</td></tr>
<tr><td>3</td><td>Ore from Ponta del maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to rotterdam 5537 Nautical miles =10254 km</td><td><i>(Iron ore | Port of Rotterdam, 2022)</i>
(Cepeda, Barros Kneipp and Caprace, 2019)
(Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)</td></tr>
<tr><td>4</td><td>Scrap metal sourced from within germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>5</td><td>Scrap metal transported dry freight containers</td><td>(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)</td></tr>
<tr><td>6</td><td>Germany's biggerst supplier of coal and coke is russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA</td><td>(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)</td></tr>
<tr><td>7</td><td>Coking Coal provided from western USA deposits</td><td>(Trippi et al., 2021)</td></tr>
<tr><td>8</td><td>69% of coal in the usa is moved by rail, thus rail transporation is assumed</td><td><i>(Freight Railroads & Coal | Association of American Railroads</i> , 2022)</td></tr>
</table>

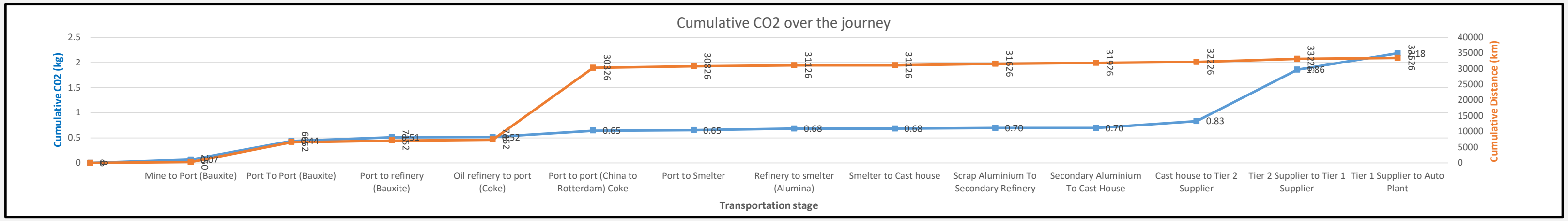
9	Transporation from usa to europe is New yourk to rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Assumptions of Hua et el (2022) assumed to be transferrable to EU context, and also confirmed by Brown et el (2021)**	(Hua et al., 2022) (Brown et al., 2021)
11	Distances based on suppliers from across europe, including eastern europe as argued by Brown et.el (2021)	(Brown et al., 2021)
12	Rod and bar steel as used incar parts has a loss factor of 1.043 i.e. 1/1.043 = 95.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)
13	GREET model states a loss factor of 1.00 for machining or stamping operations. Other data to challenge this was not found.	(Argonne GREET Vehicle Cycle Model, 2021)

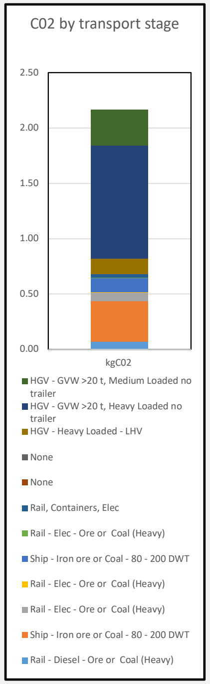
Calculator for: ICE-27 (Calculation Ref) *Blue values need to be entered.*
Chassis (w/o battery) (Subsystem)
Wrought Aluminum (Material)

1. Enter Mass of Material:	
5.5	kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km) 0 0	kgC02	Cum. C02 (kg)
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.0161	None or N/A	250	250	0.07	0.07
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.0161	Intercontinental: Guinea - Rott	6402	6652	0.37	0.44
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.0161	National - 500km	500	7152	0.07	0.51
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0016	National / Local - 300km	300	7452	0.00	0.52
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0016	None, N/A, or see Alongside	22874	30326	0.13	0.65
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0016	National - 500km	500	30826	0.01	0.65
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0071	National / Local - 300km	300	31126	0.03	0.68
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0037	None, N/A, or see Alongside	0	31126	0.00	0.68
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0021	National - 500km	500	31626	0.01	0.70
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0019	National / Local - 300km	300	31926	0.00	0.70
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	100	0.0055	National / Local - 300km	300	32226	0.14	0.83
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0055	National - 1000km	1000	33226	1.02	1.86
m.	**7**	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0055**	**National / Local - 300km**	**300**	33526	0.33	2.18
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
2	Coke used in Aluminium is a by product of the oil refinery process, with the world's main suppliers being the USA & China, with China having a global supply share of 75%. Thus for this assumption, it is assumed that the coke is supplied from China. Because it is a by-product of oil production, supply of crude oil to the refinery is not included as it arises as a by product.	(Djukanovic, 2018)
3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

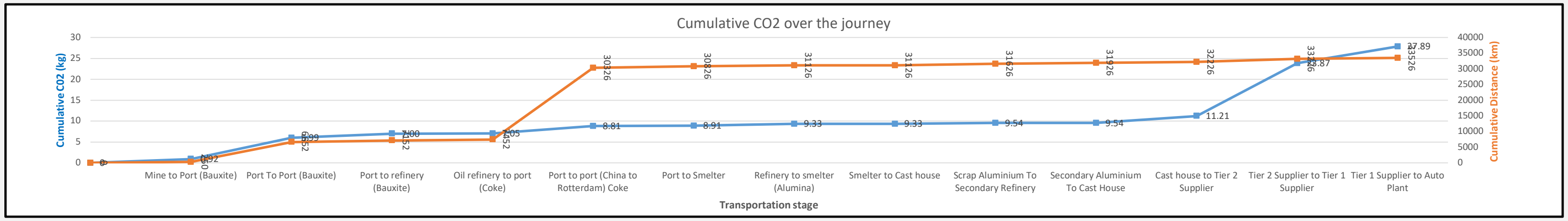
10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for hot rolled parts there is a loss factor of 3.5% whereas for cold rolled there is not. As it is not possible to know the proportion of hot rolled compared to cold rolled parts, and in the light of the relatively modest effect, this is not accounted for.	(Argonne GREET Vehicle Cycle Model, 2021)

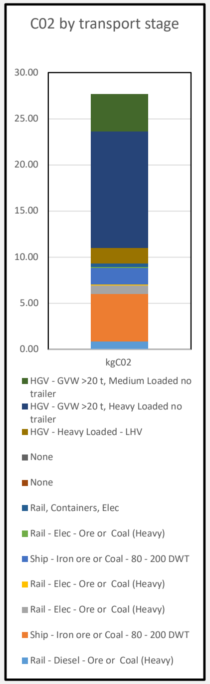
Calculator for: ICE-28 (Calculation Ref) *Blue values need to be entered.*
Chassis (w/o battery) (Subsystem)
Cast Aluminum (Material)

1. Enter Mass of Material:
68.3 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance 0 km 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a.	1, 15	**Mine to Port (Bauxite)**	Rail - Diesel - Ore or Coal (Hea	16.7	Bauxite	100	0.2202	None or N/A	250	250	0.92	0.92
b.	15, 16	**Port To Port (Bauxite)**	Ship - Iron ore or Coal - 80 - 20	3.6	Bauxite	100	0.2202	Intercontinental: Guinea - Rott	6402	6652	5.07	5.99
c.	4,10,11	**Port to refinery (Bauxite)**	Rail - Elec - Ore or Coal (Heavy	9.1	Bauxite	100	0.2202	National - 500km	500	7152	1.00	7.00
d.	2, 17	**Oil refinery to port (Coke)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0214	National / Local - 300km	300	7452	0.06	7.05
e.	3,18	**Port to port (China to Rotterdam) Coke**	Ship - Iron ore or Coal - 80 - 20	3.6	Coke	100	0.0214	None, N/A, or see Alongside	22874	30326	1.76	8.81
f.	9, 11, 7	**Port to Smelter**	Rail - Elec - Ore or Coal (Heavy	9.1	Coke	100	0.0214	National - 500km	500	30826	0.10	8.91
g.	4, 11, 19,20	**Refinery to smelter (Alumina)**	Rail, Containers, Elec	14.6	Alumina	100	0.0965	National / Local - 300km	300	31126	0.42	9.33
h.	5, 12	**Smelter to Cast house**	None	0	66% Primary Alu	51.68	0.0499	None, N/A, or see Alongside	0	31126	0.00	9.33
i.	13	**Scrap Aluminium To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Aluminiur	100	0.0281	National - 500km	500	31626	0.20	9.54
j.	6, 12	**Secondary Aluminium To Cast House**	None	0	34% Secondary	91.58	0.0257	National / Local - 300km	300	31926	0.00	9.54
k.	7,8,12, 21	**Cast house to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined Primary & Secondary Al	90.33	0.0683	National / Local - 300km	300	32226	1.68	11.21
l.	7	**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0683	National - 1000km	1000	33226	12.65	23.87
m.	**7**	**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Lo**	**196.6**	**Assemblies**	**100**	**0.0683**	**National / Local - 300km**	**300**	33526	4.03	27.89
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	As 58% of European bauxite in 2021 was is from Guinea (followed by Brazil, 11% and Sierra Leone, 10%) Guinea is assumed to be the source.	(Georgitzikis and Mancini, 2021)
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3	**Anodes are produced at Smelter plant - thus coke raw materials assumed to be supplied directly to plant**	(World-aluminium.org, 2018)
4	The Eu is a net exporter of Alumina, so it can be assumed that the alumina is sourced from the EU. The top 3 producers in the EU are Ireland (25%) Spain (22%) and Germany (14%)	(Georgitzikis and Mancini, 2021)
5	Cast house is located at smelter - distance show as zero therefore	(Aluminium Association, 2013)
6	As secondary aluminium now accounts for more than half of European Aluminium production, it is assumed that the secondary aluminium is sourced from Europe	(Georgitzikis and Mancini, 2021), (Ernesto, Umberto and Cesare, 2019)
7	Figures by Workman (2021) indicate that 80.5% of car the top 15 component imports (accounting for 87.8% of auto parts, by value) into the German Automotive sector are from surrounding European countries. Thus it is assumed that unless otherwise found, that German auto parts are sourced from Germany or Europe unless otherwise shown.	(Workman, 2021)
8	The IEA's figure of 34% of global aluminium production being from secondary aluminium is used (as at 2021)	(IEA, 2022)
9	Typically 428.6 kg anode material (coke) per 1000 kg aluminium produced	(Aluminium Association, 2013)

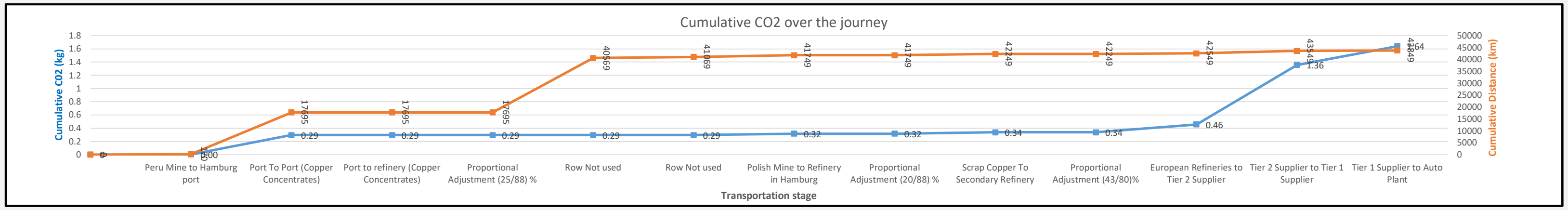
10	2281 kg of Bauxite is needed per 1000 kg alumina	(Aluminium Association, 2013)
11	Note that the coke & bauxite figures depend on the alumina mass (see notes 9 & 10 above) - all highlighted in dark red text	
12	Note that the primary and secondary figures are in a ratio as per Note 8 above - all highlighted in dark blue text	
13	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
14	1.0425 ton Unprocessed aluminium scrap is used per ton processed scrap. 1.0475 ton processed scrap is used per ton recovered aluminium (Aluminium Association, 2013). Thus the ratio of 1.0425*10475 ton unprocessed scrap is needed per ton recovered aluminium = 1.092 tons. Or, per 100 kg scrap entering the system 91.58kg secondary aluminium is produced, or 91.58%	(Aluminium Association, 2013)
15	It is assumed that the Bauxite originates in the Boke region of Guinea which has the country's main deposits, transported by rail and then shipped from the port of Conakry, the country's main port. Distance is 250km on Google maps	(Rolando Mazzuca, 2019; Alcoa.com, 2023) (African Development Bank Group, 2023) (Joshi, 2022) (Google Maps, 2023)
16	Conakry to Rotterdam is 3457 Nautical miles = 6402km	(ports.com, 2023)
17	It is assumed that the coke originates in Shandong Province, China, a major supply area in China for coke. As the province has its own coastline and several ports, it will be assumed that the distance to ship the coke falls within 300km	(Djukanovic, 2018)(Chuanjiao, 2023)(Google Maps, 2023)
18	Quingdao, Shandong, China to Rotterdam = 12351 nautical miles = 22874 km	(ports.com, 2023)
19	Alumina is typically transported in bulk, in containers	(Cargohandbook.com, 2023)
20	1935kg Alumina is required to make 1000kg primary aluminium. Therefore the % of previous stage remaining in the alumina is (1000/1935)*100=51.68%	(Aluminium Association, 2013)
21	GREET Vehicle cycle model indicates that for cast aluminium parts, 1.107 kg aluminium needed to make a 1kg part	(Argonne GREET Vehicle Cycle Model, 2021)

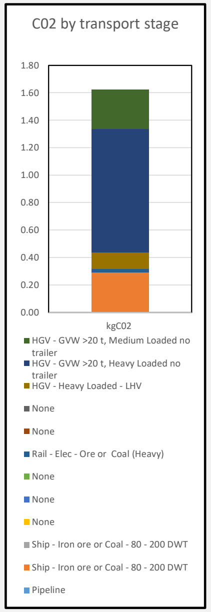
Calculator for: ICE-29 (Calculation Ref) *Blue values need to be entered.*
Chassis (w/o battery) (Subsystem)
Copper/Brass (Material)

1. Enter Mass of Material (kg): 4.9

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance	Cum. Dist. (km) 0	kgC02	Cum. C02 (kg)
				g/tkm		%	ton		km	0		
a.	1,2, 3	**Peru Mine to Hamburg port**	Pipeline	5	Copper Concentr	100	0.0046	Manual Entered Distance	170	170	0.00	0.00
b.	4	**Port To Port (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentr	100	0.0046	Intercontinental: Manual Enter	17525	17695	0.29	0.29
c.	5	**Port to refinery (Copper Concentrates)**	Ship - Iron ore or Coal - 80 - 20(	3.6	Copper Concentr	100	0.0046	None, N/A, or see Alongside	0	17695	0.00	0.29
d.	9, 10	**Proportional Adjustment (25/88) %**	None	0	Copper Concentr	30	0.0014	None, N/A, or see Alongside	0	17695	0.00	0.29
e.		***Row Not used***	None	0	Coke	100	0.0005	None, N/A, or see Alongside	22874	40569	0.00	0.29
f.		***Row Not used***	None	0	Coke	100	0.0005	National - 500km	500	41069	0.00	0.29
g.	6	**Polish Mine to Refinery in Hamburg**	Rail - Elec - Ore or Coal (Heavy	9.1	Ore	100	0.0037	Manual Entered Distance	680	41749	0.02	0.32
h.	9, 10	**Proportional Adjustment (20/88) %**	None	0		30	0.0011	None, N/A, or see Alongside	0	41749	0.00	0.32
i.	7,8	**Scrap Copper To Secondary Refinery**	Rail, Containers, Elec	14.6	Scrap Copper	100	0.0026	National - 500km	500	42249	0.02	0.34
j.	9	**Proportional Adjustment (43/80)%**	None	0		100	0.0026	None, N/A, or see Alongside	0	42249	0.00	0.34
k.		**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0049	National / Local - 300km	300	42549	0.12	0.46
l.		**Tier 2 Supplier to Tier 1 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Parts	100	0.0049	National - 1000km	1000	43549	0.90	1.36
m.		**Tier 1 Supplier to Auto Plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0049**	**National / Local - 300km**	**300**	43849	0.29	1.64
n.												





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Aurubis, Europe's largest copper producer is assumed to be the refiner and supplier at one of its facilities in Europe	(Kurlemann, 2022).
2	Chile, Peru and Brazil are the main suppliers of ore / concentrate to Germany. As Chile is the world's biggest supplier of copper this model will assume that it is supplied in Chile. Notwithstanding this, the shipping distance from Peru or Brazil is not dramatically differnt to Germany.	(Kurlemann, 2022) (International Copper Study Group, 2022)
3	Escodida, the world's largest copper mine is assumed to be the source. Concentrate is pumped 170km by pipeline to the port of Coloso	(www.mining-technology.com, 2020)
4	Copper concentrate is shipped in bulk for large quantiites. The distance from Coloso to Hamburg is 9463 nm = 17525km	(Bulkcarrierguide.com, 2010) (ports.com, 2023)
5	Aurubus's Hamburg plant is near the port of hamburg, and the concentrate is moved from the port to the plant via waterway. Thus for emissions purposes it will be assumed that this is part of the same sea journey. No addtiotnal distance therefore added	(Aurubis AG, 2021)
6	Poland is assumed to be the souirce of the ore, as its euope's largest producer of ore after Russia. Transporation assumed to be by rail, 680km	(TheGlobalEconomy.com, 2018) (Google Maps, 2023)
7	Scrap metal transported dry freight containers	(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)
8	Since 70% of copper in EU end of life products are recycled,, and given that Europe is a net exporter of scrap copper, it is assumed that the scrap copper is sourced from europe	(euric-aisbl.eu, 2020)
9	These rows adjust the propotion of copper according to each source. 43% recycled, 20% european mines and 25% imported ore or concentrate - accounting for 88% of Europeal supply. The remaining 12% is not modelled as its source cannot be accurately determined. Thus the above propotions are adjusted accordingly: Recycled at 43/88 percent, Eurpean mines at 20/88% and imported iron or concentrate at 25/88%	(Kurlemann, 2022)
10	Based on 30% copper concentrate	

Calculator for: ICE-31 (Calculation Ref) *Blue values need to be entered.*

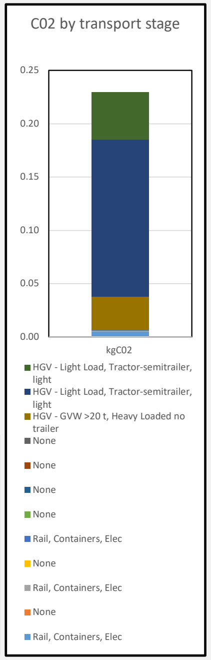
Chassis (w/o battery) (Subsystem)

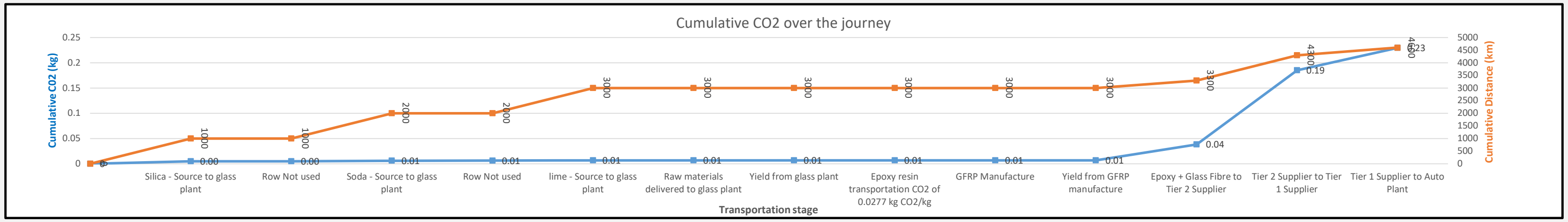
GFRP (Material)

1. Enter Mass of Material: 0.6 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a	2, 3, 4	**Silica - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0003	National - 1000km	1000	1000	0.00	0.00
		Row Not used	None	0		100		None, N/A, or see Alongside	0	1000	0.00	0.00
b	2,3, 5	**Soda - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0001	National - 1000km	1000	2000	0.00	0.01
		Row Not used	None	0		100		None, N/A, or see Alongside	0	2000	0.00	0.01
c	2,3, 6	**lime - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0000	National - 1000km	1000	3000	0.00	0.01
		Raw materials delivered to glass plant	None	0		100	0.0004	None, N/A, or see Alongside	0	3000	0.00	0.01
	1.	**Yield from glass plant**	None	0		72.25	0.0003	None, N/A, or see Alongside	0	3000	0.00	0.01
d		**Epoxy resin transportation CO2 of 0.0277 kg CO2/kg**	None	0			0.0003	None, N/A, or see Alongside	0	3000	0.00	0.01
		GFRP Manufacture	None	0			0.0006	None, N/A, or see Alongside	0	3000	0.00	0.01
d	7	**Yield from GFRP manufacture**	None	0		87.7193	0.0006	None, N/A, or see Alongside	0	3000	0.00	0.01
e		**Epoxy + Glass Fibre to Tier 2 Supplier**	HGV - GVW >20 t, Heavy Load	185.3	Bulk materials	100	0.0006	National / Local - 300km	300	3300	0.03	0.04
f	8	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0006	National - 1000km	1000	4300	0.15	0.19
g	8	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-sem**	**259.5**	**Parts**	**100**	**0.0006**	**National / Local - 300km**	**300**	4600	0.04	0.23





References and Input Assumptions

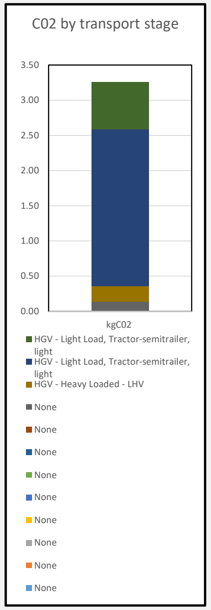
	Input Assumptions	Ref / Citation
1	Glass production at the melting stage has a yield of approx. 85%. A further reduction in yield for flat glass production is found, 85%. Total yield is therefore 85%*85%= 72.25%	Westbroek et el (2021)
2	Glass raw materials are sourced REGIONALLY in Europe.	(Glass for Europe, 2020)
3	glass comprises 75% silica sand, 15% soda ash and 10% lime.	Westbroek et el (2021)
4	Silica sand is typically transported by rail.	(Transportjournal.com, 2016; gbrailfreight.com, 2017)
5	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Cargohandbook.com, no date)
6	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Stork et al., 2014)
7	1.14 kg epoxy & glass fibre needed per 1kg GFRP. 1/1.14*100=87.7193	Keoleian et el (2012)
8	Due to low packing density of GFRP parts, it is assumed that the vehicles are "light" loaded	

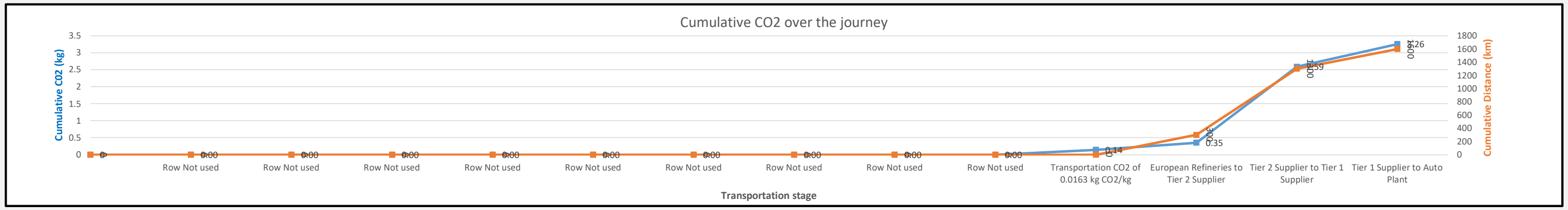
Calculator for: ICE-32 (Calculation Ref) *Blue values need to be entered.*
Chassis (w/o battery) (Subsystem)
Average
Plastic (Material)

1. Enter Mass of Material:
8.6 kg

ANSWER

Step	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance 0	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
Step	*Ref - See Below*		g/tkm		%	ton		km 0			
	Row Not used	None	0		100	0.0086	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0086	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0086	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0086	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0086	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0086	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0086	None, N/A, or see Alongside		0	0.00	0.00
	Row Not used	None	0		100	0.0086	None, N/A, or see Alongside	0	0	0.00	0.00
	Row Not used	None	0		100	0.0086	None, N/A, or see Alongside	0	0	0.00	0.00
1.	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.0086	None, N/A, or see Alongside	0	0	0.14	0.14
a	**European Refineries to Tier 2 Supplier**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0086	National / Local - 300km	300	300	0.21	0.35
b 2	**Tier 2 Supplier to Tier 1 Supplier**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0086	National - 1000km	1000	1300	2.24	2.59
c 2	**Tier 1 Supplier to Auto Plant**	**HGV - Light Load, Tractor-semi**	**259.5**	**Assemblies**	**100**	**0.0086**	**National / Local - 300km**	**300**	1600	0.67	3.26





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

Calculator for: ICE-B-47 (Calculation Ref)

Battery (Subsystem)

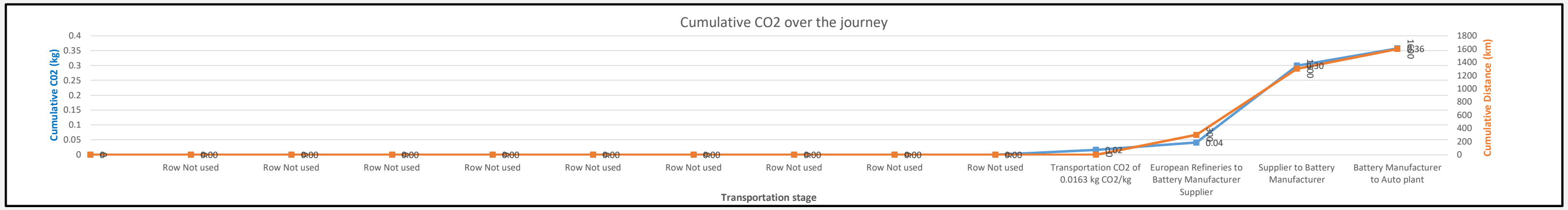
Average Plastic (Material)

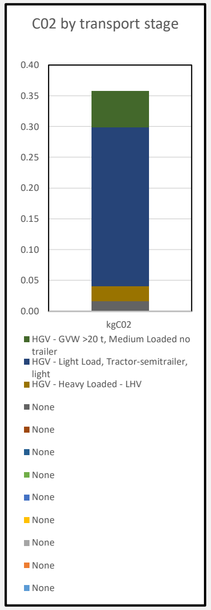
Blue values need to be entered.

1. Enter Mass of Material: 1.0 kg

ANSWER

Step		**Stage:**	2. Select Mode of transport	**Co2 factor CO2e (wtw)**	3. Form	% of prev stage	**Mass Transported**	4 Select Distance	or Enter Distance	Cum. Dist. (km) 0	**kgC02**	**Cum. C02 (kg)**
Step		*Ref - See Below*		**g/tkm**		%	**ton**		km	0		
		Row Not used	None	0		100	0.0010	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0010	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0010	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0010	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0010	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0010	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0010	None, N/A, or see Alongside		0	0.00	0.00
		Row Not used	None	0		100	0.0010	None, N/A, or see Alongside	0	0	0.00	0.00
		Row Not used	None	0		100	0.0010	None, N/A, or see Alongside	0	0	0.00	0.00
	1.	**Transportation CO2 of 0.0163 kg CO2/kg**	None	0		100	0.0010	None, N/A, or see Alongside	0	0	0.02	0.02
a		**European Refineries to Battery Manufactur**	HGV - Heavy Loaded - LHV	81.8	Combined supply	100	0.0010	National / Local - 300km	300	300	0.02	0.04
b	2	**Supplier to Battery Manufacturer**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0010	National - 1000km	1000	1300	0.26	0.30
c		**Battery Manufacturer to Auto plant**	**HGV - GVW >20 t, Medium Loa**	**196.6**	**Assemblies**	**100**	**0.0010**	**National / Local - 300km**	**300**	1600	0.06	0.36


Cumulative CO2 over the journey


C02 by transport stage

References and Input Assumptions

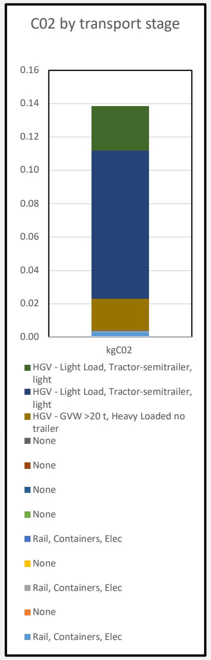
	Input Assumptions	Ref / Citation
1	The Plastics Europe transportations emissions figure of 0.0163 kg CO2 per kg is used in lieu of the above steps being calculated as discussed in the main report.	
2	Due to the low freight density of plastic components, a light loaded HGV is assumed for this journey for completed components	

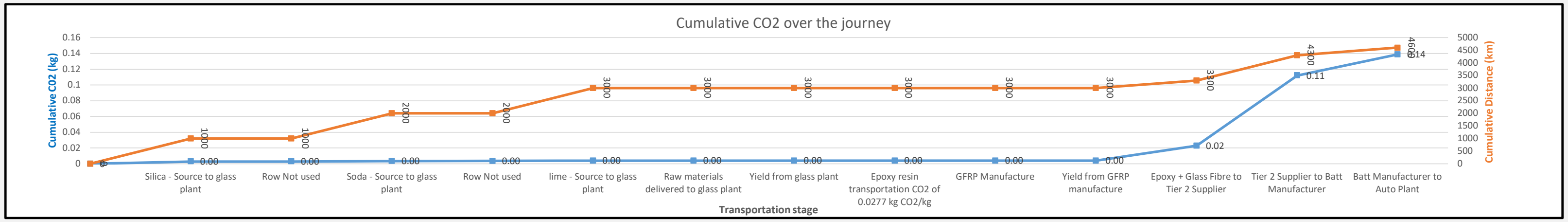
Calculator for: ICE-B-48 (Calculation Ref) *Blue values need to be entered.*
Battery (Subsystem)
GFRP (Material)

1. Enter Mass of Material:
0.3 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	Co2 factor CO2e (wtw) g/tkm	3. Form	% of prev stage %	Mass Transported ton	4 Select Distance	or Enter Distance km	Cum. Dist. (km)	kgC02	Cum. C02 (kg)
a	2, 3, 4	**Silica - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0002	National - 1000km	1000	1000	0.00	0.00
		Row Not used	None	0		100		None, N/A, or see Alongside	0	1000	0.00	0.00
b	2,3, 5	**Soda - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0000	National - 1000km	1000	2000	0.00	0.00
		Row Not used	None	0		100		None, N/A, or see Alongside	0	2000	0.00	0.00
c	2,3, 6	**lime - Source to glass plant**	Rail, Containers, Elec	14.6	bulk	100	0.0000	National - 1000km	1000	3000	0.00	0.00
		Raw materials delivered to glass plant	None	0		100	0.0003	None, N/A, or see Alongside	0	3000	0.00	0.00
	1.	**Yield from glass plant**	None	0		72.25	0.0002	None, N/A, or see Alongside	0	3000	0.00	0.00
d		**Epoxy resin transportation CO2 of 0.0277 kg CO2/kg**	None	0			0.0002	None, N/A, or see Alongside	0	3000	0.00	0.00
		GFRP Manufacture	None	0			0.0004	None, N/A, or see Alongside	0	3000	0.00	0.00
d	7	**Yield from GFRP manufacture**	None	0		87.7193	0.0003	None, N/A, or see Alongside	0	3000	0.00	0.00
e		**Epoxy + Glass Fibre to Tier 2 Supplier**	HGV - GVW >20 t, Heavy Loade	185.3	Bulk materials	100	0.0003	National / Local - 300km	300	3300	0.02	0.02
f	8	**Tier 2 Supplier to Batt Manufacturer**	HGV - Light Load, Tractor-semi	259.5	Parts	100	0.0003	National - 1000km	1000	4300	0.09	0.11
g	8	**Batt Manufacturer to Auto Plant**	**HGV - Light Load, Tractor-sem**	**259.5**	**Parts**	**100**	**0.0003**	**National / Local - 300km**	**300**	4600	0.03	0.14





References and Input Assumptions

	Input Assumptions	Ref / Citation
1	Glass production at the melting stage has a yield of approx. 85%. A further reduction in yield for flat glass production is found, 85%. Total yield is therefore 85%*85%= 72.25%	Westbroek et el (2021)
2	Glass raw materials are sourced REGIONALLY in Europe.	(Glass for Europe, 2020)
3	glass comprises 75% silica sand, 15% soda ash and 10% lime.	Westbroek et el (2021)
4	Silica sand is typically transported by rail.	(Transportjournal.com, 2016; gbrailfreight.com, 2017)
5	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Cargohandbook.com, no date)
6	Due to the large volumes used in the glass industry, bulk handling is assumed, therefore by rail.	(Stork et al., 2014)
7	1.14 kg epoxy & glass fibre needed per 1kg GFRP. 1/1.14*100=87.7193	Keoleian et el (2012)
8	Due to low packing density of GFRP parts, it is assumed that the vehicles are "light" loaded	

Rubber Calculations Rubber Transport Emissions value[1]: 0.192 kg co2 equivalent emissions per 1kg

Vehicle subsystem	Absolute Weight (kg)	Calc REF	ICE C02 emissions (Calculated [2]) (kg)	Absolute Weight (kg)	Calc REF	EV C02 emissions (Calculated [2]) (kg)
Body	13.510	ICE-08	2.594	15.526	EV-08	2.981
Powertrain System (Including BOP)	4.917	ICE-16	0.944		EV-16	0.000
Transmission System/Gearbox	4.556	ICE-24	0.875		EV-24	0.000
Chassis (w/o battery)	33.602	ICE-33	6.452	38.616	EV-33	7.414
Electronic Controller		ICE-41	0.000	3.802	EV-41	0.730

Footnotes:

1. See Section 5.3.7. of methodology chapter where this value is presented.
2. This value is obtained by multiplying the weight with the C02 emissions per kg figure

References for Calculation sheets

6 guidelines for scrap metal carriage - SAFETY4SEA (2022). Available at: https://safety4sea.com/6-guidelines-for-scrap-metal-carriage/ (Accessed: 29 July 2022).

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Appendix D - "Undefined" Materials not modelled

Where the material was labelled as "other" in the GREET data it was not modelled.
Where a material was excluded due to the modelling cutoff rules.

		ICEV: Conventional Material	EV: Conventional Material
Subsystem	**Material**	Weight (kg)	Weight (kg)
Body	Others	6.539	7.515
Powertrain System	Platinum	0.004	
Powertrain System	Others	0.009	
Transmission System/Gearbox	Others		0.389
Chassis (w/o battery)	Magnesium	0.369	0.424
Chassis (w/o battery)	Others	0.032	0.037
Electronic Controller	Others		12.741
Battery	Lead	11.267	
Battery	Water	2.302	
Battery	Sulphuric Acid	1.290	
Battery	Other	0.131	
Battery	LiPF6		7.050
Battery	Binder		9.791
Battery	Thermal insulation		13.316
Battery	Electronic Parts		4.308
Battery	Glycol		0.392

Appendix E - Weights by Subsystem for ICE and BEV from GREET Data Set

Values calculated from Argonne National Laboratory (2021).

Specification of Total Vehicle & Battery Weight

			ICEV: Conventional Material	EV: Conventional Material	
Car w/o Battery (lb)		1 kg = 0.45359237 lb	3183.471		3839.676
	(kg)		1443.998		1741.648
Battery	(lb)	Lead Acid	36.000	Li-ion	863.439
	(kg)		16.32932532		391.6492197
		Vehicle Total	**1460.328**		**2133.297**

Material Composition for each Subsystem, by weight

			ICEV: Conventional Material	EV: Conventional Material
		Material	Weight (kg)	Weight (kg)
	Subsystem:	Body		
Material:	Body	Steel	498.880	573.330
	Body	Wrought Aluminum	23.462	26.963
	Body	Cast Aluminum	1.258	1.446
	Body	Copper/Brass	14.510	16.676
	Body	Glass Fiber-Reinforced Plastic	6.489	7.458
	Body	Glass	33.947	39.013
	Body	Average Plastic	165.647	190.367
	Body	Rubber	13.510	15.526
	Body	Others		7.515
		Powertrain System (Including BOP)		
Material:	Powertrain System (Including BOP)	Steel	93.849	39.589
	Powertrain System (Including BOP)	Wrought Aluminum	10.728	0.000
	Powertrain System (Including BOP)	Cast Aluminum	49.474	0.000
	Powertrain System (Including BOP)	Copper/Brass	14.982	16.231
	Powertrain System (Including BOP)	Glass Fiber-Reinforced Plastic	5.502	0.000
	Powertrain System (Including BOP)	Average Plastic	42.098	23.357
	Powertrain System (Including BOP)	Rubber	4.917	0.000
	Powertrain System (Including BOP)	Platinum	0.004	0.000
	Powertrain System (Including BOP)	Others	0.009	0.000
		Transmission System/Gearbox		
Material:	Transmission System/Gearbox	Steel	27.337	58.892
	Transmission System/Gearbox	Copper	0.000	18.398
	Transmission System/Gearbox	Cast Iron	27.337	0.000
	Transmission System/Gearbox	Wrought Aluminum	27.337	19.468
	Transmission System/Gearbox	Average Plastic	4.556	0.195
	Transmission System/Gearbox	Rubber	4.556	0.000
	Transmission System/Gearbox	Others	0.000	0.389
		Chassis (w/o battery)		
Material:	Chassis (w/o battery)	Steel	245.216	281.811
	Chassis (w/o battery)	Wrought Aluminum	5.531	6.356
	Chassis (w/o battery)	Cast Aluminum	68.274	78.463
	Chassis (w/o battery)	Copper/Brass	4.858	5.583
	Chassis (w/o battery)	Magnesium	0.369	0.424
	Chassis (w/o battery)	Glass Fiber-Reinforced Plastic	0.567	0.652
	Chassis (w/o battery)	Average Plastic	8.620	9.906
	Chassis (w/o battery)	Rubber	33.602	38.616
	Chassis (w/o battery)	Others	0.032	0.037
		Traction Motor		
Material:	Traction Motor	Steel		58.567
	Traction Motor	Cast Aluminum		58.567
	Traction Motor	Copper/Brass		45.102
		Electronic Controller		
Material:	Electronic Controller	Steel		5.137
	Electronic Controller	Cast Aluminum		48.190
	Electronic Controller	Copper/Brass		8.425
	Electronic Controller	Rubber		3.802
	Electronic Controller	Average Plastic		24.454
	Electronic Controller	Others		12.741

Material Composition for each Subsystem, by weight (continued)

			ICEV: Conventional Material	EV: Conventional Material
Batteries	Subsystem		Actual weight (kg)	Actual weight (kg)
	Battery	Lead	11.267	0.000
	Battery	Water	2.302	0.000
	Battery	Sulphuric Acid	1.290	0.000
	Battery	Plastics	0.996	0.000
	Battery	Glass Fiber	0.343	0.000
	Battery	Other	0.131	0.000
	Battery	Copper	0.000	43.081
	Battery	Wrought Al	0.000	74.413
	Battery	Graphite / carbon	0.000	58.747
	Battery	Electrolyte - EC - Ethylene carbonate	0.000	20.757
	Battery	Electrolyte - DMC - Dimethyl carbonat	0.000	20.757
	Battery	LiMn204	0.000	129.244
	Battery	LiPF6	0.000	7.050
	Battery	PP	0.000	6.658
	Battery	PE	0.000	1.136
	Battery	PET	0.000	4.700
	Battery	Binder	0.000	9.791
	Battery	Thermal insulation	0.000	13.316
	Battery	Electronic Parts	0.000	4.308
	Battery	Steel	0.000	5.483
	Battery	Glycol	0.000	0.392

APPENDIX F - Calculation for 50kg car door

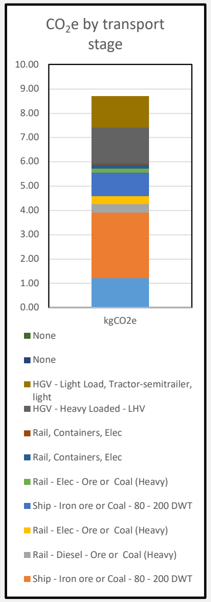
Calculator for: n/a (Calculation Ref)
Door from sheet metal (Subsystem)
Steel (Material)

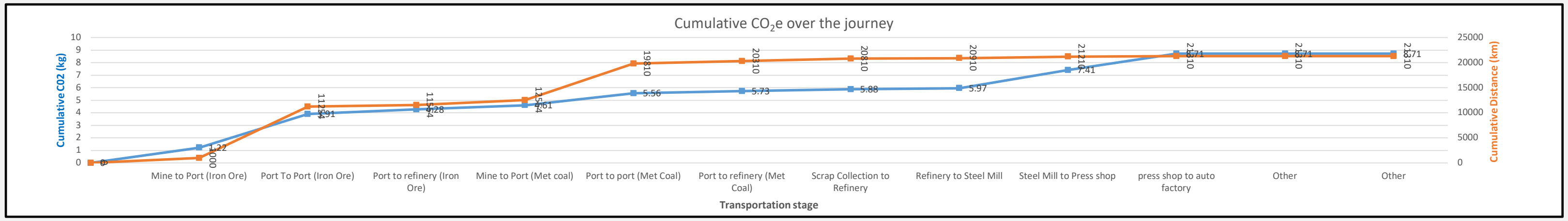
Blue vlaues need to be entered.

1. Enter Mass of Material: 50.0 kg

ANSWER

Step	Ref - See Below	Stage:	2. Select Mode of transport	CO₂ factor CO₂e (wtw)	3. Form	% of prev stage	Mass Transported	4 Select Distance	or Enter Distance 0	Cum. Dist (km)	kgCO₂e	Cum. CO₂e(kg)
				g/tkm		%	ton		km 0			
a.	1.	**Mine to Port (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	100	0.0729	National - 1000km	1000	1000	1.22	1.22
b.	1, 2,3	**Port To Port (Iron Ore)**	Ship - Iron ore or Coal - 80 - 20	3.6	Ore	100	0.0729	Intercontinental: Brazil - Rotte	10254	11254	2.69	3.91
c.	3.	**Port to refinery (Iron Ore)**	Rail - Diesel - Ore or Coal (Hea	16.7	Ore	1.18t per ton	0.0729	National / Local - 300km	300	11554	0.37	4.28
d.	6.	**Mine to Port (Met coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	100	0.0365	National - 1000km	1000	12554	0.33	4.61
e.	7. 8. 9.	**Port to port (Met Coal)**	Ship - Iron ore or Coal - 80 - 20	3.6	Coal		0.0365	Intercontinental: New york - Ro	7256	19810	0.95	5.56
f.	1.	**Port to refinery (Met Coal)**	Rail - Elec - Ore or Coal (Heavy	9.1	Coal	.59t per ton	0.0365	National - 500km	500	20310	0.17	5.73
g.	**4., 5.**	**Scrap Collection to Refinery**	Rail, Containers, Elec	14.6	Scrap metal	.34t per ton	0.0210	National - 500km	500	20810	0.15	5.88
h.	10, 13	**Refinery to Steel Mill**	Rail, Containers, Elec	14.6	Steel Ingots	100	0.0620	Local 100 km	100	20910	0.09	5.97
i.	12, 13	**Steel Mill to Press shop**	HGV - Heavy Loaded - LHV	81.8	Sheet metal roll	94.9	0.0588	National / Local - 300km	300	21210	1.44	7.41
j.	10, 11	**press shop to auto factory**	HGV - Light Load, Tractor-semi	259.5	Pressed Panel	85	0.0500	Local 100 km	100	21310	1.30	8.71
k.		**Other**	None	0		100	0.0500	None, N/A, or see Alongside	0	21310	0.00	8.71
l.		**Other**	None	0		100	0.0500	None, N/A, or see Alongside	0	21310	0.00	8.71





References and Input Assumptions

<table>
<tr><th></th><th>Input Assumptions</th><th>Ref / Citation</th></tr>
<tr><td>1.</td><td>Inputs for 1 tonne of steel
<table>
<tr><th></th><th colspan="3">Inputs</th><th>Output crude steel</th></tr>
<tr><td></td><td>Iron ore</td><td>mettalurigal coal coal</td><td>recyc steel</td><td></td></tr>
<tr><td>per tonne</td><td>1.18</td><td>0.59</td><td>0.34</td><td>1.00</td></tr>
</table></td><td>Calculated from Worldsteel.org (2019)</td></tr>
<tr><td>2</td><td>Ore from Brazil (51.7 %of German Iron ore is from brazil) (dist 8000km)</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>3</td><td>Distance from mining region to Ponta de Maderia - Approx 1000km</td><td>(Cepeda, Barros Kneipp and Caprace, 2019)</td></tr>
<tr><td>3</td><td>Ore from Ponta del maderia (Brazil) (Cepeda, Barros Kneipp and Caprace, 2019) to rotterdam 5537 Nautical miles =10254 km</td><td><i>(Iron ore | Port of Rotterdam, 2022)</i>
(Cepeda, Barros Kneipp and Caprace, 2019)
(Ponta da Madeira , Brazil to Port of Rotterdam, Netherlands - Sea route & distance - ports.com, 2022)</td></tr>
<tr><td>4</td><td>Scrap metal sourced from within germany or from Czech Republic, (21.9%) (510km) Poland(14.9%) (755 km) or Netherlands (15.9%) (469km). Thus a typical average distance of 500 km is assumed.</td><td>(Elsner et al., 2019)</td></tr>
<tr><td>5</td><td>Scrap metal transported dry freight containers</td><td>(6 guidelines for scrap metal carriage - SAFETY4SEA, 2022)</td></tr>
<tr><td>6</td><td>Germany's biggerst supplier of coal and coke is russia, at 40% in 2018. But due to sanctions the second biggest supplier is assumed, The USA</td><td>(Elsner et al., 2019), (Update: sanctions and trade restrictions against Russia | Deloitte Legal Germany, 2022)</td></tr>
<tr><td>7</td><td>Coking Coal provided from western USA deposits</td><td>(Trippi et al., 2021)</td></tr>
<tr><td>8</td><td>69% of coal in the usa is moved by rail, thus rail transporation is assumed</td><td><i>(Freight Railroads & Coal | Association of American Railroads</i> , 2022)</td></tr>
</table>

9	Transporation from usa to europe is New York to Rotterdam, 3918 nautical miles = 7256km	(Geneva, 2021) (Iron ore | Port of Rotterdam, 2022) (World seaports catalogue, marine and seaports marketplace, 2022)
10	**Journey of body panels as per Gaither & frazer and Hua et el**	(Gaither, N. and Frazier, 2002) (Hua et al., 2022)
11	15% offcut scrap average in press shop	(Lore and Czechmeister, 2013) (Dallan, 2016)
12	Typically 80 percent of European steel is sourced from Europe. Thus local distances of up to 100 km are assumed.	(*European Steel in Figures 2020* , 2020)
13	Cold rolled steel as used in body panels has a loss factor of 1.054 i.e. 1/1.0154 = 94.9% goes to next stage	(Argonne GREET Vehicle Cycle Model, 2021)

Appendix G – Alternative Methods and Critical reflections on the LCA approach.

As noted in section 1.1.4. the LCA approach was developed for the purpose of evaluating a products' environmental impact across its life time, and following its incorporation into the ISO standards, has become the most established and preferred approach for evaluating a products' environmental impact across its life time (Ness *et al.*, 2007; Guinée *et al.*, 2011; Hellweg *et al.*, 2023). Indeed during the course of this research no other approach was found which was comparable and which also took a systems approach.

However it was noted that other approaches are also used when evaluating the environmental impact of different options (as discussed by Finnveden and Moberg (2005) and by Ness et al (2007) for example). These approaches are noted below[1] and in each case appraised according to their suitability for a systems paradigm evaluation.

Ness et al (2007) make a distinction between tools which are used as indicators or indices (for example as applied to carbon emissions generated by a geographical region); tools which are product related (for example as applied to the life cycle of an automobile) and "change oriented" tools which are applied to a project, or the impact of a policy change (Finnveden and Moberg, 2005). This discussion will focus on product related tools, as the other two are outside the scope of the aims and objectives.

A critical reflection on the LCA approach follows.

G1 – Alternative approaches to the Life Cycle Assessment method.

G1.1 Life cycle costing

The main focus of the life cycle costing approach is a financial one, and thus not relevant to this research.

G1.2. Product material flow analysis

This method focusses on <u>flows</u> of material in a production system and seeks to evaluate the overall environmental impact based on the environmental impact the component materials.

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[1] Finnveden and Moberg (2005) and by Ness et al (2007) document and discuss the approaches noted here and are thus not repeatedly cited in the discussion.

While this approach is very useful where the actual values of the environmental impact of the component materials are known, it is difficult to apply to this research which is concerned with emissions arising due to logistics activities which are ancillary to the manufacture of materials. Thus, the scope of this method limits its application to research what focusses specifically on transportation emissions.

G1.3. Product energy analysis

This approach focusses on the *energy* applied when manufacturing a product. While it is normally restricted to the production of a product, although it appears to be transferrable to supporting activities such as logistics. However, as its name suggests, the focus is on energy usage, rather then carbon emissions, and thus stops short of the carbon emissions focus of this research.

G.2. Critical evaluation on the LCA approach.

As noted above, the life cycle assessment approach is widely used and has several strengths which support its wide spread popularity. In the first place the methodology of how to conduct a life cycle assessment is comprehensively documented in the ISO standards and thereby makes it a benchmark which people across the world can use to produce comparable results assuming the methodology has been consistently and accurately followed (Ness *et al.*, 2007; Guinée *et al.*, 2011; Del Pero, Delogu and Pierini, 2018; Hellweg *et al.*, 2023)..

Its popularity can also be considered a strength: because of its widespread use it is generally well understood and this it allows for comparisons from different studies where the assumptions are the same. Moreover it also office flexibility which other approaches may not have as noted below. For example the person performing the lifecycle assessment can choose which environmental criteria to focus on whereas other methodologies often are specific as to which criteria they are evaluating time (Ness *et al.*, 2007; Guinée *et al.*, 2011; Hellweg *et al.*, 2023)..

However, this does not imply that the LCA approach is without risks or challenges. This section notes three key issues when performing a LCA and how they have been balanced in this research.

They are:

- Inconsistency in LCA methodology

- Boundaries used in LCA calculations
- Collection and accuracy of data used when performing an LCA

The discussion below discusses these in greater detail, and notes how they have been mitigated in this research.

As early as 1995, authors such as Lee et al (1995) provided critique on the life cycle assessment approach. They argued that without a clear and consistent understanding of the technique, variable results could be achieved between different evaluations, and thus limiting the extent to which evaluations are credible and can be compared (more recently echoed by Gutowski (2018).

They also noted the important of selecting system boundaries (already discussed in section 2.2.1 and 2.4. (and also discussed by Del Pero et al (2018) which is cited in sections 1.1.4 and 7.2 in particular)). They note issues surrounding the collection of data, and how both these factors can affect the results. These are of particular importance when comparing results from different studies (as noted in section 7.2. and 7.2.1.).

Ayres (1995) echoes the points above and also notes the difficulty in obtaining data from published sources and notes that LCA's based on organisations' internally available "confidential" data may prove to be unreliable and are certainly unverifiable if kept confidential. Echoing these concerns on data, Bamber et al (2020) note the risk of uncertainty in LCA results, arising from data uncertainty as well as inconsistency in LCA application in methodology which may produce differing results.

These challenges surrounding data availability and relevance to this study were encountered in this research and limited the data suitable for this work (and underscore the discussion in section 4.4 and 7.2.1).

In each of the above cases, where these issues have arisen, their effect has been accounted for and mitigated in the relevant sections of the main document.

References Appendix G

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Appendix H – European Automotive Production Volumes concentrations compared.

Table H.1. Vehicle production by country in Europe – top 10 producers.

Top ten EU car producers	2023	2022
Germany	3,959,322	3,336,546
Spain	1,869,988	1,741,084
Czechia	1,395,211	1,214,746
Slovakia	1,062,058	970,275
France	959,404	948,341
Italy	542,218	484,345
Hungary	504,907	452,551
Romania	501,337	509,465
Belgium	287,211	243,293
Sweden	276,070	251,446

Source: ACEA (2023)