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CO_2e Intensity Assessment of Ryanair Aviation Activity with Sustainable Aviation Fuel

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Abstract

The aviation industry must reduce its emissions and sustainable aviation fuel (SAF) is most likely the primary method of decarbonisation in the short to medium term. A novel life cycle assessment (LCA) methodology is developed to account the CO_2e cost of aviation activity which uses SAF. The novel methodology is developed because existing LCA tools are found to lack the transparency and flexibility desired in this study. Most current LCA studies of sustainable aviation consider only the life cycle of the SAF and report results in grams of CO_2e per megajoule of fuel (gCO_2e/MJ). Since this study considers the aviation activity in full, results are reported in grams of CO_2e per revenue-passenger-kilometre (gCO_2e/RPK).

The methodology considers emissions associated with the fuel and auxiliary airport operations required for the aviation activity. The life cycle of the SAF is split into five stages: Feedstock Production, Feedstock Transportation, Fuel Production, Fuel Transportation and Blending, and Aircraft Operations. The emissions from the auxiliary airport operations are accounted in the Airport Operations stage. This methodology emphasises the use of actual supply chain data to specifically model the real-world activity as accurately as possible.

The methodology is used to model a scenario of Ryanair activity; a flight from Amsterdam to Dublin using a Boeing 737-8200 aircraft and a 40% blend of SAF derived from used cooking oil and produced by Neste. Four scenarios of feedstock sourcing are modelled. Depending on the source of the feedstock, the life cycle emission intensity of the SAF ranged from 16.5 - 24.8 gCO_2e/MJ, representing a 73 - 82% reduction compared to fossil aviation fuel. The Fuel Production stage contributes most to the life cycle emissions, mainly due to the energy intensive nature of the hydrogen production that is required for converting the feedstock to SAF. Shipping is seen make-up by far the largest share of transport emissions and highlights the need for supply chain optimisation. In scenarios of large transportation distances, shipping is a limiting factor of SAF sustainability. For the primary scenario, the aviation activity is seen to produce 50.4 gCO_2e/RPK.

Keywords: Life cycle assessment, sustainable aviation, sustainable aviation fuel, emissions calculation

List of Publications and Presentations:

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1. Introduction

Aviation accounts for approximately 2% of global CO_2 emissions, and produced more than 915 million tonnes of CO_2 in 2019 [1]. Although this is a small percentage, the absolute quantity of emissions is very large and causes a significant environmental effect. In Ireland, the Department of Transport reported that aviation fuel accounted for 21% of all energy used in the transport sector during 2016 [2]. Aviation is a very important part of the global economy, providing 65 million jobs worldwide [3] and supporting millions more by allowing quick international travel. Therefore, aviation activity will continue in the future and a sustainable way of operating must be developed and practiced. In 2021, the International Air Transport Association set the target for the industry to achieve net-zero carbon emissions by 2050 [4]; an ambitious target, especially considering the International Civil Aviation Organisation forecasts aviation demand to grow by over 4% per year from 2015 to 2045 [3].

There is a significant interest in aviation sustainability in Ireland due to the prominence of the aircraft leasing industry. 14 of the world's top 15 aircraft lessors are based in Ireland and over 60% of all leased aircraft globally are managed by Irish based leasing companies [5]. These leasing companies are invested in reducing emissions for their indirect emissions and the direct emissions of their airline clients.

Aviation has additional challenges compared to other industries and transport sectors due to the energy density and safety requirements of its fuel. Unlike road vehicles, current battery technology is not feasible for electric commercial aircraft due to the substantial weight it would add. Aviation is a very highly regulated industry; any alternative fuels must undergo strict and extensive testing before they can be certified [6] for use. Enter sustainable aviation fuels.

1.1. Sustainable Aviation Fuel

Sustainable aviation fuel (SAF) is produced from non-fossil sources and offers reduced life cycle CO_2e (carbon dioxide equivalent) emissions compared to fossil aviation fuel. SAF is produced to meet the same physical and chemical property certification requirements as fossil aviation fuel to be used as a 'drop-in' fuel. No modifications are needed to existing fuel supply infrastructure or aircraft to transport or combust SAF. These are still liquid hydrocarbon fuels and therefore produce similar direct emissions to fossil aviation fuel when combusted. The reduction in emissions comes from the fact that the carbon emitted by the SAF was already in the atmosphere and sequestered during feedstock production; it is recycled. Therefore, no new carbon previously stored within the earth is emitted to the atmosphere, as is the case for fossil aviation fuel. SAF is seen as the most viable option for the aviation industry to reduce emissions in the short to medium term. The Air Transport Action Group [7] project SAF to be responsible for 71% of aviation emission reductions by 2050 as shown by Figure 1.

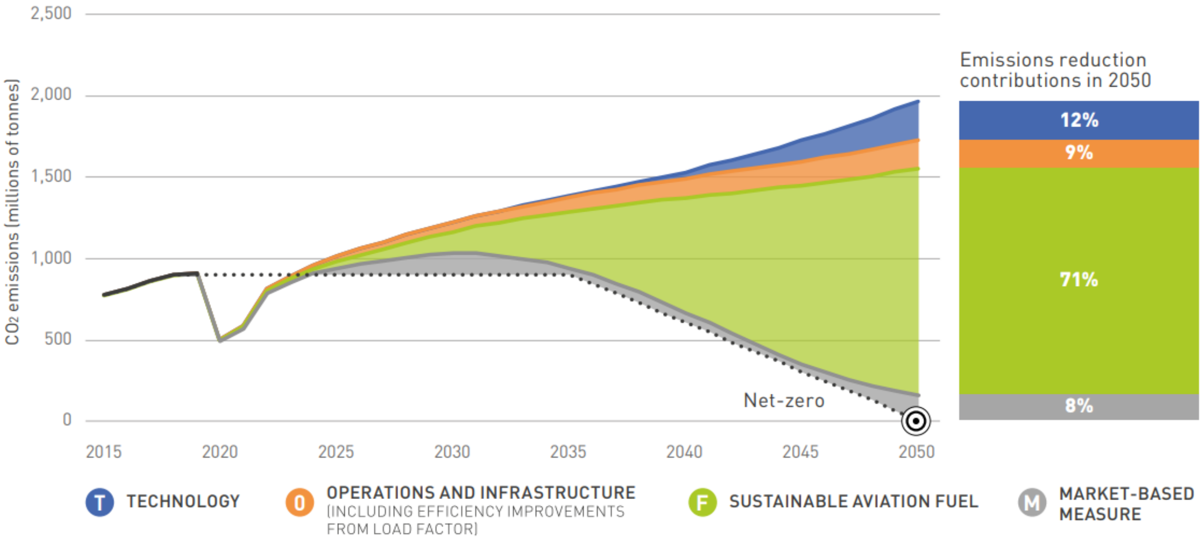


Figure 1: Emission reduction pathway for the aviation industry to reach net-zero emissions by 2050. This is the aggressive sustainable fuel deployment scenario as developed by the Air Transport Action Group [7]. Note that SAF makes up most of the emissions reduction in this projection.

There are different pathways of SAF production, at different stages of technical and commercial maturity. The hydroprocessed esters and fatty acids (HEFA) pathway, in which biologically derived feedstocks such as vegetable oils and animal fats are converted into fuel through a series of chemical processes, is well developed. Neste are currently producing SAF from the HEFA pathway. Neste's Porvoo refinery has a production capacity of 100,000 tonnes of HEFA SAF per year [8]. Other SAF production pathways include Fischer-Tropsch, alcohol-to-jet, and power-to-liquid. Certified SAFs can be blended up to 50% with fossil aviation fuel under current legislation.

There is a high demand for SAF among airlines despite the higher price when compared to fossil aviation fuel. Many airlines have already signed SAF partnerships with fuel producers. Ryanair have agreed a deal to use a 40% blend of Neste SAF on approximately one third of flights from Amsterdam Airport Schiphol [9], and have signed other agreements with OMV [10] and Shell [11]. This is contributing to Ryanair's goal of 12.5% SAF use by 2030 and the achieving of their target to reduce their emission intensity to 60 grams of CO_2e per revenue passenger kilometre (gCO2e/RPK) by 2030 [12]. Many other airlines have also agreed similar deals to secure the future supply of SAF.

1.2. Life Cycle Assessment

Life cycle assessment (LCA) is the study of a product, service, or activity's environmental impact throughout all stages of its life. This is known as a cradle-to-grave approach. For SAF, this includes the emissions generated from production, transportation, and combustion. SAFs are meant to reduce emissions compared to fossil aviation fuel and LCA is the method by which we can ensure they do. This 'carbon counting' is essential to identifying the most promising SAF feedstock, production processes and increasing the knowledge of their environmental impact.

In the fuel combustion process, CO_2 is produced. For fossil aviation fuel, this CO_2 was previously stored in crude oil beneath the surface of the earth; the process of fuel combustion resulted in the addition of this carbon to the atmosphere. When SAF is combusted, a very similar amount of CO_2 is emitted, but this CO_2 was already in the atmosphere. It was either directly captured from the air or absorbed from the air during the growth of plant matter. Therefore, there are no new CO_2 emissions associated with the combustion of SAF. However, there is a carbon cost to the intermediate processes that are needed to produce the feedstock, convert the feedstock into fuel, and transport the feedstock and fuel. LCA is used to account these emissions.

The motivation for this work stems from the current uncertainty and generalisation in SAF LCA calculations. Figure 2 shows the range of LCA values for approved SAF production pathways. There is a wide range of results depending on the production process and feedstock. While these values can be used by airlines to claim emission credits, they are general and do not represent scenarios of specific fuel use in specific aircraft. The novel methodology described in Chapter 3 aims to increase the specificity of SAF LCA results based on the feedstock used, production process and geographical location.

There are several LCA models that are available and have been used in previous LCA studies of SAF and other alternative fuels. The Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) Model [13] developed by Argonne National Laboratory, and sponsored by the United States Department of Energy is among the most popular. This tool is free to use and open source. GHGenius [14] is another open source LCA model focused on transportation fuel, developed by (S&T) Squared Consultants in Canada. Some LCA tools require a licence to use, such as SimaPro which is developed by PRé Sustainability in the Netherlands [15]. GREET and SimaPro were the most frequently used models in the literature discussed in Chapter 2.

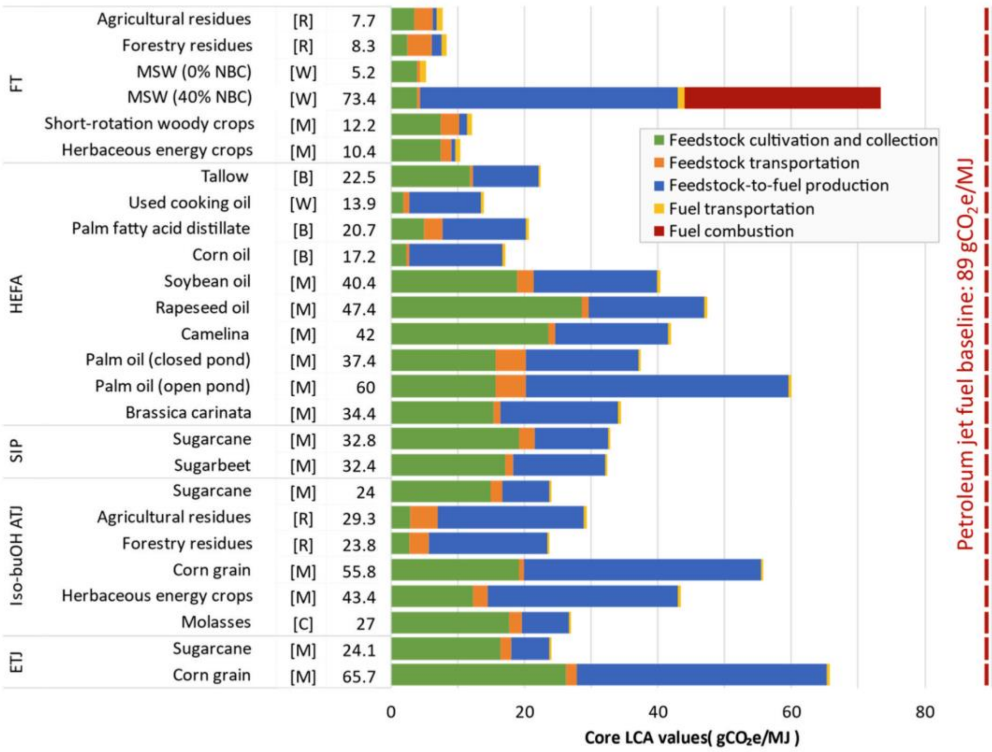


Figure 2: Default Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) LCA values of approved SAF production pathways developed by a working group. The values do not consider induced land use change. Note that pathways labelled [R] refer to residue feedstock, [W] to wastes, [M] to main-products, [B] to by-products, and [C] to co-products.

1.3. Policy Measures

One of the most relevant policy measures for aviation emissions is the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [16]. Its major objective is for the aviation industry to achieve carbon neutral growth from 2020. It informs airlines on monitoring, reporting and verification requirements of their emissions and hence offsetting requirements. Offsetting credits can be claimed from the use of CORSIA eligible fuel. The default life cycle emissions for these eligible fuels were developed by independent researchers [17] and listed in Figure 2.

The EU Emissions Trading Scheme (ETS) is the world's biggest carbon market. Under the EU ETS, EU carbon pricing applies to all intra EU flights, and flights departing from EU countries to Switzerland or the United Kingdom. In 2026, the European Commission will assess the effectiveness of CORSIA and if necessary, extend the EU ETS to flights departing EU countries for non-EU countries, if it is deemed that CORSIA is not sufficient.

The European Green Deal is a policy measure introduced by the European Commission in 2019 to ensure no new emissions of greenhouse gases in 2050 and to decouple economic growth from resource use [18]. This includes the ReFuelEU [19] legislation which sets targets for the introduction of SAF into the European aviation fuel mix: 5% SAF use by 2030, scaling up to 63% by 2050. Renewable fuels of non-biological origin (RFNBO) should contribute to at least 28% of the aviation fuel mix by 2050 due to its higher emission saving potential over SAF derived from biomass. This sub-obligation is expected to partially de-risk the investment in RFNBO research and development. The UK government [20] is also working on legislation for SAF use and decided to introduce a HEFA cap under the SAF mandate to accelerate the deployment of alternative SAF pathways.

2. Literature Review

This chapter presents a review of the relevant literature on LCA calculations of SAF. Thirty-six papers are sourced, and a summary of these studies is found in Table A1 in Appendix A. Figure 3 shows the frequency of SAF LCA publications in the literature; a notable increase is seen in recent years. Figure 4 shows the distribution of journals in which the 36 papers were published. Key learnings from these studies are discussed in this Chapter. Some LCA calculations of other alternative fuels are also included in the literature review, as learnings can be taken from these and applied to the modelling of SAF.

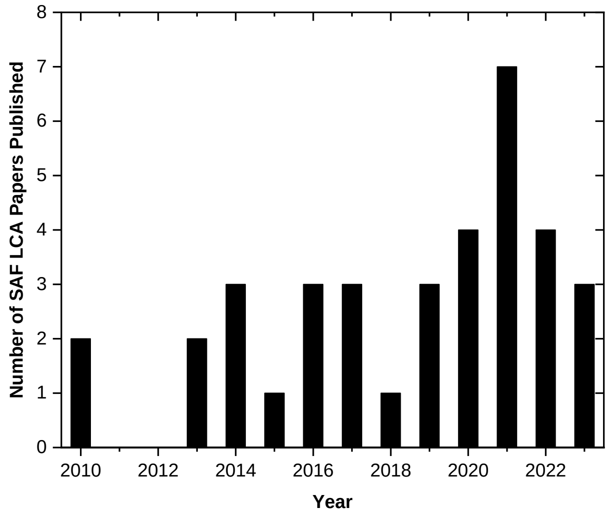


Figure 3: The number of SAF LCA papers published per year from 2010 are graphed.

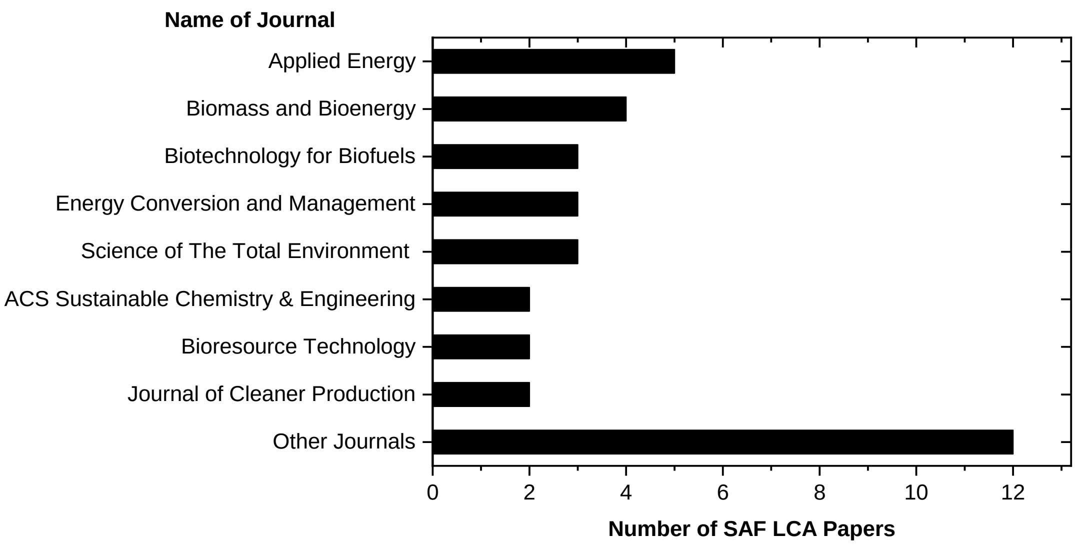


Figure 4: List of the most popular Journals in which the peer review SAF LCA literature was found from 2010 to 2023. Journals that only featured once are grouped into the 'Other Journals' category.

2.1. Feedstock Production Stage

CORSIA [21] describes four categories of SAF feedstocks: primary products, wastes, residues, and by-products. When the feedstock is not a primary product, it is assumed to incur zero emissions during feedstock production. When the feedstock is a primary product, emissions from farming machinery, chemical use, and land use change must be considered. Nitrogen fertilizer was commonly found to be a significant contributor to life cycle emissions [22-26] due to the energy intensive nature of its production. Kim et al. [27] found that fertilizer requirement changes with feedstock, and therefore the selection of feedstock influences the emissions associated with the fertiliser. Bailis and Baka [28] estimated the use of fertilizer by assuming it is applied at the rate of nutrient loss through the annual harvest; their study also found that irrigation has a small impact on the emissions of SAF production in Brazil. Rathore et al. [26] noted that nitrogen gases have an effect on acidification and eutrophication as well as global warming potential, and recommended future LCA studies to investigate these effects. Nikander [29] chose to exclude fertilizer and pesticide emissions from the system boundary. Considering that these emissions have proved to be significant in other studies, their exclusion leaves a potentially large gap and uncertainty in the results.

2.2. Fuel Production Stage

The fuel production stage of the SAF life cycle concerns the conversion of feedstock into fuel. This discussion is centred around the production stage of HEFA SAF as this is the most prominent and well-developed production pathway for SAF and is also the pathway of interest for the first scenario modelled by TCD using the methodology described in Chapter 3.

The production of hydrogen for use in the fuel production process is often cited as a large source of greenhouse gas emissions [24, 25, 28, 30]. Hydrogen is one of the main inputs during the hydrotreatment process of biomass [31]. Hydrogen usage is typically large for biomass feedstocks due to their high oxygen content [32]; one of its primary purposes is to remove this oxygen as water. Ringsred [33] studied SAF produced from forest residues via fast-pyrolysis and found that hydrogen produced via steam methane reforming accounted for 68-77% of life cycle emissions of the SAF.

Like the feedstock production stage, data for the fuel production stage of the LCA is limited. Han et. al [23] criticises LCA studies of SAF for using generic assumptions and not considering the processing requirements for different feedstocks; they describe how a detailed model of process reactions during fuel production can improve estimates of process energy usage. Ganguly et al. [34] used Aspen Plus to model the fuel production process and create mass and energy balances. This specific modelling of the fuel production process is a tenant of this study.

Neste's NExBTL process has also been modelled; this is of interest in this work. Nikander [29] conducted an LCA of biofuel produced by Neste in their Porvoo refinery as part of the Neste Oil Research Centre. The data used by Nikander was a mix of secondary data collected from the literature and primary data collected directly from the company's own documentation and actual process data. However, it is not made explicitly clear which data is taken directly from Neste. We return to the issue of transparency later.

2.3. Transportation Stage

For SAF, the transportation of feedstock from its location of production to the fuel production facility must be considered as well as the transportation of finished fuel onwards to the location of use, in an aircraft. The Greenhouse Gas Protocol [35] has developed guidance on how to calculate and report emissions associated with transportation activity. The Greenhouse Gas Protocol's preferred method is the Fuel-Based Method, where the quantity of fuel used is known and an emissions factor is directly applied, because it does not require any assumptions. Other options are the Distance-Based and Spend-Based Method if only the distance travelled, or the cost of fuel used is known. These are not favoured as Distance-Based Method relies on accurate fuel consumption data and the Spend-Based Method can vary by region.

Where hypothetical assessments are carried out, locations are assumed based on probable land availability and logistics. Ganguly et al. [34] estimated a distance of 80 km from forest residue collection to a pre-treatment facility by a mix of dirt, gravel and highway roads. Budsberg et al. [30] estimated a similar distance of 100 km from harvest to biorefinery locations and noted that this stage of the life cycle had a very small effect on the global warming potential of the fuel, possibly due to the short distance that was assumed. Ringsred et al. [33] also noted that feedstock transport had a minimal impact on carbon intensity in a GHGenius study. This is contradicted by Barbera et al. [36] who found high sensitivity to transportation when used cooking oil was used as a feedstock for HEFA SAF. This shows transportation to be a complex topic and influenced by the modelling assumptions. Nikander [29] considered the transportation of animal fat feedstock to be 322 km by road from a Finnish rendering plant to Neste's Porvoo refinery. It is not clear if this was an assumption or if this accurately represented the supply chain of actual Neste operations. The finished biofuel was then estimated to be transported 200 km by road to a pumping station. The average weight of one truck load was assumed to be 39 tonnes. The total product transport distance was set to 400 km in this case to include the return journey of the empty truck to the refinery. Budsberg [30] also considered the transport of the studied biojet fuel from biorefinery to distribution centre to include the round trip, and assumed the distance at 640 km.

2.4. Co-Product Allocation

When SAF is produced, there are usually co-products such as biodiesel, naphtha, and propane produced from the same process [31]. Allocation in LCA refers to how GHG emissions from the fuel production process is distributed among the products. There are several approaches for allocating emissions: energy, mass, or economic value of the products produced. There is also displacement, where credit is given based on the GHG intensity of the fossil fuel displaced. Figure 5 shows that many SAF LCA studies consider more than one allocation method to highlight the difference between them. Figure 6 shows that energy is the most popular method.

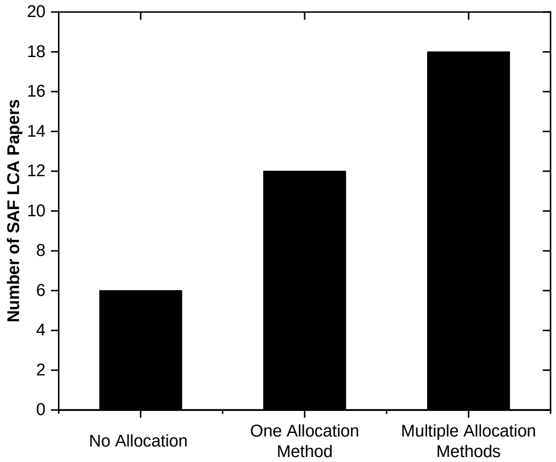


Figure 5: Number of allocation methods used in SAF LCA literature. Note that for the case of No Allocation, it may not have been considered, or all co-products may have been recycled and used internally in the fuel production process.

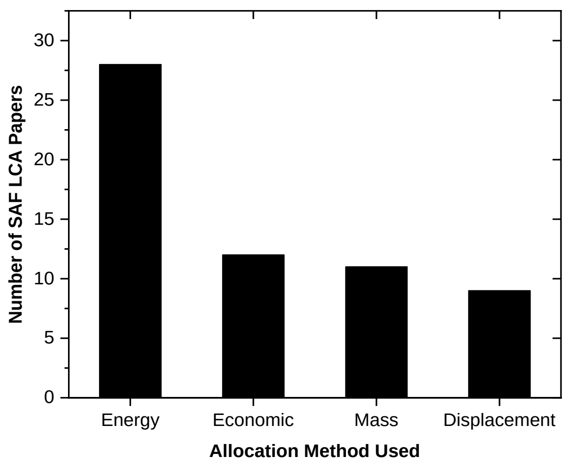


Figure 6: Allocation methods used in SAF LCA literature. Note that the total number of allocations the number of papers previously listed as some studies use multiple allocation methods.

The treatment of co-products is described as the most controversial issue in LCA [37], and can significantly change the results [26]. Prussi et al. [38] studied the results from CORSIA's calculations of SAF to develop the default life cycle values shown in Figure 2, and noted that co-product allocation had a significant effect on the results. Guidance from the standard ISO 14044 [39] advises that inputs and outputs should be partitioned to reflect the physical relationships between the products and processes, such as energy or mass. This study agrees with this and notes that economic allocation can result in regional variation depending on markets and the different values of products in different regions. This is not an issue for energy or mass which do not change regionally. Energy allocation is the most common allocation method used [32, 33, 40] in SAF LCA calculations since the product is desired for its energy content. The CORSIA methodology to calculate actual life cycle emissions of SAF [21] also recommends using energy allocation.

de Jong et. al [41] used energy allocation for the SAF and all fuel co-products but used displacement for the non-energy co-products. Fan et. al [22] employed energy, economic, and displacement allocation methods to account for coproducts used in the production of SAF derived from pennycress. Energy and economic allocation resulted in life cycle emissions of 32.7 and 44.9 gCO_2e/MJ respectively while displacement resulted in negative emissions of -18.3 gCO_2e/MJ, indicating a result of net CO_2e removal from the atmosphere. Kalnes et. al [32] observed very little difference between the results of mass and energy allocation. However, when displacement allocation was used, a large difference was seen where the emissions from camelina SAF were negative over the life cycle. These significant differences highlight co-product allocation as one of the most critical LCA methodological choices.

2.5. Land Use Change

Land use change refers to the emissions associated with the change of land use. This is relevant for SAF produced from main product crops, grown specifically for that purpose. Waste feedstocks do not involve land use change emissions. Many studies do not consider land use change in SAF LCA calculations due to the uncertainty associated with it [23, 30, 33, 42]. Twenty-eight of the thirty-six SAF LCA papers described at the beginning of this Chapter did not include land use change. It is argued that the exclusion of this significant parameter can be a decisive factor in making the biofuel compliant or not with emission mandates [43] as it is often the largest source of emissions in SAF LCA, and usually dominates over other stages of the life cycle. It is described as the greatest source of variability in SAF LCA [44].

2.6. Inventory Data

The procurement of accurate data is essential for any LCA to be representative of the real-world activity it models. In the literature, there are several databases and tools used to develop the inventory data used as inputs to the LCA calculation. The most popular life cycle database currently used in the literature is EcoInvent [45], a subscription service. One of the reasons for EcoInvent's popularity is that it includes probability distributions for almost all data items [46]. This has been used in several SAF LCA studies [30, 47, 48]. The EcoInvent database was used by Ganguly et al. [34] to set a reference value for fossil aviation fuel and is described as the only source containing full life cycle inventory for aviation fuel. Oehmichen et al. [49] also used EcoInvent as the life cycle inventory database with Umberto as the LCA tool when studying biobased SAF. There are free databases, such as the US Life Cycle Inventory database from the National Renewable Energy Laboratory. Bailis et. al [28] estimated carbon stocks of soils using default data from the Intergovernmental Panel Climate Change (IPCC), and sourced calorific values of coproducts from GREET.

In some cases, inventory data is supplied by industry partners. Fan et. al [22] was supplied with access to cultivation, transport and oil recovery data for pennycress feedstock by Arvens Technology Inc. while Honeywell UOP supplied process design data for the conversion of pennycress oil to SAF. Budsberg et al. [30] received feedstock production and harvesting data from GreenWood Resources and sourced chemical input data from the private sector, literature, EcoInvent and the US Life Cycle Inventory. The same study also calculated land use change using the Forest Industry Carbon Assessment Tool. Oehmichen et al. [49] sourced conversion process energy demand data and mass and energy flows from SAF producers and literature but did not disclose the industry sources. Aspen-Plus has been used by several studies [30, 34, 36, 50] to simulate the fuel production process and hence determine the required material and energy input.

This study emphasises the use of actual data as much as possible, however, in many cases actual data is not available. In these cases, the confidence in life cycle databases and models in providing accurate data for specific scenarios is critical.

2.7. Issues Observed in the Literature

One of the biggest issues encountered in the review of literature on SAF LCA calculations is the lack of transparency. The International Standard Organisation (ISO) [39] states all data, methods, assumptions, limitations and results are to be documented and should provide sufficient detail to allow the reader to comprehend the complexities of the calculation. However, it was observed in much of the literature that data was withheld or ignored in the reporting stage. In some cases, input data was not made available due to confidentiality issues with industry partners. This is a valid reason for censoring data. However, this case cannot be made for all studies. Oehmichen et. al [49] assumed a transportation supply chain but there was no detail on the modes of transport, or the distances travelled. Pereira et al. [37] described that current LCA models are highly sensitive to assumptions and methodological choices. Therefore, it is essential to report this thoroughly for the reader to fully appreciate the results of the calculation. O'Connell et al. [42] acknowledged that uncertainties occur in the computational phase of these calculations and that they are subject to the quality of input parameters. There is also a lack of complete input data where LCA models are used. This study attempted to reproduce one SAF LCA calculation completed in GHGenius [40], but this was not successful due to the uncertainty over modelling choices and incomplete input data. The replication study can be found in Appendix B.

There is often a cut-off for what is included in an LCA. The BioGrace calculator includes a cut-off criterion of 0.1 gCO_2e/MJ [37]. The use of cut-off criterion is an accepted practice under ISO LCA guidance [39] and three criterion are listed for determining the cut-off criterion: energy, mass, and environmental significance. However, this raises the question of how many of these small components can be neglected without compromising the rigour of the calculation. An LCA calculation cannot be fully rigorous if cut-off criteria are used.

A major factor that differs between LCA studies in the system boundary. Selecting what is included in the system boundary can have a significant effect on the result [50]. One example of this is whether to include avoided emissions in the system boundary for SAF production. van Dyk et. al [40] modelled SAF derived from forest residues that would otherwise have been burned and explains that if the avoided emissions from the current practices were included, the emission reductions of the SAF would be much greater. Ganguly et al. [34] also calculated SAF produced from forest waste and assumed that 50% of the slash pile would have been burned. These avoided emissions were credited to the fuel and resulted in a 77.9% reduction in overall GHG emissions compared to fossil aviation fuel. If no avoided emissions were credited to the fuel, the reduction would have been 73.5%.

It is generally accepted that LCA studies of bioenergy products do not consider the biogenic carbon emitted during combustion [32, 41, 42, 44, 49], but some [51] argue that the time lag between CO_2 removal and emission from and to the atmosphere should not be overlooked.

It has been suggested that standardisation of parameters such as regional default values for energy inputs and emission factors, and the treatment of co-product allocation is needed for consistency of SAF LCA studies [26, 41] and that a global system of carbon credit generation be introduced so that LCA studies could be comparable even if different regions were studied and different models used [52]. This study agrees with these suggestions due to the variation and inconsistency seen in the literature.

2.8. Summary

The key findings from this overview of the relevant literature on SAF LCA are that there have been numerous LCA calculations of SAF, using different calculators, data sources, assumptions, and considering different SAF feedstocks and fuel production pathways and that there are many differences between the methodological choices when modelling the activity.

Fuel production is generally responsible for the greatest emissions contribution due to the emission intensity of hydrogen production. The transportation of feedstock and fuel is seen to be a potentially large emission source, depending on the optimisation of the fuel supply chain. The allocation methods were seen to have great influence over the results of LCA calculations; energy allocation is the preferred method in the literature, but mass, economic, and displacement methods are also regularly used. Another factor that can influence the results is the source of inventory data. The accuracy of this directly affects the rigour of the calculation. One of the major issues observed in the literature is the lack of transparency in reporting this inventory data and the specific inputs used in the calculation.

Another key finding in this literature review is that the LCA calculations concerning sustainable aviation focus solely on the life cycle of the SAF, and not the aviation activity. Non-fuel related activity has been considered in a small number of studies, such as one by

Greer et. al [53] investigating the effect of electrification of airport gate activity, and Mokalled et. al [54] investigating the emissions associated with ground service vehicles at airports. However, no study that incorporates these auxiliary activities with the fuel and aircraft operation is known to currently exist. This is one of the research gaps that aims to be filled with this work, as the full aviation activity is to be included.

2.9. Project Objectives

The primary objective of this project is to determine the emissions associated with specific aviation activities. For this, a novel LCA methodology is developed to model specific aviation activities using actual data as much as possible. Using this methodology, LCA calculations are conducted of Ryanair's activity, specifically that which uses SAF. A novel methodology is developed because current LCA tools are found to not offer the transparency and flexibility desired for the specific calculation of aviation activity. The methodology is to consider the life cycle of the aviation activity rather than only the life cycle of the fuel. The functional unit of the methodology would therefore be an emission intensity metric expressed as a mass of emissions per revenue-passenger-kilometre (gCO_2e/RPK) instead of a mass of emissions per megajoule of fuel (gCO_2e/MJ) as is currently the default for SAF LCA calculations in the literature, as seen in Figure 7.

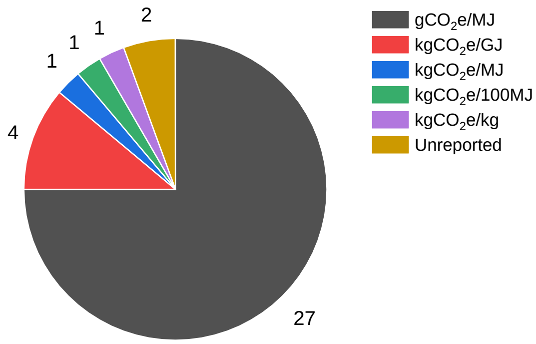


Figure 7: Functional units used in the SAF LCA literature. Note that gCO_2e/MJ and $kgCO_2e/GJ$ are equivalent but listed separately as this is how they were reported. This data is from thirty-six literature studies of SAF LCA between 2010 and 2023 discussed in Chapter 2.

The following are research questions to be considered during this project.

- What is the most suitable method of considering LCA calculations of aviation activity?
- What is the most suitable functional unit in which to report LCA calculations of aviation activity?
- Does SAF offer life cycle greenhouse gas emission reductions compared to conventional fossil jet fuel?
- What area of aviation activity provides the best opportunity for emissions reduction?
- What emission reductions will Ryanair achieve with their use of specific SAF?

3. Methodology

This is a novel methodology developed by TCD to consider life cycle assessment calculations of aviation activity which uses sustainable aviation fuel. The aviation activity is defined as the operation of a revenue generating flight. The methodology was developed to ensure transparency, authenticity, and rigour. This work emphasises the use of actual supply chain data, particular to the specific aviation activity studied. It was found that existing LCA tools have limited compatibility with this paradigm as they do not allow flexibility with how the activity is modelled.

3.1. System Boundary

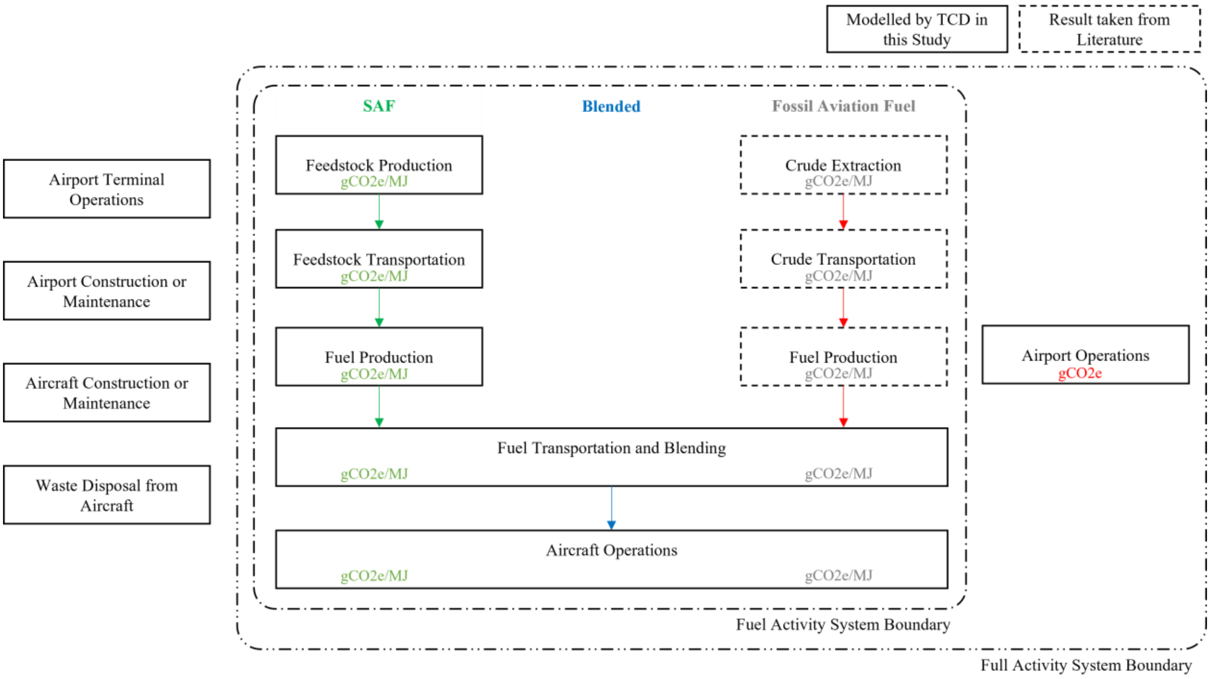


Figure 8: System boundary of the aviation activity that is considered in this methodology and functional units per stage of the LCA.

The stages considered in this methodology are categorised as either fuel activity or non-fuel activity. A system boundary for the considered stages of the methodology is shown in Figure 8. The fuel activity of SAF is divided into five life cycle stages: Feedstock Production, Feedstock Transportation, Fuel Production, Fuel Transportation and Blending, and Aircraft Operations. Fossil aviation fuel is also considered, but at present, only modelled by TCD from the point that it leaves the fuel production facility. Previously reported research values are taken for the first three stages of the fossil aviation fuel life cycle: Crude Extraction, Crude Transportation and Fuel Production. The blending of SAF and fossil aviation fuel takes place midway through the Fuel Transportation and Blending stage. After this point, the emissions associated with the transportation of the blended SAF are allocated to the SAF and fossil aviation fuel components based on the blend ratio. The non-fuel activity considered in the methodology is the auxiliary airport operations that takes place at the airport of departure and is necessary for the operation of the flight. These airport operations are further explained in Chapter 3.9.

Airport terminal operations, airport construction and maintenance, aircraft construction and maintenance, and waste disposal from the aircraft are not considered in the system boundary of the aviation activity.

3.2. Functional Unit

The greenhouse gases considered in this methodology are CO_2, CH_4 and N_2O. These greenhouse gases are converted to CO_2e using the 100-year global warming potentials from the Intergovernmental Panel on Climate Change [55] shown in Table 1.

Table 1: 100-year global warming potentials of the greenhouse gases considered in this methodology. These are the latest reported values from the Intergovernmental Panel on Climate Change [55].

Pollutant	100 Year Global Warming Potential
CO_2	1
CH_4	28
N_2O	265

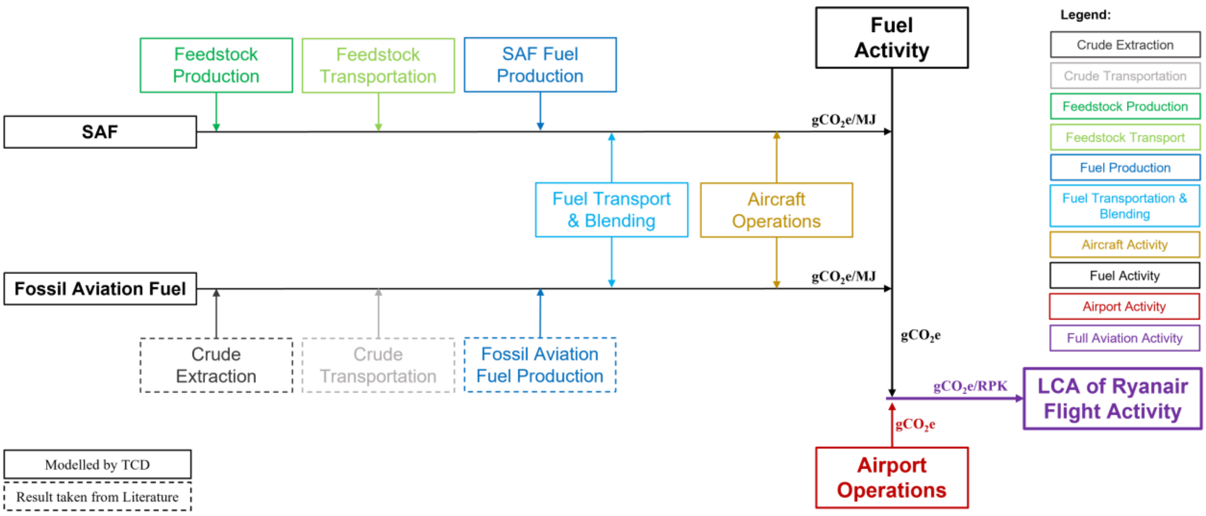


Figure 9: Diagram of the activity considered in the system boundary of this methodology. The transformation of functional units though the LCA is also shown.

A functional unit is a measure of a product or activity based on the service provided by it. Figure 9 shows the functional units used in this methodology. All fuel activity emissions are expressed as grams of carbon dioxide equivalent per megajoule of fuel (gCO_2e/MJ). This can be converted to a simple mass of CO_2e emissions for the aviation activity by *Equation* 3.2.1 and 3.2.2,

$$CO_2e\ per\ kilogram\ of\ fuel\ = CO2e\ per\ megajoule\ of\ fuel\ \cdot\ Energy\ density\ of\ fuel \qquad Equation\ 3.2.1$$

$$CO_2e\ = CO_2e\ per\ kilogram\ of\ fuel\ \cdot\ Mass\ of\ fuel\ used\ during\ activity \qquad Equation\ 3.2.2$$

where the energy density of fuel is expressed in megajoules per kilogram and the mass of fuel used during the activity is expressed in kilograms.

The second functional unit used in this methodology is gCO_2e. The total mass of emissions due to fuel activity and the auxiliary airport operations are reported in this unit and are added together to find the total mass of emissions due to the aviation activity. This total emission is then represented per revenue-passenger-kilometre according to *Equation* 3.2.3.

$$gCO2e/RPK\ = \frac{gCO2e}{Number\ of\ passengers\ onboard\ \cdot\ Kilometres\ travlled} \qquad Equation\ 3.2.3$$

$\mathrm{gCO2e/RPK}$ is the third functional unit used in the methodology. This is the unit in which the LCA result of the aviation activity is reported. It is an emissions intensity metric and considers data such as the passenger load factor which would otherwise be neglected if the LCA was only completed on the fuel used by the aircraft.

3.3. Data Procurement

The accuracy of any LCA relies on the availability and procurement of specific and accurate data and inputs for all stages of the considered activity. A tiered hierarchy of preferred data sources is developed for this methodology as shown in Table 2.

Table 2: Preference rank of methods to procure data for use in the methodology.

Rank	Data Type Used for Calculations
1	Actual Data Obtained from Industry Partners
2	Calculated Data from Standard Methods
3	Calculated Data from Research Methods
4	Calculated Data from Physical Science Relations and Logical Assumptions

It is desired to use actual data from supply chain members as much as possible. The use of actual data allows for a specific calculation of a specific scenario of activity. Where this actual data cannot be obtained from supply chain members, standard methods are used to characterise the supply chain member activity. An example of a standard method calculation is the use of standard vehicle fuel consumption data in conjunction with the distance travelled, in place of actual data on the quantity of fuel used by the vehicle. Where this standard data is also not available, research methods are used to characterise the supply chain member activity. An example of this is vehicle fuel consumption data obtained from scientific research papers. Where this research method data is also not available, physical science relations are used to characterise the supply chain member activity. This includes scientific-engineering calculations from first principles using logical assumptions.

3.4. Feedstock Production

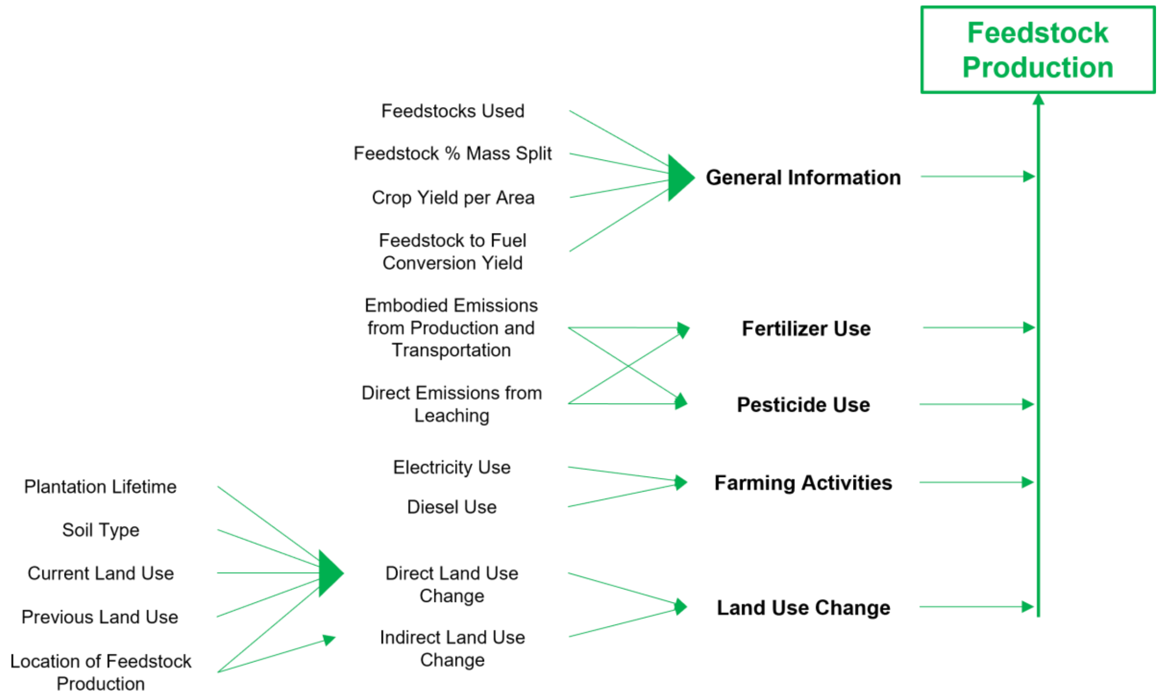


Figure 10: List of data considered in the modelling of the Feedstock Production stage of the LCA.

The Feedstock Production stage includes all activity and emissions associated with producing the SAF feedstock. The information required for this stage of the calculation is shown in Figure 10.

This stage is only relevant for main-product feedstocks which are crops grown specifically for their use in fuel production. If the feedstock is a waste such as used cooking oil, the emissions associated with the Feedstock Production stage are zero, and the life cycle is considered to start when the feedstock is collected. The TCD LCA methodology for the Feedstock Production stage has not yet been developed as only waste feedstocks have been modelled to date.

3.5. Feedstock Transportation

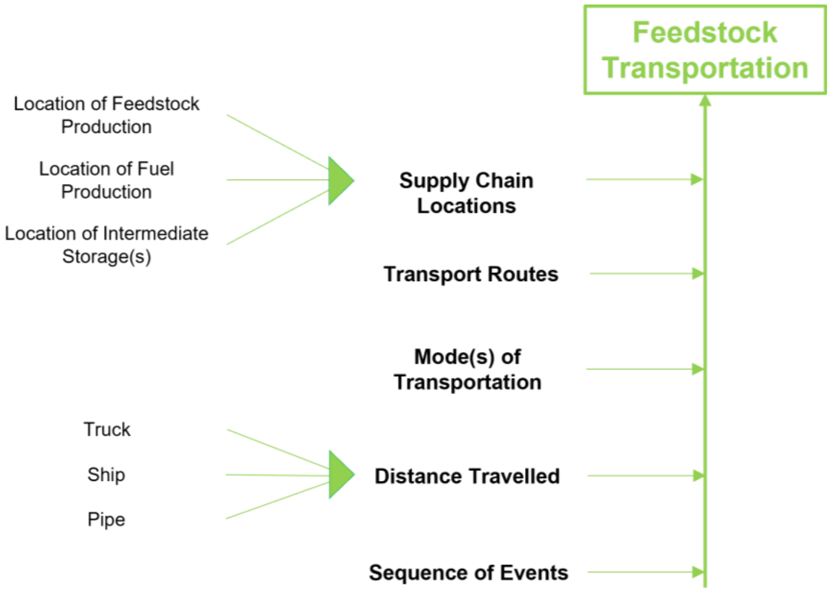


Figure 11: List of data considered in the modelling of the Feedstock Transportation stage of the LCA.

The Feedstock Transportation stage includes all activity and emissions associated with transporting the SAF feedstock from the collection location to the fuel production facility.

Prior to calculations on this stage of the LCA, the supply chain is defined. This involves listing each step of transportation activity, and storage at intermediate locations during the feedstock's journey from the collection location to the fuel production location. Figure 12 shows the place of Feedstock Transportation in the LCA methodology. Once the supply chain is defined, the transportation emissions are calculated as described in Chapter 3.11. The emissions from transportation stages are expressed in gCO_2e/MJ; this involves allocating the emissions from these transportation stages to the equivalent fuel that the feedstock is converted into. This is done by using the feedstock to fuel conversion yield on a mass basis and further described in Chapter 3.11.

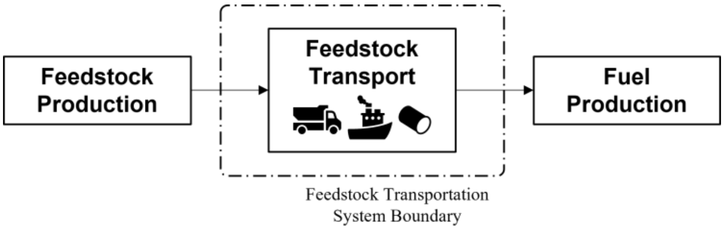


Figure 12: System boundary of the Feedstock Transportation stage of the LCA, as defined by the dashed line.

3.6. Fuel Production

The Fuel Production methodology is developed by Liam Mannion, another PhD student. Details on this stage can be found in Liam's transfer report.

3.7. Fuel Transportation and Blending

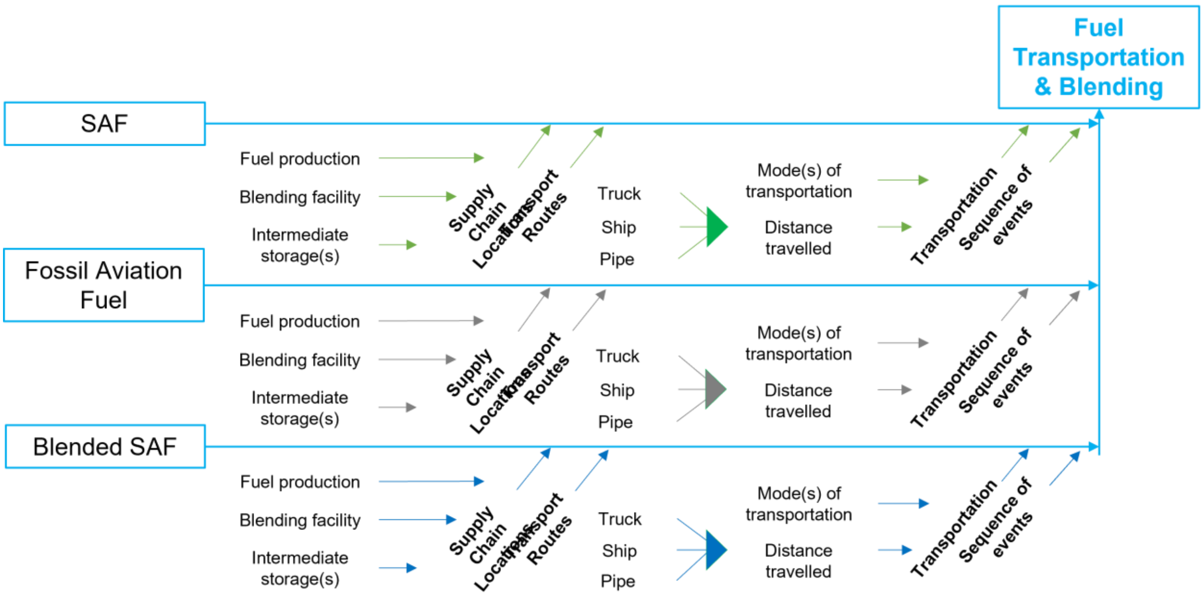


Figure 13: List of data considered in the modelling of the Fuel Transportation and Blending stage of the LCA.

The Fuel Transportation and Blending stage includes all activity and emissions associated with transporting the neat SAF and neat fossil aviation fuel from their respective fuel production facilities to the blending facility. TCD's modelling of the fossil aviation fuel is introduced in this step. The activity associated with the blending process and the transport of the blended aviation fuel from the blending facility to the aircraft is also considered.

The transportation supply chain stage is defined. This involves listing each step of transportation activity, storage at intermediate locations, and blending, involved in the transporting of SAF and fossil aviation fuel from the fuel production locations to the blending facility and when transporting the blended aviation fuel from the blending facility to the aircraft. Figure 14 shows the place of Fuel Transportation and Blending in the LCA methodology.

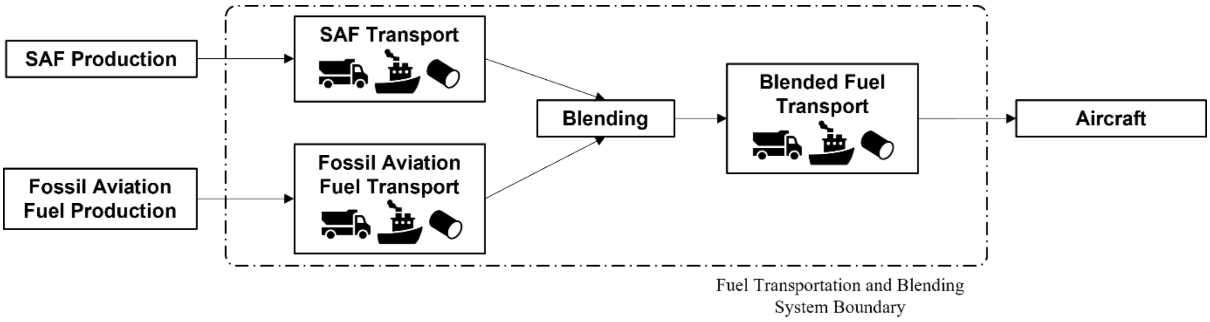


Figure 14: System boundary of the Fuel Transportation and Blending stage of the LCA, as defined by the dashed line.

Once the supply chain is defined, the transportation emissions are calculated as described in Chapter 3.11. The blending activity is modelled in the same manner as a storage tank, as described in Chapter 3.11.4. The assumptions used in the calculation of blending energy use and hence the emissions associated with the blending activity are listed in Table 3.

Table 3: Assumptions used in the modelling of energy use associated with the blending of SAF and fossil aviation fuel. These are used where actual data for the activity cannot be sourced.

	Assumptions
1	The SAF/fossil aviation fuel blending tank is modelled as a storage tank that consumes 5 kW of electricity. 5kW is not evidenced. This is the same energy use assumed at a storage stage.
2	The fluid spends an average of two hours in the blending tank. Two hours is not evidenced.
3	The blending tank is at 100% capacity during blending. This is not evidenced.
4	The calculations take the SAF blend ratio to be on a mass basis.

3.8. Aircraft Operations

The emissions generated within the Aircraft Operations stage are the direct emissions from the combustion of the fuel. The system boundary of the Aircraft Operations stage begins when the aircraft's engines are started at the airport of departure and ends when the engines are shut down at the airport of arrival.

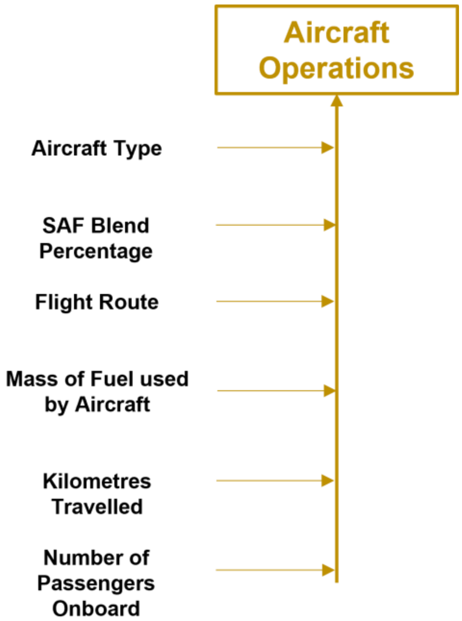


Figure 15: List of data considered in the modelling of the Aircraft Operations stage of the LCA.

Unlike the previous stages of the life cycle, the emission intensity of the fuel per megajoule is now constant for all scenarios as this is dictated by the chemical reaction of the fuel during combustion. Table 4 shows that for fossil aviation fuel, 74 gCO_2e [56] is emitted for every megajoule of fuel combusted. SAF has an emission factor of zero at this stage of the life cycle. Although the actual direct emissions for SAF is equivalent to fossil aviation fuel, this carbon is biogenic and considered to be zero as it is not a 'new' emission. It has already been sequestered from the atmosphere during crop growth and has completed a circular process. This carbon has been recycled.

This stage of the life cycle also informs on other operational parameters of the aircraft. Information on the mass of fuel used during the aviation activity is collected in this stage of the life cycle and used to convert the life cycle emission factor of the fuels to a mass of emissions as previously described in Equation 3.2.2. Other data collected here includes the number of passengers onboard the aircraft and the distance travelled. These are used to present the emissions of the activity per revenue-passenger-kilometre as described in Equation 3.2.3.

Table 4: The fossil emission factors from the combustion of fossil aviation fuel and biologically derived SAF. The modelled SAF is considered to have zero direct emissions as the carbon is sequestered during feedstock production and is recycled to the atmosphere. The emission factor for fossil aviation fuel makes up the combustion component of the EU carbon intensity baseline for fossil aviation fuel, reported as 93.1 gCO_2e/MJ by Chiaramonti [56]. This is used in place of the global 89 gCO_2e/MJ result as used by CORSIA as it is more representative of a European scenario.

Fuel	Emission Factor (gCO_2e/MJ)
Fossil Aviation Fuel	74
SAF	0

3.9. Airport Operations

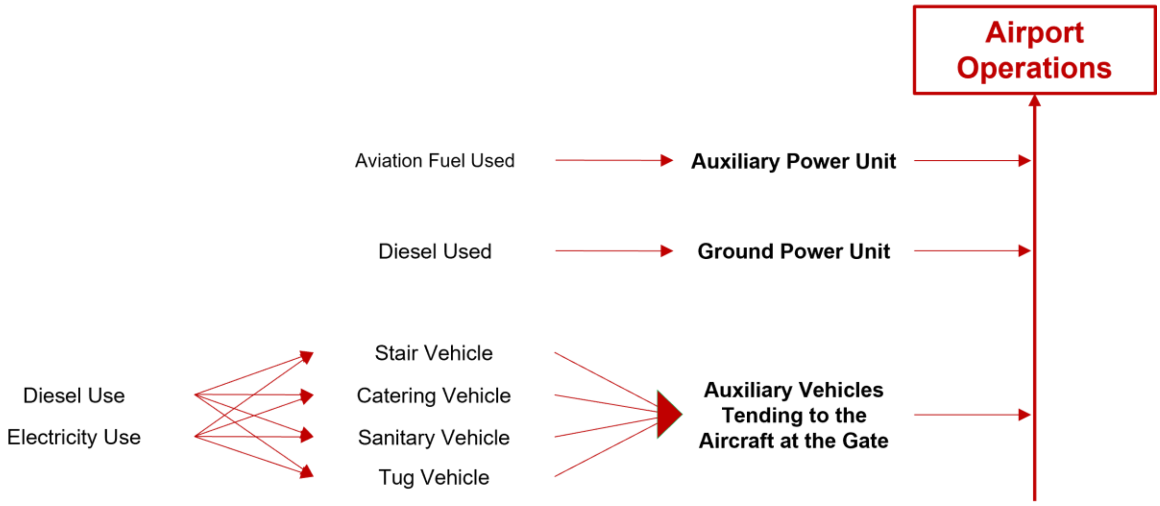


Figure 16: List of data considered in the modelling of the Airport Operations stage of the LCA.

The Airport Operations system boundary includes all auxiliary operations that occur airside at the airport of departure and are necessary for the aviation activity. The power used by the aircraft while parked at the gate, from either the auxiliary power unit or a ground power unit is considered, as is the activity of auxiliary vehicles that service the aircraft while at the gate. This includes the method of de-boarding and boarding passengers, the delivery of luggage, catering, and sanitary services, and the tug which pushes the aircraft back from the gate. The TCD methodology also models the emissions associated with buses, if used, to transport passengers from the airport terminal to the aircraft. Table 5 lists the assumptions used within this stage of the LCA.

Table 5: Assumptions used in the modelling of the Airport Operations stage of the LCA. These are used where actual data for the activity cannot be sourced.

	Assumptions
1	The fuel consumption of diesel heavy goods vehicles, luggage vehicles, stair vehicles, or buses operating short journeys at the airport is assumed to be the same as the fuel consumption for heavy goods vehicles operating in urban environments as sourced from the International Council on Clean Transportation [57].
2	The efficiency of electric heavy goods vehicles, luggage vehicles, or stair vehicles operating short journeys at the airport is assumed to be the same as an electric Volvo FH Electric truck [58]. This is not evidenced.
3	A diesel aircraft tug has a fuel efficiency of 100l/100km, higher than the standard value for heavy good vehicles in urban environments due to the energy intense nature of this vehicle's activity. This is not evidenced.
4	The difference between the energy efficiency of a diesel and electric tug vehicle is proportional to the difference between the diesel and electric heavy goods vehicles operating at the airport.
5	The ground power unit is powered by a diesel generator.

3.9.1. Auxiliary Power Unit

The data required for the calculation of auxiliary power unit emissions as user inputs is listed in Table 6. The emission factor for aviation fuel is not listed as inventory data as this is one of the outputs of the LCA calculation.

Table 6: Input data required for the modelling of emissions associated with the aircraft's use of the auxiliary power unit at the gate.

Data	Notation	Unit
Mass of Fuel Used by the Auxiliary Power Unit at the Gate	$Mass_{\substack{Aviation\ Fuel \\ APU}}$	kg

The emissions associated with the auxiliary power unit usage is calculated by *Equation* 3.9.1,

$$CO_2e_{APU} = Mass_{\substack{Aviation\ Fuel \\ APU}} \cdot Emission\ Factor_{Aviation\ Fuel} \qquad Equation\ 3.9.1$$

where CO_2e_{APU} (gCO$_2$e) is the grams of CO$_2$e emissions associated with the use of the auxiliary power unit at the gate, $Mass_{\substack{Aviation\ Fuel \\ APU}}$ (kg) is the mass of aviation fuel used by the auxiliary power unit, and $Emission\ Factor_{Aviation\ Fuel}$ (unitless) is the grams of carbon dioxide equivalent emitted per kilogram of aviation fuel combusted.

3.9.2. Ground Power Unit

The data required as user inputs for this calculation is listed in Table 7, and the inventory data required is listed in Table 8.

Table 7: Input data required for the modelling of emissions associated with the aircraft's use of the ground power unit at the gate.

Data	Notation	Unit
Mass of Diesel Used by the Ground Power Unit at the Gate	$Mass_{\substack{Diesel \\ GPU}}$	kg

Table 8: Inventory data required for the modelling of emissions associated with the aircraft's use of the ground power unit at the gate. The CO_2e emission factor for diesel is sourced from the IPCC Guidelines for National Greenhouse Gas Inventories [59]. It is calculated as the sum of the reported CO_2, CH_4, and N_2O emission factors for diesel fuel using their 100-year global warming potentials.

Notation	Value	Unit	Reference
$Emission\ Factor_{Diesel}$	3.26	$kgCO_2e/kg$	IPCC [59]

The emissions associated with the auxiliary power unit usage is calculated by *Equation* 3.9.2,

$$CO_2e_{GPU} = Mass_{\substack{Diesel \\ GPU}} \cdot Emission\ Factor_{Diesel} \qquad Equation\ 3.9.2$$

where CO_2e_{GPU} (gCO_2e) is the grams of CO_2e emissions associated with the use of the ground power unit at the gate, $Mass_{\substack{Diesel \\ GPU}}$ (kg) is the mass of diesel fuel used by the ground power unit, and $Emission\ Factor_{Diesel}$ (unitless) is the grams of carbon dioxide equivalent emitted per kilogram of diesel fuel used.

3.9.3. Luggage Activity

The TCD method of modelling the emissions associated with the delivery and collection of luggage to and from the aircraft allows for the choice of diesel or electric vehicles. If the mass of fuel or energy used by the luggage vehicles is known, the emissions can be immediately calculated using an emissions factor. The data required as inputs for these calculations, if the mass of fuel used is not known, is listed in Table 9 and the inventory data required is listed in Table 10.

Table 9: Input data required for the modelling of emissions associated with the activity of delivering and collecting luggage to and from the aircraft if the energy or fuel used by the vehicles is not known.

Data	Notation	Unit
Energy Source of Luggage Vehicle	-	-
Number of Luggage Vehicles Used	$n_{Luggage}$	-
Distance Travelled by each Luggage Vehicle	$Distance\ Travlled_{Luggage}$	km

Table 10: Inventory data required for the modelling of fuel or energy used during the activity of delivering and collecting luggage to and from the aircraft. The data on fuel consumption of a diesel luggage vehicle is sourced from the International Council on Clean Transportation [57]. The data on energy consumption of an electric luggage vehicle is sourced from a Volvo [58] press release on the Volvo FH Electric truck.

Notation	Value	Unit	Reference
$Fuel\ Consumption_{\substack{Luggage \\ Diesel}}$	57.3	L/100 km	Delgado et. al [57]
$Energy\ Consumption_{\substack{Luggage \\ Electric}}$	1.1	kWh/km	Volvo [58]

3.9.3.1. Diesel Luggage Vehicle

The diesel fuel use associated with the collection and delivery of luggage to and from the aircraft, if the vehicle is diesel powered, is calculated by *Equation* 3.9.3,

$$Mass_{\substack{Diesel \\ Luggage}} = \frac{n_{Luggage} \cdot Fuel\ Consumption_{\substack{Luggage \\ Diesel}} \cdot Distance\ Travlled_{Luggage}}{100} \cdot \rho_{diesel} \qquad Equation\ 3.9.3$$

where $Mass_{\substack{Diesel \\ Luggage}}$ (kg) is the kilograms of diesel used during the activity of delivering and collecting luggage to and from the aircraft, $n_{Luggage}$ (unitless) is the number of luggage vehicles that tend to the aircraft, $Fuel\ Consumption_{\substack{Luggage \\ Diesel}}$ (L/100km) is the fuel consumption of a diesel luggage vehicle operating airside at an airport, and $Distance\ Travlled_{Lluggage}$ (km) is the distance travelled by one luggage vehicle while tending to an aircraft. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.4.

$$CO_2e_{\substack{Luggage \\ Diesel}} = Mass_{\substack{Diesel \\ Luggage}} \cdot Emission\ Factor_{Diesel} \qquad Equation\ 3.9.4$$

3.9.3.2. Electric Luggage Vehicle

The electric energy use associated with the collection and delivery of luggage to and from the aircraft, if the vehicle is electric, is calculated by *Equation* 3.9.5,

$$Energy_{\substack{Electric\\Luggage}} = n_{Luggage} \cdot Energy\ Consumption_{\substack{Luggage\\Electric}} \cdot Distance\ Travlled_{Luggage} \qquad Equation\ 3.9.5$$

where $Energy_{\substack{Electric\\Luggage}}$ (kWh) is the electrical energy used during the activity of delivering and collecting luggage to and from the aircraft and $Energy\ Consumption_{\substack{Luggage\\Electric}}$ (kWh/km) is the energy consumption of an electric luggage vehicle operating airside at an airport. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.6,

$$CO_2e_{\substack{Luggage\\Electric}} = Energy_{\substack{Electric\\Luggage}} \cdot Emission\ Factor_{Electric} \qquad Equation\ 3.9.6$$

where, $Emission\ Factor_{Electric}$ (gCO_2e/kWh) is the emission factor of electricity production in the country where the activity takes place.

3.9.4. Boarding Activity

The TCD method of modelling the emissions associated with the de-boarding and boarding from and to the aircraft allows for a choice of passenger boarding methods; an airstair that is housed inside of the aircraft and extends down to the tarmac, a rolling stair that is pushed by ground crew to the aircraft, a stair vehicle powered by a diesel engine, an electric stair vehicle, and a jet bridge extending from the airport terminal building. It may be the case that more than one method of boarding or de-boarding passengers is used. Also included in this section is the activity of transporting passengers from the airport terminal to the aircraft by bus, if applicable. The data required as inputs for these calculations, if the mass or energy of fuel used is not known, is listed in Table 11 and the inventory data required for this calculation is listed in Table 12.

Table 11: Input data required for the modelling of emissions associated with the activity of de-boarding and boarding passengers to and from the aircraft if the energy or fuel used by the vehicles is not known

Data	Notation	Unit
Energy Source of Stair Vehicles	-	-
Number of Diesel or Electric Stair Vehicles Used	n_{Stair}	-
Distance Travelled by each Diesel or Electric Stair-Vehicle	$Distance\ Travlled_{Stiar}$	km
Energy Source of Bus Vehicle	-	-
Number of Bus Vehicles Used	n_{Bus}	-
Distance Travelled by each Bus Vehicle	$Distance\ Travlled_{Bus}$	km

Table 12: Inventory data required for the modelling of fuel or energy used during the activity of de-boarding and boarding passengers to and from the aircraft. The data on fuel consumption of a diesel stair vehicle and diesel bus is sourced from the International Council on Clean Transportation [57], and the data on energy consumption of an electric stair vehicle is sourced from a Volvo [58] press release on the Volvo FH Electric truck.

Notation	Value	Unit	Reference
$Fuel\ Consumption\ _{\substack{Stair\\Diesel}}$	57.3	L/100 km	Delgado et. al [57]
$Energy\ Consumption\ _{\substack{Stair\\Electric}}$	1.1	kWh/km	Volvo [58]
$Fuel\ Consumption\ _{\substack{Bus\\Diesel}}$	57.3	L/100 km	Delgado et. al [57]

3.9.4.1. Airstair

If an airstair is used to board or de-board passengers, no calculation is necessary. In this case, the energy required to extend and retract the air stair is provided by the aircraft, either by its engines, auxiliary power unit, or ground power unit. For any of these cases, the energy use and emissions are accounted for in other areas of this methodology.

3.9.4.2. Rolling Stair Vehicle

If a rolling stair is used to board or de-board passengers, no electric or fuel energy is consumed and therefore no calculation of emissions is necessary.

3.9.4.3. Diesel Stair Vehicle

The diesel fuel use associated with the stair vehicle, if the vehicle is diesel powered, is calculated by *Equation* 3.9.7,

$$Mass_{\substack{Diesel\\Stair}} = \frac{n_{Stair} \cdot Fuel\ Consumption_{\substack{Stair\\Diesel}} \cdot Distance\ Travlled_{Stiar}}{100} \cdot \rho_{diesel} \qquad Equation\ 3.9.7$$

where $Mass_{\substack{Diesel\\Stiar}}$ (kg) is the kilograms of diesel used by the diesel stair vehicle during the activity of de-boarding or boarding passengers from or to the aircraft, n_{Stiar} (unitless) is the number of stair vehicles that tend to the aircraft, $Fuel\ Consumption_{\substack{Stair\\Diesel}}$ (L/100km) is the fuel consumption of a diesel stair vehicle operating airside at an airport, and $Distance\ Travlled_{Stair}$ (km) is the distance travelled by one stair vehicle while tending to an aircraft. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.8.

$$CO_2e_{\substack{Stair\\Diesel}} = Mass_{\substack{Diesel\\Stair}} \cdot Emission\ Factor_{Diesel} \qquad Equation\ 3.9.8$$

3.9.4.4. Electric Stair Vehicle

The electric energy use associated with the stair vehicle, if the vehicle is electric, is calculated by *Equation* 3.9.9,

$$Energy_{\substack{Electric\\Stair}} = n_{Stair} \cdot Energy\ Consumption_{\substack{Stair\\Electric}} \cdot Distance\ Travlled_{Stair} \qquad Equation\ 3.9.9$$

where $Energy_{\substack{Electric\\Stair}}$ (kWh) is the electric energy used during the activity of de-boarding or boarding passengers from or to the aircraft and $Energy\ Consumption_{\substack{Stair\\Electric}}$ (kWh/km) is the energy consumption of an electric stair vehicle operating airside at an airport. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.10.

$$CO_2e_{\substack{Stair\\Electric}} = Energy_{\substack{Electric\\Stair}} \cdot Emission\ Factor_{Electric} \qquad Equation\ 3.9.10$$

3.9.4.5. Diesel Bus

The methodology currently only allows for the calculation of passenger transport by bus if the bus vehicle is diesel powered. The diesel fuel use associated with the diesel bus, if used, is calculated by *Equation* 3.9.11,

$$Mass_{\substack{Diesel \\ Bus}} = \frac{n_{Bus} \cdot Fuel\ Consumption_{\substack{Bus \\ Diesel}} \cdot Distance\ Travlled_{Bus}}{100} \cdot \rho_{diesel} \qquad Equation\ 3.9.11$$

where $Mass_{\substack{Diesel \\ Bus}}$ (kg) is the kilograms of diesel used by the diesel bus vehicle during the activity of transporting passengers from the airport terminal to the aircraft, n_{Bus} (unitless) is the number of bus vehicles that tend to the aircraft, $Fuel\ Consumption_{\substack{Bus \\ Diesel}}$ (L/100km) is the fuel consumption of a diesel bus vehicle operating airside at an airport, and $Distance\ Travlled_{Bus}$ (km) is the distance travelled by one bus vehicle while tending to an aircraft. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.12.

$$CO_2e_{\substack{Bus \\ Diesel}} = Mass_{\substack{Diesel \\ Bus}} \cdot Emission\ Factor_{Diesel} \qquad Equation\ 3.9.12$$

3.9.5. Catering Activity

The TCD method of modelling the emissions associated with the delivery of catering services to the aircraft allows for the choice of diesel or electric vehicles. The data required as inputs for these calculations, if the mass of fuel used is not known, is listed in Table 13 and the inventory data required is listed in Table 14.

Table 13: Input data required for the modelling of emissions associated with the activity of delivering of catering services to the aircraft if the mass of fuel used by the vehicles is not known.

Data	**Notation**	**Unit**
Energy Source of Catering Vehicle	-	-
Number of Catering Vehicles Used	$n_{Catering}$	-
Distance Travelled by each Catering Vehicle	$Distance\ Travlled_{Catering}$	km

Table 14: Inventory data required for the modelling of fuel or energy used during the activity of delivering of catering or sanitary services to the aircraft. The data on fuel consumption of a diesel catering or sanitary vehicle is sourced from the International Council on Clean Transportation [57]. The data on energy consumption of an electric catering or sanitary vehicle is sourced from a Volvo [58] press release on the Volvo FH Electric truck.

Notation	**Value**	**Unit**	**Reference**
$Fuel\ Consumption_{\substack{Diesel\ HGV \\ Urban}}$	57.3	L/100 km	Delgado et. al [57]
$Energy\ Consumption_{\substack{Electric\ HGV \\ Urban}}$	1.1	kWh/km	Volvo [58]

3.9.5.1. Diesel Catering Vehicle

The diesel fuel use associated with the catering vehicle, if the vehicle is diesel powered, is calculated by *Equation* 3.9.13,

$$Mass_{\substack{Diesel\\Catering}} = \frac{n_{Catering}\, Fuel\ Consumption_{\substack{Diesel\ HGV\\Urban}} \cdot Distance\ Travlled_{Catering}}{100} \cdot \rho_{diesel} \quad Equation\ 3.9.13$$

where $Mass_{\substack{Diesel\\Catering}}$ (kg) is the kilograms of diesel used by the diesel catering vehicle during the activity of delivery of catering services to the aircraft, $n_{Catering}$ (unitless) is the number of catering vehicles that tend to the aircraft, $Fuel\ Consumption_{\substack{Diesel\ HGV\\Urban}}$ (L/100km) is the fuel consumption of a diesel heavy goods vehicle operating airside at an airport, and $Distance\ Travlled_{Catering}$ (km) is the distance travelled by one catering vehicle while tending to an aircraft. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.14.

$$CO_2e_{\substack{Catering\\Diesel}} = Mass_{\substack{Diesel\\Catering}} \cdot Emission\ Factor_{Diesel} \qquad Equation\ 3.9.14$$

3.9.5.2. Electric Catering Vehicle

The electric energy use associated with the catering vehicle, if the vehicle is electric, is calculated by *Equation* 3.9.15,

$$Energy_{\substack{Electric\\Catering}} = n_{Catering} \cdot Energy\ Consumption_{\substack{Electric\ HGV\\Urban}} \cdot Distance\ Travlled_{Catering} \quad Equation\ 3.9.15$$

where $Energy_{\substack{Electric\\Catering}}$ (kWh) is the electric energy used by the electric catering vehicle during the activity of delivery of catering services to the aircraft and $Energy\ Consumption_{\substack{Electric\ HGV\\Urban}}$ (kWh/km) is the energy consumption of an electric heavy goods vehicle operating airside at an airport. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.16.

$$CO_2e_{\substack{Catering\\Electric}} = Energy_{\substack{Electric\\Catering}} \cdot Emission\ Factor_{Electric} \qquad Equation\ 3.9.16$$

3.9.6. Sanitary Activity

The TCD method of modelling the emissions associated with the delivery of sanitary services to the aircraft allows for the choice of diesel or electric vehicles. The data required as inputs for these calculations, if the mass of fuel used is not known, is listed in Table 15. The inventory data required is the same as for the calculation of the catering vehicle and listed in Table 14.

Table 15: Input data required for the modelling of emissions associated with the activity of delivering of sanitary services to the aircraft if the mass of fuel used by the vehicles is not known.

Data	**Notation**	**Unit**
Energy Source of Sanitary Vehicle	-	-
Number of Sanitary Vehicles Used	$n_{Sanitary}$	-
Distance Travelled by each Sanitary Vehicle	$Distance\ Travlled_{Sanitary}$	km

3.9.6.1. Diesel Sanitary Vehicle

The diesel fuel use associated with the sanitary vehicle, if the vehicle is diesel powered, is calculated by *Equation* 3.9.17,

$$Mass_{\substack{Diesel\\Sanitary}} = \frac{n_{Sanitary}\ Fuel\ Consumption_{\substack{Diesel\ HGV\\Urban}} \cdot Distance\ Travlled_{Sanitary}}{100} \cdot \rho_{diesel} Equation\ 3.9.17$$

where $Mass_{\substack{Diesel\\Sanitary}}$ (kg) is the kilograms of diesel used by the diesel sanitary vehicle during the activity of delivery of sanitary services to the aircraft, $n_{Sanitary}$ (unitless) is the number of sanitary vehicles that tend to the aircraft, and $Distance\ Travlled_{Sanitary}$ (km) is the distance travelled by one sanitary vehicle while tending to the aircraft.. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.18.

$$CO_2e_{\substack{Catering\\Diesel}} = Mass_{\substack{Diesel\\Sanitary}} \cdot Emission\ Factor_{Diesel} \qquad Equation\ 3.9.18$$

3.9.6.2. Electric Sanitary Vehicle

The electric energy use associated with the sanitary vehicle, if the vehicle is electric, is calculated by *Equation* 3.9.19,

$$Energy_{\substack{Electric \\ Sanitary}} = n_{Sanitary} \cdot Energy\ Consumption_{\substack{Electric\ HGV \\ Urban}} \cdot Distance\ Travlled_{Sanitary} \quad Equation\ 3.9.19$$

where $Energy_{\substack{Electric \\ Sanitary}}$ (kWh) is the electric energy used by the electric sanitary vehicle during the activity of delivering sanitary services to the aircraft. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.20.

$$CO_2e_{\substack{Sanitary \\ Electric}} = Energy_{\substack{Electric \\ Sanitary}} \cdot Emission\ Factor_{Electric} \qquad Equation\ 3.9.20$$

3.9.7. Tug Activity

The TCD method of modelling the emissions associated with the activity of pushing the aircraft back from the gate allows for the choice of a diesel or electric tug. The data required as inputs for these calculations, if the mass of fuel used is not known, is listed in Table 16, the inventory data required is listed in Table 17, and the assumptions used in the modelling of tug activity are listed in Table 18.

Table 16: Input data required for the modelling of emissions associated with the activity of the tug pushing the aircraft back from the gate if the mass of fuel used by the vehicles is not known.

Data	Notation	Unit
Energy Source of Tug	-	-
Distance Travelled by Tug	$Distance\ Travlled_{Tug}$	km

Table 17: Inventory data required for the modelling of fuel or energy used during activity of the tug pushing the aircraft back from the gate. This fuel and energy consumption data are assumptions, as described in Table 18.

Notation	Value	Unit	Reference
$Fuel\ Consumption_{\substack{Tug \\ Diesel}}$	100	L/100 km	Assumption
$Energy\ Consumption_{\substack{Tug \\ Electric}}$	1.9	kWh/km	Assumption

Table 18: Assumptions used in the modelling of energy use associated with the activity of the tug pushing the aircraft back from the gate. These are used where actual data for the activity cannot be sourced.

	Assumptions
1	It is assumed that the fuel consumption of the tug will be greater than that of a heavy goods vehicle operating in an urban environment. A fuel consumption of 100 L/100km is assumed. This is not evidenced.
2	It is assumed that the fuel difference in energy consumption between an electric HGV and an electric tug is proportional to the difference that of a diesel HGV and a diesel tug. Therefore, it is calculated that an electric tug has an energy consumption of 1.9 kWh/km. This is not evidenced.

3.9.7.1. Diesel Tug

The diesel fuel use associated with the pushing back of the aircraft, if the tug is diesel powered, is calculated by *Equation* 3.9.21,

$$Mass_{\substack{Diesel\\Tug}} = \frac{Fuel\ Consumption_{\substack{Tug\\Diesel}} \cdot Distance\ Travlled_{Tug}}{100} \cdot \rho_{diesel} \qquad Equation\ 3.9.21$$

where $Mass_{\substack{Diesel\\Tug}}$ (kg) is the kilograms of diesel used by the diesel tug during the activity pushing the aircraft back from the gate, $Fuel\ Consumption_{\substack{Tug\\Diesel}}$ (L/100km) is the fuel consumption of a diesel tug, and $Distance\ Travlled_{Tug}$ (km) is the distance travelled by the tug while tending to an aircraft. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.22.

$$CO_2e_{\substack{Luggage\\Diesel}} = Mass_{\substack{Diesel\\Luggage}} \cdot Emission\ Factor_{Diesel} \qquad Equation\ 3.9.22$$

3.9.7.2. Electric Tug

The electric energy use associated with the pushing back of the aircraft, if the vehicle is electric, is calculated by *Equation* 3.9.23,

$$Energy_{\substack{Electric\\Tug}} = Energy\ Consumption_{\substack{Tug\\Electric}} \cdot Distance\ Travlled_{Tug} \qquad Equation\ 3.9.23$$

where $Energy_{\substack{Electric \\ Tug}}$ (kWh) is the electric energy used by the electric tug during the activity of shing the aircraft back from the gate and $Energy\ Consumption_{\substack{Tug \\ Electric}}$ (kWh/km) is the energy consumption of an electric tug operating airside at an airport. The CO_2e emissions associated with this activity is calculated by *Equation* 3.9.24.

$$CO_2e_{\substack{Tug \\ Electric}} = Energy_{\substack{Electric \\ Tug}} \cdot Emission\ Factor_{Electric} \qquad Equation\ 3.9.24$$

3.10. Fossil Aviation Fuel

The life cycle of the fossil aviation fuel up to the stage of Fuel Transportation and Blending with SAF is not yet included in this TCD methodology. The unmodelled life cycle of the fossil aviation fuel life cycle is broken into three stages: Crude Extraction, Crude Transportation and Fuel Production. These stages are comparable to the Feedstock Production, Feedstock Transportation and Fuel Production stages of the SAF life cycle. While these life cycle stages of the fossil aviation fuel are unmodelled by TCD, reported emissions factors are taken from a research study by Chiaramonti et al. [56]. These values can be found in Table 19.

Table 19: Emission factors for the life cycle stages of fossil aviation fuel that are currently not modelled by TCD. This data is reported by Chiaramonti et al. [56] and is relevant for fossil aviation in a European context. Chiaramonti also reports the life cycle stages of fossil aviation fuel that are modelled by TCD: Fuel Transportation and Combustion with emission factors of 1 and 74 gCO_2e/MJ respectively. This makes up the EU carbon intensity baseline for fossil aviation fuel, reported as 93.1 gCO_2e/MJ. This is used in place of the global 89 gCO_2e/MJ result as used by CORSIA as it is more representative of a European scenario

Life Cycle Stage of Fossil Aviation Fuel	**Emission Factor (gCO_2e/MJ)**
Crude Extraction	10
Crude Transportation	2
Fuel Production	6.1

3.11. Calculation of Transportation Emissions

This section of the methodology describes the calculation transport emissions associated with the shipping, trucking, pumping, and storing of feedstock and fuel in the Feedstock Transportation and Fuel Transportation stages of the LCA. These emissions are embodied in the fuel.

All transport vehicles are assumed to operate at full capacity. The emissions associated with repositioning of transport vehicles and unladen transportation are not considered as their inclusion would add additional unverifiable assumptions and increase the uncertainty of the calculation. It is preferred to know that these factors are not included than to not know their specifics if they are included.

3.11.1. Transport by Ship

The TCD methodology allows for two pathways of calculating the shipping emissions of feedstock or fuel: one method if the quantity of fuel used by the ship during the transport stage is known, and another is the quantity of fuel used is not known.

3.11.1.1. Shipping: Known Fuel Usage

The input data required for this calculation is listed in Table 20, the inventory data required for the calculation is listed in

Table 21 and the modelling assumptions used are listed in Table 22.

Table 20: Input data required for the modelling of emissions associated with the activity of shipping feedstock or fuel, if the mass of fuel used by the ship is known.

Data	**Notation**	**Unit**
Fluid Transported (Feedstock or Fuel)	-	-
Mass of Fuel used by Ship	$Mass_{\substack{Marine\ Fuel \\ Ship}}$	kg

Table 21: Inventory data required for the modelling of fuel or energy used during activity of shipping feedstock or fuel, if the mass of fuel used by the ship is known. The CO_2e emission factor for marine fuel is sourced from the IPCC Guidelines for National Greenhouse Gas Inventories [59] and calculated as the sum of CO_2, CH_4, and N_2O emission factors for marine fuel using their 100-year global warming potentials. The feedstock to SAF conversion yield on a mass percentage basis is also required but this is a function of the specific feedstock and production pathway. The volume capacity of the ship is an assumption as described in Table 22.

Notation	**Value**	**Unit**	**Reference**
$Emission\ Factor_{Marine\ Fuel}$	3.22	$kgCO_2e/kg$	IPCC [59]
$Volume\ Load_{Ship}$	95,400,000	L	Assumption

Table 22: Assumptions used in the modelling of energy use associated with the activity of shipping of feedstock or fuel, if the mass of fuel used by the ship is known. These are used where actual data for the activity cannot be sourced.

	Assumptions
1	It is assumed that the volume capacity of the ship is 95,400,000 L. This is based on an Aframax class ship. This is not evidenced.

If the mass of fuel used by the ship during a stage of ship transport is known, the emissions associated with the activity are calculated by using an emission factor as described in *Equation* 3.11.1 for the case of finished fuel transport, and *Equation* 3.11.2 for the case of feedstock transport. In the case of feedstock transport, the feedstock to SAF conversion yield on a mass percentage basis is used to allocate the emissions of the transport stage to the equivalent quantity of SAF that the feedstock is later converted into.

$$CO_2e_{Ship} = \frac{Mass_{\substack{Marine\ Fuel \\ Ship}} \cdot Emission\ Factor_{Marine\ Fuel}}{Volume\ Load_{Ship} \cdot Density_{Fuel} \cdot Energy\ Density_{Fuel}} \quad Equation\ 3.11.1$$

$$CO_2e_{Ship} = \frac{Mass_{\substack{Marine\ Fuel \\ Ship}} \cdot Emission\ Factor_{Marine\ Fuel}}{Volume\ Load_{Ship} \cdot Density_{Feedstock} \cdot Yield_{\ SAF} \cdot Energy\ Density_{Fuel}} \quad Equation\ 3.11.2$$

CO_2e_{Ship} (gCO_2e/MJ) is the mass of carbon dioxide equivalent emissions associated with the shipping of the feedstock or fuel per MJ of fuel, $Mass_{\substack{Marine\ Fuel \\ Ship}}$ (kg) is the mass of marine fuel used during the transport stage, $Emission\ Factor_{Marine\ Fuel}$ (unitless) is the grams of carbon dioxide equivalent emitted per kilogram of marine fuel used, $Volume\ Load_{Ship}$ (L) is the volumetric quantity of feedstock or fuel being transported by the ship, $Density_{Fuel}$ (kg/L) is the density of the fuel transported, $Energy\ Density_{Fuel}$ (MJ/kg) is the energy density of the finished fuel, $Density_{Feedstock}$ (kg/L) is the density of the feedstock transported, and $Yield_{\ SAF}$ (unitless) is the feedstock to SAF conversion yield on a mass percentage basis.

3.11.1.2. Shipping: Unknown Fuel Usage

If the mass of fuel used is not known, the emissions a considered stage of feedstock or fuel transportation by ship is calculated with emission intensity data sourced from the Smart Freight Centre [60]. The data required as inputs for these calculations is listed in Table 23, the inventory data required for the calculation is listed in Table 24 and the assumptions are listed in Table 25.

Table 23: Input data required for the modelling of emissions associated with the activity of shipping feedstock or fuel, if the mass of fuel used by the ship is not known.

Data	Notation	Unit

Fluid Transported (Feedstock or Fuel)	-	-
Distance Travelled by Ship	$Distance\ Travlled_{Ship}$	km

Table 24: Inventory data required for the modelling of fuel or energy used during activity of shipping feedstock or fuel, if the mass of fuel used by the ship is not known. This emission factor for shipping is sourced from the Global Logistics Emissions Council Framework for Logistics Emissions Accounting and Reporting [60]. This is the value reported for a 60 – 200 deadweight tonnage oil tanker operating on heavy fuel oil and under heavy load conditions.

Notation	**Value**	**Unit**	**Reference**
$Emission\ Factor_{Ship}$	8.8	gCO_2e/t-km	GLEC [60]

Table 25: Assumptions used in the modelling of energy use associated with the activity of shipping of feedstock or fuel, if the mass of fuel used by the ship is not known. These are used where actual data for the activity cannot be sourced.

	Assumption
1	The emission factor for a 60 – 200 deadweight tonnage oil tanker operating on heavy fuel oil and under heavy load conditions, as reported by the Smart Freight Centre [60], is representative of the ship used to transport the feedstock and fuel.

If the fluid transported by ship is a finished fuel, the emissions associated with the shipping stage of the LCA are calculated by *Equation* 3.11.3, and if the fluid transported is a SAF feedstock and not a finished fuel, the emissions are allocated to the equivalent quantity of SAF based on the feedstock to SAF conversion yield by mass as calculated by *Equation* 3.11.4,

$$CO_2e_{Ship} = \frac{Distance\ Travlled_{Ship} Emission\ Factor_{Ship}}{1000} \ / \ Energy\ Density_{Fuel} \quad Equation\ 3.11.3$$

$$CO_2e_{Ship} = \frac{Distance\ Travlled_{Ship} Emission\ Factor_{Ship}}{1000} \ / \ (Yield_{\ SAF} \cdot Energy\ Density_{Fuel}) \quad Equation\ 3.11.4$$

where $Distance\ Travlled_{Ship}$ (km) is the distance travelled by the ship and $Emission\ Factor_{Ship}$ (gCO_2e/t-km) is the mass of carbon dioxide equivalent emissions associated with the shipping of the fuel per tonne-kilometre travelled by the ship.

3.11.2. Transport by Truck

The TCD methodology allows for two pathways of calculating the trucking emissions of feedstock or fuel; one method if the quantity of fuel used by the truck during the transport stage is known, and another is the quantity of fuel used is not known. The methodology currently models these emissions based on a diesel truck. The list of assumptions for the truck transport stage of feedstock or fuel are shown in Table 26.

Table 26: Assumptions used in the modelling of energy use associated with the activity of shipping of feedstock or fuel. These are used where actual data for the activity cannot be sourced.

	Assumption
1	The truck that is transporting the feedstock or fuel is assumed to always operate at full capacity.
2	When the mass of fuel used on not known, but calculated as per section 3.11.2.2, it is assumed that the fuel consumption of the truck is represented by data for tractor-trailer fuel consumption collected by the International Council on Clean Transportation [57].
3	It is assumed that a general purpose tanker with a capacity of 35,000L as described by Crown Oil [61] is used to transport feedstock or fuel by truck.

3.11.2.1. Trucking: Known Fuel Use

The input data required for this calculation is listed in Table 27 and the inventory data required for the calculation is listed in Table 28.

Table 27: Input data required for the modelling of emissions associated with the activity of trucking feedstock or fuel, if the mass of fuel used by the truck is known.

Data	Notation	Unit
Fluid Transported (Feedstock or Fuel)	-	-
Mass of Fuel used by Truck	$Mass_{\substack{Diesel \\ Truck}}$	kg

Table 28: Inventory data required for the modelling of fuel or energy used during activity of trucking feedstock or fuel, if the mass of fuel used by the truck is known. The CO_2e emission factor for diesel is sourced from the IPCC Guidelines for National Greenhouse Gas Inventories [59]. It is calculated as the sum of the reported CO_2, CH_4, and N_2O emission factors for diesel fuel using their 100-year global warming potentials. The volume load of the truck is reported by Crown Oil [61] in the description of their fuel tanker fleet.

Notation	Value	Unit	Reference
$Emission\ Factor_{Diesel}$	3.22	$kgCO_2e/kg$	IPCC [59]
$Volume\ Load_{Truck}$	35,000	L	Crown Oil [61]

If the mass of fuel used by the truck during a stage of truck transport is known, the emissions associated with the activity are calculated by using an emission factor as described in *Equation* 3.11.5 for the case of finished fuel transport, and *Equation* 3.11.6 for the case of feedstock transport. In the case of feedstock transport, the feedstock to SAF conversion yield on a mass percentage basis is used to allocate the emissions of the transport stage to the equivalent quantity of SAF that the feedstock is later converted into.

$$CO_2e_{Truck} = \frac{Mass_{\substack{Diesel \\ Truck}} \cdot Emission\ Factor_{Diesel}}{Volume\ Load_{Truck} \cdot Density_{Fuel} \cdot Energy\ Density_{Fuel}} \quad Equation\ 3.11.5$$

$$CO_2e_{Truck} = \frac{Mass_{\substack{Diesel \\ Truck}} \cdot Emission\ Factor_{Diesel}}{Volume\ Load_{Truck} \cdot Density_{Feedstock} \cdot Yield\ _{SAF} \cdot Energy\ Density_{Fuel}} \quad Equation\ 3.11.6$$

CO_2e_{Truck} (gCO_2e/MJ) is the mass of carbon dioxide equivalent emissions associated with the trucking of the feedstock or fuel per MJ of fuel, $Mass_{\substack{Diesel \\ Truck}}$ (kg) is the mass of diesel fuel used during the activity, and $Volume\ Load_{Truck}$ (L) is the volumetric capacity of the truck.

3.11.2.2. Trucking: Unknown Fuel Use

If the mass of fuel used by the truck is not known, it is calculated using fuel consumption data of heavy goods vehicles and the distance travelled by the truck. The input data required for this calculation is listed in Table 29 and the inventory data required is listed in Table 30.

Table 29: Input data required for the modelling of emissions associated with the activity of trucking feedstock or fuel by truck, if the mass of fuel used by the ship is not known.

Data	Notation	Unit
Distance Travelled by Truck on Highway Roads	$Distance\ Travelled_{\substack{Diesel\ HGV \\ Highway}}$	km
Distance Travelled by Truck on Urban Roads	$Distance\ Travelled_{\substack{Diesel\ HGV \\ Urban}}$	km

Table 30: Inventory data required for the modelling of fuel or energy used during activity of trucking feedstock or fuel, if the mass of fuel used by the truck is not known. This fuel consumption data for the truck is sourced from the International Council on Clean Transportation [57]. Data for the density of diesel is sourced from Ireland's National Inventory Report 2019 [62].

Notation	Value	Unit	Reference
$Fuel\ Consumption_{\substack{Diesel\ HGV \\ Highway}}$	36.2	L/100km	Delgado et. al [57]
$Fuel\ Consumption_{\substack{Diesel\ HGV \\ Urban}}$	57.3	L/100km	Delgado et. al [57]
$Density_{Diesel}$	0.845	kg/L	Duffy et. al [62]

The calculation is performed as per *Equation* 3.11.7,

$$Mass_{\substack{Diesel\\Truck}} = \left(\frac{Fuel\ Consumption_{\substack{Diesel\ HGV\\Highway}} \cdot Distance\ Travelled_{\substack{Diesel\ HGV\\Highway}}}{100} + \frac{Fuel\ Consumption_{\substack{Diesel\ HGV\\Urban}} \cdot Distance\ Travelled_{\substack{Diesel\ HGV\\Urban}}}{100} \right) \cdot Density_{Diesel} \quad Equation\ 3.11.7$$

where $Mass_{\substack{Diesel\\Truck}}$ (kg) is the mass of diesel used by the truck during a stage of feedstock or fuel transport by truck, $Fuel\ Consumption_{\substack{Diesel\ HGV\\Highway}}$ and $Fuel\ Consumption_{\substack{Diesel\ HGV\\Urban}}$ (L/100km) are the standard fuel consumption data of the truck operating in a highway and urban environment respectively, $Distance\ Travelled_{\substack{Diesel\ HGV\\Highway}}$ and $Distance\ Travelled_{\substack{Diesel\ HGV\\Urban}}$ (km) are the distances travelled by the truck on highway and urban roads respectively.

Once this mass of fuel is found, the calculation continues as described in Chapter 3.11.2.1.

3.11.3. Transport by Pipe

For the stages of feedstock or fuel transportation by pipe, the pumping power required is calculated first. There are then different treatments depending on if the fluid pumped is a feedstock or a fuel, like previously described for the shipping and trucking stages. The emissions are calculated from the energy used, and there are two pathways for the supply of pumping energy: the electric grid, and the diesel engine of a fuel truck.

3.11.3.1. Pumping Energy Calculations

For stages of feedstock or fuel transport by pipe, physical science relations are used to determine the energy required to pump the fluid and hence the emissions associated with the pipe transport stage. The input data required is listed in Table 31, the data inventory of fluid transport vehicles and storage locations is listed in Table 32, the data inventory of piping parameters is listed in Table 33 and the assumptions for these calculations are listed in Table 34.

Table 31: Input data required for the modelling of emissions associated with the activity of transporting feedstock or fuel by pipe.

Data	Notation	Unit
Fluid Transported (Feedstock or Fuel)	-	-
Start Location of Pumping Stage	-	-
End Location of Pumping Stage	-	-
Length of Pipe	L	m
Diameter of Pipe	d	m
Material of Pipe	-	-
Average Fluid Velocity in Pipe	v	m/s
Number of Valves in the Piping System	n_{Valves}	-
Number of Elbows in the Piping System	n_{Elbows}	-

Table 32: Inventory data of piping locations required for the modelling of emissions associated with the activity of pumping feedstock or fuel. These locations make up start and end points of pumping stages. This data is used in Equation 3.11.8 to determine the pumping power required by each piping stage. The elevation, z, is the only differing factor, as it is assumed for all vehicles and storage locations that the atmospheric pressure, p, at the fluid surface is 101,325Pa, the fluid velocity at the fluid surface, v, is zero, and the kinetic energy correction factor at the fluid surface, α, is zero. The fluid density is not listed as this depends on the feedstock and fuel pumped.

Notation	Value	Unit	Reference
$z_{Feedstock\ Collection\ Reservoir}$	2	m	Assumption
$z_{Fuel\ Truck}$	3	m	Assumption
$z_{Storage\ Tank}$	8.5	m	Assumption
z_{Ship}	10	m	Assumption
$z_{Blending\ Facility}$	10	m	Assumption
$z_{Refinery}$	10	m	Assumption
$z_{Aircraft}$	5	m	Assumption

Table 33: Inventory data of the loss factors associated with common pipe fittings, roughness's of common pipe materials reported by Cengel [63], and efficiencies of components involved in the pumping of feedstock or fuel.

Notation	Value	Unit	Reference
$Loss\ Factor_{Entrance}$	0.5	-	Cengel et. al [63]
$Loss\ Factor_{Exit}$	1.05 (for fully developed turbulent flow)	-	Cengel et. al [63]
$Loss\ Factor_{Valve}$	10	-	Cengel et. al [63]
$Loss\ Factor_{Elbow}$	0.9	-	Cengel et. al [63]
$\varepsilon_{\text{Smooth Rubber}}$	10	10^{-6} m	Cengel et. al [63]
$\varepsilon_{\text{Copper/Brass}}$	1.5	10^{-6} m	Cengel et. al [63]
$\varepsilon_{\text{Cast Iron}}$	260	10^{-6} m	Cengel et. al [63]
$\varepsilon_{\text{Galvanised Iron}}$	150	10^{-6} m	Cengel et. al [63]
$\varepsilon_{\text{Wrought Iron}}$	46	10^{-6} m	Cengel et. al [63]

$\varepsilon_{\text{Stainless Steel}}$	2	10^{-6} m	Cengel et. al [63]
$\varepsilon_{\text{Commercial Steel}}$	45	10^{-6} m	Cengel et. al [63]
$Efficiency_{Pump}$	60%	-	Evans [64]
$Efficiency_{Diesel\ Engine}$	39.1%	-	Thiruvengadam et. al [65]
$Efficiency_{Alternator}$	55%	-	Bradfield [66]

Table 34: Assumptions used in the modelling of energy use associated with the activity of piping of feedstock or fuel. These are used where actual data for the activity cannot be sourced.

	Assumption
1	It is assumed that all valves in the piping systems are fully open globe valves.
2	It is assumed that all piping stages pipe fluid from one large fluid body to another large fluid body without passing through a third large fluid body. Therefore, there is one loss factor for an entrance and one loss factor for an exit in each pumping stage.
3	It is assumed that every elbow in the piping system is a smooth 90° bend.
4	The fluid in the feedstock collection reservoir, transport truck, storage tanks, storage onboard the ship, refinery, blending facility, and aircraft (when first uplifted) is vented to atmospheric pressure. This is not evidenced.
5	The fluid in the feedstock collection reservoir, transport truck, storage tanks, storage onboard the ship, refinery, blending facility, and aircraft are assumed to be large fluid bodies and vertical velocity of the surface of the fluid is negligible. This is not evidenced.
7	The kinetic energy correction factor is unity for fluid in the feedstock collection reservoir, transport truck, storage tanks, storage onboard the ship, refinery, blending facility, and aircraft. This is not evidenced.
8	The relative elevation of the fluid surfaces at various points in the feedstock and fuel supply chain are assumed as described in Table 32.

The pumping power required by the considered stage of pipe transport is calculated by applying the steady incompressible-flow energy equation [63] between the start and end points of the piping system. This equation is shown in *Equation* 3.11.8,

$$\frac{p_1}{\rho g} + \frac{a_1 {v_1}^2}{2g} + z_1 + h_{Pump} = \frac{p_2}{\rho g} + \frac{a_2 {v_2}^2}{2g} + z_2 + h_{Turbine} + h_{Loss} \qquad Equation\ 3.11.8$$

where p (Pa), v (m/s), a (unitless), and z (m) are the static pressures, average fluid velocities, kinetic energy correction factors, and relative elevations respectively at points of the fluid system denoted by the subscript. ρ (kg/m^3) is the fluid density, g (m/s^2) is acceleration due to gravity. All previously mentioned terms are listed in the inventory data used for the calculation of pumping emissions in Table 32. Each term in this equation is called a 'head' and has the units of metres. Heads are used to represent fluid energy arising from pressure, velocity, and elevation in a common format. h_{Pump} (m) is the 'pump head'. This is a measure of mechanical energy delivered to the fluid by a pump. $h_{Turbine}$ (m) is the turbine head, a measure of the energy removed from the fluid by a turbine, if present; h_{Loss} (m) is the head loss due to friction, fittings, and bends in the piping system. *Equation* 3.11.8 is rearranged to find h_{Pump}, which allows the electrical power required by the pump to be calculated.

The h_{Loss} term is calculated by summing the losses due to friction and pipe fittings as described in *Equation* 3.11.9,

$$h_{Loss} = \left(\frac{f \cdot L}{d} + \sum Loss\ Factors\right)\left(\frac{v^2}{2 \cdot g}\right) \qquad Equation\ 3.11.9$$

where f (unitless) is the friction factor, L (m) and d (m) are the length and diameter of the pipe and $\sum Loss\ Factors$ (unitless) is the sum of minor loss factors due to pipe fittings, pipe elbows, and entrances and exits to and from large fluid bodies.

The sum of loss factors is found from *Equation* 3.11.10,

$$\sum Loss\ Factors = Loss\ Factor_{Entrance} + (Loss\ Factor_{Valve} \cdot n_{Valves}) + (Loss\ Factor_{Elbow} \cdot n_{Elbows}) + Loss\ Factor_{Exit} \qquad Equation\ 3.11.10$$

where $Loss\ Factor_{Entrance}$, $Loss\ Factor_{Valve}$, $Loss\ Factor_{Elbow}$, $Loss\ Factor_{Exit}$ are unitless loss factors for entrances to large fluid bodies, valves, elbows and exits from large fluid bodies respectively. The loss factors for common pipe fittings are found in Table 33.

The friction factor is found from the Colebrook equation. However, the Colebrook equation requires an iterative approach to calculate the friction factor. Haaland [63] derived an approximate equation, explicit in f, that is accurate to within 2% as shown in *Equation* 3.11.11,

$$f = \left(\frac{1}{-1.8 log_{10}\left(\frac{6.9}{Re} + \left(\frac{\varepsilon}{d}\right)^{1.11}\right)}\right)^2 \qquad Equation\ 3.11.11$$

where Re (unitless) is the Reynolds number, a measure of the turbulence of the flow and ε (m) is the roughness of the pipe material. Common pipe material roughness's are shown in Table 33.

The Reynold's number is found from *Equation* 3.11.12,

$$Re = \frac{\rho \cdot v \cdot d}{\mu} \qquad Equation\ 3.11.12$$

where μ (kg/ms) is the dynamic viscosity of the fluid. The dynamic viscosity is part of the data inventory; however, it is not listed in a data inventory table as it is scenario specific to the feedstock or fuel pumped.

Once h_{Pump} is found from *Equation* 3.11.8, it is used to determine the pumping power required by the piping system. This calculation is expressed by *Equation* 3.11.13,

$$Pumping\ Power = \frac{\rho \cdot g \cdot Q \cdot h_{Pump}}{Efficiency_{Pump}} \qquad Equation\ 3.11.13$$

where $Pumping\ Power$ (W) is the electrical pumping power required by the system, Q (m^3/s) is the volume flow rate of fluid through the pipe, and $Efficiency_{Pump}$ (unitless) is the efficiency of the pump.

The pumping power is then expressed as the pumping energy required per unit mass of the fluid pumped and converted from joules to kilowatt hours by dividing the energy by $3.6 \cdot 10^6$. This is calculated in *Equation* 3.11.14,

$$Pumping\ Energy\ per\ unit\ mass = \frac{Pumping\ Power}{\dot{m} \cdot 3.6 \cdot 10^6} \qquad Equation\ 3.11.14$$

where $Pumping\ Energy\ per\ unit\ mass$ (kWh/kg) is the electrical pumping energy required per mass of fluid pumped and $\dot{m}$ (kg/s) is the mass flow rate of the fluid pumped.

As previously described, the embodied emissions from transportation stages are reported in the unit gCO_2e/MJ. Therefore, it is necessary to convert the pumping energy from a per mass basis to a per energy basis.

If the fluid pumped is a fuel, the energy required per unit energy of the fuel is calculated by *Equation* 3.11.15, and if the fluid pumped is a feedstock, the energy required per unit energy of the fuel is calculated by *Equation* 3.11.16. In the case of feedstock pumping, the feedstock to SAF conversion yield on a mass percentage basis is used to allocate the emissions of the transport stage to the equivalent quantity of SAF that the feedstock is later converted into.

$$Pumping\ Energy\ per\ unit\ energy = \frac{Pumping\ Energy\ per\ unit\ mass}{Energy\ Density_{Fuel}} \quad Equation\ 3.11.15$$

$$Pumping\ Energy\ per\ unit\ energy = \frac{Pumping\ Energy\ per\ unit\ mass}{Yield_{SAF} \cdot Energy\ Density_{SAF}} \quad Equation\ 3.11.16$$

$Pumping\ Energy\ per\ unit\ energy$ (kWh/MJ) is the energy required to pump one megajoule of fuel and $Energy\ Density_{Fuel}$ (MJ/kg) is the energy density of the fuel if the fluid pumped is fuel. Note that the unit kWh/MJ appears to be unitless as both terms are energy terms, however the kWh is the electrical energy required to pump the fuel and the MJ is the energy of the fuel that is pumped. $Energy\ Density_{SAF}$ (MJ/kg) is the energy density of the SAF that the feedstock is converted to.

3.11.3.2.Pumping Emissions Calculation

Once the specific pumping energy per unit mass is calculated, the emissions associated with this activity can be found. This methodology provides two options for the source of the pumping energy: the first is the electric grid that operates a pump and the second is a diesel engine onboard a fuel truck that operates an onboard pump.

3.11.3.2.1. Electric Grid Power Supply

In the case of pumping power being supplied from the electric grid, the emissions associated with the stage of pumping are calculated from *Equation* 3.11.17,

$$CO_2e_{Pipe} = Pumping\ Energy\ per\ unit\ energy \cdot Emission\ Factor_{Electric} \qquad Equation\ 3.11.17$$

where CO_2e_{Pipe} (gCO_2e/MJ) is the specific carbon dioxide equivalent emissions per megajoule of fuel pumped.

3.11.3.2.2. Diesel Engine Power Supply

In the case of pumping power being supplied by a diesel engine onboard a fuel truck, the mass of diesel fuel is first calculated for this pumping stage as per *Equation* 3.11.18,

$$mass_{\substack{Diesel \\ Pumping}} = \frac{Pumping\ Energy\ per\ unit\ energy}{Efficiency_{Diesel\ Engine} \cdot Efficiency_{Alternator}} / (3.6 \cdot Energy\ Density_{Diesel}) \quad Equation\ 3.11.18$$

where $mass_{\substack{Diesel \\ Pumping}}$ (kg/MJ) is the kilograms of diesel fuel used to pump one megajoule of feedstock or fuel during this pumping stage, $Efficiency_{Diesel\ Engine}$ (unitless) is the efficiency of the diesel engine in converting the fuel energy input to a power output, $Efficiency_{Alternator}$ is the efficiency of the alternator in converting the power output from the diesel engine to electrical power used by the pump, and $Energy\ Density_{Diesel}$ (MJ/kg) is the energy density of diesel fuel. Note that the diesel energy density is multiplied by a factor of 3.6. This is to convert the units from MJ/kg to kWh/kg and ensure unit consistency with the $Pumping\ Energy\ per\ unit\ energy$ (kWh/MJ) term. Also note that the mass term $mass_{\substack{Diesel \\ Pumping}}$ is lower case. This is to show that this is a specific mass per unit energy of fuel pumped, and not an absolute mass of emissions as has been the case in previous sections.

Once the mass of diesel is found, the emissions associated with this stage of pumping is calculated from *Equation* 3.11.19.

$$CO_2e_{Pipe} = mass_{\substack{Diesel \\ Pumping}} \cdot Emission\ Factor_{Diesel} \qquad Equation\ 3.11.19$$

3.11.4. Storage

For the stages of feedstock or fuel storage, the energy cost due to lighting, heating, and monitoring systems of the facility is modelled. There are different treatments depending on if the fluid stored is a feedstock or a fuel. The emissions are then calculated from the energy used.

The list of inputs required for this calculation is listed in Table 35, the list of inventory data required for the calculation listed in Table 36, and the list of assumptions for this calculation is listed in Table 37.

Table 35: Input data required for the modelling of emissions associated with the activity of storing feedstock or fuel.

Data	Notation	Unit
Fluid Transported (Feedstock or Fuel)	-	-
Time Spent by Fluid in Storage Tank	$Time_{Tank}$	hours

Table 36: Inventory data required for the modelling of energy used during activity of storing feedstock or fuel. The power consumed by a storage tank is an assumption as described in Table 37 and the volume capacity of a storage tank is modelled on a fuel storage tank at Dublin Airport.

Notation	Value	Unit	Reference
$Power_{Tank}$	5	kW	Assumption
$Volume\ Load_{Tank}$	5,000,000	L	DAA [67]

Table 37: Assumptions used in the modelling of energy use associated with the activity of storage of feedstock or fuel. These are used where actual data for the activity cannot be sourced.

	Assumption
1	The storage tank is assumed to be at 50% capacity, to model the average value during the processes of filling and emptying. This is not evidenced.
2	The volume capacity of a storage tank is modelled to be 5,000,000 L. This is the size of the each of the three fuel storage tanks at Dublin airport. This is not evidenced.
3	The storage tank is assumed to consume 5 kW of electric power. This is not evidenced.

3.11.4.1. Storage Energy Calculations

If the fluid stored is a fuel, the energy associated with the storage is calculated from *Equation* 3.11.20, and in the case where the fluid stored is a feedstock, the energy associated with the storage is calculated from *Equation* 3.11.21,

$$Energy_{Storage} = \frac{Power_{Tank} \cdot Time_{Tank}}{Volume\ Load_{Tank} \cdot Density_{Fuel} \cdot Energy\ Density_{Fuel}} \qquad Equation\ 3.11.20$$

$$Energy_{Storage} = \frac{Power_{Tank} \cdot Time_{Tank}}{Volume\ Load_{Tank} \cdot Density_{Feedstock} \cdot Yield_{SAF} \cdot Energy\ Density_{SAF}} \quad Equation\ 3.11.21$$

where $Energy_{Storage}$ (kWh/MJ) is the kilowatt-hours of energy used by the storage tank per megajoule of fluid stored in it, $Power_{Tank}$ (kW) is the power consumption of the tank, $Time_{Tank}$ is the time spent by the fluid in the tank, and $Volume\ Load_{Tank}$ (L) is the volumetric quantity of feedstock or fuel being stored in the tank

3.11.4.2. Storage Emissions Calculations

The emissions associated with the activity of storing a feedstock or fuel is calculated as described in *Equation* 3.11.22.

$$CO_2e_{Storage} = Energy_{Storage} \cdot Emission\ Factor_{Electric} \quad Equation\ 3.11.22$$

4. Scenario Details

This chapter describes the scenario of aviation activity modelled. The specific supply chain of this scenario is modelled using the methodology described in Chapter 3.

4.1. Scenario Description

There are three primary considerations for an aviation scenario using this methodology: aircraft type, route, and fuel. The considered scenario in this work considers the following.

Table 38: Description of the aircraft, route, and fuel choice for the scenario studied. The airport codes listed in the route description follow International Air Transport Association airport naming convention.

Consideration	Scenario Choice
Aircraft:	Ryanair Boeing 737-8200
Route:	Amsterdam Schiphol Airport (AMS) to Dublin Airport (DUB)
Fuel:	40% of Neste HEFA SAF derived from used cooking oil blended with fossil aviation fuel.

The Ryanair Boeing 737-8200 is the selected aircraft as this is the newest and most efficient aircraft in the Ryanair fleet and represents a best-in-class benchmark for the coming several years. The route of Amsterdam Schiphol Airport to Dublin Airport is chosen as this is a route that is operated by Ryanair, Ryanair has secured a SAF supply deal at this airport [9], and Amsterdam Schiphol Airport received funding under the Demonstrating Lower Polluting Solutions for Sustainable Airports [68] across Europe Research and Innovation action plan. Neste HEFA SAF was chosen as this is a fuel that Ryanair has a purchase agreement for. The SAF is modelled to be derived from used cooking oil; this is reported in SAF purchase dockets that Ryanair received from Neste. The blend ratio of 40% represents the fuel described in the Neste-Ryanair agreement [9].

4.2. Global Data

Based on the definition of the scenario, there is some data that is used in all stages of the LCA calculations. This data includes densities, energy densities and other properties of feedstocks and fuel and is listed in Table 39.

The emission factors of grid electricity are another set of data that is used through all stages of this LCA calculation. This is sourced from a dataset published by the Joint Research Centre of the European Union [69]. The IPCC default emission factors are listed as well as an LCA value.

It is assumed that the LCA approach considered further emissions associated with electrical losses in the transmission and distribution of electricity, whereas the IPCC approach considers only the production and assumes ideal transmission and distribution. It is not fully understood how this LCA emission factor is calculated and not all countries have an LCA emission factor whereas all do have an IPCC emission factor. Therefore, it was chosen to use the IPCC emission factor. The emission factors of grid electricity in countries relevant for the calculation of this scenario are listed in Table 40.

Table 39: Physical properties of the feedstock and fuels considered during this scenario calculation. The density and viscosity of the used cooking oil feedstock were sourced from literature. The dynamic viscosity of used cooking oil was converted from the reported kinematic viscosity using the density. The density and energy density of fossil aviation fuel and neat SAF derived from used cooking oil was sourced from a study by Gawron et. al [70]. The dynamic viscosity of fossil aviation fuel is calculated from an average of four reported kinematic viscosities from samples of petroleum-derived aviation fuel where measurements were taken at 293.15 K [71]. The dynamic viscosity of the neat SAF is calculated from an average of two reported kinematic viscosities from samples of biomass-derived HRJ where measurements were taken at 293.15 K [71]. The properties of the blended fuel were interpolated from the fossil aviation fuel and neat SAF data by assuming the properties scale linearly with the blend percentage.

Property	Data	Unit	Reference
Used Cooking Oil			
Density	0.873	kg/L	[72]
Dynamic Viscosity	$3.58 \cdot 10^{-5}$	kg/m·s	[73]
Fossil Aviation Fuel			
Density	0.790	kg/L	[70]
Energy Density	43.307	MJ/kg	[70]
Dynamic Viscosity	$2.35 \cdot 10^{-6}$	kg/m·s	[71]
HEFA SAF derived from Used Cooking Oil			
Density	0.771	kg/L	[70]
Energy Density	43.744	MJ/kg	[70]
Dynamic Viscosity	$1.17 \cdot 10^{-6}$	kg/m·s	[71]
40% Blend of SAF with Fossil Aviation Fuel			
Density	0.783	kg/L	Interpolated
Energy Density	43.482	MJ/kg	Interpolated
Dynamic Viscosity	$1.82 \cdot 10^{-6}$	kg/m·s	Interpolated

Table 40: Emission factors of grid electricity in countries relevant for the calculation of this scenario, sourced from the Joint Research Centre of the European Union [69]. Data for EU countries is averaged between 2017-2019. Data for rest of world is averaged between 2013-2015. These are the most recent non-Covid affected years available.

Country	Grid Electricity Emission Factor (gCO_2e/kWh)
Netherlands	844
Finland	76
Indonesia	824
China	818
USA	545
Germany	538
Belgium	702

4.3. Feedstock Production

The feedstock for the SAF in this scenario is used cooking oil. There are no life cycle emissions associated with the feedstock prior to its collection and transportation to the fuel production facility as it is a waste.

4.4. Feedstock Transportation

There are four scenarios of feedstock transport considered. SAF delivery dockets supplied to Ryanair from Neste show that used cooking oil is sourced from at least four countries; Indonesia, China, the United States, and Germany. Indonesia was the most common feedstock source in these documents and is the primary case study in this report.

It is assumed that there is a reservoir of used cooking oil, where it is collected; this is the first activity considered in the Feedstock Transportation system boundary. It is assumed that a truck transports the used cooking oil to a port, where it is stored for a time. It is then assumed to be shipped to the fuel production facility where it is again stored for a time. The fuel production is modelled to take place at Neste's Porvoo facility in Finland, which has its own port. It is then pumped into the facility where it is converted into SAF. For all storage stages in this supply chain, a storage time of 24 hours is assumed.

The pumping stages to and from the truck have an assumed transport distance of 30m, while the pumping stages to and from the ship have an assumed transport distance of 500m. The pumping distance from the storage tank at the fuel production facility to the refinery is also assumed to be 500m. These assumptions are developed using local maps. All other pumping inputs remain constant for all pumping stages and are listed in Table 41. The pumping stage from the collection reservoir to the truck is assumed to be powered by the diesel engine of the truck; all other pumping stages are assumed the be powered by grid electricity.

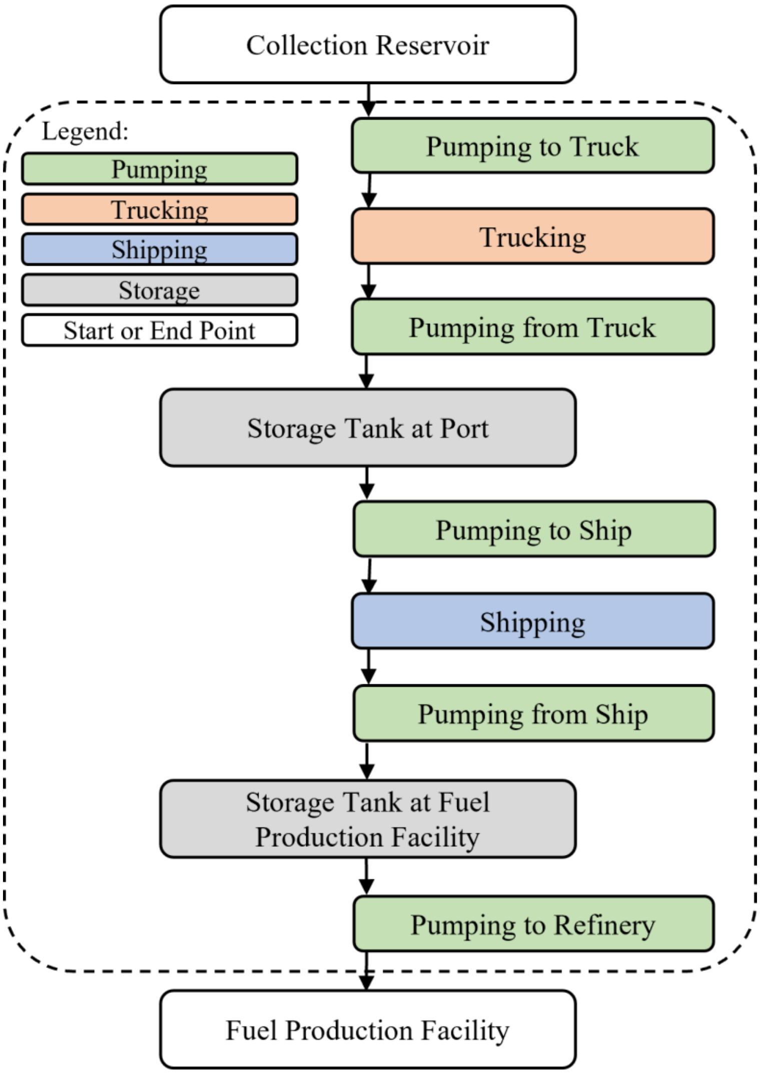


Figure 17: Supply chain of Feedstock Transportation for the modelled scenario. This supply chain was developed using logical assumptions and is not evidenced.

Table 41: Scenario input data for all pumping stages in the Feedstock Transport and Fuel Transportation and Blending supply chains. These inputs are developed using logical assumptions and are not evidenced.

Input	Data	Unit
Pipe Diameter	0.2	m
Pipe Material	Smooth Rubber	-
Average Fluid Velocity	1	m/s
Turbine Present?	No	-
Number of Valves	1	-
Number of Elbows	0	-

The trucking stage is assumed to be 100km, of which 60km is completed on highways and 40km on urban roads. This trucking assumption is held constant for the four scenarios of feedstock supply chain. The only transport distance that changes for each scenario considered is the shipping. The shipping distances are listed in Table 42.

Table 42: Shipping distances of the Feedstock Transportation supply chain. This data was collected by using an online calculator that measured shipping distances between ports using common shipping routes [74]. For each feedstock scenario, the busiest port in each country was selected to model. This is not evidenced.

Route	Distance (km)
Port of Hamburg, Germany to Port of Porvoo, Finland	2,315
Port of New York, USA to Port of Porvoo, Finland	8,690
Port of Anyer Terminal, Indonesia to Port of Porvoo, Finland	20,205
Port of Shanghai, China to Port of Porvoo, Finland	24,767

4.5. Fuel Production

The Fuel Production stage of this scenario calculation models the emissions associated with the Neste SAF derived from used cooking oil. Scenario specific details of this stage can be found in Liam Mannion's transfer report.

4.6. Fuel Transportation and Blending

The supply chain of the fuel is assembled as shown in Figure 18. This supply chain is an assumption; the only fuel transport data acquired from industry partners is the location of fuel production, the location of blending SAF with fossil aviation fuel, and the transport mode used to transport the blended fuel to the airport. The fossil aviation fuel is assumed to have the same supply chain as the SAF until to the point of blending. This is because the location of fuel production and the supply chain is not known for the fossil aviation fuel.

The first considered activity in the Fuel Transportation and Blending system boundary is the pumping of fuel from the refinery after the feedstock has been converted to fuel. It is assumed that the fuel is stored for a time, then shipped to the blending facility and stored again. The blending process is modelled to take place at the Port of Ghent, Belgium. After the blending, the fuel is assumed to be stored for a time, then shipped to the Port of Amsterdam. From the Port of Amsterdam, the fuel is pumped to Amsterdam Schiphol Airport where it is again stored for a time before the underground hydrant system is used to transport it to the aircraft. For all storage stages in this supply chain, it is assumed that the fuel is stored for 24 hours.

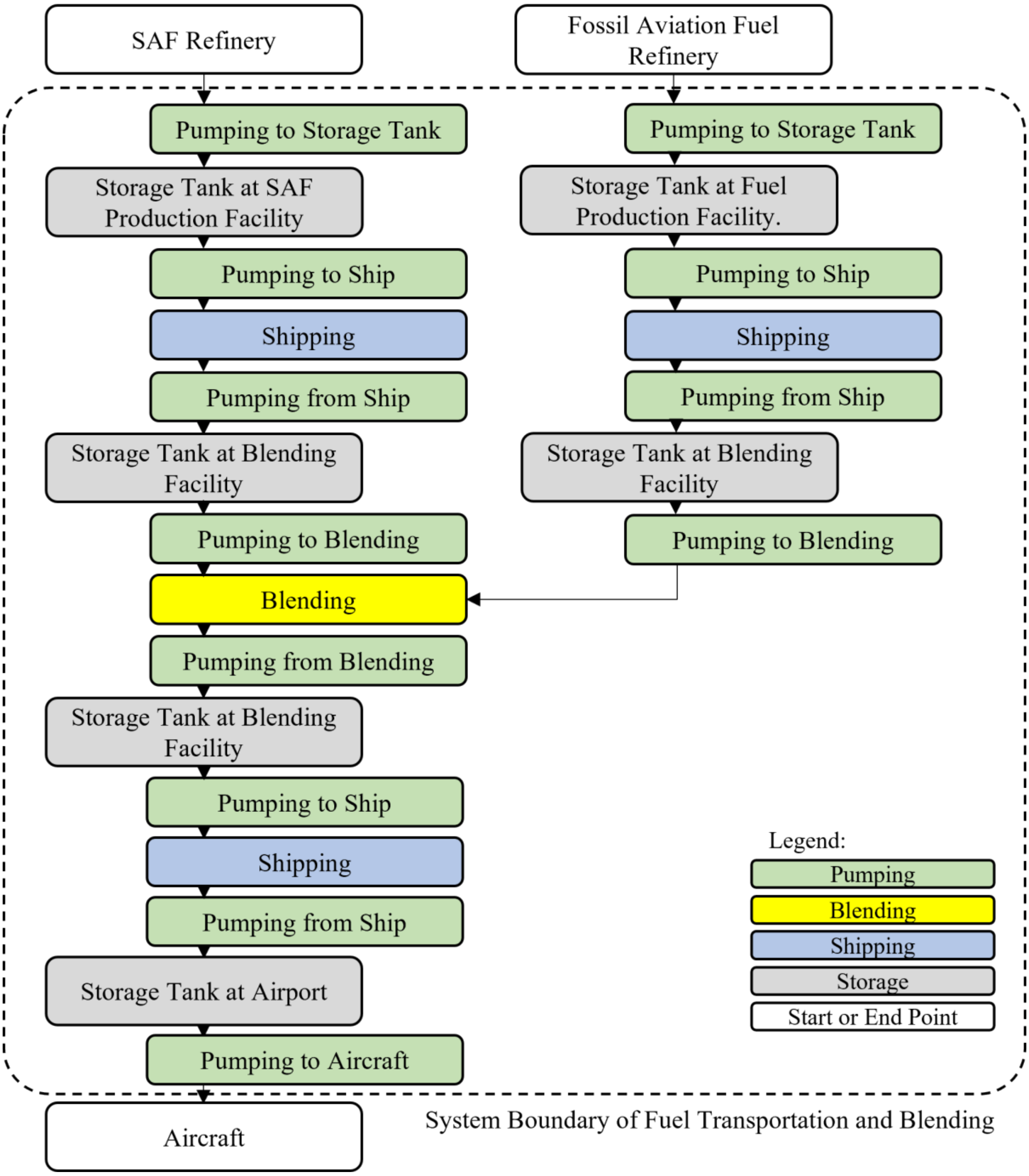


Figure 18: Supply chain of Fuel Transportation and Blending for the modelled scenario. This supply chain was developed using logical assumptions and is not evidenced.

All pumping stages have an assumed transport distance of 500m, except for the final two pumping stages of blended fuel. The distance from the ship at the Port of Amsterdam to the storage tank at Amsterdam Schiphol Airport is assumed to be 13.140 km and the distance from the storage tank at Amsterdam Schiphol Airport to the aircraft is assumed to be 4 km. These distances are assumed from local maps. All other inputs for pumping remain constant for all stages, are the same as those for the Feedstock Transportation stage of the LCA and are listed in Table 41. All pumping stages are assumed the be powered by grid electricity.

The shipping stage from the fuel production in Porvoo, Finland to the blending in Ghent, Belgium is assumed to be 2,822km. The shipping stage from the blending in Ghent, Belgium to the Port of Amsterdam is assumed to be 339km. This data was collected by using an online calculator for shipping distances between ports [74].

The TCD modelling of fossil aviation fuel begins at this stage. It is assumed that fossil aviation has the same supply chain as the SAF during the Fuel Transportation and Blending stage of the LCA.

4.7. Aircraft Operations

Table 43: Operational parameters of the aviation activity collected in the Aircraft Operations stage of the LCA. The mass of fuel used is calculated by TCD as discussed in the succeeding paragraph. However, it is desired to obtain this mass directly from the airline for the specific aviation activity. The SAF blend percentage represents the scenario described in Chapter 4.1. The distance travelled is the straight-line distance between the origin and destination airport of the scenario and the number of passengers transported is calculated by assuming the average pre-Covid Ryanair load factor of 96%.

Input	Data	Unit
Fuel Used by Aircraft	2521.5	kg
SAF Blend Percentage	40%	-
Distance Travelled	749	km
Passengers Transported	189	-

The fuel used by the aircraft is desired to be sourced directly from the aircraft operator and be specific to this aviation activity, but currently this is calculated by TCD based on fuel use data provided by Ryanair from ten random flights using the Boeing 737-8200 aircraft. The fuel used during the taxi, take-off, climb, descent, and landing stages of flight is averaged. The average fuel use during cruise is expressed as a burn rate with the units of kg/hour. Flight data for the route of Amsterdam Schiphol Airport to Dublin Airport is sourced from a flight tracking website [75] and used to find the average duration of the cruise stage during this flight. The SAF blend percentage is described in Chapter 4.1. The distance travelled is taken as the straight-line distance between Amsterdam Schiphol Airport to Dublin Airport, calculated from Google Maps. The number of passengers onboard is also desired to be directly obtained from the aircraft operator, however this is currently an assumption, calculated by multiplying the capacity of a 737-8200 in Ryanair specification, 197, by the average Ryanair load factor as reported in their 2022 annual report, 96% [12].

4.8. Airport Operations

The inputs used for the Airport Operations stage of the LCA are listed in Table 44. These inputs are all assumptions.

Table 44: Input data used in the calculation of the Airport Operations stage of the LCA for the modelled scenario. The notation corresponds to the notation of the term in the methodology chapter. These inputs are developed using logical assumptions and are not evidenced.

Data	Notation	Input	Unit
Mass of Aviation Fuel Used by Auxiliary Power Unit at the Gate	$Mass_{\substack{Aviation\ Fuel \\ APU}}$	0	kg
Mass of Diesel Used by Ground Power Unit at the Gate	$Mass_{\substack{Diesel \\ GPU}}$	10	kg
Energy Source of Luggage Vehicles	-	Diesel	-
Number of Luggage Vehicles	$n_{Luggage}$	3	-
Distance Travelled by each Luggage Vehicle	$Distance\ Travlled_{Luggage}$	0.5	km
Energy Source of Stair Vehicles	-	Unpowered	-
Number of Diesel or Electric Stair Vehicles	n_{Stair}	1	-
Distance Travelled by each Diesel or Electric Stair Vehicle	$Distance\ Travlled_{Stiar}$	0.2	km
Energy Source of Bus Vehicle	-	Diesel	-
Number of Bus Vehicles	n_{Bus}	0	-
Distance Travelled by Each Bus Vehicle	$Distance\ Travlled_{Bus}$	n/a	km
Energy Source of Catering Vehicles	-	Diesel	-
Number of Catering Vehicles	$n_{Catering}$	1	-
Distance Travelled by each Catering Vehicle	$Distance\ Travlled_{Catering}$	0.5	km
Energy Source of Sanitary Vehicles	-	Diesel	-
Number of Sanitary Vehicles	$n_{Sanitary}$	1	-
Distance Travelled by each Sanitary Vehicle	$Distance\ Travlled_{Sanitary}$	0.5	km
Energy Source of Tug	-	Diesel	-
Distance Travelled by Tug	$Distance\ Travlled_{Tug}$	0.3	km

5. Results and Discussion

5.1. Feedstock Production

There are no emissions associated with the Feedstock Production stage of the LCA because used cooking oil is the considered feedstock, a waste material.

5.2. Feedstock Transportation

Table 45: Life cycle emissions embodied in the SAF from activity within the Feedstock Transportation System Boundary. Note that the difference in these values originates from the different shipping distances for the feedstocks and the different emission factors of grid electricity which effects the emissions from pumping and storage emissions.

Locations of Feedstock Souring	gCO_2e/MJ
Germany	0.66
USA	3.25
Indonesia	7.33
China	8.95

The summary of Feedstock Transportation results is shown in Table 45. A large variation in results is seen that depends on the feedstock sourcing location. The fuel production is modelled to take place in Porvoo, Finland, and therefore the feedstock sourcing locations with the highest transportation distances to Finland have the highest emissions associated with them. Table 46 and Table 47 list the complete results of Feedstock Transportation per stage of transport activity. Table 46 focuses on the Indonesia scenario and shows percent contribution for each of the transport stages; Indonesia is the primary scenario studied as this is where most of the feedstock was sourced from in the documents obtained from Ryanair and Neste.

It is noted that there are minor differences in the emissions from stages of feedstock pumping and storage in the country of feedstock sourcing where the power is provided by grid electricity. This is due to the different emission factors of grid electricity in each of the scenario countries.

Table 46 and Table 47 also show that the emissions from the trucking component of the supply chain remains constant for all feedstock sourcing scenarios, since the same assumption for distance travelled is used in all scenarios and the emission factor for the mass of diesel used is also constant.

Table 46: Life cycle emissions embodied in the SAF per stage of activity within the Feedstock Transportation system boundary for the case of feedstock sourced from Indonesia. These stages of feedstock transportation reference the supply chain that is described in Figure 17.

Stage of Feedstock Transportation Activity	gCO_2e/MJ	%Contribution
Pumping of Feedstock from Collection Reservoir to Truck	$1.34 \cdot 10^{-5}$	0.00%
Trucking of Feedstock from Collection Reservoir to Port	$1.62 \cdot 10^{-1}$	2.21%
Pumping of Feedstock from Truck to Port Storage	$9.42 \cdot 10^{-6}$	0.00%
Storage of Feedstock at Port	$1.83 \cdot 10^{-3}$	0.02%
Pumping of Feedstock from Port Storage to Ship	$9.50 \cdot 10^{-6}$	0.00%
Shipping of Feedstock from Port of Feedstock Procurement to Port of Fuel Production	$7.17 \cdot 10^{0}$	97.76%
Pumping of Feedstock from Ship to Storage at Fuel Production Facility	$8.35 \cdot 10^{-7}$	0.00%
Storage of Feedstock at Fuel Production Facility	$1.68 \cdot 10^{-4}$	0.00%
Pumping of Feedstock from Storage at Fuel Production Facility to Refinery	$8.77 \cdot 10^{-7}$	0.00%
Total	7.33	

Table 47: Life cycle emissions embodied in the SAF per stage of activity within the Feedstock Transportation system boundary for feedstock sourced from Germany, the United States, and China. These stages of feedstock transportation reference the supply chain that is described in Figure 17.

Stage of Feedstock Transportation Activity	gCO_2e/MJ		
	Germany	USA	China
Pumping of Feedstock from Collection Reservoir to Truck	$1.34 \cdot 10^{-5}$	$1.34 \cdot 10^{-5}$	$1.34 \cdot 10^{-5}$
Trucking of Feedstock from Collection Reservoir to Port	$1.62 \cdot 10^{-1}$	$1.62 \cdot 10^{-1}$	$1.62 \cdot 10^{-1}$
Pumping of Feedstock from Truck to Port Storage	$6.15 \cdot 10^{-6}$	$6.23 \cdot 10^{-6}$	$9.35 \cdot 10^{-6}$
Storage of Feedstock at Port	$1.19 \cdot 10^{-3}$	$1.21 \cdot 10^{-3}$	$1.81 \cdot 10^{-3}$
Pumping of Feedstock from Port Storage to Ship	$6.21 \cdot 10^{-6}$	$6.29 \cdot 10^{-6}$	$9.43 \cdot 10^{-6}$
Shipping of Feedstock from Port of Feedstock Procurement to Port of Fuel Production	$4.92 \cdot 10^{-1}$	$3.08 \cdot 10^{0}$	$8.79 \cdot 10^{0}$
Pumping of Feedstock from Ship to Storage at Fuel Production Facility	$8.35 \cdot 10^{-7}$	$8.35 \cdot 10^{-7}$	$8.35 \cdot 10^{-7}$
Storage of Feedstock at Fuel Production Facility	$1.68 \cdot 10^{-4}$	$1.68 \cdot 10^{-4}$	$1.68 \cdot 10^{-4}$
Pumping of Feedstock from Storage at Fuel Production Facility to Refinery	$8.77 \cdot 10^{-7}$	$8.77 \cdot 10^{-7}$	$8.77 \cdot 10^{-7}$
Total	0.66	3.25	8.95

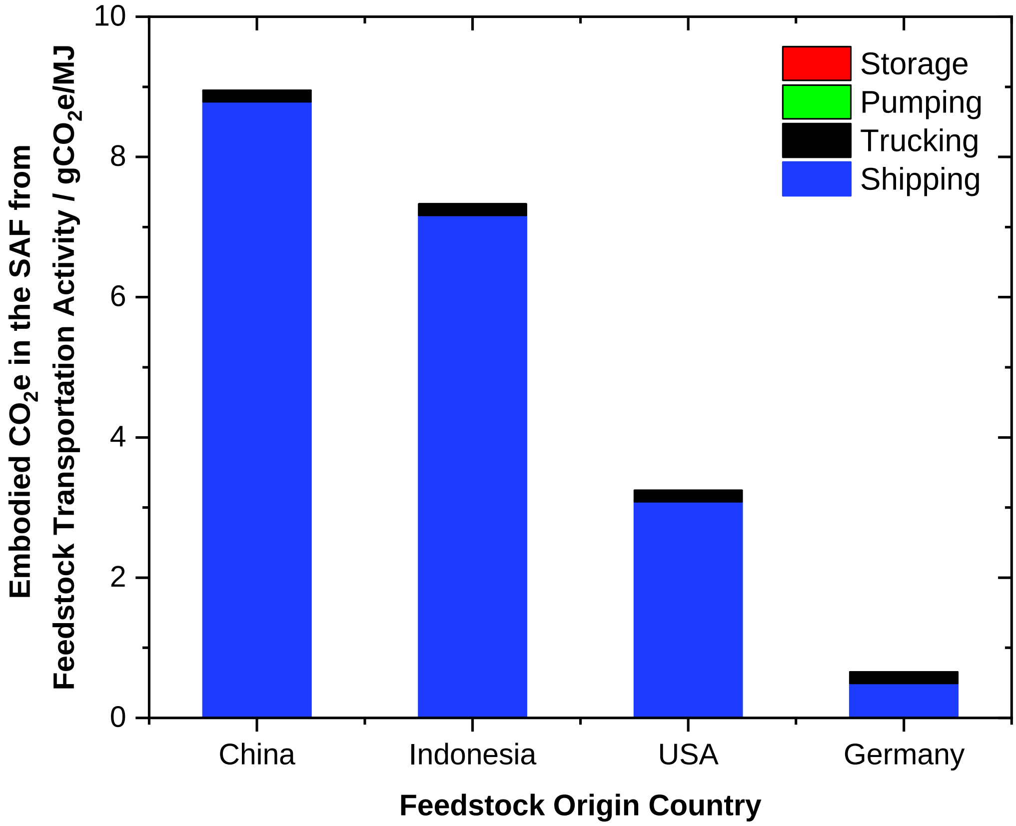


Figure 19: Embodied GHG emissions of the modelled SAF from activity within the Feedstock Transportation system boundary. The results are broken down by transport mode and four scenarios of feedstock sourcing locations are included, based on data provided to TCD by Ryanair and Neste. Note that the trucking emissions are constant for the four scenarios as the trucking distance and diesel emission factor are kept constant. The shipping emissions vary due to different shipping distances. The pumping and storage emissions also vary due to different emission factors of grid electricity in each of the feedstock sourcing countries.

It is seen that shipping makes up almost all the different emissions between the feedstock sourcing locations. Figure 19 shows the dominance of shipping in the make-up of Feedstock Transportation emissions. In the case of Indonesian feedstock, the shipping component of the feedstock supply chain makes up 98% of the emissions within the Feedstock Transportation system boundary.

5.3. Fuel Production

Table 48: Life cycle CO_2e emissions embodied in the SAF from activity within the Fuel Production system boundary. This result is obtained from work completed by Liam Mannion and is further described in his transfer report.

Allocation Method used for Fuel Production Emissions	gCO_2e/MJ
Energy Allocation	15.3

The results of the embodied emissions from activity within the Fuel Production system boundary are shown in Table 48. Energy allocation was chosen as the most suitable method to allocate the emissions among the co-products produced. If no allocation method is used, the emission intensity of the Fuel Production stage of the LCA is 24.0 gCO_2e/MJ. If mass allocation is used, the result is 15.1 gCO_2e/MJ, similar to the energy allocation method. Further discussion on this result is available in Liam Mannion's transfer report.

5.4. Fuel Transportation & Blending

The results of the Fuel Transportation and Blending stage of the LCA are shown in Figure 20, Table 49, and Table 50. Figure 20 shows the embodied emissions in the SAF and fossil aviation fuel from activity within the Fuel Transportation and Blending system boundary per mode of transport used to transport the SAF and fossil aviation fuel from the fuel production facility to the blending facility and finally to the aircraft.

Once again, as was the case for the Feedstock Transportation stage, shipping is the dominant source of these embodied emissions. Shipping is responsible for 99.7% of embodied emissions in the SAF for this stage of the LCA, and 99.6% for the fossil aviation fuel. Note that there are slight differences between the results for SAF and fossil aviation fuel even though the same supply chain is assumed for both; this is because of the slight differences in physical properties such as density, energy density and viscosity.

The emissions from this stage of the LCA are an order of magnitude smaller than the emissions from the Feedstock Transportation stage, mainly due to the significantly shorter transport distances in the Fuel Transportation and Blending stage. This highlights the importance of supply chain optimization and the geographical location choice of feedstock sourcing, fuel production, blending, and fuel use. Another factor that influences the transport emissions is the fluid transported. In this case, during Feedstock Transportation, not all the used cooking oil is converted into SAF. Liam Mannion's Fuel Production modelling shows that the mass conversion yield is 57%. Since a significant amount of mass is lost to other co-products during Fuel Production, the feedstock should be transported the shortest distance possible as the emissions are allocated to the quantity of SAF that it produces. It is more efficient to transport the finished fuel.

Table 49: Life cycle emissions embodied in the SAF per stage of activity within the Fuel Transportation and Blending system boundary. These stages of fuel transportation and blending reference the supply chain that is described in Figure 18. Note that from the point of blending onwards, the transport emissions of the blended fuel are calculated and allocation to the SAF and fossil aviation fuel components according to the blend ratio.

Stage of SAF Transportation Activity	**gCO_2e/MJ**	**%Contribution**
Pumping of Neat SAF from Refinery to Storage at Fuel Production Facility	$5.12 \cdot 10^{-7}$	0.00%
Storage of Neat SAF at Fuel Production Facility	$1.08 \cdot 10^{-4}$	0.02%
Pumping of Neat SAF from Storage at Fuel Production Facility to Ship	$5.39 \cdot 10^{-7}$	0.00%
Shipping of Neat SAF from Port of Fuel Production to Port of Blending	$5.68 \cdot 10^{-1}$	97.76%
Pumping of Neat SAF from Ship to Storage at the Blending Facility	$4.73 \cdot 10^{-6}$	0.00%
Storage of Neat SAF at Blending Facility	$9.99 \cdot 10^{-4}$	0.17%
Pumping of Neat SAF from Storage at the Blending Facility to the Blending Facility	$4.98 \cdot 10^{-6}$	0.00%
Blending of Neat SAF with Fossil Aviation Fuel	$1.66 \cdot 10^{-5}$	0.00%
Pumping of Blended Fuel from Blending Facility to Storage at Blending Facility	$1.88 \cdot 10^{-6}$	0.00%
Storage of Blended Fuel at Blending Facility	$3.96 \cdot 10^{-4}$	0.07%
Pumping of Blended Fuel from Storage at Blending Facility to Ship	$1.98 \cdot 10^{-6}$	0.00%
Shipping of Blended Fuel from Port of Blending to Port of Fuel Delivery	$1.10 \cdot 10^{-2}$	1.89%
Pumping of Blended Fuel from Ship to Storage at the Airport	$4.63 \cdot 10^{-6}$	0.00%
Storage of Blended Fuel at Airport	$4.76 \cdot 10^{-4}$	0.08%
Pumping of Blended Fuel from Storage at the Airport to the Aircraft	$2.84 \cdot 10^{-6}$	0.00%
Total	$5.81 \cdot 10^{-1}$	

Table 50: Life cycle emissions embodied in the fossil aviation fuel per stage of activity within the Fuel Transportation and Blending system boundary. These stages of fuel transportation and blending reference the supply chain that is described in Figure 18. Note that from the point of blending onwards, the transport emissions of the blended fuel are calculated and allocation to the SAF and fossil aviation fuel components according to the blend ratio.

Stage of Fossil Aviation Fuel Transportation Activity	**gCO_2e/MJ**	**%Contribution**
Pumping of Neat SAF from Refinery to Storage at Fuel Production Facility	$5.08 \cdot 10^{-7}$	0.00%
Storage of Neat SAF at Fuel Production Facility	$1.07 \cdot 10^{-4}$	0.02%
Pumping of Neat SAF from Storage at Fuel Production Facility to Ship	$5.34 \cdot 10^{-7}$	0.00%
Shipping of Neat SAF from Port of Fuel Production to Port of Blending	$5.73 \cdot 10^{-1}$	96.81%
Pumping of Neat SAF from Ship to Storage at the Blending Facility	$4.69 \cdot 10^{-6}$	0.00%
Storage of Neat SAF at Blending Facility	$9.85 \cdot 10^{-4}$	0.17%
Pumping of Neat SAF from Storage at the Blending Facility to the Blending Facility	$4.93 \cdot 10^{-6}$	0.00%
Blending of Neat SAF with Fossil Aviation Fuel	$2.50 \cdot 10^{-5}$	0.00%
Pumping of Blended Fuel from Blending Facility to Storage at Blending Facility	$2.82 \cdot 10^{-6}$	0.00%
Storage of Blended Fuel at Blending Facility	$5.94 \cdot 10^{-4}$	0.10%
Pumping of Blended Fuel from Storage at Blending Facility to Ship	$2.97 \cdot 10^{-6}$	0.00%
Shipping of Blended Fuel from Port of Blending to Port of Fuel Delivery	$1.65 \cdot 10^{-2}$	2.78%
Pumping of Blended Fuel from Ship to Storage at the Airport	$6.94 \cdot 10^{-6}$	0.00%
Storage of Blended Fuel at Airport	$7.14 \cdot 10^{-4}$	0.12%
Pumping of Blended Fuel from Storage at the Airport to the Aircraft	$4.26 \cdot 10^{-6}$	0.00%
Total	$5.92 \cdot 10^{-1}$	

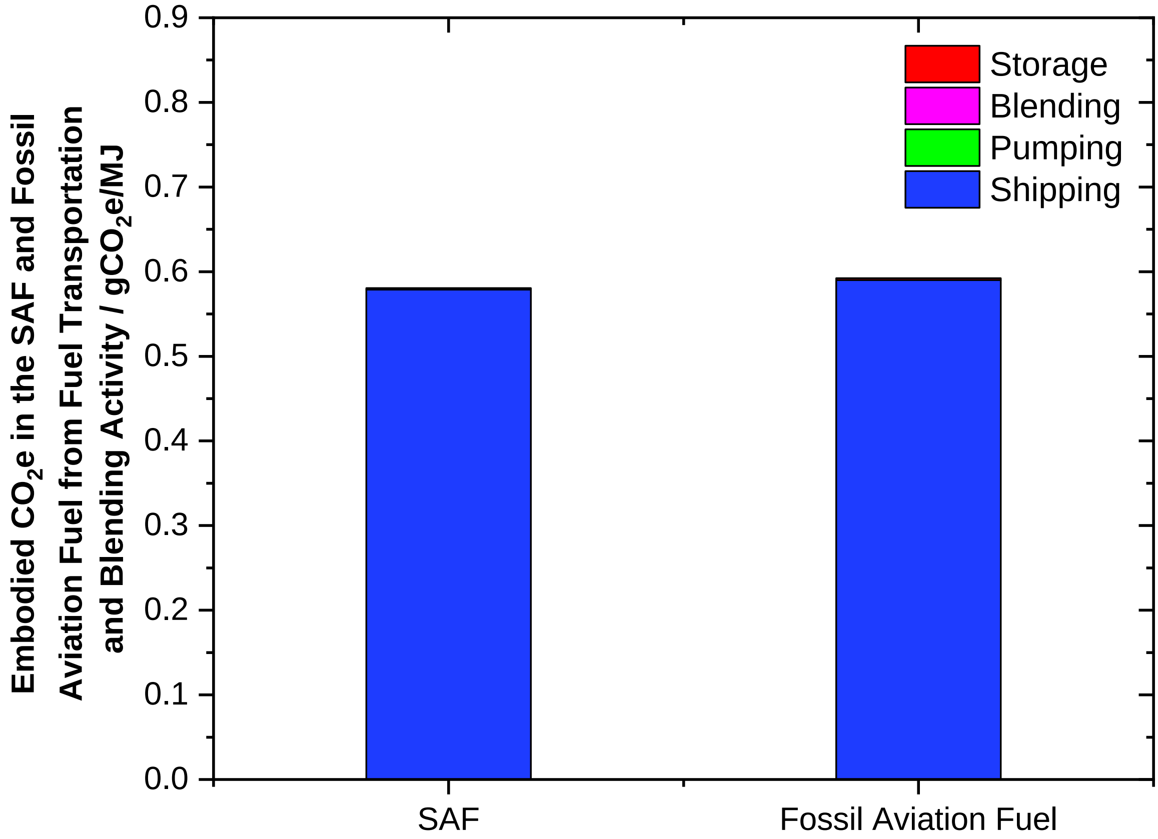


Figure 20: Embodied GHG emissions of the modelled SAF and fossil aviation fuel from activity within the Fuel Transportation and Blending system boundary. The results are broken down by transport mode. Note that the emissions assosiated with the SAF and fossil aviation fuel are very similar but vary slightly due to their different physical properties such as density, energy density and viscosity.

5.5. Aircraft Operations

Table 51: The combustion emission factors for fossil aviation fuel and biologically derived SAF. The modelled SAF is considered to have zero direct emissions as the carbon is sequestered during feedstock production and is recycled to the atmosphere. The emission factor for fossil aviation fuel makes up the combustion component of the EU carbon intensity baseline for fossil aviation fuel, reported as 93.1 gCO_2e/MJ by Chiaramonti [56]. This is used in place of the global 89 gCO_2e/MJ result as used by CORSIA as it is more representative of a European scenario.

Fuel	Emission Factor (gCO_2e/MJ)
Fossil Aviation Fuel	74
SAF	0

As described in Chapter 3.8, this stage of the LCA also collects the fuel use data during the aviation activity. In this scenario, 2,521.5 kg was consumed. This is a value calculated by TCD using actual flight data of the Boeing 737-8200 as described in Chapter 4.7.

Table 43 shows the specific mass of aviation fuel used during the considered aviation activity. Chapter 5.8 details the total fuel emissions of the aviation activity, considering the five relevant stages of the SAF LCA: Feedstock Production, Feedstock Transportation, Fuel Production, Fuel Transportation & Blending, and Aircraft Operations.

5.6. Airport Operations

The result of the Airport Operations stage of the LCA in Table 52 and Figure 21 show that 87% of the emissions from airport activity come from the use of a ground power unit. There were no emissions associated with the auxiliary power unit as it was assumed that the ground power unit was used instead. There were also no emissions from the activity of de-boarding and boarding passengers due to the assumptions outlines in Chapter 4.8.

There is uncertainty in this result as the mass of fuel used by the ground power unit and the duration of ground power unit use are assumptions and have a significant effect on the emissions from this stage of the LCA.

Table 52: Emissions associated with activity within the Airport Operations system boundary for the considered aviation activity. The activity listed here references the Airport Operations inputs as described in Figure 16. Note that these emissions are reported as a mass of CO_2e. This is not fuel activity; the emissions are not embodied in the fuel.

Stage of Airport Operations Activity	**gCO_2e**	**Contribution**
Use of Auxiliary Power Unit at the Gate	$0.00 \cdot 10^0$	0.00%
Use of Ground Power Unit at the Gate	$3.26 \cdot 10^4$	87.23%
Delivery and Collection of Luggage to and from the Aircraft	$2.37 \cdot 10^3$	6.34%
De-boarding and Boarding of Passengers from and to the Aircraft	$0.00 \cdot 10^0$	0.00%
Delivery of Catering Supplies to and from the Aircraft	$7.89 \cdot 10^2$	2.11%
Delivery of Sanitary Services to and from the Aircraft	$7.89 \cdot 10^2$	2.11%
Use of Tug to Push-Back the Aircraft	$8.26 \cdot 10^2$	2.21%
Total	$3.74 \cdot 10^4$	

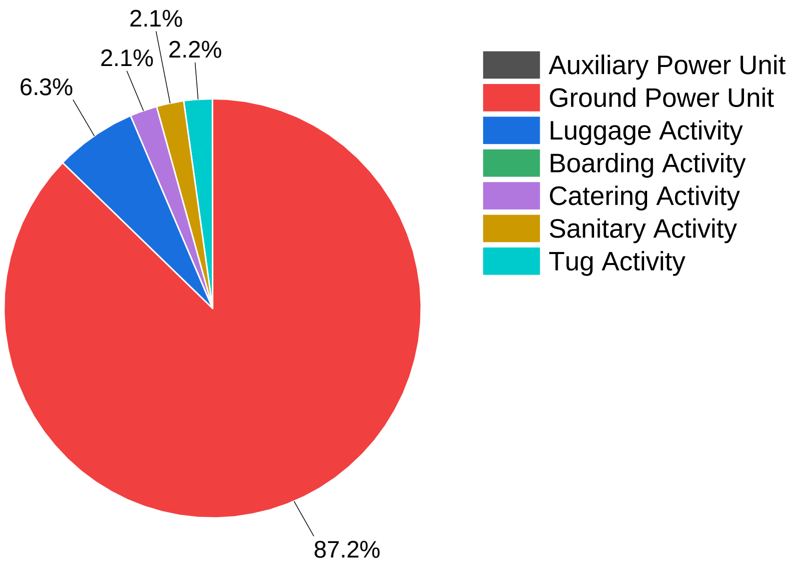


Figure 21: Pie-chart of GHG emissions associated with the activity within the Airport Operations system boundary. The results are broken down by stage of airport operations activity as described in Chapter 3.9. Note that there are no emissions from the use of the auxiliary power unit or the activity of de-boarding and boarding passengers from and to the aircraft due to assumptions used when modelling this scenario as described in Chapter 4.8.

5.7. Fossil Aviation Fuel

As discussed in Chapter 3.10, the activity of fossil aviation fuel is not yet modelled by TCD until the Fuel Transportation and Blending Stage. Therefore, literature results are used for the previous stages of fossil aviation fuel: Crude Extraction, Crude Transportation, and Fuel Production. These results are reported by Chiaramonti et al. [56] and are representative of fossil aviation fuel in a European scenario and listed in Table 53.

Table 53: Emission factors for the stages of the fossil aviation fuel life cycle that are currently not modelled by TCD. This data is reported by Chiaramonti et al. [56] as a baseline for fossil aviation in a European context, and make up a life cycle emission factor of 93.1 gCO_2e/MJ. This is used in place of the global 89 gCO_2e/MJ result as used by CORSIA as it is more representative of a European scenario.

Life Cycle Stage of Fossil Aviation Fuel	Emission Factor (gCO_2e/MJ)
Crude Extraction	10
Crude Transportation	2
Fuel Production	6.1

The Crude Extraction is seen to be a relatively emission intensive activity, especially when compared to the equivalent stage of SAF: Feedstock Production, which has no emissions associated for waste feedstocks such as used cooking oil. The Crude Transportation stage has a comparable result to Feedstock Transportation in this study, assuming the crude is transported approximately 5,000 km. The Fuel Production stage has 60% less emissions that the same stage for the SAF. It is generally accepted that the feedstock to SAF conversion process is more energy intensive that the fossil aviation fuel production process, so this is expected.

5.8. Activity Summary

The life cycle emissions of the modelled SAF ranges from 16.5 to 24.8 gCO2e/MJ for the four scenarios of feedstock sourcing locations. The results per stage of the LCA are listed in Table 54 and graphed in Figure 22. Note that the results of all stages of the LCA are constant except for Feedstock Transportation. The only difference between these four SAFs is the location of feedstock sourcing, and the range of results is 8.3 gCO2e/MJ. These results again highlight the importance of feedstock sourcing locations and the optimisation of the supply chain. Since shipping makes up almost all the transportation results, this is highlighted as the greatest challenge and source of uncertainty in the life cycle emissions of SAF.

Table 54: Life cycle emission intensity of the modelled SAF per stage of the LCA for the four scenarios of feedstock sourcing locations as described in Chapter 4.4. Note that the Feedstock Transportation is the only stage of the LCA that varies with feedstock sourcing location.

Life Cycle Stage of SAF	**Emission Factor (gCO_2e/MJ)**			
	China	Indonesia	USA	Germany
Feedstock Production	0.00	0.00	0.00	0.00
Feedstock Transportation	8.95	7.33	3.25	0.66
Fuel Production	15.3	15.3	15.3	15.3
Fuel Transportation and Blending	0.58	0.58	0.58	0.58
Aircraft Operations	0.00	0.00	0.00	0.00
Total	24.8	23.2	19.1	16.5

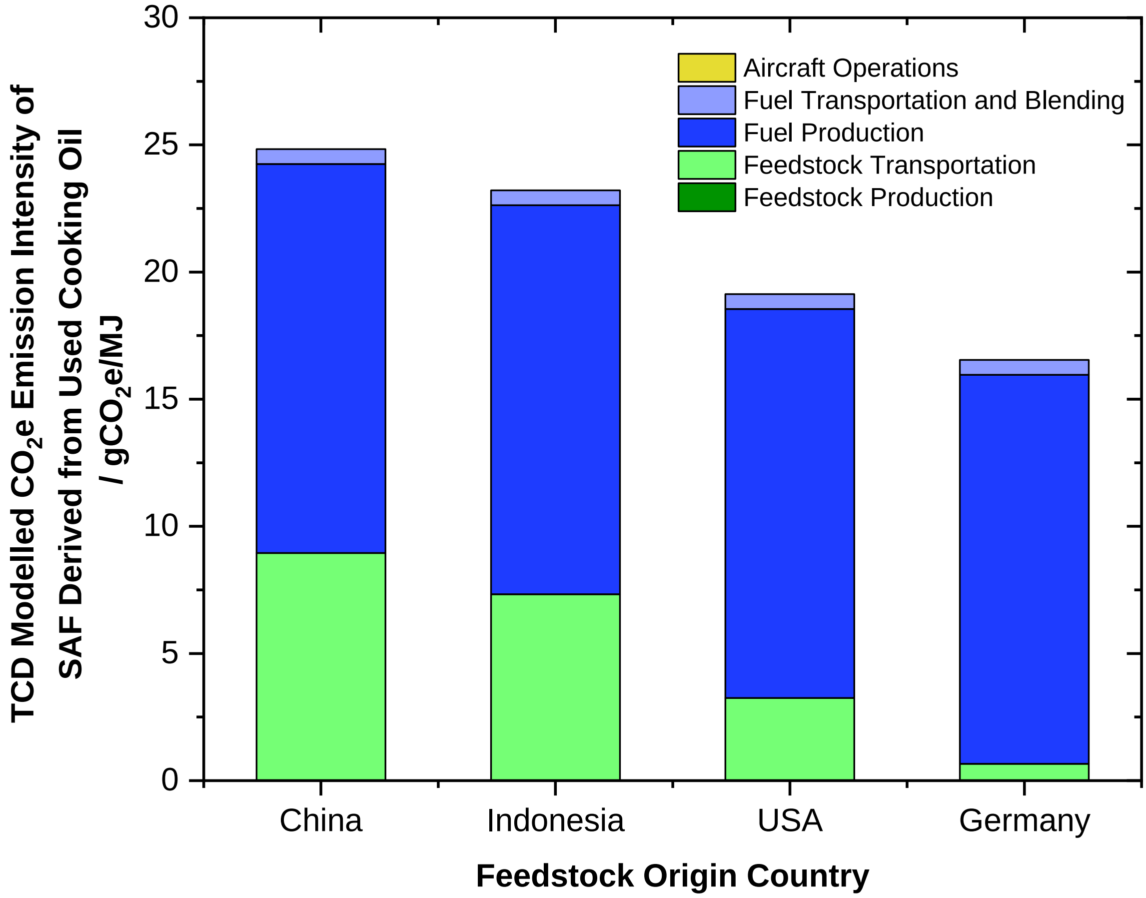


Figure 22: Life cycle GHG emission intensity of the modelled SAF for the four scenarios of feedstock sourcing locations as described in Chapter 4.4. Note that the Feedstock Transportation is the only stage of the LCA that varies with feedstock sourcing location. The results are broken down by stage of the LCA calculation.

As discussed in Chapter 5.2, the Indonesian scenario of SAF feedstock sourcing is selected as the primary case for this aviation activity. The life cycle results of this SAF are compared to the results of the fossil aviation fuel in Figure 23. This SAF is seen to offer a 75% life cycle emissions reduction over the fossil aviation fuel. The major different between the two fuels is in the Aircraft Operations stage of the LCA where combustion emissions are considered. As discussed in Chapter 3.8, SAF that is derived from biomass feedstock such as used cooking oil is considered to have zero combustion emissions as this is biogenic carbon recycled to the atmosphere.

Table 55 lists the life cycle results of the fossil aviation fuel used in this aviation activity. As previously mentioned, only the Fuel Transportation and Blending, and Aircraft Operations are modelled by TCD. The result of 92.7 gCO2e/MJ for the fossil aviation fuel is similar but different the CORSIA default value of 89 gCO2e/MJ. The value presented in this study is thought to be more representative of fossil aviation fuel in a European context and therefore more relevant and specific for use in the LCA calculation of this aviation activity.

As discussed in Chapter 5.2, the Indonesian scenario of SAF feedstock sourcing is selected as the primary case for this aviation activity. The life cycle results of this SAF are compared to the results of the fossil aviation fuel in Figure 23. This SAF is seen to offer a 75% life cycle emissions reduction over the fossil aviation fuel. The major different between the two fuels is in the Aircraft Operations stage of the LCA where combustion emissions are considered. As discussed in Chapter 3.8, SAF that is derived from biomass feedstock such as used cooking oil is considered to have zero combustion emissions as this is biogenic carbon recycled to the atmosphere.

Table 55: Life cycle emission intensity of the modelled fossil aviation fuel, per stage of the LCA. Note that the results for the Crude Extraction, Crude Transportation, and Fuel Production stages of the fossil aviation fuel are not modelled by TCD and a literature value is taken from Chiraramonti et. al [56].

Life Cycle Stage of Fossil Aviation Fuel	**Emission Factor (gCO_2e/MJ)**
Crude Extraction	10.0
Crude Transportation	2.00
Fuel Production	6.10
Fuel Transportation and Blending	0.59
Aircraft Operations	74.0
Total	92.7

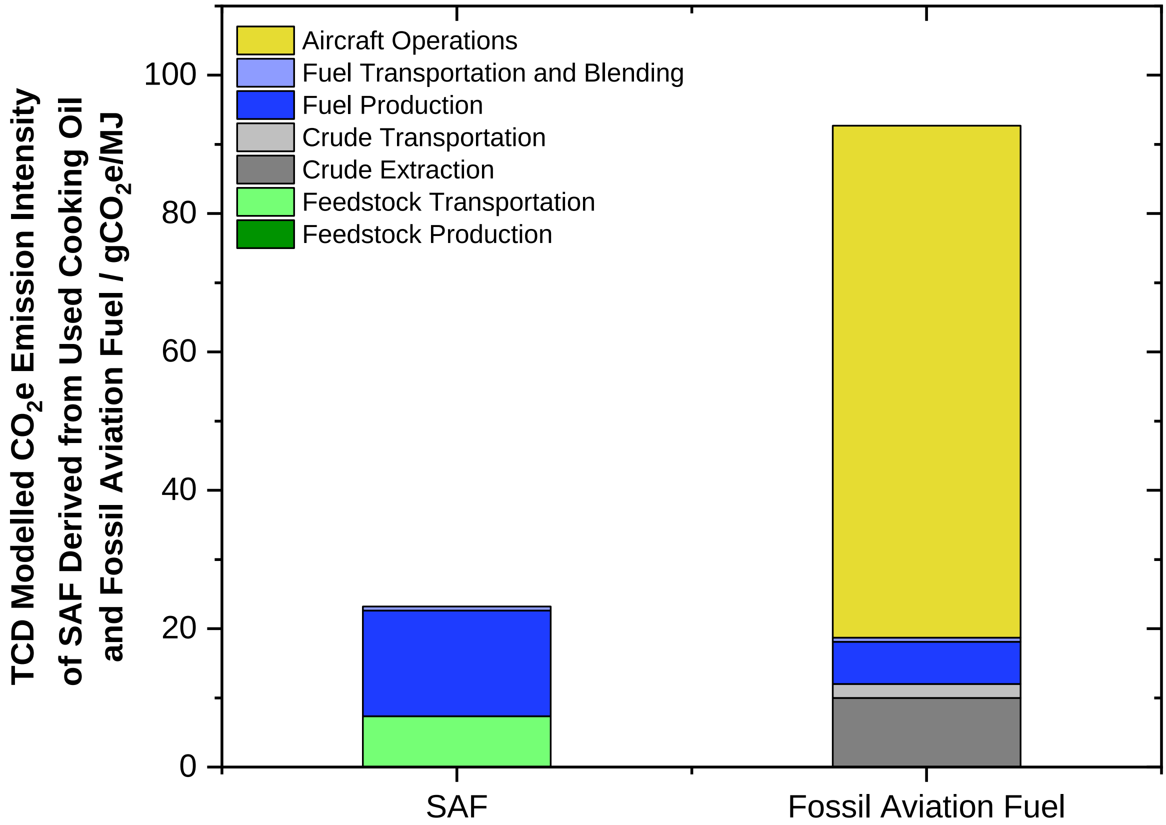


Figure 23: Comparison of life cycle GHG emission intensity of the modelled SAF and fossil aviation fuel. The results of both fuels are broken down by stage of the LCA calculation. Note that this SAF result is for the case of an Indonesian feedstock. Note also that the results for the Crude Extraction, Crude Transportation, and Fuel Production stages of the fossil aviation fuel are not modelled by TCD and a literature value is taken from Chiaramonti et. al [56].

The life cycle emissions results of the SAF and fossil aviation fuel listed in Table 54 and Table 55 are converted from a per energy basis to a per mass basis using the known densities. Table 56 lists the emissions factors per mass of fuel; these are used with the SAF blend ratio and the total mass of fuel used during the aviation activity to calculate the total emissions from the activity due to fuel activity. Table 57 adds this total emission from fuel activity to the total emission from airport activity to it, resulting in the total emissions from the aviation activity due to all stages of the LCA from this methodology. As expected, the fuel activity makes up most of these emissions and airport activity contributes only 0.5%. Finally, this total emission is divided by the number of passengers onboard and the distance travelled to find the emission intensity metric of the activity, presented in CO_2e emission per revenue passenger kilometre. This is a standard metric in the aviation industry and the primary reporting unit from this study.

The life cycle emissions of the modelled SAF ranges from 16.5 to 24.8 gCO2e/MJ for the four scenarios of feedstock sourcing locations. The results per stage of the LCA are listed in Table 54 and graphed in Figure 22. Note that the results of all stages of the LCA are constant except for Feedstock Transportation. The only difference between these four SAFs is the location of feedstock sourcing, and the range of results is 8.3 gCO2e/MJ. These results again highlight the importance of feedstock sourcing locations and the optimisation of the supply chain. Since shipping makes up almost all the transportation results, this is highlighted as the greatest challenge and source of uncertainty in the life cycle emissions of SAF.

Table 56: The life cycle emissions of the modelled SAF ranges from 16.5 to 24.8 gCO2e/MJ for the four scenarios of feedstock sourcing locations. The results per stage of the LCA are listed in Table 54 and graphed in Figure 22. Note that the results of all stages of the LCA are constant except for Feedstock Transportation. The only difference between these four SAFs is the location of feedstock sourcing, and the range of results is 8.3 gCO2e/MJ. These results again highlight the importance of feedstock sourcing locations and the optimisation of the supply chain. Since shipping makes up almost all the transportation results, this is highlighted as the greatest challenge and source of uncertainty in the life cycle emissions of SAF.

Table 54: Life cycle emission intensity of the modelled SAF per stage of the LCA for the four scenarios of feedstock sourcing locations as described in Chapter 4.4. Note that the Feedstock Transportation is the only stage of the LCA that varies with feedstock sourcing location. Results from Table 54 and Table 55 are multiplied by the fuel energy densities to find these gCO_2e/kg emission factors.

Fuel	**gCO_2e/kg**
SAF	$1.02 \cdot 10^3$
Fossil Aviation Fuel	$4.01 \cdot 10^3$

Table 57: Total life cycle emissions from the modelled aviation activity expressed as a mass of CO_2e. The total fuel activity emissions are calculated by multiplying the life cycle emission factors of the SAF and fossil aviation fuel from Table 56 by the mass of fuel used by the aircraft from Table 43. The airport operations emissions are the results of Table 52.

Activity	**gCO_2e**	**Contribution**
Fuel Activity	$7.10 \cdot 10^6$	99.5%
Airport Operations Activity	$3.74 \cdot 10^4$	0.5%
Total Activity	$7.13 \cdot 10^6$	

Table 58: Total life cycle emission intensity of the modelled aviation activity expressed as mass CO_2e per revenue-passenger-kilometre. This result is calculated by dividing the total mass of emissions from Table 57 by the number of passengers onboard and the distance travelled.

Activity	**gCO_2e/RPK**
TCD-Ryanair Scenario 1	50.4

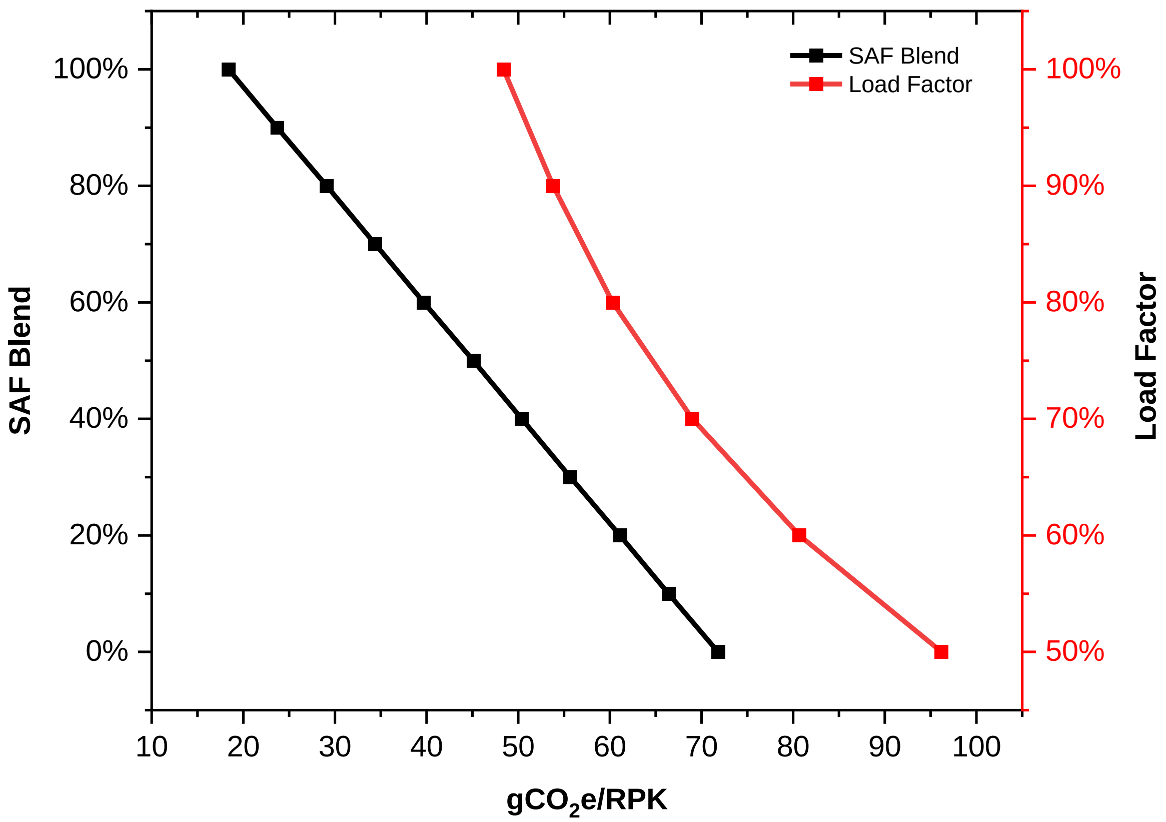


Figure 24: Effect of varying SAF blend percentage and aircraft load factor on the emission intensity of the aviation activity per revenue-passenger-kilometre. The Indonesian case of SAF feedstock sourcing is used. A constant load factor of 96% is maintained when varying the SAF blend percentage. This is the default load factor used in the described scenario and is Ryanair's most recent reported load factor, pre-2020. A constant SAF blend percentage of 40% is maintained when varying the load factor. This is the default SAF blend percentage used in the described scenario.

Figure 24 shows the effect of the SAF blend ratio and load factor on the emission intensity of the aviation activity. If the aircraft is operated on 100% fossil aviation fuel, the emission intensity is greater than 70 gCO2e/RPK but it is shown that it could be less than 20 gCO2e/ RPK if 100% of the fuel is SAF. This highlights the issue with the current limit of a 50% blend ratio as there is a significant amount of emission reductions that are not possible due to policy. The importance of high load factors is also highlighted. When the SAF blend is held constant at 40%, changing the load factor from 50-100% results in the emission intensity reducing from 96.2 to 48.4 gCO2e/ RPK.

6. Conclusion

This report highlights the need for the aviation industry to reduce emissions and the important role that SAF will play as the primary method of emission reductions in the short to medium term. LCA's role is paramount to account the total CO_2e emissions associated with aviation activity and inform on the development of sustainable fuels, practices, and policies. Multiple issues are found with the current state of art in SAF LCA literature. There are many inconsistencies in its modelling, such as the choice of allocation method, functional unit, LCA tool and modelling assumptions.

The methodology described in this report is novel and developed to address the issues previously highlighted with LCA calculations of aviation activity. The calculation of activity emissions is modelled from first principles and does not use an existing LCA tool, which are found to not offer the transparency and flexibility desired in this project. The aviation activity that is analysed represents an actual Ryanair flight scenario. This methodology considers the full aviation activity rather than just the fuel as is currently the case in the literature. There have been numerous studies that perform LCA calculations on SAF, and a small number that have studied other activity such as airport operations. However, no study was found to incorporate the full aviation activity in one LCA calculation. In previous studies that only consider LCA of the fuel, the functional unit has been gCO2e/MJ. However, the functional unit of this study is gCO2e/RPK, to include the specific details of the aviation activity such as the passenger load factor of the aircraft and the distance travelled by the aircraft.

The key learnings from this research to date is that the Fuel Production stage of the SAF life cycle has the most emissions associated with it. Within this stage, the production of hydrogen that is necessary for hydrotreating the used cooking oil feedstock is the largest contributor to emissions. The location of feedstock sourcing also has a major impact of the life cycle greenhouse gases of the SAF. In the case where feedstock is sourced from Germany and transported a relatively short distance to the fuel production facility in Finland, the Feedstock Transportation stage of the LCA accounts for 4% of the total embodied emissions of the SAF. However, this rises to 36% when the feedstock was sourced from China and transported a much larger distance by ship. Shipping is seen to be the predominant source of transportation emissions. When the feedstock is sourced from China, shipping accounts for 98% of transportation emissions embodied in the SAF. Shipping is a limiting factor for the sustainability of SAF and the optimisation of the fuel supply chain is critical. The SAF modelled is seen to reduce total embodied emissions of the fuel between 73-82% compared to fossil aviation fuel, depending on the feedstock sourcing location. This translates to a 28-32% reduction in total greenhouse gas emissions per revenue passenger kilometre when a 40% blend of SAF is used.

This calculation employs many assumptions where specific and actual data is not obtained from supply chain members of the activity. The uncertainty of this calculation is to be reduced in future work, where more specific inputs will be sought to replace the assumptions currently in place.

In conclusion, it is seen that the use of SAF can reduce the life cycle emissions of Ryanair flight activity, but the reduction amount is dependent on several factors of SAF supply chain particulars and blend ratio with fossil aviation fuel.

7. Future Work

A plan of the future work and publications from this project is presented.

Publication 1: A novel life cycle assessment methodology to account the CO_2e cost of aviation activity. (First Author)

- The first planned publication is an extended version of the methodology presented in this transfer report to determine the total CO_2e cost of aviation activities. This is mostly complete and is to be made available online and will also make-up a submission to the Gold Standard. The Gold Standard is a non-profit organisation based in Switzerland that assesses and verifies the rigour of carbon counting practices and approves projects and methodologies for use in the development of carbon credits.
- The methodology is to be adapted and extended to scenario details as required over the remainder of the project. For example, the Feedstock Production stage of the LCA methodology has not yet been developed because it was not required in the first scenario studied. The sourcing of more specific and reliable data for use in the calculations will also continue.

Publication 2: A novel fuel production mass conservation model to account the CO_2e cost of HEFA SAF production from first principles validated to fuel composition. (Second Author)

- This work is led by another PhD researcher, Liam Mannion, who has developed the Fuel Production stage of the LCA methodology. The motivation for this work comes from the issue of transparency and uncertainty in the current LCA tools that model Fuel Production. A key point of this work is the validation of this model to fuel composition data. The measuring and modelling of which is another piece of research ongoing and led by PhD researcher Tiarnán Murphy.

Publication 3: An investigation of the effect of air traffic management on the CO_2e cost of aviation activity from a life cycle assessment perspective. (First Author)

- This planned publication emphasises the use of actual flight data and aircraft fuel use information to determine the additional CO_2e cost of inefficient air traffic management and disruption. Examples of this include non-optimised flight routes and closed airspace due to drone activity, military activity, and air traffic control strikes. This can be shown as low hanging fruit for aviation emission reductions that do not require technically challenging solutions. Analysis of these situations can be made to demonstrate the quantity of SAF needed to offset the additional emissions from a flight that travelled further than necessary due to closed airspace, for example.

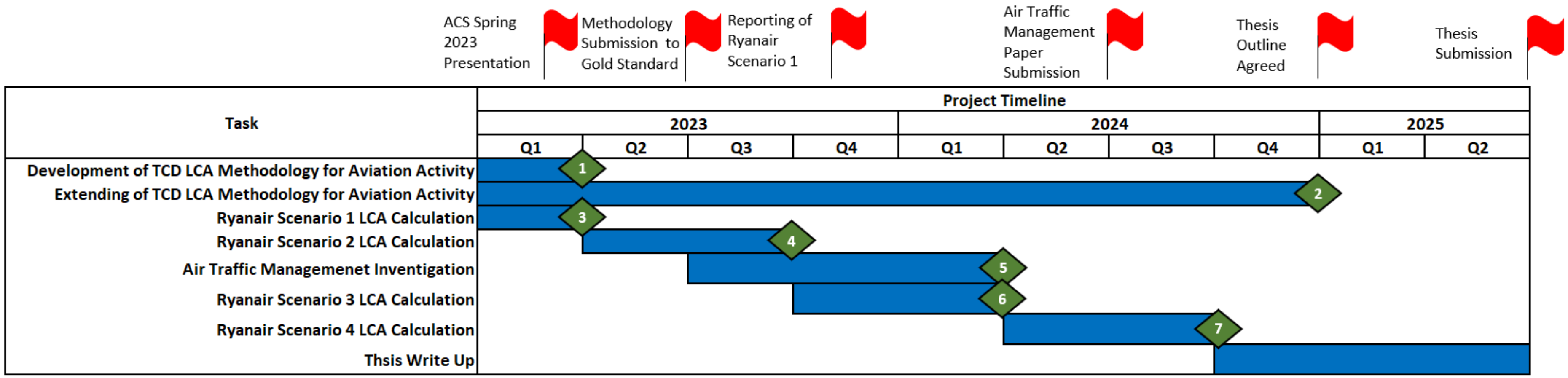
Publication 4: A novel fuel production model to account the CO_2e cost of Power-to-Liquid SAF production from first principles validated to fuel composition. (Second Author)

- This Fuel Production modelling is again led by Liam Mannion. It is planned to model multiple pathways of fuel production to adapt and extent the primary LCA methodology to further scenarios of aviation activity.

There are other ideas for publications on the topic of LCA of aviation activities. These include:

- A study on Ryanair operational efficiency and how they have industry leading emission intensities. Factors that can be discussed in this work are the efficient aircraft, high load factors, selection of routes and speedy turnaround times between flights.
- An investigation of the CO_2e cost of airport operations, based on the Airport Operations stage of this LCA methodology. Different scenarios could be modelled, and airports compared for their sustainability credentials. This work can identify the best pathways to emission reductions in this stage of the LCA.

A Gantt chart has been created to display the planned schedule of the project and can be found as Figure 25.



Milestones:

1: The internal reporting of the TCD LCA methodology is complete.

2: The TCD LCA methodology is complete and has been extended to model multiple scenarios of aviation activity which uses SAF.

3: The calculation of the first Ryanair scenario using the TCD LCA methodology is complete. This is the scenario described in Chapter 4 of this report.

4: The calculation of the second Ryanair scenario using the TCD LCA methodology is complete. This is planned to be a scenario of Ryanair's activity in Spain.

5: The invenstigation of the effect of air traffic management on the CO_2e cost of aviation activity is complete.

6: The calculation of the third Ryanair scenario using the TCD LCA methodology is complete. This scenario has not yet been defined.

7: The calculation of the fourth Ryanair scenario using the TCD LCA methodology is complete. This scenario has not yet been defined.

Figure 25: Gantt chart of future workplan.

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Appendix A

Summary Table of Literature

Table A1: Summary of literature on the topic of SAF LCA calculations. A list of abbreviations* succeeds the table.

Year	Author	Production Pathway	Feedstock	LCA Model	Allocation Method	Land Use Change	Functional Unit	Reference
2021	Ringsred	HEFA	Wood Pellets	GHGenius	Energy	No	gCO2e/MJ	[33]
2021	Mousavi	HEFA	Pennycress	OpenLCA	Energy	No	kgCO2e/GJ	[25]
2019	van Dyk	HEFA	Softwood	GHGenius	Energy	No	n/a	[40]
2019	Shi	HEFA	Various Oilseeds	Unreported	Energy, Displacement	No	gCO2e/MJ	[76]
2019	Vasquez	HEFA	Jatropha, Camelina, Rapeseed, Pennycress, Soybean	SimaPro	Energy	No	gCO2e/MJ	[77]
2017	Guo	HEFA	Microalgae	GREET	Energy	No	gCO2e/MJ	[78]
2016	Guo	HEFA	Microalgae	GREET	None	No	gCO2e/MJ	[79]
2014	Cox	HEFA	Microalgae, Pongamia Pinnata, Sugarcane Molasses	Unreported	Economic, Displacement	No	kgCO2e/ 100MJ	[80]
2013	Fan	HEFA	Pennycress	SimaPro	Energy, Economic, Displacement	No	gCO2e/MJ	[22]
2010	Shonnard	HEFA	Camelina	SimaPro	Energy	No	gCO2e/MJ	[81]
2013	Han	HEFA, FT	Various Oilseeds, Corn-Stover	GREET	Energy, Displacement	Yes	gCO2e/MJ	[23]
2022	Seber	HEFA	Jatropha, Pennycress, Castor, Energy Tobacco, Salicornia	Unreported	Energy, Mass, Economic	Yes	gCO2e/MJ	[82]
2021	Prussi	HEFA	Algae	E3Database	Energy	No	gCO2e/MJ	[83]
2020	Obnamia	HEFA	Canola	GREET	Energy	Yes	gCO2e/MJ	[44]
2016	Ukaew	HEFA	Canola	Environmental Policy Integrated Climate	Energy, Economic, Displacement	Yes	gCO2e/MJ	[84]
2014	Seber	HEFA	Used Cooking Oil, Tallow	GREET	Energy, Mass, Economic	No	gCO2e/MJ	[85]
2022	Oehmichen	HEFA, ATJ	Tallow	Umberto	None	No	gCO2e/MJ	[49]
2021	Capaz	HEFA, FT, ATJ	Used Cooking Oil, Beef Tallow, Residues	Unreported	Energy	Yes	gCO2e/MJ	[86]
2017	Wise	HEFA, FT, ATJ	Corn, Oilseeds	GCAM	None	Yes	Unreported	[87]
2017	de Jong	HEFA, FT, ATJ	Sugarcane, Corn, Poplar, Willow, Corn Stover, Forestry Residues, Used Cooking Oil, Jatropha and Camelina	GREET	Energy, Displacement	No	gCO2e/MJ	[41]
2023	Liu	FT	Agriculture Residue	Beihang-AF3E	Energy, Mass	No	gCO2e/MJ	[88]

Year	Author	Production Pathway	Feedstock	LCA Model	Allocation Method	Land Use Change	Functional Unit	Reference
2020	Liu	FT	Algae, Jatropha	Beihang-AF3E	Energy, Mass	No	gCO2e/MJ	[89]
2022	Fernanda	PtL	Captured Carbon	SimaPro	Energy	No	gCO2e/MJ	[90]
2021	Lim	PtL	Captured Carbon	ReCiPe	None	No	kgCO2e/kg	[91]
2023	Wang	ATJ	Corn-Cob	GREET	Energy, Economic, Displacement	No	gCO2e/MJ	[92]
2022	Moretti	ATJ	Potato By-Products	Unreported	Energy, Economic	Yes	n/a	[93]
2020	Vela-Garcia	ATJ	Cellulosic Isobutanol	SimaPro	None	No	gCO2e/MJ	[48]
2015	Lokesh	HEFA	Camelina, Microalgae, Jatropha	ALCEmB	Mass	No	gCO2e/MJ	[94]
2010	Bailis	HEFA	Jatropha	SimaPro	Energy, Mass, Displacement	Yes	kgCO2e/GJ	[28]
2020	Barbera	CTH	Used Cooking Oil	Unreported	Energy, Mass, Economic	No	kgCO2e/MJ	[36]
2014	Fortier	HTL	Microalgae	SimaPro	None	No	kgCO2e/GJ	[95]
2021	Moretti	Novel	Potato By-Products, Sugar Beets	Unreported	Energy, Mass, Economic	No	gCO2e/MJ	[96]
2021	Pamula	Novel	Switchgrass	GREET	Energy, Mass, Economic, Displacement	Yes	gCO2e/MJ	[97]
2021	Resurreccion	Novel	Camelina	Unreported	Energy, Mass, Economic	No	gCO2e/MJ	[98]
2018	Ganguly	Novel	Wood	GREET	Energy, Mass, Economic	No	kgCO2e/GJ	[34]

*HEFA = Hydrotreated Esters and Fatty Acids, FT = Fischer-Tropsch, ATJ = Alcohol to Jet, HTL = Hydrothermal Liquefaction, PtL = Power to Liquid, CTH = Catalytic Transfer Hydrogenation.

Appendix B

Replication Study

Replication of Biojet Fuel LCA Study using GHGenius

Aron Bell, Stephen Dooley

This document outlines the reasoning, methodology and results of a life cycle assessment replication study based on the 2019 research paper by van Dyk et al. named “Potential yields and emission reductions of biojet fuels produced via hydrotreatment of biocrudes produced through direct thermochemical liquefaction” as published in the Biotechnology for Biofuels journal. [40]

The reasoning for replicating previous work was to understand the assumptions and methodology used by researchers and the GHGenius life cycle assessment (LCA) model. It also served as a familiarisation exercise in how to approach and conduct an LCA study and how to use and interpret the GHGenius calculator.

The paper chosen examined three biocrude production pathways and two upgrading pathways to produce the finished biojet fuel. This replication was solely focused on the fast pyrolysis pathway for biocrude production.

Results

The results shown in Table B3 highlight several major differences. Some result fields were populated for van Dyk’s study but were empty in this study, and other fields were populated in this study but empty for van Dyk. Results for every stage of fuel production were different between van Dyk and this study. The fuel production stage had the closest result output, but it was still not the same.

The results of this replication work were taken from column CH on the ‘Upstream Results HHV’ sheet in GHGenius version 5.01c. This is the same version as used by van Dyk.

The inputs used to replicate the work were sourced from the life cycle assessment section of the paper on page eleven and Table S1 in the ‘Additional file 1’. The results were compared to Table S2. In table S1 and S2, only the first column of inputs and results were considered as this was the only pathway used in this replication. Table B1 lists the inputs that were obtained from the van Dyk paper and inputted into GHGenius. Table B3 displays the results on a step-by-step basis as inputs were added one at a time.

	A	CH
6		
7	Fuel ------>	**Bio Oil**
8	Feedstock ------>	**Wood Residue**
9	Fuel dispensing	255
10	Fuel distribution and storage	2,034
11	Fuel production	1,926
12	Feedstock transmission	2,067
13	Feedstock recovery	183
14	Feedstock upgrading	0
15	Land-use changes, cultivation*	5,356
16	Fertilizer manufacture	2,180
17	Gas leaks and flares**	0
18	CO2, H2S removed from NG^	0
19	Emissions displaced - co-produc	0
20	**Total**	**14,001**

Figure B126: Source of GHGenius Result on the 'Upstream Results HHV' sheet.

Uncertainty 1: The feedstock used by van Dyk was quoted as 'forest residues', however there was no explicit input found for this in GHGenius.

TCD Assumption 1: Wood was assumed to be the GHGenius feedstock.

Uncertainty 2: The GHGenius pathway used was not stated.

TCD Assumption 2: The GHGenius pathway used was assumed to be Bio Oil.

This was a fundamental assumption that may have set the entire replication study in the wrong direction.

Table B1: List of inputs used for replication study.

Test	Parameter Changed	Cell	Default GHGenius	van Dyk
A	Target Year	Input!B7	2020	2018
B	Region	Input!B4	Canada	BC
C	Density (kg/L)	'Fuel Char'!E175	1.2	1.197
D	Oxygen %	'Fuel Char'!I175	0.373	0.475
E	MJ/L (HHV)	'Fuel Char'!B175	21	21.5
F	kg wood/litre oil	Input!M246	1.65	1.88
G	kg wood/MJ oil			0.087
H	MJ gas/MJ oil			0.62

I	kWh/litre oil	Input!M242	0.24	0.1
J	NG, MJ/litre oil	Input!M244	0.00090838	0.5
K	Nitrogen, kg/litre oil			0.035
L	Nitrogen, kg/tonne oil	Input!D216	0	29

Parameters A and B were obtained from the life cycle assessment section on page eleven of the paper. Parameters C – L were obtained from Table S1 of the additional file. It was claimed that all other inputs were set to their default values unless otherwise specified.

Uncertainty 3: It was not clear what parameters C, D and E pertained to.

TCD Assumption 3: It was assumed that parameters C, D and E pertained to the bio-oil produced.

Uncertainty 4: Parameter G was not located in GHGenius.

TCD Assumption 4: Parameter G was assumed to be another way to express parameter F, which was already included.

Uncertainty 5: Parameter H was not located in GHGenius, and it was unclear what was meant by this.

TCD Assumption 5: Parameter H was assumed to be a co-product, but it did not specify which gas, so it was not used.

Uncertainty 6: Parameter K was not inputted as the units presented by van Dyk did not match the GHGenius units.

TCD Assumption 6: The units for Parameter K were converted, and parameter L was created in place of parameter K. It is thought that an error occurred at this step as a large difference was introduced for land use change and fertilizer manufacture as seen in Table B3.

After all available inputs were used, there were two stages where van Dyk reported outputs but were blank for this work (feedstock transmission and feedstock recovery). Two more tests were conducted, populating these fields with estimated inputs as shown in Table B2.

Table B2: List of estimated inputs used for replication study.

Test	Parameter Changed	Cell	Default GHGenius	Assumed by TCD
AA	Distance wood is transported by truck (km)	Input!J80	0	100
AB	Diesel used per hectare of wood	Input!B136	0	5

Uncertainty 7: The way in which the feedstock transmission field was populated. The transport was only briefly mentioned in the paper, stating a 100 km supply radius was assumed for the biomass. No exact input was provided.

TCD Assumption 7: The transportation distance for the wood was set to 100 km (by truck). The feedstock transmission results were now very close but not exact.

Uncertainty 8: The way in which the feedstock recovery field was populated.

TCD Assumption 8: Five litres of diesel were assumed to be used per hectare of wood during the feedstock recovery stage. This may not have been inputted into the correct place in GHGenius and/or there were other inputs for this stage as the results were very different. This value may also have been inappropriate.

Uncertainty 9: If there are any other inputs not mentioned.

TCD Assumption 9: It was assumed that there were no other inputs.

Uncertainty 10: How the ‘fuel dispensing’ and ‘fuel distribution and storage’ fields were nil.

TCD Assumption 10: It was assumed that the ‘fuel dispensing’ and ‘fuel distribution and storage’ fields were removed from the result after the calculation as they are not relevant for the biocrude production stage.

To complete this replication study more rigorously, clarifications to the above uncertainties are needed. It would be most beneficial and efficient to obtain the GHGenius file used for the van Dyk study as this would allow an analysis of all inputs and assumptions used.

Stage of production	**Van Dyk**	GHGenius	TCD Tests												**Van Dyk**	TCD "Guessing" Tests		
	gCO2e/GJ	Default	A	B	C	D	E	F	G	H	I	J	K	L	**gCO2e/GJ**	AA	AB	ABB
Fuel dispensing	-	555	569	257	256	256	250	250			250	250		250	-	250	250	removed
Fuel distribution and storage	-	2,129	2,147	2,038	2,033	2,033	1,986	1,986			1,986	1,986		1,986	-	1,986	1,986	removed
Fuel production	**2,320**	2,869	2,940	1,385	1,385	1,385	1,353	1,387			1,026	2,417		2,417	**2,320**	2,417	2,417	2,417
Feedstock transmission	**2,277**	-	-	-	-	-	-	-			-	-		-	**2,277**	2,307	2,307	2,307
Feedstock recovery	**3,572**	-	-	-	-	-	-	-			-	-		-	**3,572**	-	204	204
Feedstock upgrading	-	-	-	-	-	-	-	-			-	-		-	-	-	-	-
Land-use changes, cultivation	**11**	-	-	-	-	-	-	-			-	-		6,124	**11**	6,124	6,124	6,124
Fertilizer manufacture	-	-	-	-	-	-	-	-			-	-		2,678	-	2,678	2,678	2,678
Gas leaks and flares	-	-	-	-	-	-	-	-			-	-		-	-	-	-	-
CO2, H2S removed from NG^	-	-	-	-	-	-	-	-			-	-		-	-	-	-	-
Emissions displaced - co-products	-	-	-	-	-	-	-	-			-	-		-	-	-	-	-
Total	**8,180**	5,552	5,655	3,680	3,674	3,674	3,589	3,623			3,262	4,653		13,455	**8,180**	15,762	15,966	13,730
Error		-32%	-31%	-55%	-55%	-55%	-56%	-56%			-60%	-43%		64%		93%	95%	68%

Table B3: Replication results and comparison to original. The column labelled Van Dyk shows the results that this study tried to replicate. After twelve attempts, the closest result was a 43% difference. Additional attempts were completed where TCD tried to guess what the original work had modelled.