ROAD trailer design - Use of Type V theRmoplastic tubes with light composite structure for HYdrogen transPort

D32 D8.1 Metal and type IV LCA

Life Cycle Assessment Type I & IV Trailers

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I. Introduction

Nowadays, existing trailer transportation solutions use tubes with a working pressure between 200 and 300 bar. This is not efficient in terms of quantities or cost to address large refuelling stations knowing the upcoming ramp-up of fuel cell-based vehicles.

The overall objective of the ROAD TRHYP project is to develop and validate a trailer integrating new thermoplastic composite tubes (Type V) to reach Clean Hydrogen Partnership objectives by maximising the quantity of H_2 transported while satisfying end-user requirements (safety, ability to be decontaminated) and enforced regulations with a low TCO. By the end of the project, the consortium will design a trailer capable of handling a payload of 1.5 tonne of H_2 with 700 bar tubes and a capex lower than 400 €/kg. This enables the decrease of the number of transport rotations between the site of production and the delivery site, consequently the reduction of the environmental footprint of transporting compressed hydrogen, but also a downsizing of the compressor at the Hydrogen Refueling Station (HRS). In the meantime, the project will heavily investigate new fire testing methodologies and safety barriers for type V adoption, results which will be disseminated to key policy makers and regulatory committees.

ROAD TRHYP's overall ambition is to develop Europe's value chain of type V technologies. More specifically, the project intends to address all manufacturers across Europe who could benefit from the project's innovative process and materials. Beyond the targeted commercial type V trailers applications, the knowledge developed on composite materials could benefit main actors in the mobility sectors or the hydrogen storage for inter-seasonal energy storage. As a consequence, the project would help achieve the European Green Deal making hydrogen a widespread energy carrier, by 2030.

The project is divided into several work packages and **WP8** aims to realize an environmental study of different trailer technologies. This report will present the study carried out for Type I and Type IV trailer. It is an intermediate report and the final report will be published later in the project (M30) to present a final comparison between the three tubes technologies. This first report will provide an initial comparison between steel and composite tubes and will serve as a reference for comparison with the tubes under development in the final report.

These reports will set out the different stages involved in carrying out the LCA, including defining the objectives and scope of the study, the life cycle inventory of the system modelled and the various assumptions made, and finally the results and their interpretation. The data in this report can be refined during the rest of the project to ensure that the final report is as representative as possible of the different systems.

II. Goal and scope definition

A. Goal

The objective of WP8 is to analyse and compare the environmental impacts of hydrogen transport for different tubes technologies. In this first report, the comparison will be focus on type I and type IV tubes. This study will comprehensively examine the entire life cycle of the product, from the extraction of raw materials through the manufacturing, distribution and use phases to the end of the product's life. Another objective is to investigate the eco-design and the circular economy approach of the materials. The target audience for this study is primarily an internal audience at Air Liquide as well as the different members of the ROAD TRHYP collaborative project. This study is an attributional LCA that takes into account interactions with other systems. This allows, for example, to take into account the impacts avoided by the effective recycling of a product.

B. Product and Function Description

A hydrogen transport vehicle is made of several components:

- A prime mover (or tractor)
- A chassis
- **A MEGC (Multi Element Gas Container)**
- **A Frame**

In this study, only two parts of the hydrogen transport vehicle will be studied: The **Frame** and the **MEGC.** The product studied is therefore the trailer without the chassis. The prime mover and chassis are not taken into account as they can be considered the same for the different trailers. The function of the system studied is to transport hydrogen from a filling centre[1] to the site of an Air Liquide's customers.

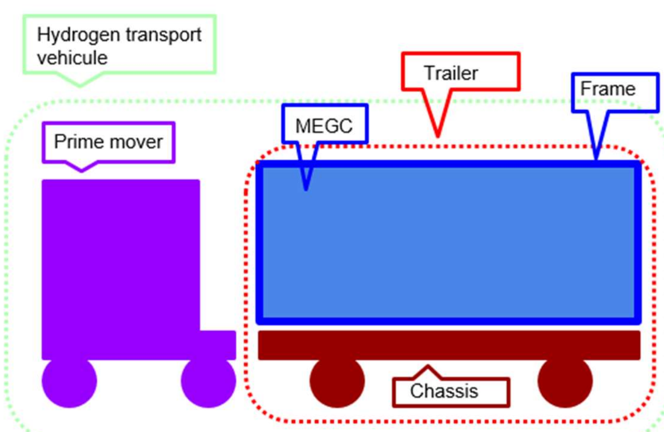


Figure 1: Diagram of a truck-trailer used to transport hydrogen

[1] Centre to fill the trailer with Hydrogen. Maybe an Air Liquide facility or third party

C. Functional Unit

The functional unit chosen to quantify the main function is the transport of 1 kg of hydrogen over 100 km distance with a defined standard itinerary. The following tables show the basic conditions of the functional unit.

Characteristic	Value
Number of journeys	• 1 return trip a day (with empty return) • 5 days a week • For 40 years
Distance travelled (one way)	150 km
Total distance covered	3,120,000 km

Table 1: Basic conditions of functional unit

D. System Boundaries

This study is a cradle-to-grave study covering the entire life cycle of the product from raw material extraction, through manufacture, use phase to the final management of the trailer as waste. The materials and production sites are not the same for the three different technologies; the geographical limits will therefore be detailed on a case-by-case basis. On the other hand, the use phase for both trailer is the same, with use on a similar route assumed in France. The origin of the raw materials is assumed to come from different locations around the world. For the type I, the entire manufacturing phase take place in USA and the assembly of the system is realised in France. Concerning the type IV, the manufacturing and the assembly take place in Germany. Figure 2 shows a simple flow diagram, which defines the system boundaries for the study.

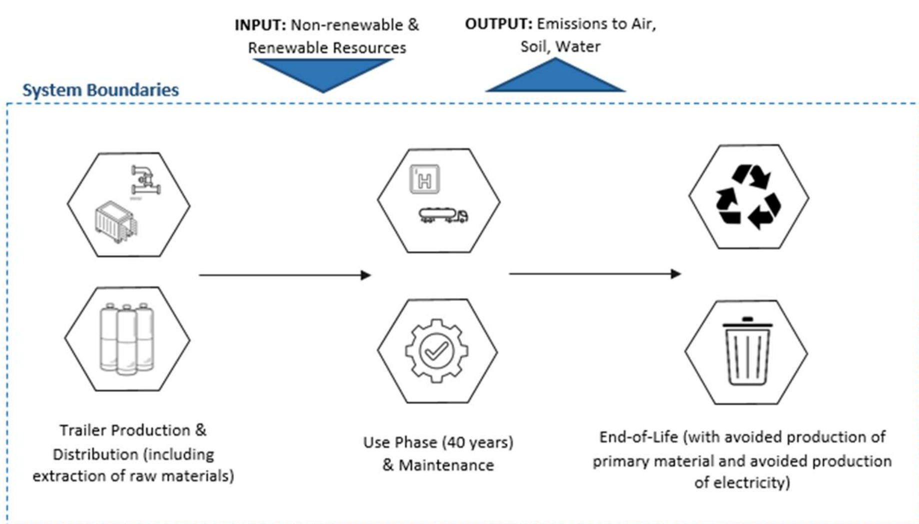


Figure 2: LCA System Boundaries

This study is made in 2023 based mainly with secondary data from MLC[2] database. For most of the processes used, the reference year is 2022 and sometimes 2019 (for the electricity mix), and these data are valid until at least 2024.

E. Exclusions

Certain elements of the life cycle have been excluded to ensure the scope of the study remains feasible, although no specific cut-off criteria have been applied. The following materials and processes have been excluded:

- Manufacturing of the Prime Mover
- Manufacturing of the chassis
- Hydrogen Production
- Energy used during the maintenance process due to limited data availability
- All sort of packaging used from raw materials to the End Product is excluded.
- The study includes maintenance but not repairs

F. Allocations and system expansion

Product life cycle systems occasionally yield other products or services as well as the functional unit. According to ISO 14044, allocation should be preferably avoided and a subdivision or system expansion should be used. To model the End of life in this study, system expansion will be used. This allows the system to be credited with the avoided burdens. For metal recycling, this credit is a net value corresponding to the difference between the scrap used as an input and the scrap available at the end of the product's life. Credit will also be granted for electricity generation using the composite incineration process for Type IV tubes. It will be assumed that this electricity will replace the electricity produced in France.

For the different secondary data from MLC database, allocations procedure are detailed in the software documentation for each process.

G. Data Quality

Most data used in this study are from MLC database. MLC is a database developed by Sphera and implemented in the LCA FE software. Updated regularly, Sphera's Managed LCA Content is built on robust data from primary sources. They include official datasets from over 60 industry associations, consistently modelled with Sphera's LCA background data.

H. Limitations

The following are limitations of this study:

- Due to lack of data, the type I piping system is modelled as part of the frame without any details on the material composition. The piping system assembly processes are not modelled either.

[2] Sphera Managed LCA Content, the LCA database developed by Sphera.

- Use phase is not modelled with specific data but only with a MLC process used to model the transport of goods. This assumption will be discussed in the interpretation of results.
- Carbon fibres are modelled with primary data but with a certain amount of uncertainty. The fibre manufacturing process is very energy-intensive, and depending on the fibre quality required and the type of energy used, the results can vary widely.

I. Impact assessment methods and impact categories

The impact assessment method used in this LCA is EF 3.1[3]. To make a selection from the various impact categories in the EF 3.1 method, a normalization and weighting study was carried out. This study is available in Annex 1.

The impact categories studied in this study are as follows:

- **EF 3.1 Climate Change – total (kg CO_2 eq):** This impact category describe the global warming potential and is calculated in carbon dioxide equivalents (CO_2-Eq.), meaning that the greenhouse potential of an emission is given in relation to CO_2. Since the residence time of gases in the atmosphere is incorporated into the calculation, a time range for the assessment must also be specified. A usual period is 100 years.
- *The abiotic depletion potential (ADP) covers some selected natural resources as metal containing ores, crude oil and mineral raw materials. Abiotic resources include raw materials from non-living resources that are non-renewable. This impact category describes the reduction of the global amount of non-renewable raw materials. Non-renewable means a period of at least 500 years. The abiotic depletion potential is typically split into two sub-categories, elements and fossil (i.e., energy).*

- **EF 3.1 Resource use, mineral and metals (kg Sb eq):** Abiotic depletion potential (elements) covers an evaluation of the availability of natural elements like minerals and ores, including uranium ore. The reference substance for the characterization factors is typically antimony and the calculation is based on ultimate reserve (i.e., the total mineral content in the earth crust).

- **EF 3.1 Resource use, fossils (MJ):** The depletion of fossil resources describes the amount of energy used in the different stages of the life cycle and takes into account the fossil energy carriers (crude oil, natural gas, coal resources). This method does not take into account the specific scarcity[4] of each fossil resource. A MJ of coal is weighted in the same way as a MJ of oil.

- **EF 3.1 Ionising radiations, human health (kBq U235 eq):** This impact category aims to measure the effects on human health resulting from exposure to ionizing radiation. The effect factors are based on disease statistics resulting from relatively high exposure typically associated with

[3] Environmental Footprint

[4] Scarcity is the concept that resources are only available in limited supply, whereas society's demand for those resources is unlimited.

work or accidents. However, in LCA, exposure doses are generally very low. Therefore, the value based on relatively high exposure is adjusted for the difference in cancer incidences per exposure dose, approximating a marginal approach.

- **EF 3.1 Particulate matter formation (diseases incidences):** This impact category uses the unit deaths per kg of emission including the impact of secondary particle formation as a combination of the UNEP and Riskpoll model. The Riskpoll model evaluates human health impacts from primary particles emitted directly and from secondary particles formed in the air by emitted substances.

J. Software and database

The software used to model the life cycle in this study is LCA for Experts version 10.7.1.28 (formerly GaBi) developed by Sphera. This software includes the database MLC[5] 2023 which is compliant as data source for studies and assessments based on ISO 14040 and 14044.

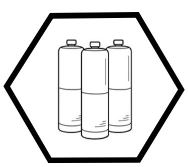
III. Life Cycle Inventory (LCI) – Type I

The life cycle inventory (LCI) describes the methodology of data collection of the entire system on the chassis (frame + MEGC containing the piping system and the tubes). This section will also be used to explain the different choices of processes from the MLC database, which are as close to reality as possible.

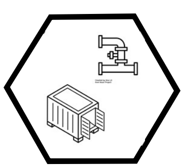
A. Life Cycle Studied

1. Production and Distribution phase

The different data modelled in this section concern:



The production of the 10 steel tubes used to transport the hydrogen and their distribution from their production site in Ohio (US) to the Air Liquide site in Waziers (France).

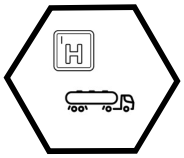


The production of the piping system, the frame, and their distribution from their production site in Ohio (US) to the Air Liquide site in Waziers (France).

[5] Managed LCA Content

2. Use Phase

The different data modelled in this section concern:

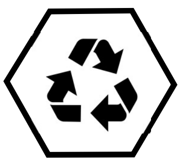


The daily transport of hydrogen between a filling centre and the site of one of their customers for 40 years. This phase takes into account all the emissions during the use phase (well to the wheel[6] analysis).

The different maintenance procedures during the life cycle of the product studied.

3. End-of-Life

The different data modelled in this section concern:



The end-of-life treatment of the system studied at the end of its life, which is essentially metal recycling for type I.

B. Modelling and Assumptions on missing data

1. Production phase

Type I Tube	
[Perimeter]	This section covers the entire tube manufacturing process. The tubes are first produced using a forging process without welding, before being painted using a sandblasting process.
[Modelled data]	>> Numbers of tubes **= 10** << >> Tube Mass = **2,481 kg** << >> Paint Mass = **2.71 kg** << >> Supply Distance = 6,660 km << A diagram of the distribution stage can be found in Annex 2. • **760** km by truck (US): **Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity** • **5,600** km by cargo: **Container ship, 5.000 to 200.000 dwt payload capacity, deep sea**

[6] A well-to-wheel analysis can be subdivided into two parts: the well to tank (energy provision) and the tank-to-wheel (vehicle efficiency) analysis.

	• **300** km by truck (FR): **Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity**
[Exclusions]	There are no exclusions within this perimeter.
[Assumptions]	The tube mass corresponds to the total mass of the tube, which also includes the layer of paint that covers it. The calculation of paint mass is detailed in Annex 3. Tubes are made of Chrome Molybdenum steel and modelled with the following MLC database process: **DE: Steel billet (20MoCr4).** The tubes are painted with polyurethane paint. There was no polyurethane paint in the MLC database, so the paint is modelled using the following process**: RER: Solvent paint white** (a paint specifically used on metal parts). The process used to model sandblasting is **GLO: Blasting process (1m2 steel part). Silica sand (flour)** is used as blasting agent. The process used to model forging is **DE: Steel forging Part (0.4 to 1 kg).** The forging process requires electricity, so the **US: Electricity Grid mix** was chosen. The free parameters for the truck transportation are selected "by default" (i.e. driving share urban, rural and motorway, sulphur content in diesel….). Default value are available in Annex 2. Tube production has a material yield of around 95% (this includes scrap from steel plate preparation, forging, etc.). Losses are reintegrated into the process (closed loop).
Type I Frame + Piping System	
[Perimeter]	This section covers the entire frame and piping system manufacturing. Considering that the mass of the piping system is negligible compared to that of the frame, there is no differentiation between these two modules. The whole system is modelled in galvanised steel.
[Modelled data]	>> Number = **1 system (piping system + frame)** << >> System Mass= **3,726 kg** << >> Welding Length = **500 m** << >> Supply Distance = 6,660 km << A diagram of the distribution stage can be found in Annex 2. • **760** km by truck (US): **Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity** • **5,600** km by cargo: **Container ship, 5,000 to 200,000 dwt payload capacity, deep sea**

	• **300** km by truck (FR): **Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity**
[Exclusions]	The piping system is modelled as part of the framework. The different materials and assembly processes are therefore not taken into account.
[Assumptions]	The process **GLO: Steel hot dip galvanised Worldsteel** is used to model the whole system. Hot-dip galvanising is preferred to electro-galvanising because electro-galvanising is a method used for buildings and structures, whereas electro-galvanising is preferred for small materials. The system is modelled as a single material for the entire piping system and structure because detailed information on the composition of these two systems is not known. This is a limitation of this study. The free parameters for the truck transportation are selected "by default" (i.e. driving share urban, rural and motorway, sulphur content in diesel….) The total weld lengths for assembling the reinforcement are unknown. An upward estimate of 500 metres of weld has therefore been made. The process **GLO: Steel sheet (1 to 4 mm) MIG/MAG welding** is used.

2. Use phase & maintenance

Use Phase	
[Perimeter]	This section covers the use phase of the system, which is the daily transport of hydrogen between Air Liquide's hydrogen production site and the site of one of their customers for 40 years. 5 journeys of 300 km (150 km outward and 150 km return) per week for 40 years. This phase is mainly dependant of the truck process used. The maintenance of the system is also included in this phase.
[Modelled data]	>> Daily Distance **= 300 km** << >> Total Distance (40 years) = **3,120,000 km** << >> Hydrogen Mass (per tube) = **32.82 kg** << >> Hydrogen Mass (10 tubes) = **328.2 kg** << >> Hydrogen Mass transported (40 years) = **3,413,586 kg** << >> Gas losses during use phase = **0.2 %** << >> Energy required to compress hydrogen to 200 bar = **2.2 kWh / kg** << >> Energy required to compress hydrogen to 200 bar (40 years) = **7,509,888 kWh** << >> Number of maintenance operations = **3** <<

	>> Filling tubes with water = **21,970 L** << >> Paint Mass = **2.71 kg** << >> Piping System Replacement = **30 kg** <<
[Truck Trailer Parameters]	>> MLC Process = **Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity <<** >> Payload = **328.8 kg** << >> Driving share motorway = **70 %** << >> Driving share urban = **15 %** << >> Driving share rural = **15 %** << >> Utilization = **0.5** << *Default Settings:* >> Sulphur content in diesel = **10 ppm** << >> Share of biogenic Carbon in fuel= **5 %** <<
[Exclusions]	The energy used for the different maintenance tests is not modelled.
[Assumptions]	Hydrogen mass is calculated from the NIST[7] database. At a temperature of 15°C and a pressure of 200 bar, the density of hydrogen is 14.94 kg/m^3. The mass of hydrogen in a tube can be found by multiplying this value by the volume of the tube. The **FR: Electricity Grid** mix is used to model electricity consumption required to compress hydrogen. Specific data relating to vehicle emissions during its life cycle are not known. A transport process from the MLC database was therefore parameterised and used. This process is parameterised for the transport of goods. It gives as a result the emissions associated with the transport of X kg of a good over a distance Y. This truck has a payload of 27 tonnes, but in our case, the payload corresponds to the maximum mass of hydrogen that can be transported, i.e. 328.2 kg. However, a truck with a total mass ranging from 34 to 40 tonnes is required, as the entire system weighs just over 28 ton. Information on how to use and set up this process can be

[7] National Institute of Standards and Technology

found in the document *Sphera Managed LCA Content (MLC) Duty Vehicles LCI Modelling 2023* [1].

Delivering hydrogen means making an empty return journey. The modelling of an empty return journey is explained in the LCA FE manual. Empty return trips (with the same distance for both the forward and return trip) can be modelled with a single transport process with following utilization [1]:

$$utilisation_{empty\ return} = \frac{utilisation_{forward\ trip}}{2}$$

The distance must be set to the one-way distance, so 150 km in our case. On the outbound journey, the truck is 100% full, so the utilisation must be set at 0.5.

There are 3 maintenance operations during the life cycle studied (1 maintenance every 10 years).

During the maintenance, the tubes are filled with water. Only the quantity of water used to fill the 10 tubes will be modelled, as the emission information of the various devices used are not known (e.g. energy consumed by the compressor).

During the maintenance stage, the 10 tubes are repainted and sandblasted.

Maintenance information for the piping system is not available or the data is incomplete. The hypothesis of a total replacement of the system will therefore be taken into account.

For simplification purposes, the piping system is modelled as part of the framework for the production phase. However, for maintenance purposes, the piping system will be replaced with 316 Stainless steel. The mass of the entire piping system is around 30 kg, so there will be **30 kg** of 316 stainless steel for each maintenance phase.

3. End-of-Life Phase

For the type I trailer, all the different parts are made with steel so the end-of-life method is almost the same for the different parts. In this study, the hypothesis of recycling in France has been selected, and in order to model the different stages the modelling is based on a study conducted by ADEME[8] and FEDEREC[9] [2]. After the 40 years use phase the different end-of-life stages are as follows:

1. Scrap collection: In our case, this stage involves transporting our scrap metal from its end-of-life location to a scrap dealer. This distance can vary and in this study, a distance of **200 km** will be used.

[8] Agence de la transition écologique
[9] Fédération professionnelle des entreprises du recyclage

2. Sorting / Preparation: The second stage is the sorting and preparation stage. According to an assumption made in the study [2], the energy consumed during this stage is **46 MJ/ton**. Energy source is diesel. The efficiency of this stage is 98%. After the sorting stage, different options are possible. Scrap metal can be cut with a blowtorch, sheared or shredded.

For scrap metal used in a product, the breakdown between torch cutting, shearing and shredding is 10%, 45% and 45% respectively (FEDEREC).

For new scrap, the breakdown between shearing and direct shipment to the intermediate materials process is 20% and 80% respectively (FEDEREC).

Transport between the sorting stage and the RPM (Recycled Primary Materials) production site was estimated at **345 km**.

3. RPM Production: For this stage, only the energy consumption of each process will be modelled and the infrastructure will not be taken into account.

- Shredding: **30 kWh / ton** (electricity): losses = **3 %**
- Shearing: **15 kWh / ton** (electricity) : losses = **2 %**
- Torch cutting: **1,2 kg** of propane/ton : losses = **2 %**

4. Final Transport: The last step before the production of new steel is the transport between the RPM production place and the steel production plant. As in the study, several production sites are possible, and so the distribution of transports will be:

- 51% of the waste will go to a factory in France (500 km of road per lorry)
- 45% of waste will go to a plant in Europe (1000 km of road per lorry)
- 5% outside the European Union (500 km by truck + 5000 km by sea freight)

All the transport stages are carried out using trucks with a payload of 24.7 tonnes and an utilisation rate of 100%. The other parameters are set by default. A diagram illustrating the different stages is provided in Annex 5, along with the plan modelled on LCA FE. The losses produced during the different stages are sent to landfill. Modelling is carried out using the process: **RER: Ferro metals on landfill.**

System expansion is used for end-of-life modelling so for steel that is recycled, a credit is applied as follows:

Net scrap = (Amount of steel recycled at end-of-life) – (Scrap input)

The different processes for modelling steel in LCA FE represent what is done in reality, and there is no such thing as 100% virgin or 100% secondary production. All steel is therefore partly made from scrap. The table below gives the quantities of scrap for the processes used in this project.

MLC Process	Scrap input (for producing 1 kg of steel)
DE: Steel Billet (20 MoCr4)	1.03
GLO: Steel hot dip galvanised	0.147
RER: Stainless steel cold rolled coil (316)	0.719

Table 2: Scrap Input for Steel production

In our study, a distinction will be made between recycling credits for carbon steel and stainless steel. In both cases, the value of the credits corresponds to the inverse of the "value of scrap" defined by Worldsteel or "Stainless steel product (316) – value of scrap" defined by EuroFer.

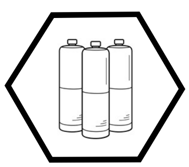
IV. Life Cycle Inventory (LCI) – Type IV

The life cycle inventory (LCI) describes the methodology of data collection of the entire system on the chassis (frame + MEGC containing the piping system and the tubes). This section will also be used to explain the different choices of processes from the MLC database, which are as close to reality as possible.

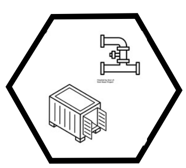
A. Life Cycle Studied

1. Production and Distribution phase

The different data modelled in this section concern:



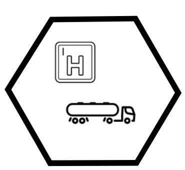
The production of the 114 thermosets composites tubes used to transport the hydrogen and their distribution from their production site in Germany to an Air Liquide site in Germany too. However, the lifespan of Type IV tubes is only 30 years, and as the study is being carried out over a 40-year period, the production of 38 additional tubes must be taken into account.



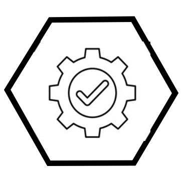
The production of the piping system, the frame, and their distribution from their production site in Germany to an Air Liquide site in Germany too.

2. Use Phase

The different data modelled in this section concern:



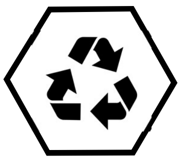
The daily transport of hydrogen between a filling centre and the site of one of their customers for 40 years. This phase takes into account all the emissions during the use phase (well to the wheel analysis).



The different maintenance procedures during the life cycle of the product studied.

3. End-of-Life

The different data modelled in this section concern:



The end-of-life treatment of the system studied at the end of its life.

B. Modelling and Assumptions on missing data

1. Production phase

Type IV Tube	
[Perimeter]	This section covers the entire tube manufacturing process. Type IV tubes are manufactured with an HDPE liner and an epoxy carbon fibres composite with a fibre density of 60% (volumetric). There are also two 316 stainless steel bases.
[Modelled data]	>> Numbers of tubes **= 114** << >> Tube Mass = **95 kg** << >> Filament Winding = **2.7 MJ / kg** << >> Composite Curing Oven = **35.25 kWh / tube** << >> Supply Distance = **80 km** << **80** km by truck (DE): **Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity**
[Exclusions]	The energy required to assemble the different elements of the tube is not modelled (welding between the composite and the boss[10], assembly of the liner with the composite…).
[Assumptions]	The mass of a tube corresponds to the mass of the liner + the mass of the epoxy carbon composite + the mass of the steel bosses (embase). The mass of the HDPE liner is 7 kg with 5 % loss rate. The initial quantity of material for 1 tube is therefore 7.35 kg. The mass of the carbon fibre-filled composite is 80 kg with a fibre content of 60% by volume. The following formula is applied to determine the fibre mass ratio.

[10] Metallic part joined to the liner that allows screwing a valve for Type IV cylinders.

	$$M_f = \frac{V_f}{(V_f + \left(\frac{\rho_m}{\rho_f}\right) * (1 - V_f))}$$ With a loss rate of 5%, the initial fibre mass is 58.91 kg and the final mass is 56.1 kg. With a loss rate of 10%, the initial quantity of epoxy is 26.29 kg and the final mass is 23.9 kg. The carbon fibres used are long fibres produced from polyacrylonitrile (PAN). To produce 1 kg of carbon fibres, 2.36 kg of precursor (PAN) is required. This value is derived from a scientific publication by Sujit Das [3]. Other studies consulted also provided a similar order of magnitude. The process **RER: Polyacrylonitrile Fibres (PAN)** is used to model that. The energy consumption to convert PAN fibres into carbon fibres is 128 kWh per kilogram of fibres, as provided by Arkema. Multiple fibre suppliers have been identified, primarily from Japan and Korea. For the reference scenario, the Japanese mix will be utilized since the Korean mix is not available in the database. Additionally, the Japanese mix is more carbon-intensive than the Korean mix, representing the "worst-case" scenario. Other scenarios will also be considered. The study will also analyze the production of carbon fibers using French, European, and a global "green" (renewable) energy mix. Steel boss is made with 316 Stainless Steel. There are 2 of them, each weighing 4 kg. The HDPE liner is produced with a blow moulding process. The process **DE: Polyethylene (HDPE/PE-HD) blow moulding** is used to model that. The process includes an air compression step with three options for process power consumption (low, medium, high). The medium value is chosen. Filament winding process is not available in the MLC database and is therefore modelled from a scientific publication [4]. Only the electricity of the process is modelled. **DE: Electricity Grid mix** is used to model the energy consumption of the process. The calculation of the energy used for curing in ovens is detailed in Annex 6.
Type IV Frame	
[Perimeter]	This section covers the frame manufacturing process. The frame is fully made with galvanised steel.
[Modelled data]	>> Number = **1** << >> System Mass = **6,040 kg** << >> Welding Length = **1,000 m** << >> Supply Distance = **300 km** <<

	• **300** km by truck (DE): **Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity.**
[Exclusions]	There are no major exclusions, but the assembly is only defined by a welding process that can only be estimated approximately.
[Assumptions]	The process **GLO: Steel hot dip galvanised Worldsteel** is used to model the whole system. Hot-dip galvanising is preferred to electro-galvanising because it is a method used for buildings and structures, whereas electro-galvanising is preferred for small materials. The free parameters for the truck transportation are selected "by default" (i.e. driving share urban, rural and motorway, sulphur content in diesel….) The total weld lengths for assembling the reinforcement are unknown. An upward estimate of 1,000 metres of weld has therefore been made. The process **GLO: Steel sheet (1 to 4 mm) MIG/MAG welding** is used.
Type IV Piping System	
[Perimeter]	This section cover the piping system manufacturing process. The system is modelled as being manufactured exclusively from stainless steel.f
[Modelled data]	>> Number = **1** << >> System Mass = **528 kg** << >> Supply Distance = 300 km << • **300** km by truck (DE) : **Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity**
[Exclusions]	The various assembly processes are not taken into account. The piping system is also made up of other materials whose mass is negligible and therefore modelled as stainless steel.
[Assumptions]	The process **RER: Stainless steel cold rolled coil (316)** is used to model the whole system. The free parameters for the truck transportation are selected "by default" (i.e. driving share urban, rural and motorway, sulphur content in diesel….)

2. Use Phase & Maintenance

Use Phase	
[Perimeter]	This section covers the use phase of the system, which is the daily transport of hydrogen between Air Liquide's hydrogen production site and the site of one of their customers for 40 years.

	5 journeys of 300 km (150 km outward and 150 km return) per week for 40 years. This phase is mainly dependant of the truck process used. The maintenance of the system is also included in this phase.
[Modelled data]	>> Daily Distance **= 300 km** << >> Total Distance (40 years) = **3,120,000 km** << >> Hydrogen Mass (per tube) = **7.40 kg** << >> Hydrogen Mass (114 tubes) = **843.95 kg** << >> Hydrogen Mass transported (40 years) = **8,777,126 kg** << >> Energy required to compress hydrogen to 200 bar = **2.2 kWh / kg** << >> Energy required to compress hydrogen to 200 bar (40 years) = **19,309,677 kWh** << >> Gas losses during use phase = **0.4 %** << >> Number of maintenance operations = **2** << >> Filling tubes with water = **39,900 L** << >> Piping System Replacement = **528 kg** <<
[Truck Trailer Parameters]	>> MLC Process = **Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity <<** >> Payload = **843.95 kg** << >> Driving share motorway = **70 %** << >> Driving share urban = **15 %** << >> Driving share rural = **15 %** << >> Utilization = **0.5** << *Default Settings:* >> Sulphur content in diesel = **10 ppm** << >> Share of biogenic Carbon in fuel= **5 %** <<

[Exclusions]	The energy used for the different maintenance tests is not modelled.
[Assumptions]	Hydrogen mass is calculated from the NIST[11] database. At a temperature of 15°C and a pressure of 300 bar, the density of hydrogen is 21.15 kg/m^3. The mass of hydrogen in a tube can be found by multiplying this value by the volume of the tube. The **FR: Electricity Grid** mix is used to model electricity consumption required to compress hydrogen. Specific data relating to vehicle emissions during its life cycle are not known. A transport process from the MLC database was therefore parameterised and used. This process is parameterised for the transport of goods. It gives as a result the emissions associated with the transport of X kg of a good over a distance Y. This truck has a payload of 27 tonnes, but in our case, the payload corresponds to the maximum mass of hydrogen that can be transported, i.e. 801.1 kg. However, a truck with a total mass ranging from 34 to 40 tonnes is required, as the entire system weighs just over 28 ton. For the parameter "Utilization", the method used is the same as for Type I. There are only 2 maintenance operations because tubes have a service life of 30 years. Modelling is also based on a 40-year life cycle, which means that tube production and end-of-life must be taken into account 4/3 times. During the maintenance, the tubes are filled with water. Only the quantity of water used to fill the 10 tubes will be modelled, as the emission information of the various devices used are not known (e.g. energy consumed by the compressor, energy used by the endoscope, etc.) Maintenance information for the piping system is not available or the data is incomplete. The hypothesis of a total replacement of the system will therefore be taken into account. The mass of the entire piping system is 528 kg, so there will be **528 kg** of 316 stainless steel for each maintenance phase.

3. End-of-Life

For the different steel and stainless steel parts, the end-of-life stages are the same as for Type I with the same processes, loss rates... The only difference concerns the end-of-life of composite tubes. These are incinerated and the modelling is done using the following process: **DE: Commercial waste (AT, DE, IT, LU, NL, SE, and CH) on landfill**. Details of the LCA FE plan can be found in Annex 6.

[11] National Institute of Standards and Technology

V. Life Cycle Inventory Assessment (LCIA)

The environmental results of this study will be presented in several ways. Firstly, the raw results will be presented, taking into account all the environmental impacts over the life cycle (production, use for 40 years, maintenance and end of life). This first way of presenting the data will essentially be used to observe the breakdown of impacts between the different stages of the life cycle.

Then, the results will be standardized to a common unit for comparing Type I and Type IV. As specified in the functional unit, the environmental results will then be presented for the transport of 1 kg of hydrogen over a distance of 100 km.

A. Allocation of impacts across life cycle stages

The following graph shows the breakdown of environmental impacts between the different stages of the life cycle for the type I. The graph shows the results for the 5 environmental indicators chosen for this study. What is very clear from this graph is that the use phase has by far the greatest impact on the majority of environmental impacts. The only impact on which the production phase has a significant impact is the category relating to the depletion of mineral and metal resources.

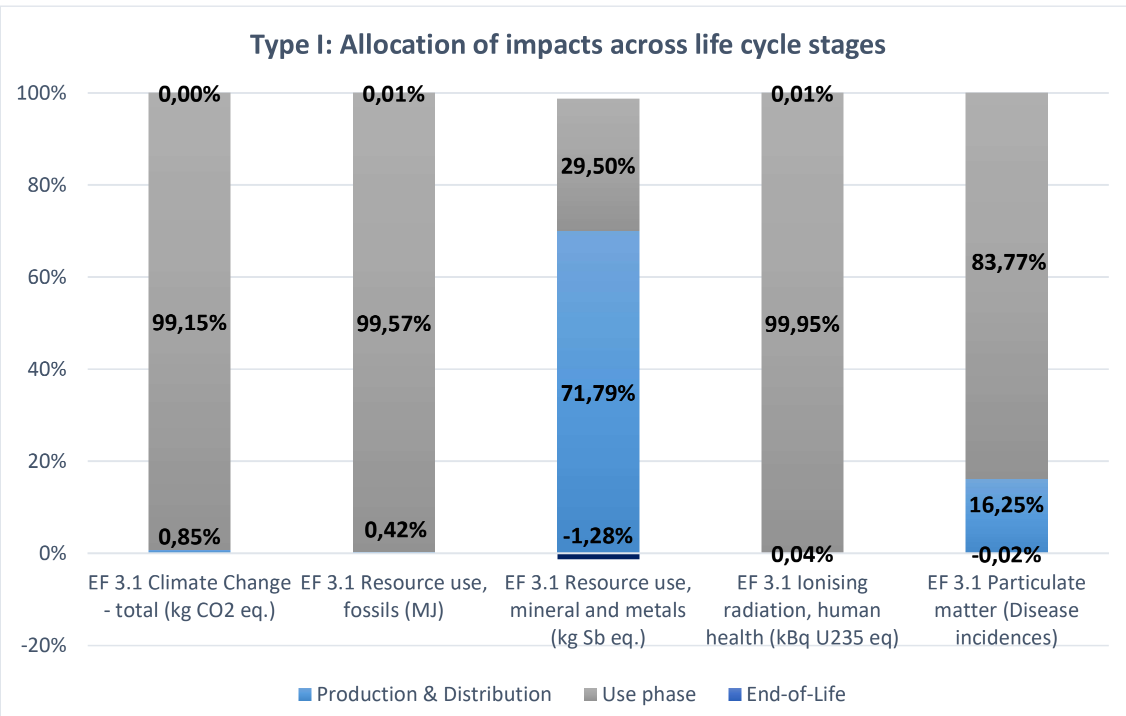


Figure 3: Allocation of impacts across life cycle stages - Type I

Looking at the same chart for Type IV, the use phase is also significantly dominant, although the manufacturing phase seems to have a greater impact. In both cases, this is because the distance covered during the life cycle is very large and that the truck used to deliver the hydrogen runs on diesel. The environmental impacts are therefore mainly linked to the production and combustion of diesel.

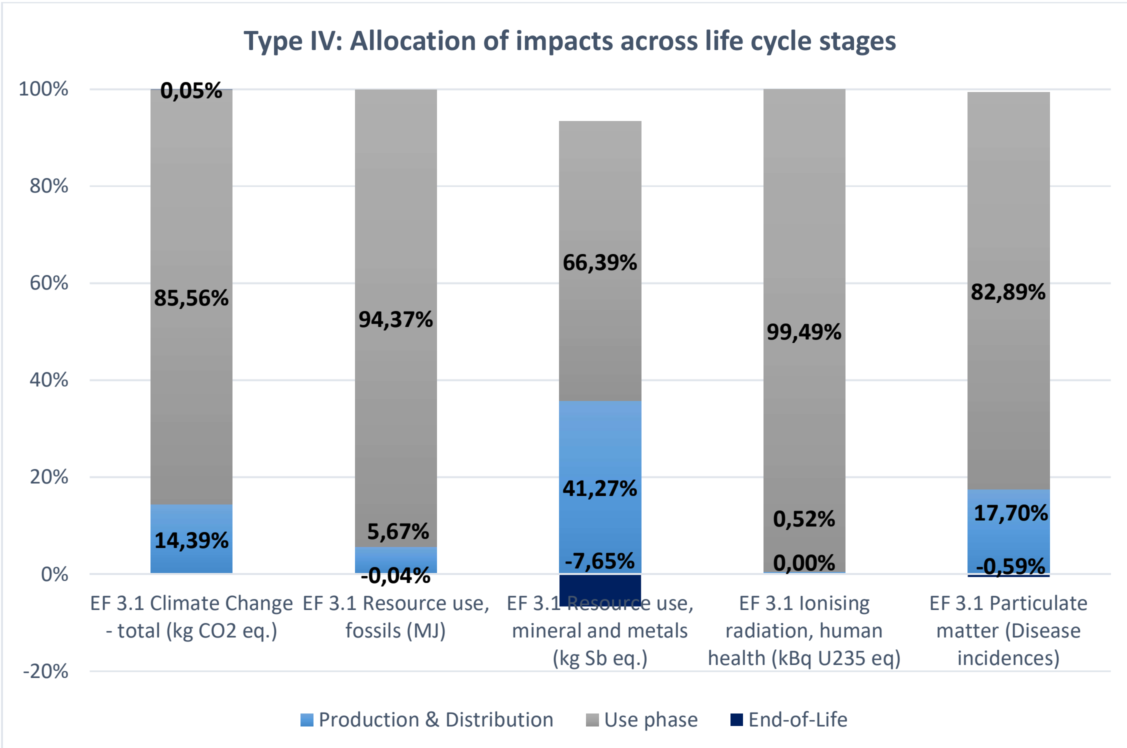


Figure 4: Allocation of impacts across life cycle stages - Type IV

Before looking in more detail at the different phases of the life cycle, the overall results between the two types of technology for the transport of 1 kg of hydrogen over a 100 km distance will be compared.

B. Comparison of environmental impacts between type I and type IV

1. Complete Life Cycle

To be able to compare the two systems, results must be expressed in a common unit. The main advantage of Type IV tubes is that hydrogen can be stored at higher pressures and a larger quantity of gas can be transported on each journey. With one trip, Type I tubes can carry 328.2 kg, while Type IV tubes can carry 843.9 kg. The results must be standardized to the same quantity of hydrogen transported for both systems. The reference will be the transport of 1 kg of hydrogen. In addition, the raw results obtained from the software are given for the transport of hydrogen for 40 years, i.e. over a total distance of 3,120,000 km. In this study, the selected reference distance for comparing different systems is a distance of 100 km

The graph below compares the potential global warming impacts of transporting 1 kg of hydrogen over a distance of 100 km. For this indicator, the results for Type IV are slightly less than half of those for Type I. Since the use phase is significantly predominant compared to other life cycle stages, it logically results in lower outcomes for Type IV. This result makes sense, since for both systems; the use phase is largely predominant and this phase is modelled using the same MLC process. The only data that changes in the modelling is the quantity of hydrogen transported, which is 2.57 times greater for Type IV. However, the quantity of transported hydrogen is not the only determining parameter for the study results. In fact, the emissions for transporting one kilogram of hydrogen over a distance of 100 km are 1.82 times lower for Type IV compared to Type I, even though 2.57 times more hydrogen is being transported. The graph illustrates that the manufacturing phase has a much greater impact for Type IV. Additionally, by considering the compression of hydrogen, which is the same for both systems, the gap further decreases (proportionality).

Finally, the process used is designed for a truck-trailer with a total weight ranging from 34 to 40 tonnes, and exact mass is not a parameter that is taken into account in the LCA FE process. With the modelled data, the mass of the trailer without a chassis is 28.8 tonnes for type I and 18.2 tonnes for type IV. If adding the mass of the chassis and tractor results in different overall masses, the fuel consumption of the two trucks will be different, and the current modelling does not account for this. Specific data would be required to best approximate the real-world situation.

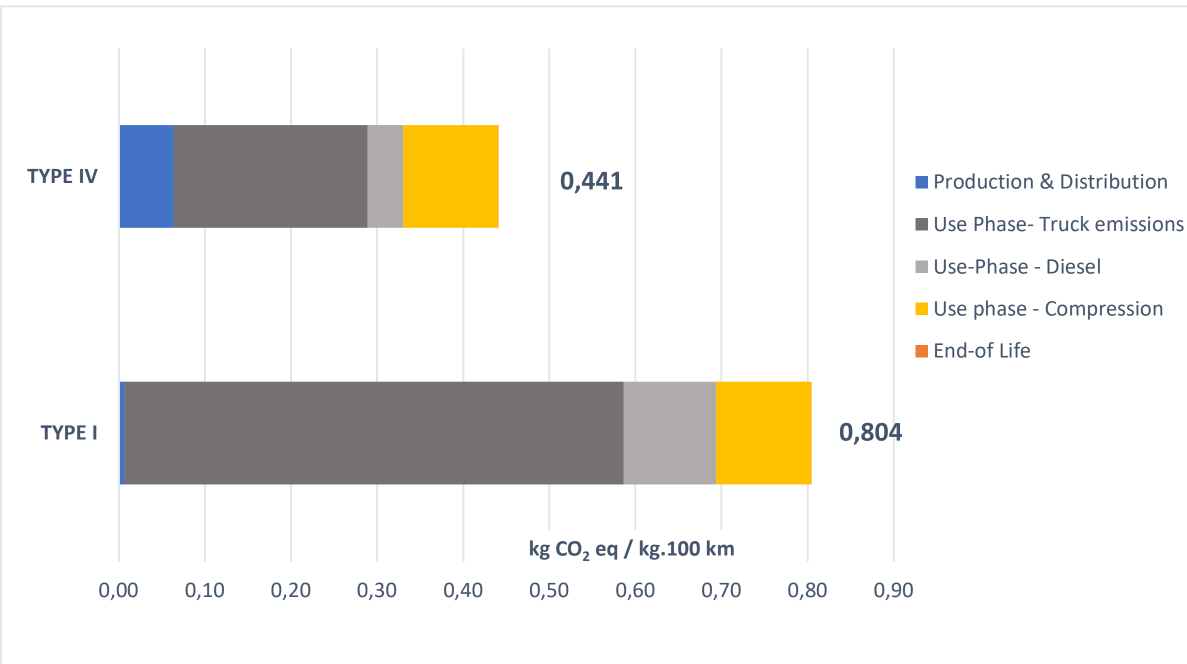


Figure 5: EF 3.1 – Climate Change - Environmental impact of transporting 1 kg of H_2 over a distance of 100 km

The results for the other environmental indicators are presented in the following table, but in general, it is noticeable that the results for type IV are lower than for type I. For ionising radiation, the impact is similar for both systems as it is primarily related to the compression of hydrogen, which is the same for both 200 and 300 bar. This stage uses electricity produced in France, mainly from nuclear energy. For indicator "Resource use, fossils", it is also largely related to the compression of hydrogen. In general, if this parameter is predominant in an impact category, the difference between Type I and Type IV will be less significant because the compression value is the same.

Environmental impact of transporting 1 kg of H_2 over a distance of 100 km				
	Type I	Type IV	Unit	Reduced impacts between type I and type IV trailers
EF 3.1 Climate Change – total (kg CO_2 eq)	0.80	0.44	kg CO2 eq / kg. 100 km	**- 45 %**
EF 3.1 Resource use, fossils (MJ)	21.58	16.81	MJ / kg. 100 km	**- 22 %**
EF 3.1 Resource use, mineral and metals (kg Sb eq)	2.76E-07	1.03E-07	kg Sb eq / kg. 100 km	**- 63 %**
EF 3.1 Ionising radiation, human health (kBq U235 eq)	0.99	0.99	kBq U235 eq / kg. 100 km	**0 %**
EF 3.1 Particulate matter (Disease incidences)	1.61E-08	5.16E-09	Disease incidences / kg. 100 km	**- 68 %**

Table 3: Environmental impact of transporting 1 kg of H2 over a distance of 100 km for different impact categories

It is interesting to compare the results obtained with already available data. A Life Cycle Assessment (LCA) study was conducted by ADEME in 2020 on various hydrogen production methods as well as hydrogen delivery [5]. In this study, data is available for hydrogen transport at 200 bar. The value obtained in the study is **1.12 kg CO2 eq/kg H_2.100 km**. This value is higher than the results from our study. However, in the ADEME study, the capacity for Type I tubes is only 200 kg. Additionally, the modelling assumptions and the datasets used are not necessary the same. Nevertheless, the order of magnitude is similar, and the link between the quantity of transported hydrogen and the associated environmental impact is evident.

2. Use Phase

As mentioned earlier, the modelling of the use phase is the same for both systems. The chart below provides the raw results obtained over the entire life cycle. Therefore, we have the same values for the production and combustion of diesel because the distance travelled is the same. However, electricity consumption is higher for Type IV simply because a larger mass of hydrogen is transported over this period.

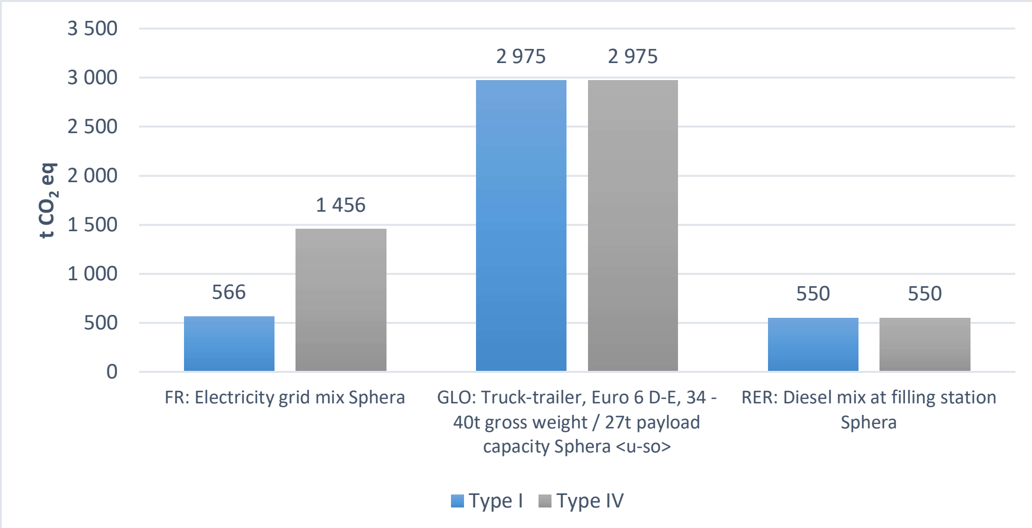


Figure 6: EF 3.1 – Climate change - Impact distribution for the Use phase – complete life cycle

In addition, by expressing the previous results in the functional unit of the study, we indeed find identical electricity consumption for hydrogen compression at 200 and 300 bar. We also observe a lower impact for the combustion and production of diesel for Type IV, attributable to a larger mass of transported hydrogen.

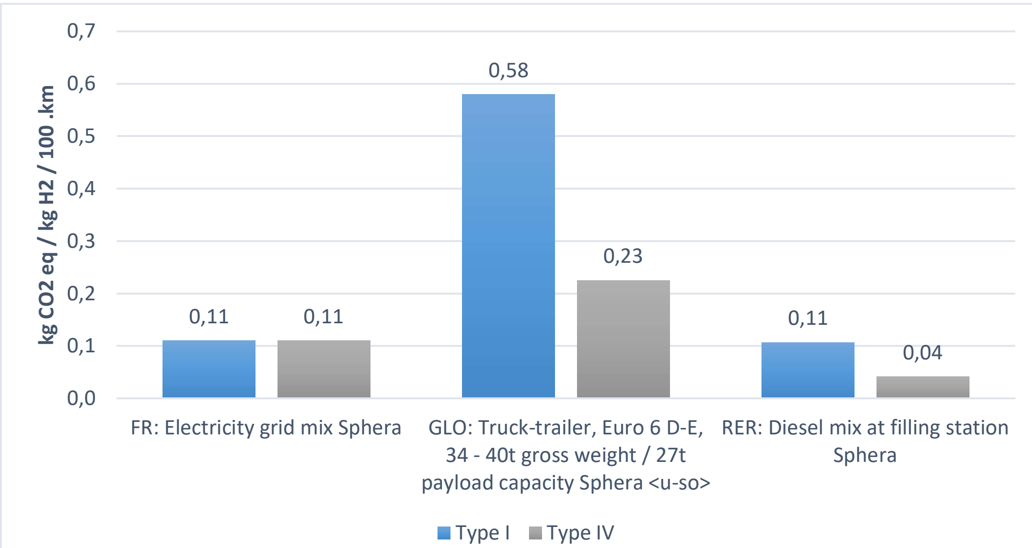


Figure 7: Use phase – EF 3.1 Climate Change: CO_2 emissions for the transport of 1 kg of hydrogen over a distance of 100 km

3. Production Phase

After the quantity of transported hydrogen, what will differentiate our two systems is the manufacturing phase. Indeed, the materials used to make the tubes involve two different technologies. Type I tubes are 100% steel, whereas Type IV tubes are made with composite materials reinforced with carbon fibres. The chart below clearly shows that the use of these composite materials results in significantly higher environmental impacts for some impact categories.

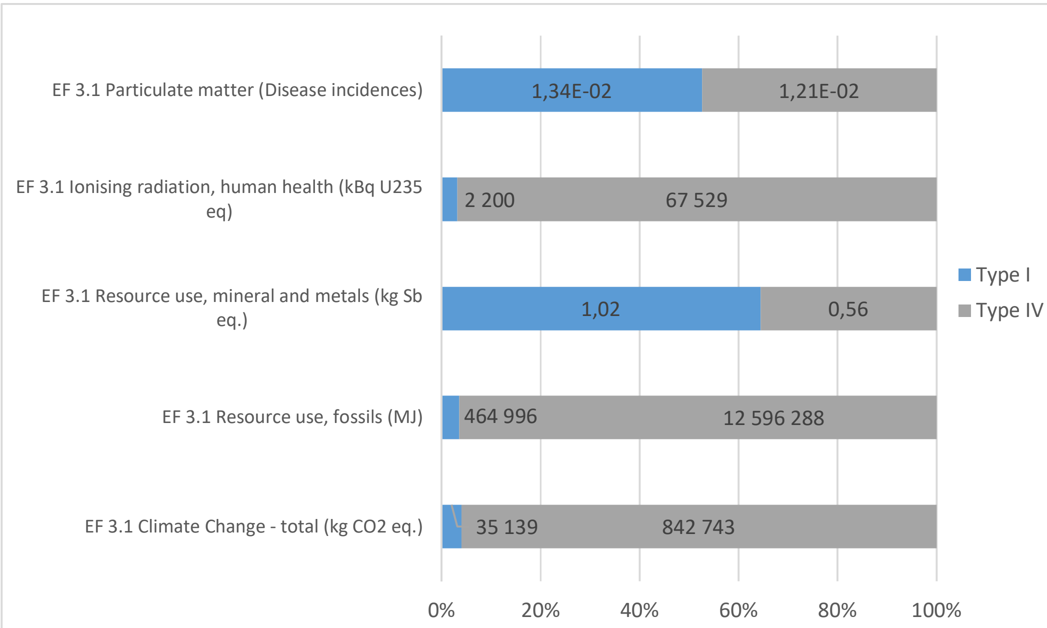


Figure 8: Environmental impacts associated with the production and distribution of Type I and Type IV

The ratios between the production of Type I and Type IV for various environmental impact categories are presented in the table below:

Production Phase	
Unit	Ratio Type IV / Type I
EF 3.1 Particulate matter	0.9
EF 3.1 Ionising radiation	30.7
EF 3.1 Resource Use. mineral and metals	0.6
EF 3.1 Resource use. fossils	27.1
EF 3.1 Climate Change	24

Table 4: Ratio between Type I & IV – Production & Distribution stage

We note that for certain impact categories, the variation is highly notable between the two systems, while the results for mineral and metal resource depletion and particle emissions are relatively close. Regarding mineral and metal resources, this can be explained by the fact that the impacts mainly come from the use of metals, and Type IV only has the framework and a small portion of the tubes that are made of steel. For particle emissions, they result from tube blasting for Type I and the use of the Japanese electricity mix for carbon fibre manufacturing for Type IV. For other impact categories, it is necessary to delve a bit more into the manufacturing phase to understand the origins of the impacts. The distribution of impacts for the production of Type IV is presented in the following chart.

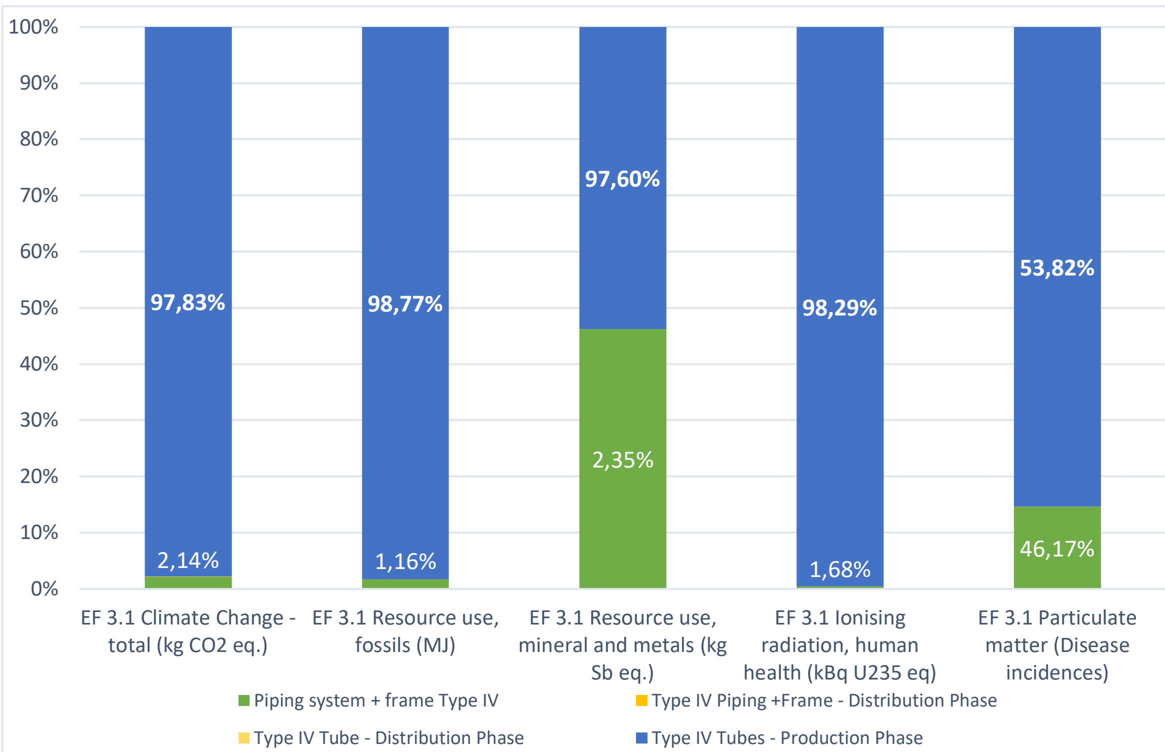


Figure 9: Distribution of impacts for the production and distribution of Type IV

The chart below clearly shows that the production of carbon fibre-reinforced composite tubes is by far the major contributor. Percentages for the distribution of tubes and framework are not provided, as they are not necessary in this case. If we now focus on the detailed breakdown of environmental impacts for the production of tubes *(Figure 10),* we observe that the production of carbon fibres is the primary source of impact. Since the carbon fibre production process is electricity-intensive, the results are highly dependent on the electricity mix of the country of production. A sensitivity analysis will be presented in the next section.

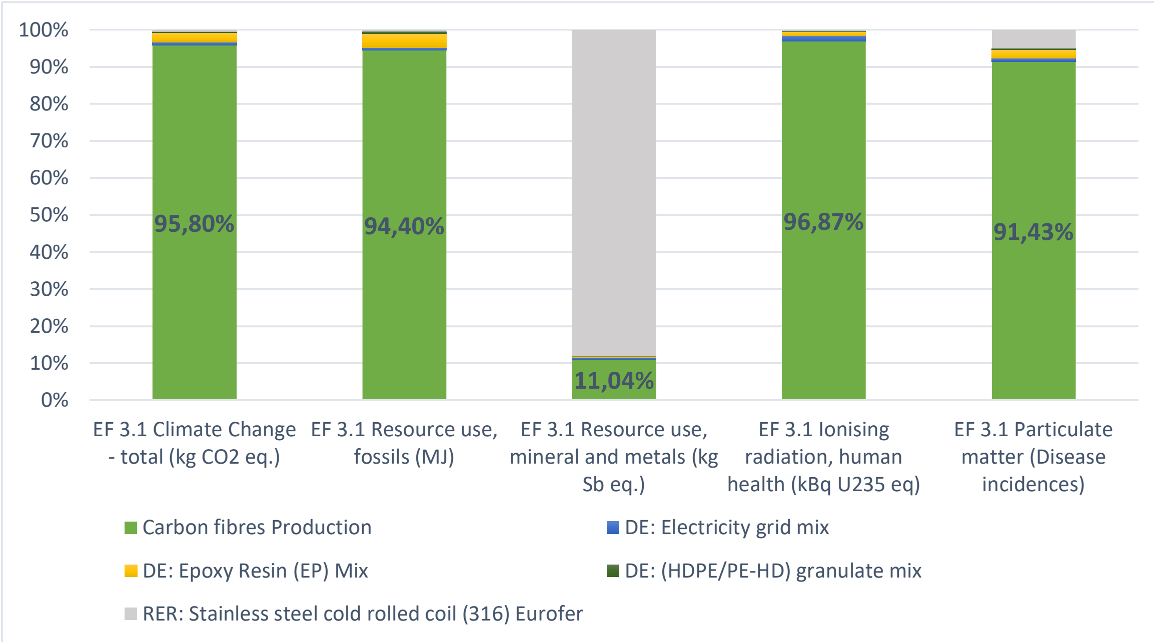


Figure 10: Distribution of impacts for the production of Type IV tubes

4. End-of-Life

In the chart illustrating outcomes for the entire life cycle, the end-of-life stage is quite negligible. The table below outlines the contribution of end-of-life for Type I and Type IV across various impact categories. Except for mineral and fossil resource depletion, the values are very low for the other categories.

Influence of end-of-life on the entire life cycle for Type I and Type IV		
Impact Categories	Type I	Type IV
EF 3.1 Climate Change	0.00%	0.05%
EF 3.1 Resource use, fossils	0.01%	-0.04%
EF 3.1 Resource Use. mineral and metals	-1.28%	-7.65%
EF 3.1 Ionising radiation	0.01%	0.00%
EF 3.1 Particulate matter	-0.02%	-0.59%

Table 5: Influence of end-of-life on the complete life cycle for Type I and Type IV

The method used to model end-of-life is a system expansion method that considers recycling credits. The chart below presents the results of the end-of-life stage as well as the distribution among different steps (transport, landfilling, credits, etc.). However, for Type I, one might expect a larger credit, as almost all of the steel is recycled (with some losses during various stages). Nevertheless, this method considers net recycling credits, and the various steels used are almost entirely manufactured from scrap. As this credit value is relatively low, the various stages of steel transportation will increase CO_2 emissions, and more broadly, the results for other impact categories. This is particularly the case for the use of fossil resources, which are relatively significant. It is important to note that specific information on the recycling process was not available, and recycling was modelled based on a report on recycling in France.

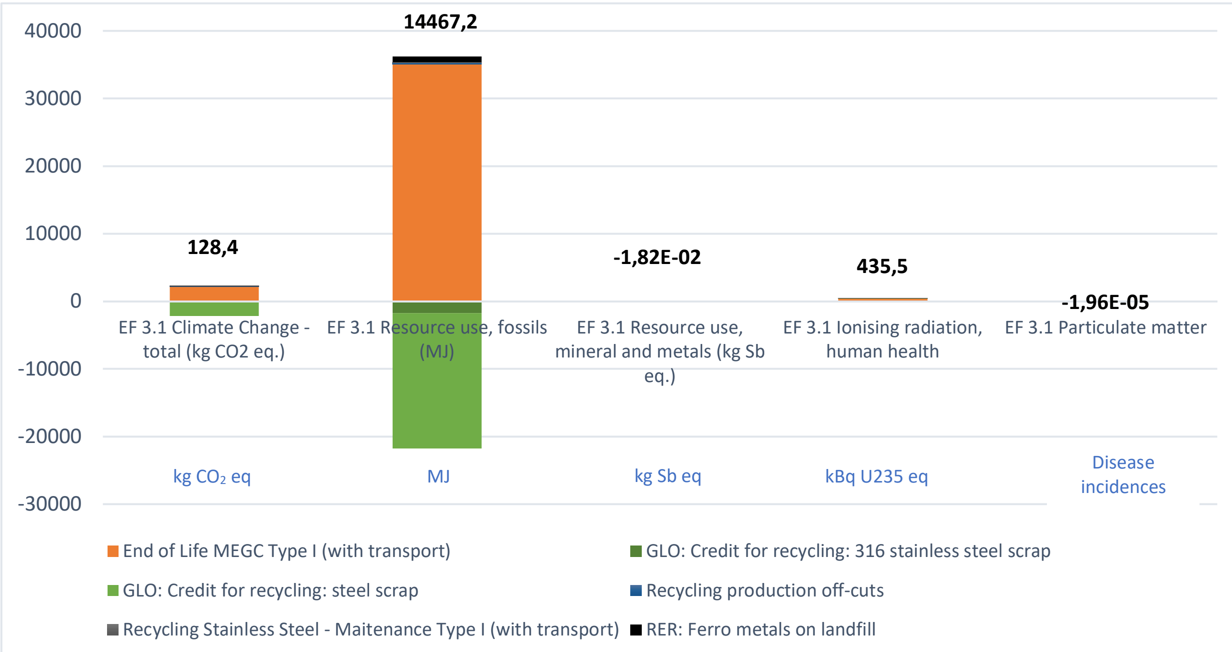


Figure 11: Distribution of impacts among different stages of end-of-life - Type I

As for the end-of-life stage for Type I, the results for the use of fossil resources are significantly negative. This outcome is primarily linked to the fact that a larger mass of galvanized steel is used, and it only requires 147 kg of scrap for the production of one ton of steel. Therefore, net credits are higher at the end of life. Moreover, the electricity recovery during landfilling is taken into account, further increasing the value of this credit.

For the impact on climate change, landfilling will emit approximately 12 tons of CO2. However, the overall impact on this indicator is only 2.6 tons, thanks to the recycling credits for galvanized steel. Finally, material recovery has the most significant impact on the category of depletion of mineral and metal resources. Even though its importance is not huge over the entire life cycle, it is in this category that the end-of-life stage plays a 'more significant' role.

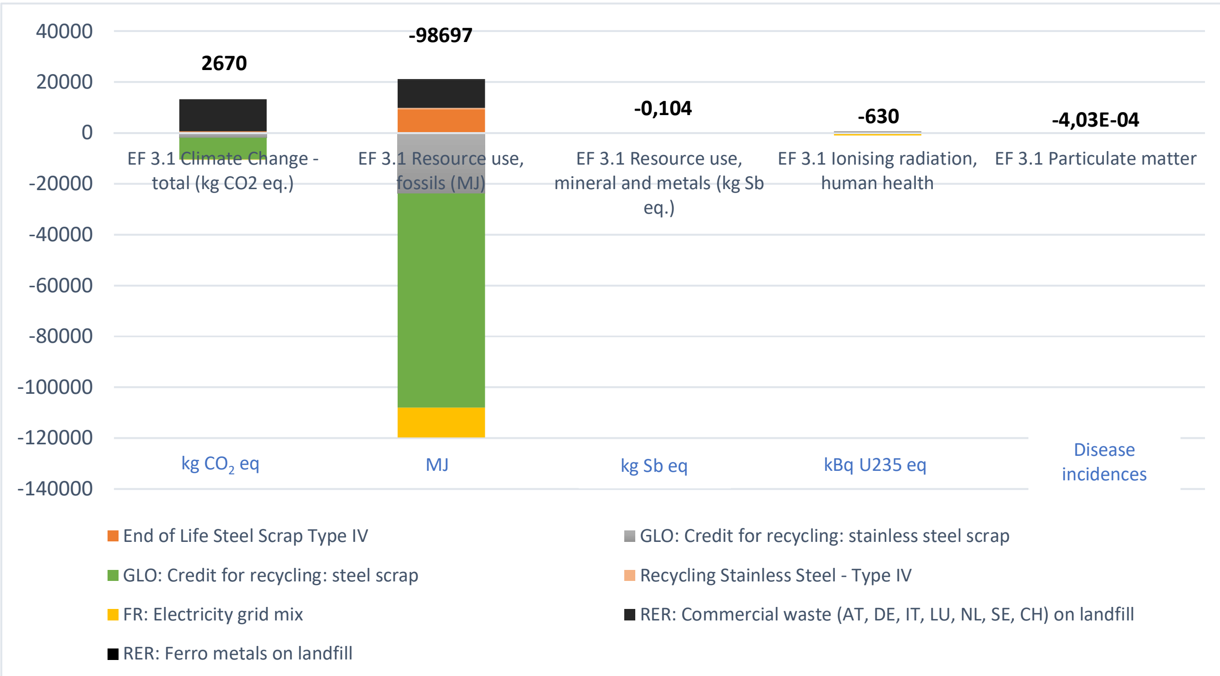


Figure 12: Distribution of impacts among different stages of end-of-life - Type IV

The interesting aspect to study will be particularly in the continuation of the work with a comparison of the end-of-life stage between Type IV and Type V. Indeed, the Type V tank is made with composites using thermoplastic matrix materials and these polymers can be melted down, unlike thermosetting plastics. However, once reinforced with fibres, recycling becomes more complex, and the concept of value loss during recycling becomes significant

VI. Interpretation and sensitivity analysis

A. Influence of the country of production of carbon fibres

As explained earlier, the carbon fibre manufacturing process is electricity-intensive. Therefore, it is interesting to examine the differences that may arise depending on the country of carbon fibre production. This sensitivity analysis will focus on the following three electricity mixes (in addition to the Japanese mix used as the reference case):

- French electricity mix
- European electricity mix
- Global green electricity mix (world)

The chart below illustrates the equivalent CO_2 emissions for the production and distribution phase of Type IV, depending on the electricity mix used for carbon fibre production.

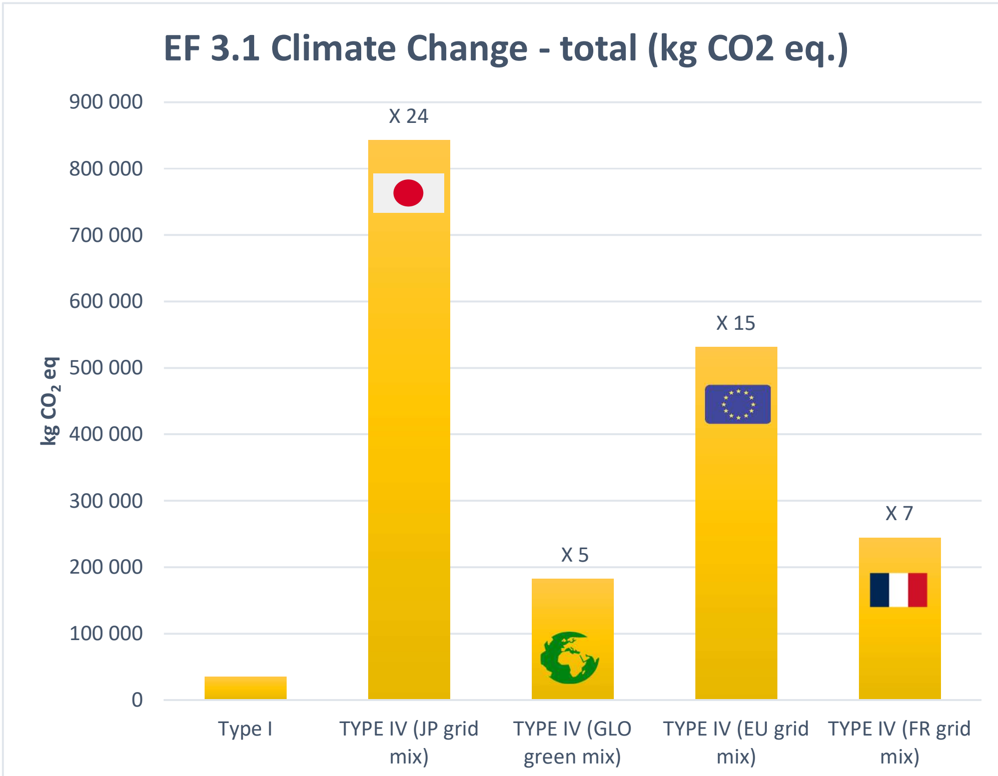


Figure 13: EF 3.1 – Climate Change – Comparing Production Methods: Type I vs Type IV tubes using carbon fibres from various country.

The reference case yields significantly higher results for these impact category because Japanese electricity is largely produced from gas and coal. The European mix already reduces the impacts by half, but it is with the use of a decarbonized electricity or a "green electricity mix" that a drastic reduction in impacts can be observed. Focusing now on the reduction brought to the overall life cycle, it is not negligible, with a reduction of up to -12.7% for the use of a "green electricity mix". The choice of fibre supplier is, therefore, of significant environmental importance.

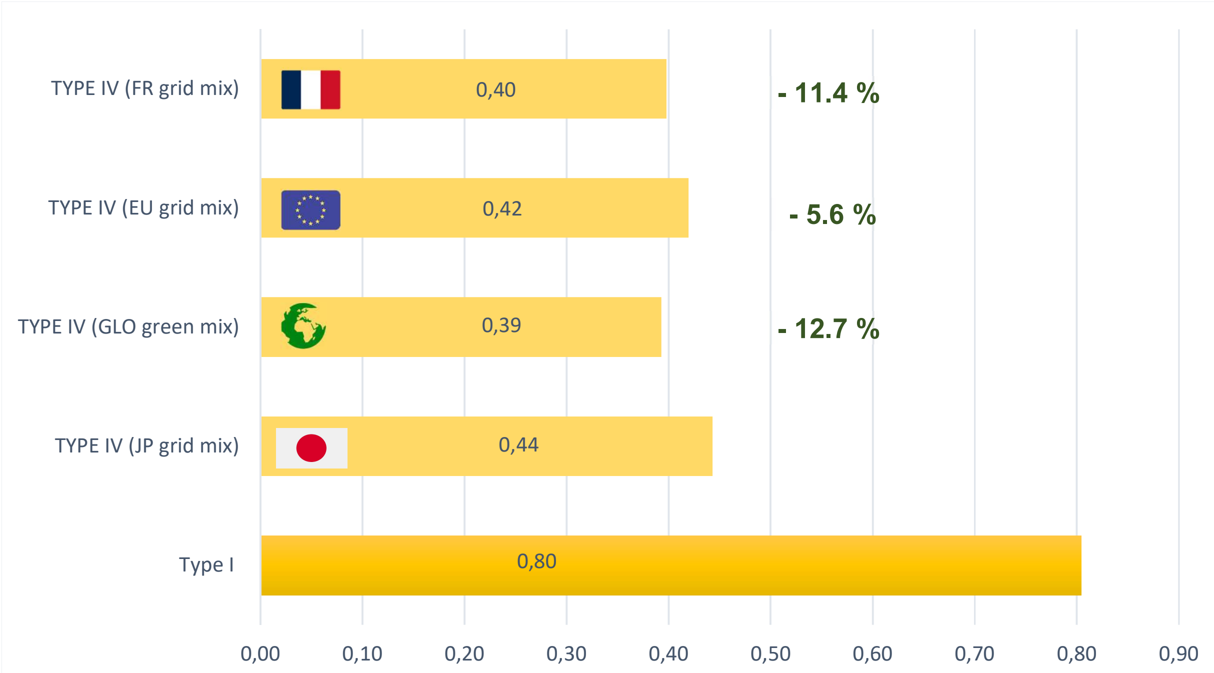


Figure 14: EF 3.1 Climate Change: Environmental impact of transporting 1 kg of H_2 over a distance of 100 km for different carbon fibre production countries

If we look at other environmental indicators, the trend is not always the same. For ionizing radiation, the French mix yields significantly higher results than others due to the high proportion of electricity produced from nuclear sources. For mineral resource depletion, the results are generally equivalent, with a slightly higher value for the global green electricity mix. This can be explained by the use of resources in the construction of solar panels and wind turbines.

Particle emissions are approximately 2 times higher for the Japanese and European electricity mixes. This is mainly linked to electricity production from coal, natural gas, or lignite. Finally, for fossil resource depletion, equivalent results are obtained, except for the green electricity mix, which allows a significant reduction in impacts in this category.

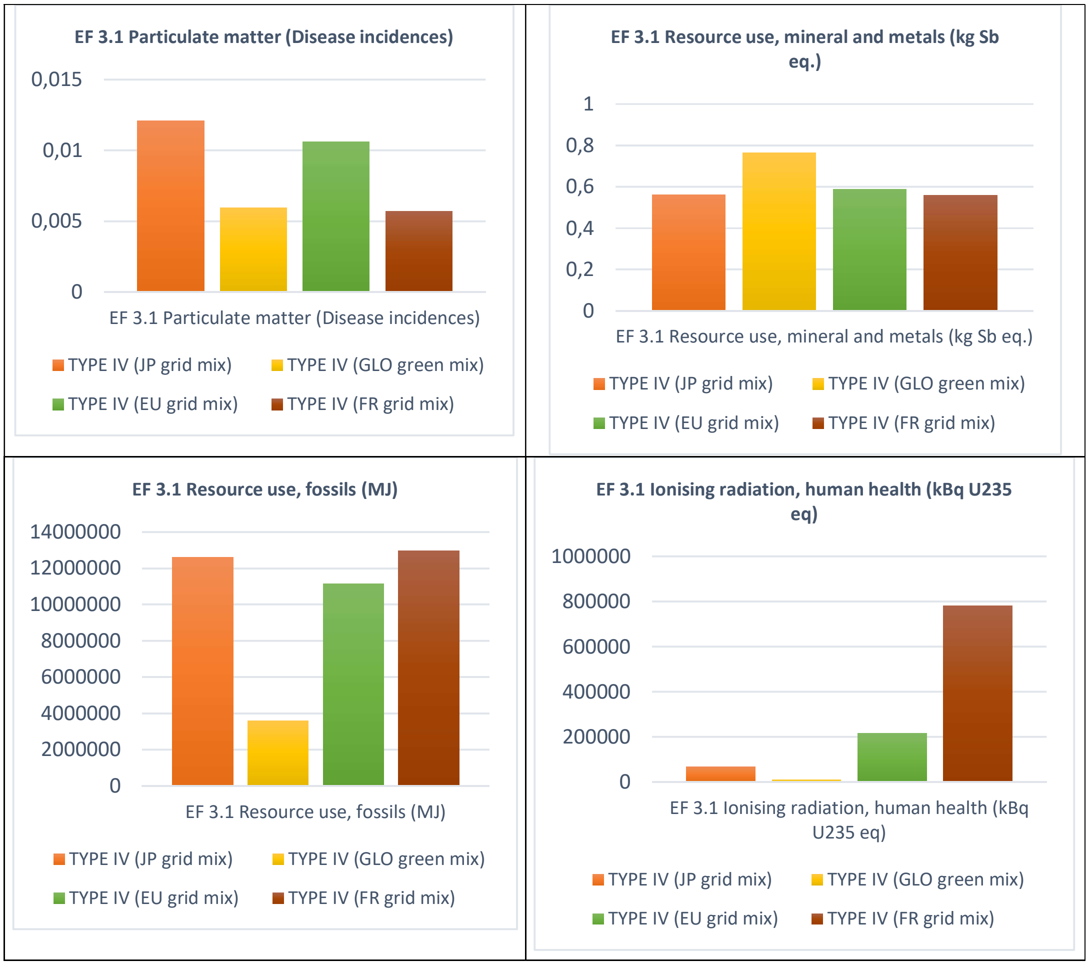


Table 6: Influence of the country of fibre production for other environmental categories.

B. Influence of hydrogen compression country at 200 / 300 bar

Another parameter to study is the country in which the hydrogen compression stage is carried out. Indeed, this stage has a significant impact, and the reference scenario models hydrogen compression carried out in France. A comparison with hydrogen compression using a German mix will be examined. The following chart presents the results for the reference scenario (compression in France) and also for a scenario with compression in Germany. The results are shown for Type I and Type IV.

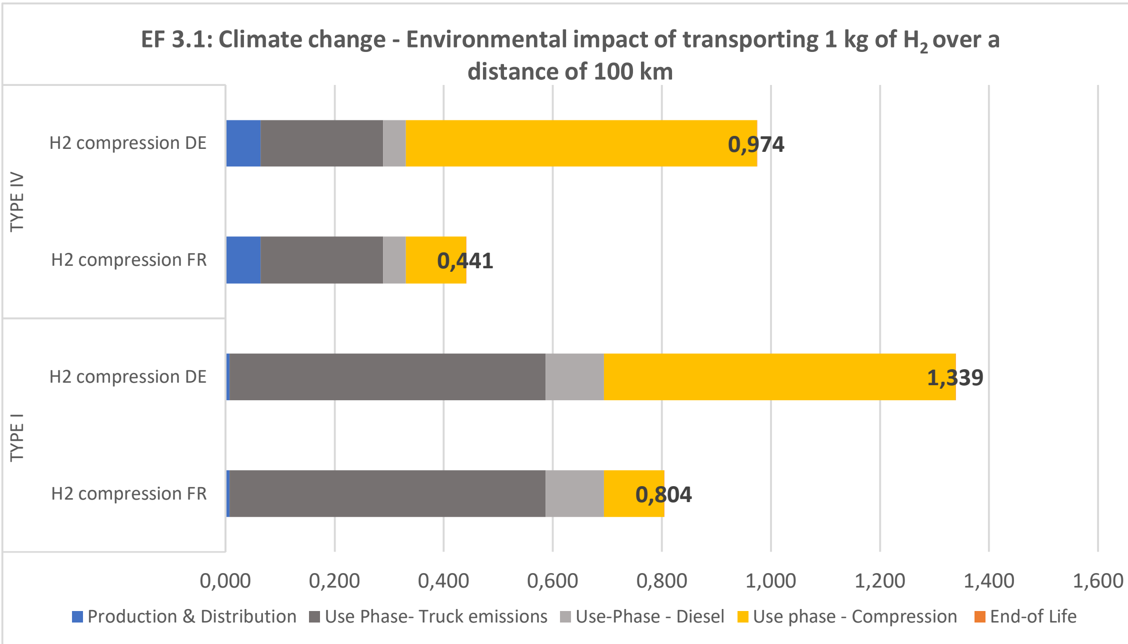


Figure 15: EF 3.1 Climate Change: Environmental impact of transporting 1 kg of H2 over a distance of 100 km depending on the "hydrogen compression country"

The results obtained show that the use of German electricity (which is much more carbon-intensive) significantly increases the impacts of the compression stage, as well as the overall impacts over the entire life cycle. For Type I, the impacts are multiplied by 1.7, and for Type IV, the impacts are multiplied by 2.2. In addition to this, the gap between Type I and Type IV for the transport of 1 kg of hydrogen over 100 km narrows, decreasing from a ratio of 1.82 to 1.37.

Focusing on the ratio between the results of Type IV, and I the gap narrows for all environmental indicators, except for the category related to fossil resource depletion. These results are visible in the chart below, and the evolution of the ratio between Type IV and Type I is presented in the table below.

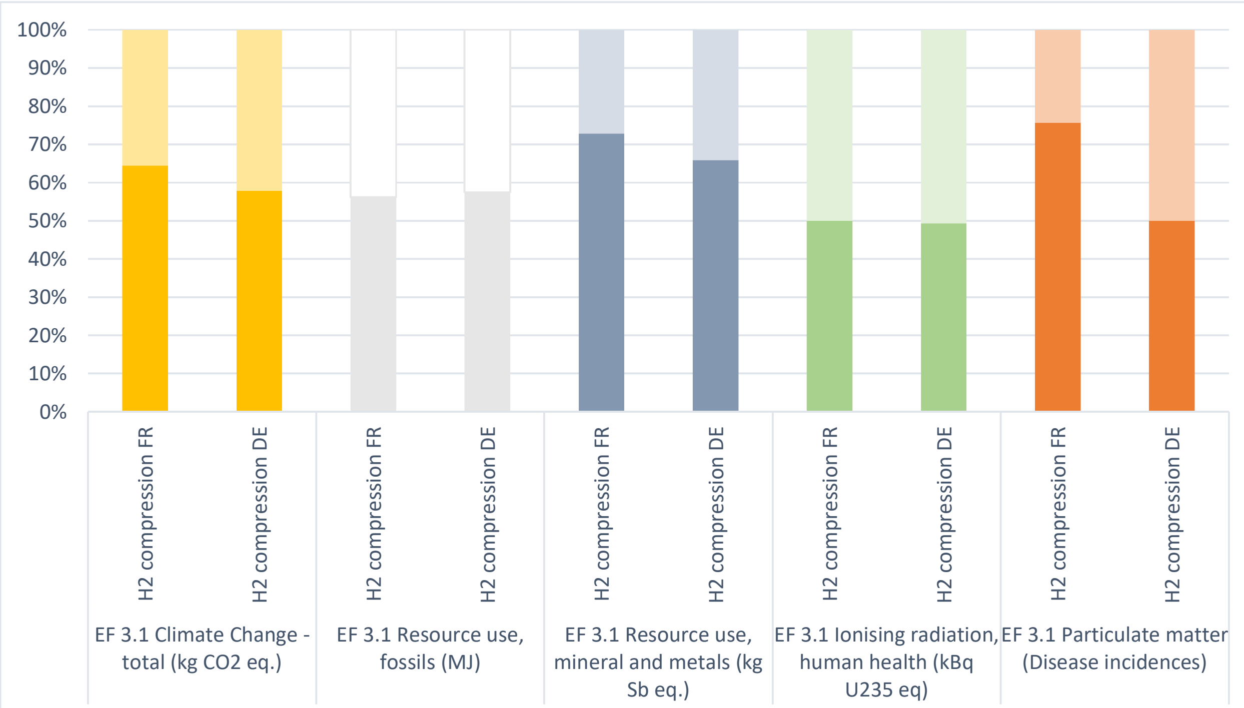


Figure 16: Comparison of environmental impacts depending on the country in which the hydrogen is compressed

Impact Categories	Ratio Type I / Type IV	
	FR H_2 compression	DE H_2 compression
EF 3.1 Climate Change	1.82	1.37
EF 3.1 Resource use, fossils (MJ)	1.28	1.35
EF 3.1 Resource Use. mineral and metals	2.68	1.93
EF 3.1 Ionising radiation	1	0.97
EF 3.1 Particulate matter (Disease incidences)	3.12	2.03

Table 7: Ratio between type I and IV depending of the hydrogen compression country

We could see from *Figure 15* that using a German electrical mix, which is more carbon-intensive than the French mix, significantly increases environmental impacts. Additionally, it reduces the gap between Type I and Type IV. Indeed, by examining *Figure 16* and *Table 7*, it is evident that the difference between Type I and Type IV narrows when the compression stage is performed in Germany. This can be explained by assuming that the energy for hydrogen compression is identical in this study and that the compression phase is significant in the life cycle studied. In summary, compressing hydrogen in Germany increases environmental impacts and "narrows the gap" between Type I and Type IV. Once again, a similar conclusion to what was mentioned for the variation in the carbon fibre production electricity mix can be drawn. The use of decarbonized electricity, and ideally green electricity, significantly reduces the results for various environmental categories.

C. Hydrogen-powered truck for Use phase

The most impactful phase of the life cycle is by far the use phase, corresponding to the daily delivery of hydrogen. Since the delivery is done using diesel-powered trucks, an interesting alternative would be to use trucks powered directly by hydrogen. To model this, it is necessary to know the consumption of a hydrogen-powered truck as well as the impacts associated with hydrogen production. The table below provides the consumption of different trucks in kilograms of hydrogen to cover a distance of 100 km.

Truck Model	Hydrogen Consumption (kg H_2/100km)
NIKOLA TRE FCEV [6]	8.7
HYZON HYMAX 46 T [7]	8.8
Mercedes-Benz GenH2	8

Table 8: Hydrogen consumption for different truck reference

The consumption of trucks is approximately 8 kg of H_2 / 100 km, and a study from “Mobilité France Hydrogène” [8] confirms this, providing a consumption range between 7 and 9 kg of H_2 / 100 km. The reference value taken in this case study will be 8 kg of H_2 / 100 km.

The other parameter to consider is the production of hydrogen. The different hydrogen production processes are not available in the LCA FE database. However, data from the ADEME Carbon Database [9] are accessible and provide the CO2 emissions associated with hydrogen production. Even if environmental impacts for all indicators are not available, this study will provide an initial overview of the evolution of CO_2 emissions based on the energy used to operate the truck and its production.

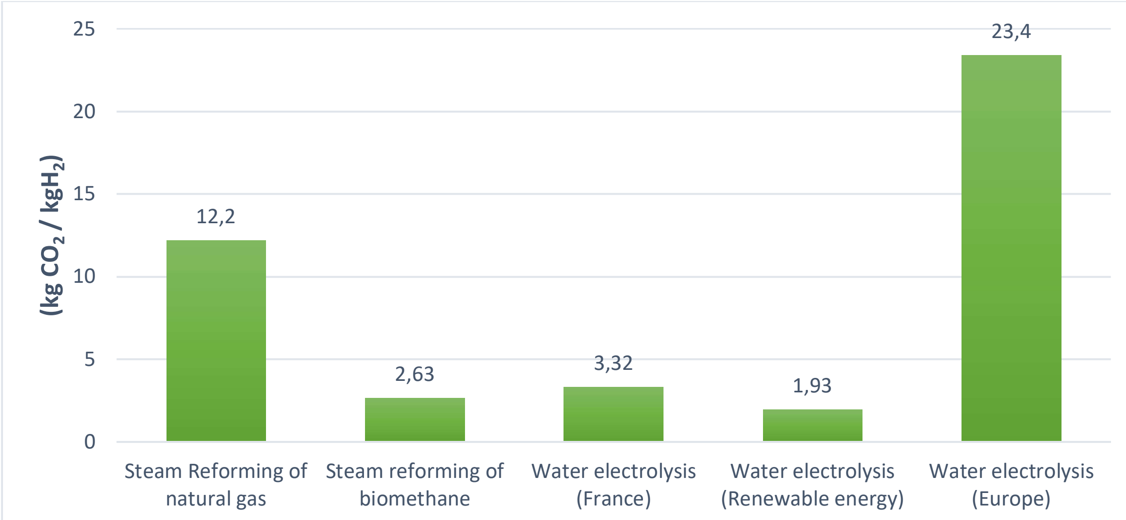


Figure 17: CO2 emissions for the provision of 1 kg of hydrogen at a fuelling station

This chart demonstrates that there is a significant disparity depending on the type of hydrogen production and that the results over the entire life cycle will be strongly influenced by the source of hydrogen production. The modelling of the empty route cannot be simulated as it is done with the diesel truck process, and the round-trip emissions are fully considered. Error bars account for a consumption ranging from 7 to 9 kg of H2 per 100 km.

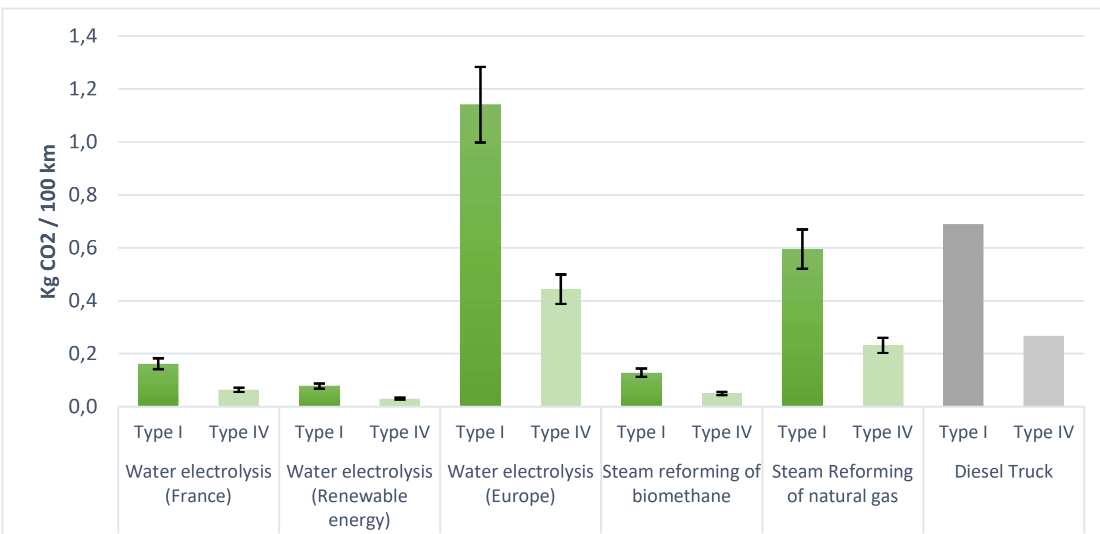


Figure 18: Environmental impact of transporting 1 kg of H2 over a distance of 100 km - Use Phase

Looking at the results over the entire life cycle, the main conclusion that can be drawn is that, for a significant reduction in environmental impacts, the hydrogen production process must have a low carbon intensity. However, the data used should be taken with caution as only a single environmental indicator is considered, and the truck consumption data is not specific to the case study.

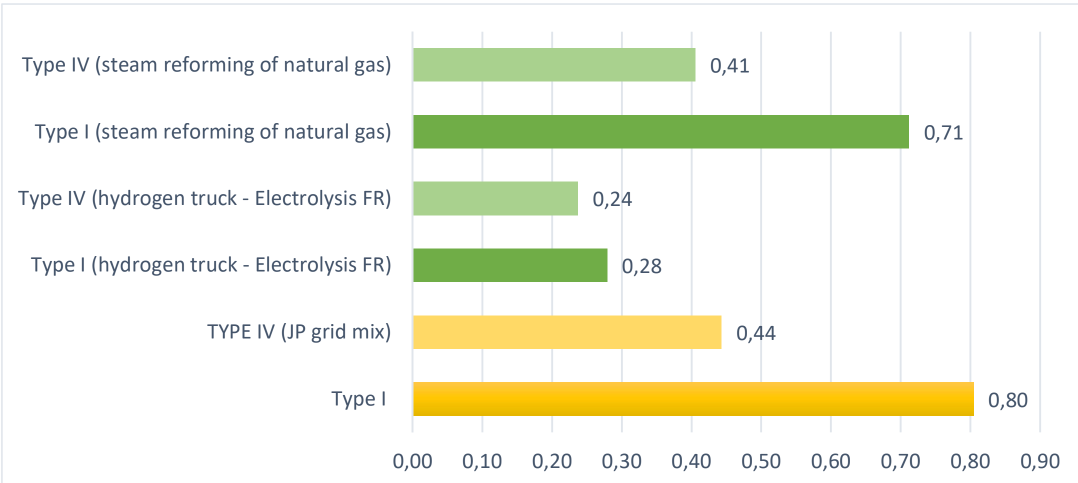


Figure 19: EF 3.1: Climate change - Environmental impact of transporting 1 kg of H2 over a distance of 100 km

VII. Study's conclusion

This intermediate study provides a thorough analysis of the environmental impacts associated with type I and type IV hydrogen trailer. Preliminary results highlight a significant reduction in CO_2 emissions when using type IV trailer, reaching up to 45% in the reference case. However, this reduction varies depending on various parameters, underscoring the importance of a comprehensive contextual assessment to fully understand potential environmental benefits.

Furthermore, the study demonstrates an overall decrease in environmental impacts for most indicators with the use of type IV tanks. This study has shown that the electric mix employed in various stages of the life cycle significantly influences the outcomes, particularly during the manufacturing phases and daily hydrogen compression. Moreover, the use of numerous generic data sets has been employed, and the utilization of specific data could yield more representative results. Additionally, it is worth noting that these conclusions come from an intermediate study, and comprehensive results will be presented in the final report, which will also include a complete analysis of type V tanks.

This report also identifies strategic levers to mitigate environmental impacts. On-site hydrogen production or the reduction of transport distances emerge as promising solutions to minimize environmental impacts since the daily distribution of hydrogen is the primary contributor for the majority of environmental categories. However, in scenarios where these solutions are not applicable, intermodal transport appears to be an interesting avenue. Further research in this regard will be conducted in the final report.

An aspect also explored in this report concerns the use of hydrogen-powered trucks for hydrogen transportation. Initial results appear to indicate improved performances, and this is the case for most hydrogen production methods. However, these findings should be interpreted with caution and require further investigation in subsequent research.

The inclusion of type V in the study will broaden the perspective and provide a more holistic understanding of the environmental performance of hydrogen tanks. Although detailed results for type V are not yet available, it is plausible to assume a downward trend in environmental impacts, given its increased capacity to transport a larger quantity of hydrogen than type IV.

This anticipated approach suggests that type V tanks could offer additional environmental benefits, underscoring the importance of further research to confirm this hypothesis. Considering this study as a starting point, the final report will offer a more comprehensive view, allowing an in-depth evaluation of the environmental performance of different hydrogen tank technologies. These results will significantly contribute to informed decision-maker in choosing hydrogen transport technologies.

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IX. Figure table

X. Annexes

A. Annex 1: Normalization & Weighting

To begin with, here is a definition of normalisation and weighting in an LCA study.

Normalization: Normalization is an impact assessment method that involves expressing the results of various environmental indicators relative to a common reference, allowing for standardized units of measurement. In the EF 3.1 method, the results of different categories are divided by the emissions of a European citizen.

Weighting: Weighting involves multiplying the results of normalization by a weighting factor reflecting the importance of each category. This coefficient ranges from 0 to 1, and the sum of the coefficients equals 1. This step allows decision-makers to prioritize and aggregate environmental impacts according to their significance in a particular context. Weighting enables the transformation of impact scores into a single value. The weighting factors for the EF3.1 method are provided in the following table.

Impact Categories	TYPE I
Total	100 %
EF 3.1 Acidification	6.20%
EF 3.1 Climate Change - total	21.06%
EF 3.1 Ecotoxicity, freshwater - total	1.92%
EF 3.1 Particulate matter	8.96%
EF 3.1 Eutrophication, freshwater	2.80%
EF 3.1 Eutrophication, marine	2.96%
EF 3.1 Eutrophication, terrestrial	3.71%
EF 3.1 Human toxicity, cancer - total	2.13%
EF 3.1 Human toxicity, non-cancer - total	1.84%
EF 3.1 Ionising radiation, human health	5.01%
EF 3.1 Land Use	7.94%
EF 3.1 Ozone depletion	6.31%
EF 3.1 Photochemical ozone formation, human health	4.78%
EF 3.1 Resource use, fossils	8.32%
EF 3.1 Resource use, mineral and metals	7.55%
EF 3.1 Water use	8.51%

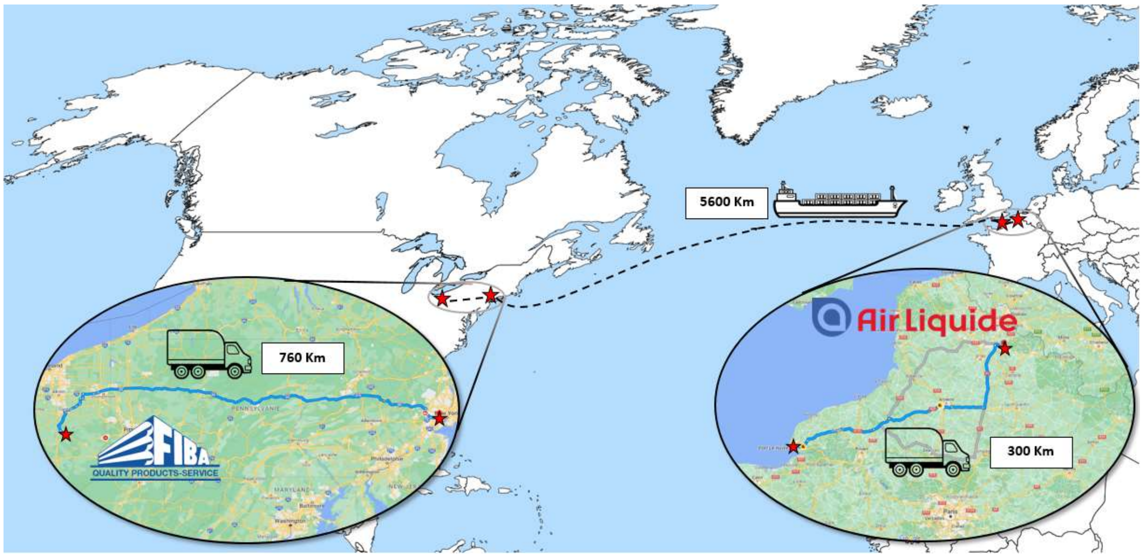
The calculations were performed for Type I and Type IV, and after normalization and weighting, they were divided by the quantity of transported hydrogen for comparability. The values given in the table are therefore not significant; it is only the ratio between different categories that matters.

Impact Categories	TYPE I	TYPE IV	Ratio TYPE I/ TYPE IV	Robustness
Total	1296.10	863.62	1.50	
EF 3.1 Acidification	19.32	11.88	1.63	2
EF 3.1 Climate Change - total	436.59	226.85	1.92	1
EF 3.1 Ecotoxicity, freshwater - total	49.33	22.96	2.15	2 to 3
EF 3.1 Eutrophication, freshwater	1.03	0.52	1.98	2
EF 3.1 Eutrophication, marine	7.42	4.86	1.53	/
EF 3.1 Eutrophication, terrestrial	12.19	7.50	1.63	/
EF 3.1 Human toxicity, cancer - total	4.86	2.96	1.64	2 to 3
EF 3.1 Human toxicity, non-cancer - total	18.67	8.40	2.22	2 to 3
EF 3.1 Ionising radiation, human health	183.26	183.65	1.00	2
EF 3.1 Land Use	9.42	5.03	1.87	3
EF 3.1 Ozone depletion	0.00	0.00	0.87	1
EF 3.1 Particulate matter	40.95	13.37	3.06	1
EF 3.1 Photochemical ozone formation, human health	16.40	10.30	1.59	2
EF 3.1 Resource use, fossils	485.18	357.64	1.36	2
EF 3.1 Resource use, mineral and metals	5.37	2.01	2.67	2
EF 3.1 Water use	6.12	5.68	1.08	3

To limit the amount of information to present, 5 impact categories have been selected. In making this choice, both the categories with the highest scores and the robustness of the calculation methods were taken in account. Category **Climate Change** and **Resource use, fossils** were chosen as they have the highest scores and are at the level 1 of robustness.

The categories **Ionising Radiation** and **Particulate matter** were then selected. While several other categories could have been chosen, Category **Resource Use, mineral and metals** was selected because it demonstrates a significant ratio between Type I and Type IV, and in a life cycle breakdown (not presented here), it is one of the few categories with a balanced distribution of impacts across different life cycle phases.

B. Annex 2: Type I Distribution Phase



C. Annex 3: Paint Mass Calculation

The tube mass correspond to the total mass of the tube, which also includes the layer of paint that covers it. To determine the paint mass, the value of the surface area of the tube was required, but this information was not available. Therefore, the surface area of the tube was calculated as being equal to the surface area of a cylinder with the same dimensions (i.e. a length of 10,465 mm and a diameter of 559 mm) as presented in Figure 3.

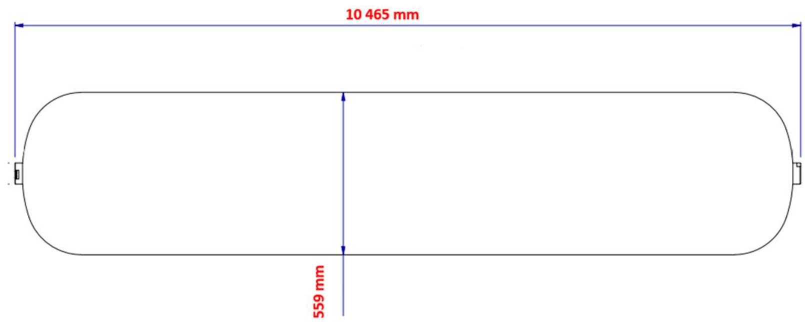


Figure 20: Tube Dimensions

The following formula was then used to calculate the paint thickness:

$$m_{peinture} = \rho_{peinture} * (\pi * L_{réservoir} * [r_{ext}^2 - r_{int}^2] + 2 * \pi * e_{peinture}) = 2.71 \text{ kg}$$

With,

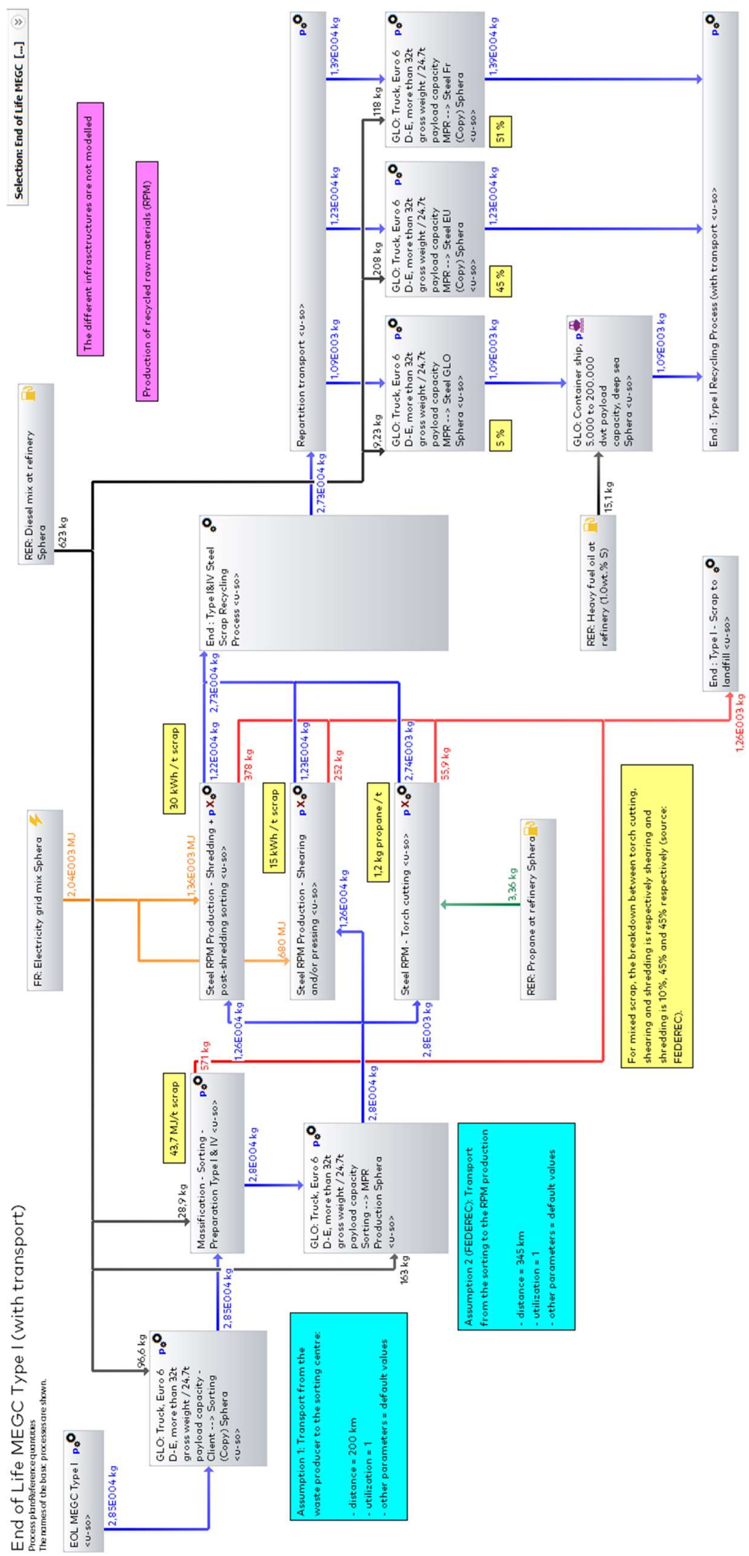
$\rho_{paint} = 1{,}200\ kg/m^3$ (Paint density)
$L_{tube} = 10{,}465\ mm$ (Tube length)
$r_{int} = 279.5\ mm$ (Tube inner radius)
$e_{paint} = 0.00012\ m$ (Paint thickness)
$r_{ext} = r_{int} + e_{peinture}$ (Tube external radius)

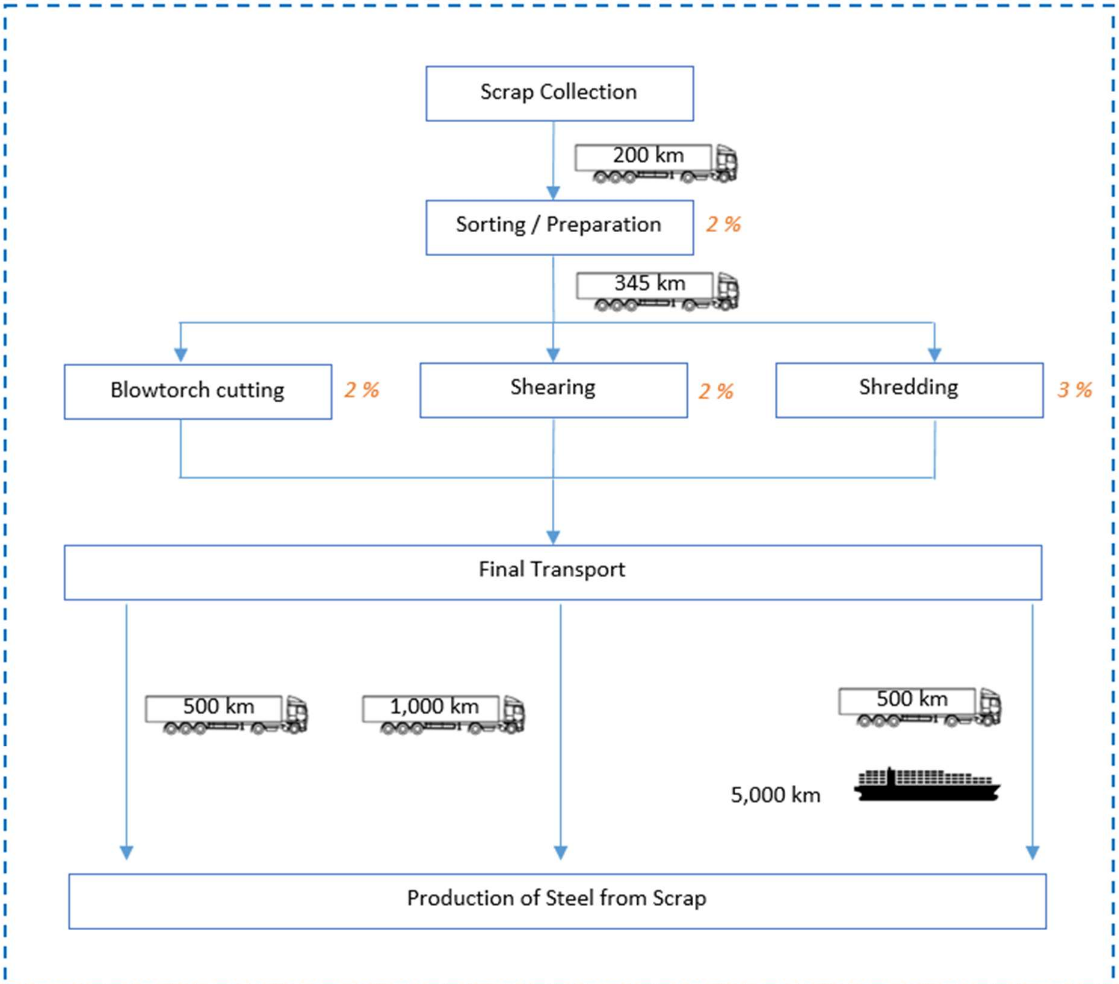
D. Annex 4: Default Parameters Truck-Trailer

Parameters

Parameter	Formula	Value	Minimum	Maximum	Standard deviation	Comment, units, defaults
distance		100			0 %	[km] distance start - end, default = 100 km
payload		27			0 %	[t] default = 27 t
ppm_sulfur		10	0	2E003	0 %	[ppm] sulphur content in diesel, default Europe = 10 ppm
share_check	share_mw + share_ru + share_ur	1				Check - value must be 1
share_CO2_b		0,05	0	1	0 %	[-] share of biogenic C in fuel
share_mw		0,56			0 %	[-] driving share motorway , default = 0,56
share_ru		0,28			0 %	[-] driving share rural , default = 0,28
share_ur		0,16			0 %	[-] driving share urban , default = 0,16

E. Annex 5: End-of-Life Steel scrap



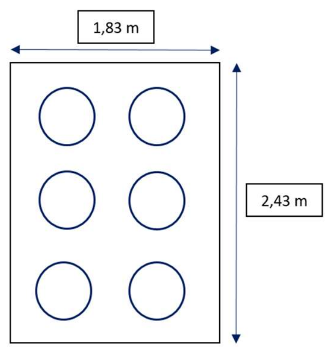

Scrap Collection
200 km
Sorting / Preparation
2 %
345 km
Blowtorch cutting
2 %
Shearing
2 %
Shredding
3 %
Final Transport
500 km
1,000 km
500 km
5,000 km
Production of Steel from Scrap

F. Annex 6: Composite Curing Oven

Composite tube curing involves placing them in an oven at 140°C for 4 hours. To determine the energy used during this step, a technical sheet from a LEWCO brand oven was utilized.

Model (NFPA Class B)	Overall Dimensions "W	"D	"H	Door Swing Radius	Workspace Dimensions "W	"D	"H	Workspace Volume (cubic ft.)	Heater Bank (kW)	Circulating Fan(s) (CFM)	Motor(s) (HP)	Air Changes per Minute	Exhaust Fan Capacity (CFM)	Exhaust Motor (HP)	Solvents per Batch (Gals.)	Ships Fully Assembled
EWR03ED-72-120-96	125	198	108	36"	72	120	96	480	72	20,000	15	41.67	N/A	N/A	0	Yes

According to the dimensions of the oven, it can be assumed that six tubes can be placed simultaneously inside it.



The power of the oven is 72 kW and the maximum temperature is 177 °C. Therefore, only 73% of the heating capacity is required. For a 4-hour run, this would result to an energy consumption of 72*4*0.73 = 211.53 kWh. Reducing this value to one tube gives an energy consumption of 35.25 kWh.

G. Annex 7: Commercial waste (AT, DE, IT, LU, NL, SE, and CH) on landfill.