Master Thesis

# Life cycle assessment of a high-speed vacuum transport system


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## Note on confidentiality

The original version of the thesis partly contains confidential information. These have been removed and marked accordingly in this version for the purpose of sharing the work.

OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG

FACULTY OF PROCESS AND SYSTEMS ENGINEERING

**Task of the Master Thesis for Mr. Paul Beckert, Matr.-No. 236623**

Topic: Life cycle assessment of a high-speed vacuum transport system

Setting of tasks:

Vacuum Transport represents the next evolution in rail-based transport. Also known as Hyperloop, the technology is supposed to be fast, sustainable, comfortable and aims at replacing air transport in a climate-friendly way and is in line with the UN Sustainable Development Goals (SDGs). It is a high-speed and rail-guided transport system in which the vehicles or so-called pods for both passengers and goods travel in a network of vacuum tubes. Depending on geographical conditions, this happens underground or on the Earth's surface. (EuroTube, 2022)

As part of a potential analysis for the integration of vacuum transport systems for public transport in Switzerland, an environmental life cycle assessment (LCA) is performed. This assessment covers the entire life cycle of the vacuum transport system (design, construction, use, end-of-life) and is carried out in cooperation with the Paul Scherrer Institute (PSI).

The following items represent key elements of the LCA and thus the master thesis:

- Literature and norm research on LCA.
- Literature research on high-speed vacuum transport systems.
- Conduct data research on the energy and material flows of the transport system in coordination with EuroTube and the ecoinvent database for secondary data.
- Design of the LCA model with the Brightway2 LCA framework.
- Generation of parameterised data sets/systems.
- Quantification of Life Cycle Impact Assessment (LCIA) results for the vacuum transport system and comparison of those with comparable transport systems (train, aircrafts) from ecoinvent. LCIA will include a range of impact categories, for example on impacts on climate change, land and resource consumption, impacts on human health and ecosystems.
- Sensitivity analysis of the results regarding key parameters identified in the LCIA.

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Signature

Responsible University Reviewer

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And of course, I would also like to thank the rest of the colleagues in the Laboratory for Energy Systems Analysis at PSI, especially the Technology Assessment Group.

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Last but not least, I would like to thank my family who have always believed in me and shaped me into the person I am today.

## Abstract

As part of a master's thesis, the life cycle assessment of an overground high-speed vacuum transport system in Switzerland was carried out. The main focus is on the construction phase and energy consumption of the transport system where four different construction scenarios were compared.

Ecoinvent 3.8 was mainly used for the background system and in addition, the premise database was used, which made it possible to generate prospective models. The Foreground system was modelled with EuroTube's cooperation. As an allocation method, the cut-off system model was used to ensure compatibility with the additional prospective data.

The assessment of different impact methods was carried out using today's Swiss electricity mix and the three other prospective electricity mixes and their predicted compositions for the year 2040. The influence of the electricity mix was further examined in a sensitivity analysis, which means that the results can also be applied to other regions. In addition, the different results were then compared with a conventional train and aircraft (with and without e-kerosene) and a sensitivity analysis of the load was carried out to increase the comparability.

It turned out that electrical energy consumption, for the specific case of Switzerland, does not have the biggest impact, but it can easily turn into the main contributor with a more greenhouse gas intensive electricity mix. In contrast, the tube, or more precisely the aluminium and concrete used for it, showed the greatest impact in all scenarios. It was possible to show that the VT system's ecological impact is comparable to that of a conventional train and that there is therefore a large potential for reducing the environmental impact compared to aircraft.

## Zusammenfassung

Im Rahmen einer Masterarbeit wurde die Lebenszyklusanalyse eines oberirdischen Hochgeschwindigkeits-Vakuumtransportsystems in der Schweiz durchgeführt. Der Hauptfokus liegt auf der Konstruktionsphase und dem Energieverbrauch des Verkehrssystems, wobei vier verschiedene Konstruktionsszenarien verglichen wurden.

Ecoinvent 3.8 wurde hauptsächlich für das Hintergrundsystem verwendet, zusätzlich wurde die premise Datenbank genutzt, die es ermöglichte, prospektive Modelle zu erstellen. Das Vordergrundsystem wurde in Kooperation mit der EuroTube Foundation modelliert. Als Allokationsmethode wurde das cut-off Systemmodel verwendet, um die Kompatibilität mit den zusätzlichen prospektiven Daten zu gewährleisten.

Die Bewertung der verschiedenen Auswirkungsmethoden wurde anhand des heutigen Schweizer Strommixes und der drei weiteren prospektiven Strommixe und deren prognostizierten Zusammensetzungen für das Jahr 2040 durchgeführt. Der Einfluss des Strommixes wurde in einer Sensitivitätsanalyse weiter untersucht, so dass die Ergebnisse auch auf andere Regionen übertragbar sind. Darüber hinaus wurden die verschiedenen Ergebnisse mit einem konventionellen Zug und einem Flugzeug (mit und ohne E-Kerosin) verglichen und eine Sensitivitätsanalyse der Auslastung durchgeführt, um die Vergleichbarkeit zu erhöhen.

Es zeigte sich, dass der elektrische Energieverbrauch im spezifischen Fall der Schweiz nicht den größten Einfluss hat, aber bei einem treibhausgasintensiveren Strommix leicht zum Hauptverursacher werden kann. Der Tube, genauer gesagt das dafür verwendete Aluminium und der Beton, hatte dagegen in allen Szenarien die größten Auswirkungen. Es konnte gezeigt werden, dass die Umweltauswirkungen des VT-Systems mit denen eines konventionellen Zuges vergleichbar sind und dass daher ein großes Potenzial zur Verringerung der Umweltauswirkungen im Vergleich zu Flugzeugen vorhanden ist.

## Affidavit

I hereby confirm that my thesis entitled *Life cycle assessment of a high-speed vacuum transport system* is the result of my own work. I did not receive any help or support from commercial consultants. All sources and / or materials applied are listed and specified in the thesis.

Furthermore, I confirm that this thesis has not yet been submitted as part of another examination process neither in identical nor in similar form.

Villigen, 6th September 2022

Place, Date

Signature

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## List of Acronyms

| | |
|---|---|
| m*a | 1-metre and year |
| ADP | Abiotic depletion potential |
| AR6 | Sixth Assessment Report |
| BR | Blockage ratio |
| CED | Cumulative Energy Demand |
| CFC-11 | Trichlorofluoromethane |
| CFD | Computational fluid dynamics |
| CFRP | Carbon fibre reinforced plastic |
| CH | Switzerland |
| $CO_2$-eq. | Carbon dioxide equivalent |
| $CTU_h$ | Comparative Toxic Unit for humans |
| EDS | Electrodynamic suspension |
| EF | Environmental Footprint |
| eLCAr | Guidelines for the LCA of electric vehicles |
| ENTSO-E | European Network of Transmission System Operators for Electricity |
| ETF | EuroTube Foundation |
| GUI | Graphical User Interface |
| GWP | Global warming potential |
| HTS | High-temperature superconductors |
| HVAC | Heating, ventilation, and air conditioning |
| IAM | Integrated Assessment Models |
| IEA | International Energy Agency |
| ILCD | International Reference Life Cycle Data System |
| IPCC | Intergovernmental Panel on Climate Change |
| LCA | Life cycle assessment |
| LCC | Life cycle costing |
| LCI | Life cycle inventory analysis |
| LCIA | Life cycle impact assessment |
| LIB | Lithium-ion batteries |
| LIM | Linear induction motor |
| Li-NMC | Lithium nickel manganese cobalt oxide |
| $LN_2$ | Liquid nitrogen |
| Maglev | Magnetic levitation |
| MCDA | Multiple-criteria decision analysis |
| MCS | Monte Carlo Simulation |
| MNA | Modified Nodal Analysis |
| ODP | Ozone depletion potential |
| PCM | Phase change material |
| pkm | person-kilometre |
| pLCA | Prospective life cycle assessment |
| PMF | Particulate matter formation |
| PMSM | Permanent Magnet Synchronous Motor |
| RCP | Representative Concentration Pathway |
| SAF | Sustainable aviation fuel |
| Sb | Antimony |
| SFR | Swiss federal railways |
| SFRC | Steel fibre reinforced concrete |
| S-LCA | Social life cycle assessment |
| vkm | vehicle-kilometre |
| VT | Vacuum transport |


Figure 1: Conceptual design of the ETF's vacuum transport system [1]

# 1. Introduction

## 1.1 Motivation

The availability of a high-quality public transport system has become crucial to the high standard of living in developed countries [2]. At the same time, the increase in population and economic growth inevitably lead to higher demand for transport. Emissions from the transport sector accounted for over 27 % of global $CO_2$ emissions in 2019 [3] and continue to rise rapidly, mainly due to the rapid growth of air travel. For this reason, there is an urgent need for more sustainable transport infrastructures to reduce emissions and achieve global climate goals.

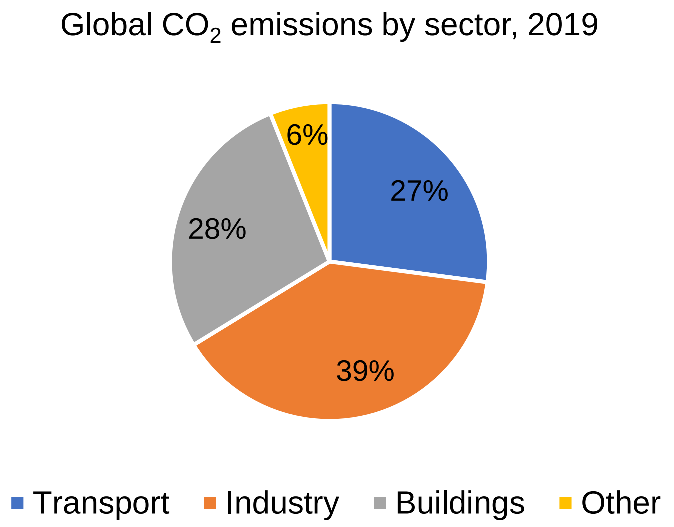


Figure 2: Relative global $CO_2$ emissions by sector in 2019 according to the International Energy Agency (IEA); total emissions: 31.4 Gt.

Figure 3: Traffic jams, which are becoming more and more frequent globally and waste energy and resources [4].

Transport by railway is often portrayed as the best mode of land transport and, depending on the electricity mix and passenger volumes, it can carry goods and passengers with the smallest environmental footprint [5] [6]. However, railways suffer from tight constraints on capacity, and expanding their throughput or introducing high-speed services often requires the construction of new lines [7], which have significant landscape and environmental impacts [8]. Furthermore, for conventional high-speed trains, most of the energy consumed is due to aerodynamic drag[1], which increases with the square of the train speed (see Figure 4).

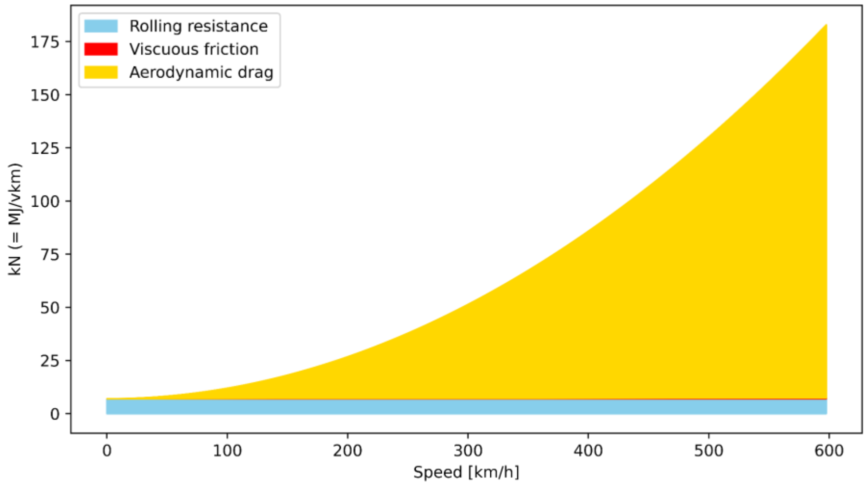


Figure 4: Analysis of the resistance forces affecting a train at constant speed. Based on TGV measurements [9]; vkm = vehicle-kilometre.

Airports are already reaching their saturation point in terms of volume [10] [11] with a very high footprint at the same time [5] [6]. Sustainable aviation fuels (SAF) are not a sufficient solution either, as biogenic fuels compete with other sectors due to the biomass required [12] and synthetic fuels require extremely high amounts of energy, which also makes them economically questionable [13]. Lastly, non-$CO_2$ climate forcers associated with aviation (primarily contrails) would not necessarily be mitigated by SAF [14].

One solution to meet the human need for mobility [15] without causing significant environmental impact at high speeds could be *vacuum transport* (VT) as a sustainable mobility alternative. VT systems carry passengers and/or cargo above or below ground through low-pressure tubes, achieving greater efficiency through reduced friction and drag. This opens up the potential for VT to provide high-speed transport with lower energy consumption.

[1] $F_D = \frac{1}{2}\,\rho\, v^2 c_d A$

To achieve the climate neutrality decided upon in the transport sector [16], various far-reaching measures need to be implemented quickly. To achieve these measures, an analysis must be undertaken in order to determine for which scenarios of transportation systems it makes sense. A *life cycle assessment (LCA)* can be of great importance in the decision-making process. Therefore, within the framework of this thesis, a comprehensive LCA of VT transport systems for Switzerland is to be compiled in order to examine its suitability as a means of transport.

## 1.2 Goal of the thesis

In this thesis, a holistic LCA of a VT system is to be conducted, which does not yet exist in the literature. This assessment covers the entire life cycle of the VT system (design, construction, use, end-of-life). This should apply specifically to the case of the *EuroTube Foundation*[2] (ETF) in Switzerland but can also be applied to a certain extent to other geographical regions.

The following items represent key elements of the work:

- Literature and norm research on LCA.
- Literature research on high-speed VT systems.
- Generation of four different VT system designs in Brightway.
- Generation of one current and three prospective scenarios for all VT systems.
- Quantification of life cycle impact assessment results for VT which include a range of impact categories, for example impacts on climate change, land, and resource consumption, impacts on human health and ecosystems.
- Comparison of VT results with train and aircraft (using conventional and synthetic kerosene).
- Identification of particularly promising VT system designs.
- Sensitivity analysis of the results regarding key parameters identified in the impact assessments.

[2] For more information on ETF see: https://eurotube.org/

## 1.3 Overarching research project (BAV ESöV)

As part of the *Energy strategy for Public Transport 2050*[3] (ESPT 2050) programme of the *Federal Office of Transport* (FOT) of Switzerland, ETF has been tasked with carrying out a potential analysis of VT technologies in the public transport infrastructure of Switzerland as their mission is to build the first test track in Europe [1]. The project includes two phases: firstly, a full LCA of the VT technology with focus on energy consumption and environmental impact and secondly, a techno-economical assessment of two use cases based on a Swiss and a European VT route.

This master thesis is part of work package 6 of the first phase and it aims to aid the compilation of the life cycle inventory and to carry out the final LCA of the VT technology.

## 1.4 Literature review

This chapter aims to provide an overview of which studies have been found on the topic and on which study or set of data, this LCA is built or related. It should be noted that there are just a few studies on energy consumption of the VT system but no comprehensive LCA on the VT system in the literature so far, which is why this literature review is extended to the key items that turned out to be significant in the LCA. In chapter 2. Concept of vacuum transport systems, the general concept of the VT system is examined in more detail and also backed up with current literature. Many authors use the term *Hyperloop*, which has the same meaning as VT system.

**Vacuum Transport Systems**

The number of published papers on the topic of VT has risen considerably in recent years [17] [18]. There are also more precise energy and $CO_2$ emissions analyses, but no holistic LCAs to date.

In a multiple-criteria decision analysis (MCDA) from Janić [19], high-speed trains, Transrapid Maglev (magnetic levitation) and VT systems for passengers between Moscow and St. Petersburg were examined with the result that VT achieves the best ecological and economic results.

A further analysis in terms of energy and emissions was carried out by Hirde et al. [20] who examined the possible routes Mumbai-Pune, Dubai-Abu Dhabi and Chicago-

[3] For more information on ESPT 2050 see: https://www.bav.admin.ch/bav/en/home/general-topics/research-and-innovation/research-and-innovation-programmes/energie-2050.html

Pittsburgh and concluded that the Hyperloop's energy consumption per passenger kilometre for the Indian route is 40 % more efficient than that of an aircraft, but three times more energy-intensive than the E5 Bullet Train and the Transrapid Maglev. Furthermore, there is an analysis by Janić [21] of the direct emissions and energy consumption of high-speed train, Maglev train, hyperloop and aircraft for passenger transport. There it was shown that Maglev and Hyperloop can achieve the most promising results under certain circumstances such as, higher distance and capacity, but it is also pointed out that the scope needs to be extended to an LCA for more robust results.

**Prospective LCA**

The number of published prospective LCAs (pLCA) has increased significantly recently [22], especially to assess emerging technologies [23] [13] [24]. Many approaches are used, such as the generation of structured scenarios in the LCA models [25], the use of statistical time-resolved data [26] or research into market-related impacts through consequential LCA [27]. Meanwhile, tools such as premise have been introduced to facilitate the generation of prospective inventories for pLCA through the integration of scenarios created by Integrated Assessment Models [28]. The superstructure approach represents a further progress in the generation of pLCAs [29], solving the problem of generating many scenario inventories and significantly simplifying the linking of multiple foreground and background systems.

**Battery**

Meanwhile, there is a larger amount of LCAs for batteries. Here, however, the uncertainties are particularly high, as there are many factors that influence the result. For example, consideration needs to be given to the material used for the manufacturing of the battery, the location (and thus the electricity mix) and how the EOL approach was chosen is also of great importance. One study [30] has shown that the emissions of the entire life cycle of Lithium-ion batteries (LIB) are in the range of 38–356 kg $CO_2$-eq./kWh (Carbon dioxide equivalent). The reason for these huge differences in results is the assessment of different chemical processes and technologies, the use of data from different production scales and the use of different approaches and assumptions to the modelling of the entire life cycle of LIB [30].

Until recently, the ecoinvent database had only one LIB (with a lithium manganese oxide cathode), which originated from the research of Notter et al. [31] and was used in numerous LCAs. Further cathode materials were finally provided by Dai et al. [32] and were adapted to ecoinvent by Crenna et al. [33].

## 2. Concept of vacuum transport systems

### 2.1 History

The first references to the vacuum transportation concept date back to the 17th century when the French physicist Denis Papin envisioned the delivery of mail through compressed air tubes. These ideas were later realised with the engineering of the so-called London Pneumatic Dispatch Company from the United Kingdom, unveiled in 1868 (see Figure 5) [34]. During the same period, Alfred E. Beach in New York invented a somewhat similar system which was the first concept for suburban mobility (see Figure 6) [35].

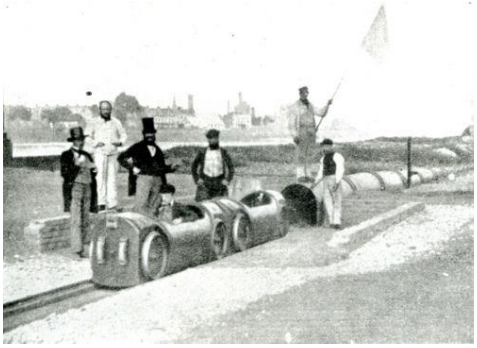

Figure 5:Test track of the London Pneumatic Dispatch Company [36].

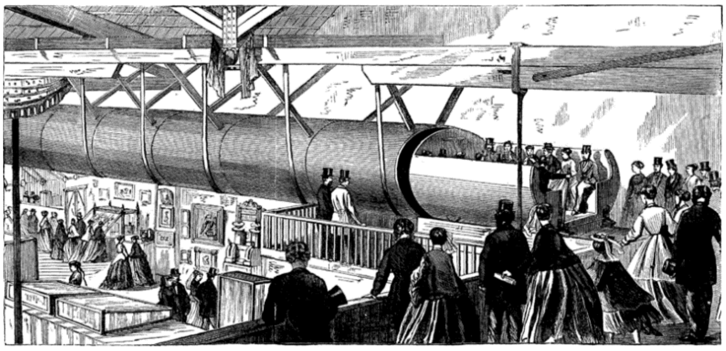

Figure 6: Alfred Ely Beach's American Institute Fair Exhibit in 1867 [35].

The Hyperloop concept was (re-)introduced by Elon Musk in 2013 [37] as a new magnetically levitated, super-fast train travelling under low pressure in a tube using magnetic levitation technology. There are currently several technological developments based on this concept [38] in America [39], Europe [40] and Asia [41] as well various research programs [42] [43]. The VT concept may have some similarities with the high-speed trains developed in the 20th century, such as the Maglev trains [44], which, however, do not use a tube under near-vacuum.

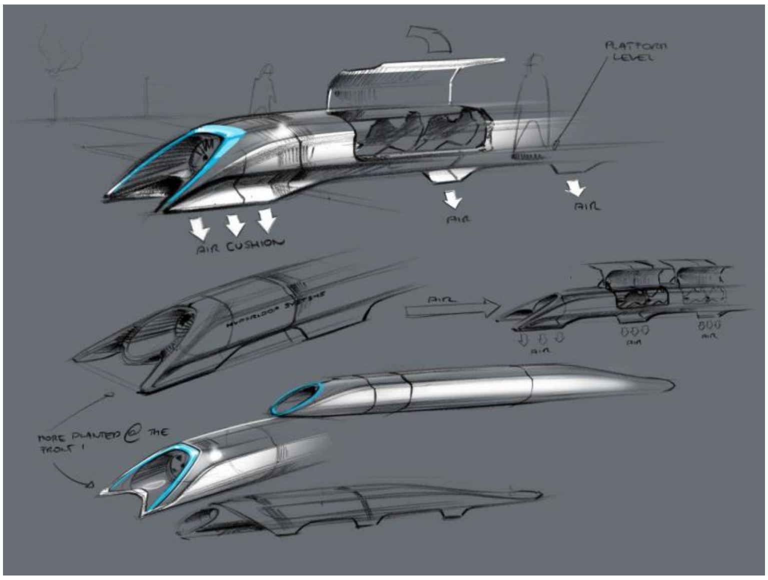


Figure 7: Conceptual design of the Hyperloop Alpha [37].

Today, the goal of this technology is for it to be used in freight and passenger transport to connect routes of 1,000 km with velocities up to 1,200 km/h [18].

## 2.2 Technical background

### 2.2.1 Explanation of vacuum transport

Figure 8 illustrates an overlook of the various parts of a VT system from a more functional perspective and outlines the key elements that are included in any VT system, regardless of the specific technical design. However, this explanation mainly refers to the conceptual design of the ETF [45].

There are three subsystems that affect the management of the overall system, which are described in the following pages.

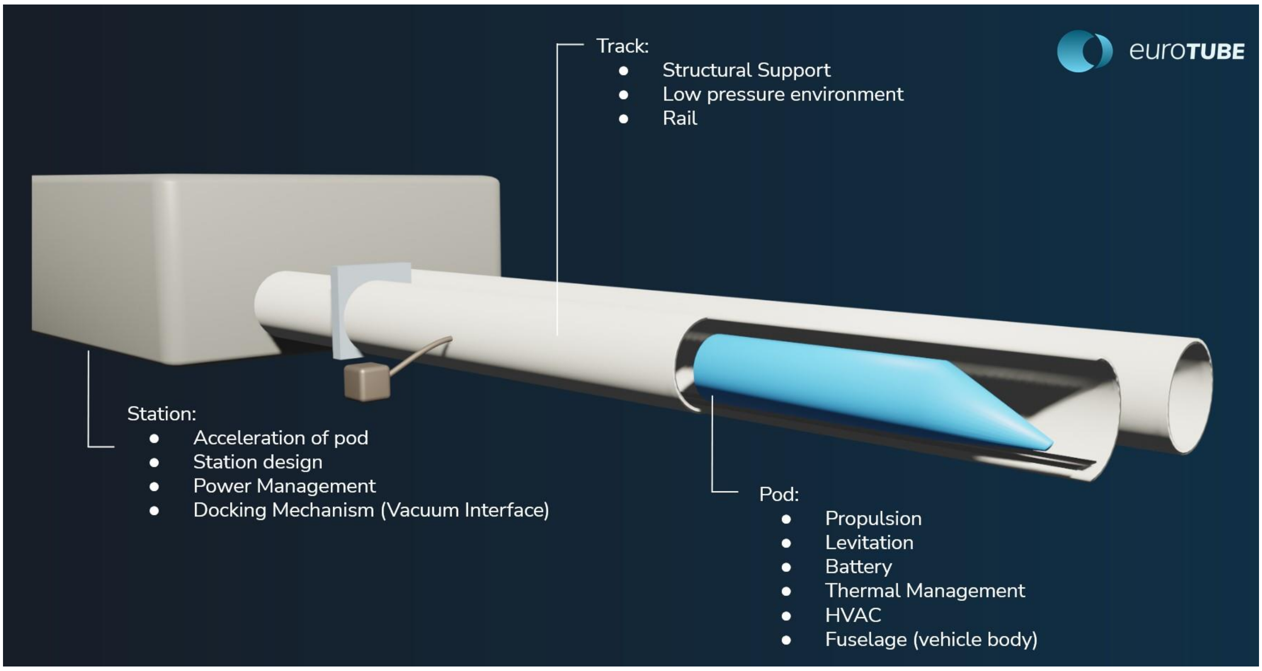

Figure 8: Significant subsystems with the corresponding components that are included in a VT system [45].

**Pod**

To be able to reach the high travelling speed, a mechanism is needed to accelerate the vehicle, which is called *pod* here, to its maximum speed in a short time. When the top speed is reached, propulsion of the vehicle is still required because the drag forces such as air resistance that slow down the pod are still existent, even if they are much lower under near-vacuum conditions. Unlike the train, there is no direct contact with the rails and the vehicle therefore floats, which allows a much higher speed and almost no wear and tear of the track. The environmental exposure is, after all, more similar to that of a spacecraft than to that of an aircraft or a train. Hence, a cooling system must be included for different heat sources. In addition, an HVAC (Heating, Ventilation and Air Conditioning) system is required to guarantee the comfort and safety of the passengers.

**Track/Tube[4]**

As the VT system is supposed to achieve its high travelling speed through lower air resistance than conventional trains, the pod travels in a tube in which there is low pressure. The main function is provided by the tube itself, which is either above ground, supported by pillars as in a viaduct, or underground as in a tunnel. The pod levitates and hovers over the rail in the tube. The low-pressure environment is often referred to as *vacuum*, even if there is residual pressure (typically between 1 and 100 mbar,

[4] The terms track and tube can be used interchangeably in this work.

depending on the design). This pressure level can first be achieved by a primary pump-down procedure and then maintained by an insulating material in or around the tube and additional vacuum pumping down to offset remaining leakages. The ETF focuses on an approach with modular concrete tubes and low pressures (1–10 mbar) in order not to require a compressor on the pod.

**Station**

Stations have different functions. They serve to allow passengers to board the pods, but unlike trains, they must also serve as an interface between the atmospheric environment where passengers wait to board the vehicles and the vacuum tubes where the pods travel at high speed. Depending on the propulsion strategy (track-side or pod-side), the stations can have the function of refuelling or recharging the pods. In particular, a combination is possible in which the pods bring their own energy for the journey but are first accelerated by the track (as with aircraft carriers). The stations will also act as refuelling stations for heat removal systems and HVAC (e.g., oxygen).

**Traffic Management and Safety**

The VT system must be capable of operating in a complete network, rather than node-to-node, and therefore a switch design is required that is different for levitated pods than for conventional trains. A bypass and venting system must also be provided to allow access into and out of the tube in the event of traffic disruptions and emergencies. Access for maintenance must also be provided.

### 2.2.2 Concept of the ETF

For each of the mentioned functionalities of a VT system, there are different approaches and technical solutions (see Table 1) that are being researched [18]. As reported on the following pages, the model is able to compare important design decisions such as different levitation systems.

Table 1: Technological concepts of a VT system, options modelled in the ETF design are marked in bold. If no option is marked, the choice has no direct impact on the outcome of the model. [45]

| VT Subsystem | Functionality | Options |
|---|---|---|
| Pod | Propulsion at cruise | **Pod-side (various motor types)** |
| | | Track-side |
| | Levitation | Various Technologies |
| | | Top or **bottom** |
| | HVAC | **$CO_2$ removal** |
| | | Carry-on breathing air |
| | | Filtering of air in tube |
| | Thermal Management | **Phase-change material (e.g., ice-water)** |
| | | Salt-based thermal batteries |
| | | Heating of fuselage + cooling |
| | Fuselage | Various materials investigated by vehicle companies |
| | Onboard battery | **Li-Ion** |
| | | Solid state |
| | | Hydrogen fuel cell |
| | Compressor | yes/**no** |
| | Lateral stability / Turning | **attractive**/repulsive |
| Tube | Structural part | **Concrete** |
| | | Steel |
| | Vacuum assurance | **Concrete + Liner** |
| | | Steel |
| | Rail | Depending on levitation technology |
| | Vacuum Generation | Pumping |
| Station | Low pressure interface | Boarding in Vacuum |
| | | **Airlock (Valve)** |
| | Acceleration of pod | **Track-side acceleration** |
| | | Pod-side acceleration |
| | Electrical battery charging | **Swapping at station** |
| | | Charging at station |
| | Thermal battery charging | Swapping at station |
| | | Charging at station |
| | Recuperator (device for recovery of kinetic energy) | **yes**/no |
| Traffic Management & Safety | Switches | Levitation dependent |
| | Station handling | High and low speed lines, on and off ramps |

The overview should suffice here and the LCI in chapter 5 will go into more detail about the individual components.

## 2.2.3 Propulsion and levitation

In order to better understand the system of the VT, the linear induction motor (LIM) used, propulsion and levitation are briefly explained in this chapter.

### Linear induction motor

In the high-speed range of a VT system, the use of catenary and pantograph systems is not feasible due to the mechanical and electrical limitations, which is why the use of LIMs for traction is preferred as an alternative [46].

The LIM can be understood as a rotary motor that has been cut and unrolled (see Figure 9) to produce a linear motion instead of a rotary motion. It consists of two parts, the primary stator, which creates a travelling magnetic field, and the passive secondary rotor (i.e., an aluminium block), in which eddy currents are induced according to Lenz's law (see Figure 10). The conducting block never manages to catch up with the linearly moving magnetic field, so it constantly creating a net force in one direction.

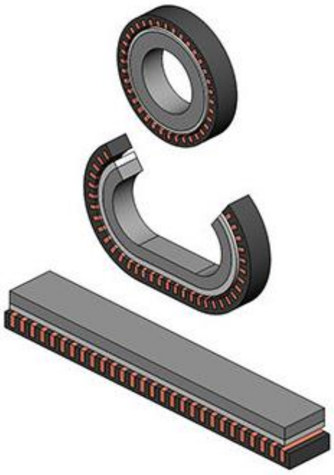

Figure 9: General illustration of a LIM using the example of a rotary motor [47]. The rotor here, when unrolled, is the reaction plate on top.

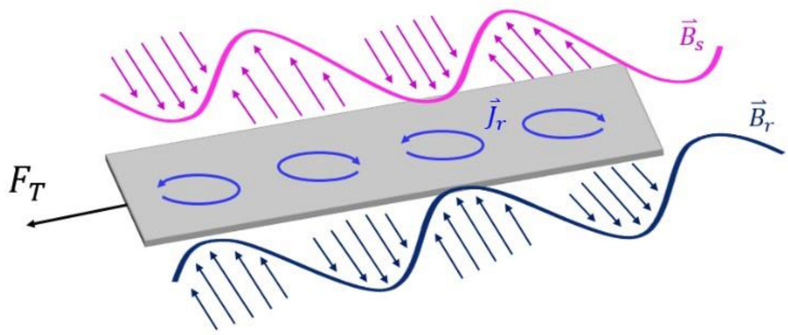


Figure 10: The travelling stator magnetic field (pink) induces eddy currents (light blue) in the rotor, which create an equal and opposite rotor field (dark blue) [48].

Either the stator or rotor can be stationary while the other moves. There are various types of LIM that are capable of propelling the pod without contact to the track, which do not need to be discussed further here for this LCA.

### Electromagnetic propulsion

In terms of the design of the propulsion system, there is the possibility that the track actively propels the pod and therefore has to be equipped with a motor for the entire distance, or whether the maintenance of the cruising speed is ensured by an on-board motor. The ETF has chosen an active track for the acceleration phase due to the high energy requirements and a passive track along the cruise in order to reduce costs and environmental impact as well as to simplify the construction process; the pod is therefore equipped with a motor to propel itself during cruise.
However, for this LCA both LIMs are modelled: in the launching section the active stator is on the track and the rotor is a fin installed on the pod; during cruise the active stator is on the pod and the track is equipped with the rotor-like fin (see Figure 11).

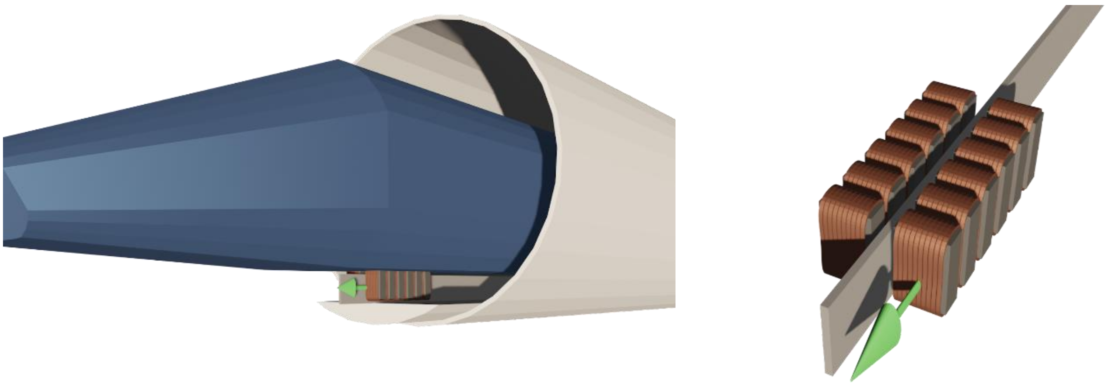

Figure 11: Schematic illustration of the pod with LIM below (left) and a more detailed view of the placement of the fin and LIM (right) [45].

### Electromagnetic levitation

There are various types of levitation systems that can be considered. One well-known concept is the SC Maglev in Japan [44], which, unlike the ETF design, requires an active track. Figure 12 shows an overview of the electromagnetic levitation technologies that provide a passive track, i.e., they are neither electric nor can exert a force independently. Due to the scope, only the design of the ETF will be focused on.

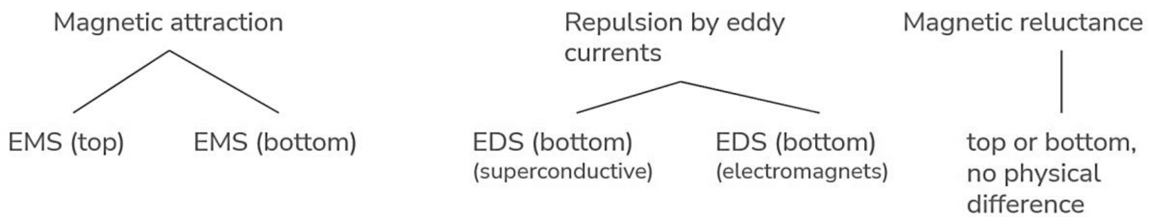


Figure 12: Technological solutions for magnetic levitation systems using a passive track [45].

The ETF follows the principle of *electrodynamic suspension (EDS)* using *high-temperature superconductors (HTS)*. The pod is equipped with magnets that glide over a conductive and not primarily magnetic rail on the track-side. When the rail is undergoing a change in the magnetic field due to the passing pod, eddy currents are generated that counteract this change and thus create a field that is opposite to that of the pod, causing the vehicle to be repelled and levitate. The advantages of this technique are that, firstly, the system is intrinsically stable, i.e., the force acting on the pod when it is pushed out of equilibrium height counteracts the change, and secondly, the track can be built on the bottom of the tube, allowing for a cheaper and simpler construction, while at the same time allowing for a completely passive switching system.

In Figure 13 and Figure 14 the bottom of a pod with the levitation system is shown. In Figure 13, the pod is moving at high speed and the HTS coils submerged in liquid nitrogen ($LN_2$) create a strong magnetic field (red) in the conductive track, which in turn creates an opposing magnetic field (orange) to counteract the change in magnetic flux density caused by the moving pod.

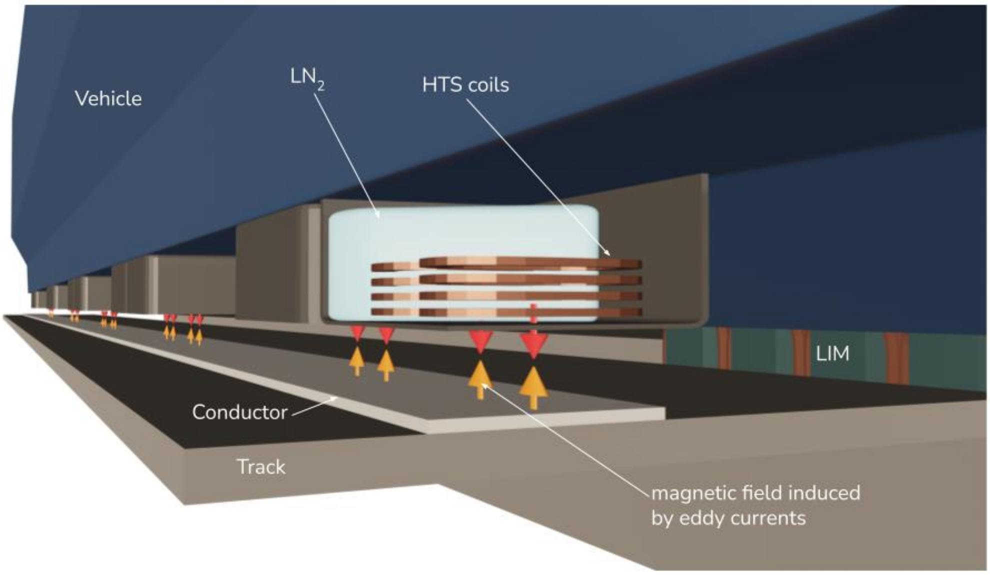


Figure 13: Possible configuration of the levitation system moving at high speeds (above the levitation threshold) [45].

When the pod decelerates below the threshold speed (about 30 km/h), the lift generated is no longer sufficient to counteract gravity. As a result, landing wheels, such as those shown in Figure 14, are needed.

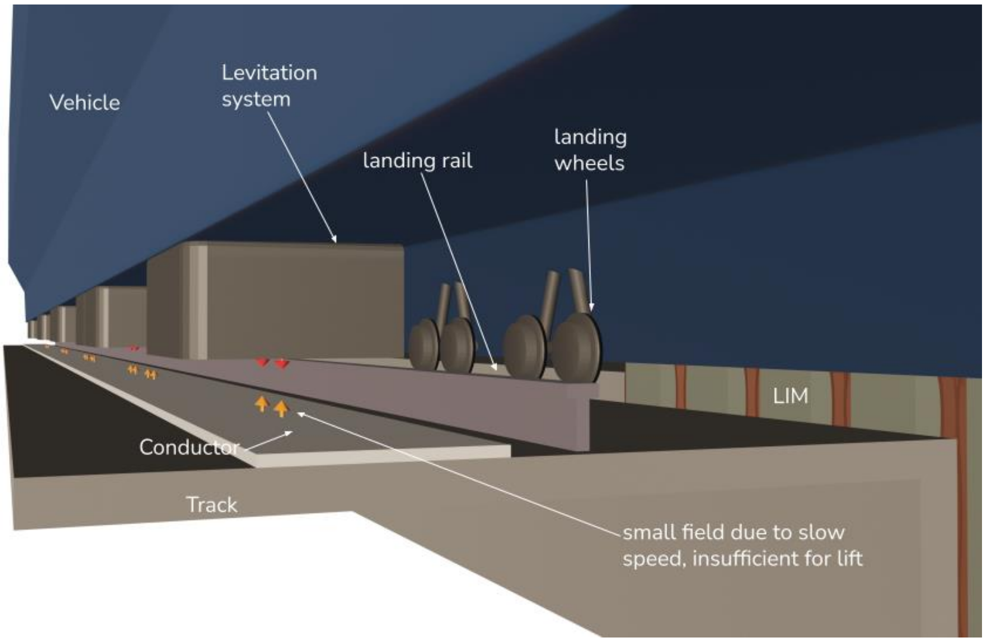


Figure 14: Possible configuration of the levitation system at slow speeds with landing wheels [45].

## 3. Method of life cycle assessment

LCA originated as early as the 1960s, when environmental burdens and especially access to resources became a concern. However, it only gained greater interest in the 1990s, especially when it became apparent that this method was the perfect tool for tackling the waste management problem occurring at the time [49]. It was methodically improved and since the beginning of this century LCAs are based on ISO 14040:2006 and ISO14044:2006 standards.

To give the user more precise instructions and to ensure comparability with other LCAs, there are guidelines that will help to do so. The European Commission published the *International Reference Life Cycle Data System (ILCD) Handbook* in 2010 and the *Guidelines for the LCA of electric vehicles (eLCAr)* in 2013. This study follows all the guidelines mentioned above.

This chapter is also intended as an introduction to the methods of LCA.

An LCA is divided into four phases (Figure 15). In the first phase, the *Goal and scope definition* of the investigation are defined, and various basic definitions are made with regards to the form and content of further work. The second phase, the so-called *Life cycle inventory analysis (LCI)*, is used to determine all mass and energy flows of the so-called product system. In the third phase, the *Life cycle impact assessment (LCIA)*, environmental effects are allocated to the identified mass and energy flows are quantified. The fourth and final phase, the *Interpretation*, involves the results to be reviewed and organized into an understandable presentation for the recipient of the investigation [50].

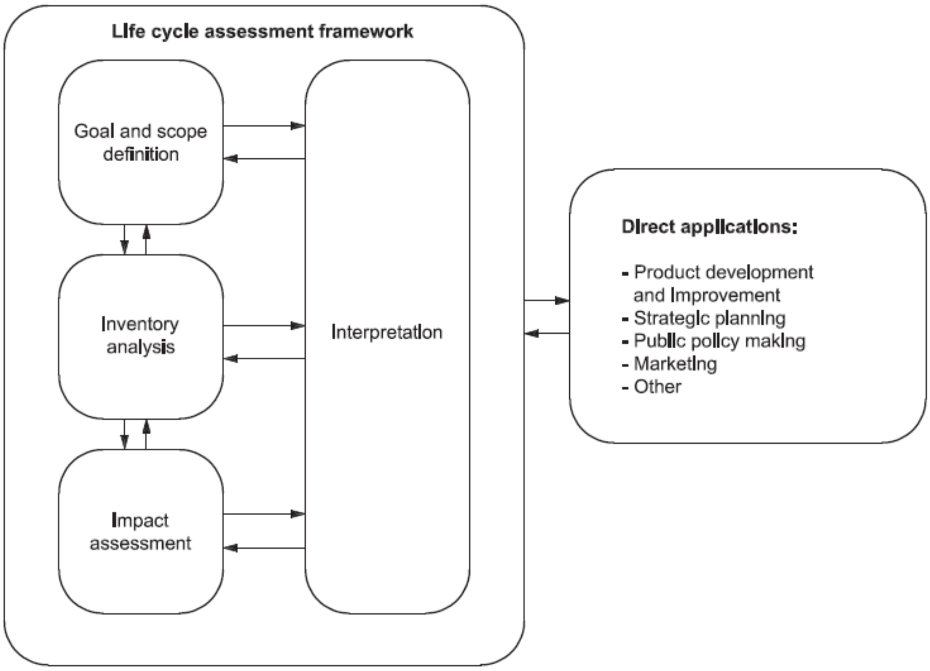


Figure 15: Phases of an LCA [51].

LCAs can be divided into two distinct studies, *comparative,* and *non-comparative*. In the first case, the question relates to the identification of the processes with maximum environmental impact in the life cycle of a product. In the second case, it is about a comparison of different products to each other or to products with similar services [52].

## 3.1 Goal and scope definition

Having a clear definition of the goal and scope of the assessment comprises a clear plan of the working time of an LCA and considers the requirement for transparency. Clear information on the goal, the expected application of the study and the addressee of the results (e.g., company or association) are essential requirements for ensuring that the procedure can be assessed appropriately by external experts, that the interests of the client are disclosed and that the comprehensibility of the LCA is guaranteed. At the same time, this information forms the basis for defining the physical and temporal system boundaries and the delimitation of the product system. On this basis, the various elements included in this LCA step will be discussed below [50].

## 3.2 Life cycle inventory analysis

The aim of the LCI analysis is to identify all mass and energy flows that go from the *ecosphere* into the *technosphere* as defined by the scope and is then released back into the ecosphere. To this end, an understanding of this technosphere must first be achieved, i.e., the individual processes within the system and their connection via intermediates or even waste must be identified and described [51] [53]. Subsequently, the necessary data and information on processes and material flows must be collected. This is generally the most complex and time-consuming step of an LCA. Based on the data obtained, the necessary calculations of the entire material flow from the environment into the system and vice versa can then be carried out [50].

**Cut-off criteria**

In a complex product system, it is usually not possible to track all mass and energy flows. This is also not necessary for the completion of an LCA. However, the system must have a clear and complete description in the sense that all relevant information and the data required for the assessment must be available and complete [52].

**Data gaps**

Data gaps can arise during data research, some examples include: it may not be possible to determine data on relevant material flows, no knowledge may be available, or the measured data may not be accessible. This can represent a substantial problem in the results of an LCA and must therefore be clearly indicated [52].

**Multi-product processes**

A methodological problem occurs in so-called multi-product processes. These are technical plants or processes that generate more than one product. Typical examples of these are chemical processes that produce a main product as well as by-products, examples of these are combined heat and power plants that supply electricity and heat, or the reprocessing of ores from which several metals are extracted. For the calculation of the product system, it is necessary to comprise the input and output flows of each process in exactly one reference flow. To make this possible for multi-product processes, input and output flows must be allocated proportionally to the products involved. This approach is called *allocation* [50].

Such allocations can be carried out in different ways. The preference is determined by the underlying physical relationship between the products [52]. In practice, this means that the inputs and outputs of the process are sorted in proportion to the masses or the energy contents of the products. If this is not possible, the inputs between the products and functions should be mapped in such a way that they reflect other relationships between them [51].  Such a relationship would be possible if the economic value of the products or services is considered frequently, a procedure that is also common in operational cost accounting when allocating costs to co-products [53].

The result of an LCI may depend on the allocation approach chosen. Accordingly, the different approaches have been and will be discussed extensively. This is another reason why the standards recommend avoiding allocation as far as possible [51] [52].

**Software and database**

Extensive information and a large amount of data is required to carry out an LCI and an LCIA, the collection of which usually accounts for a large proportion of the total research effort. The calculation of the LCI and the LCIA can be carried out with the use of spreadsheet programs. However, this quickly becomes unwieldy due to large balance sheets. More convenient is therefore the use of specific software for LCA, which makes the calculation of the LCI easier and clearer, enables the integration of databases, and has integrated different methods of LCIAs [50].

There is now a wider range of LCA software and databases available. Differences can occur, especially with different databases. This should be considered when comparing to other LCAs. Widely used software programs include: GaBi, SimaPro, openLCA and Umberto. Ecoinvent and the GaBi database are often used as databases [54].

*Brightway*[5] (version 2.4.2) is an open-source framework for LCA modelling in Python and is used for this study. The mix of a modular design, the expressiveness and interactivity of Python and especially Jupyter notebooks, and coordinated calculation paths enables new research directions in LCA [55], including fast dynamic LCA with user-defined convolution functions, regionalized LCA, linking parameterized LCA with building energy models, screening and global sensitivity tests with large LCA databases, and the integration of LCA into manufacturing process models [56].

Building on this is the *Activity Browser*[6] (version 2.6.9), also an open-source software for advanced LCA, which is also used for this study. This software provides a Graphical User Interface (GUI) for brightway and therefore serves as a productivity tool for example, for sensitivity analyses, parametric LCAs or scenario LCAs [29].

[5] For more information about brightway see: https://2.docs.brightway.dev/intro.html
[6] For more information about AB see: https://github.com/LCA-ActivityBrowser/activity-browser

With the use of *ecoinvent*[7] (version 3.8) as the main database, an extensive data collection is available. It is a comprehensive and transparent LCI database with around 19,000 inventories in many sectors like energy, agriculture, transport, biofuels, and biomaterials, as well as specific chemicals, building materials, wood, and recycling from around the world [57].

However, even ecoinvent reaches its limits for pLCAs like this, which is why the *premise*[8] database is additionally used here. Premise allows the LCIs contained in the ecoinvent database to be matched with the results of Integrated Assessment Models (IAM) such as REMIND [58] or IMAGE [59] to create LCI databases under future policy scenarios for each year between 2005 and 2100 [28]. In addition to the global IAM scenarios, there are specific projections for Switzerland [60] according to its *Energy Perspective 2050+* [61], which have been coupled together.

## 3.3 Life cycle impact assessment

The phase of the LCIA is a fundamental requirement for the completion of an LCA, beyond the quantitative recording of material flows, it also plays a part in recording their effects on the environment. The aim is to enable a comprehensive assessment of all environmental impacts and to make different effects on the environment comparable. However, such comparability can only be achieved by including assessment steps [50]. Therefore, this phase of LCIA consists of both mandatory and optional elements (see Figure 16).

[7] For more information about ecoinvent see: https://ecoinvent.org/
[8] For more information about premise see: https://premise.readthedocs.io/en/latest/introduction.html

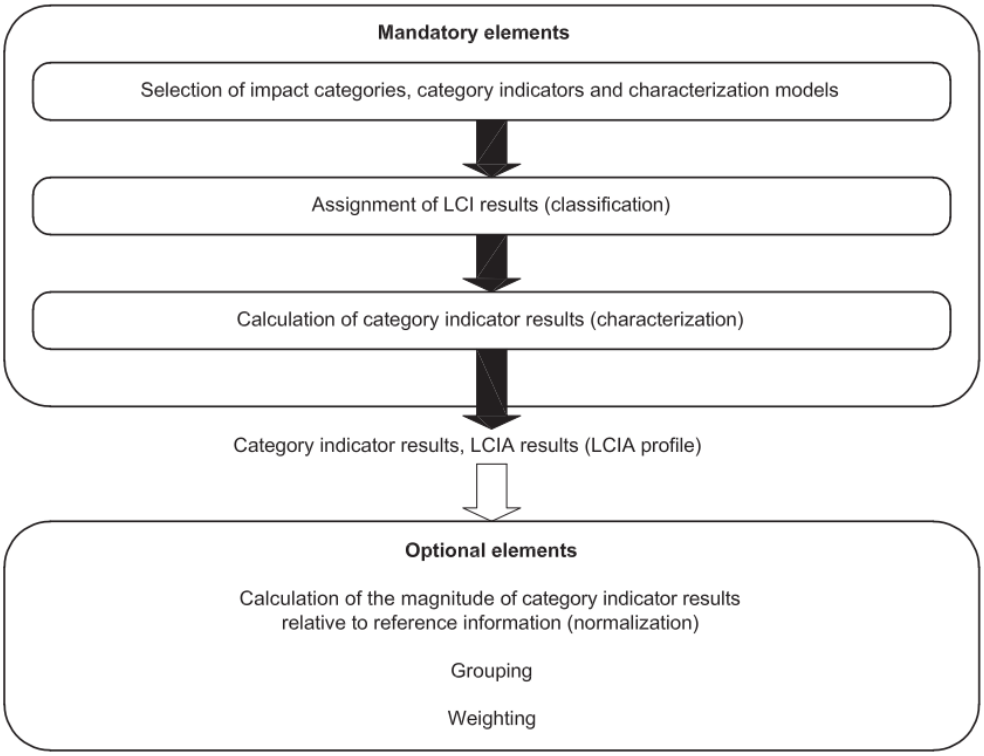


Figure 16: Elements of the LCIA phase [51].

**Impact indicators**

The mandatory elements of the LCIA include three steps: selection of impact categories, classification, and characterization.

The first mandatory element in the LCIA is the *selection of impact categories*. Each impact category represents a specific environmental problem (e.g., climate change). The selection of impact categories is part of the first phase of the LCA (i.e., goal and scope), but it must be checked here, based on findings from the LCI, and modified if necessary [22].

In the second step of the LCIA, the *classification*, each elementary flow determined in the LCI is assigned to an impact category. In general, several flows contribute to an impact category. However, one elementary flow can also contribute to several impact categories [22].

The third step, *characterization*, is to calculate the values of the selected impact indicator (*category indicator result*) for each elementary flow associated with a category. For each elementary flow, the result of the LCI is multiplied by the characterization factor of this substance for the respective impact category. As a result, all elementary flows associated with an impact category are converted into a common unit. The sum of all the partial contributions of the individual elementary flows gives the result for the effect category [22].

An example of such a calculation is shown in Table 2.

Table 2: Examples for characterizing the results of the LCI (impact category climate change) [62]; GWP = Global warming potential.

| | | | |
|---|---|---|---|
| Impact category | Climate change | | |
| Impact model | GWP100years[9] | | |
| Impact indicator | Increase in radiative forcing ($W/m^2$) | | |
| Elementary flow | Results LCI in kg emissions/functional unit | Characterizing factor (GWP) in kg $CO_2$-eq./kg emission | Indicator results in kg $CO_2$-eq./ functional unit |
| $CO_2$ | 5 | 1 | 5 |
| $CH_4$ | 0.5 | 28 | 14 |
| $N_2O$ | 0.01 | 265 | 2.65 |
| Result of the characterization for the impact category climate change | | | 21.65 |

The optional elements of the LCIA contain the three steps of normalization, grouping and weighting.

The *normalization* compares the results of characterization with a reference value and thus shows the specific share of the impact of a product or service. In the example of the impact category, climate change, the amount of $CO_2$-eq. of the product can be compared to the total amount of greenhouse gases (GHG) emitted in in a country, also calculated as $CO_2$-eq. [50].

The *grouping* divides the results of the characterization into several groups and structures them according to relevance. For example, it is possible to order the results in terms of geographical relevance (local, regional, global). Or the impact categories themselves are structured according to the urgency of the environmental problem. The aim of this grouping is to prioritize, for example, the groups can be ordered according to a high, medium, or low priority [50].

[9] It should be noted that the Intergovernmental Panel on Climate Change (IPCC) has started to publish its Sixth Assessment Report (AR6) in 2021. However, the updates to the characterisation factors do not result in any significant changes and IPCC AR5 from 2013 is still currently used in GHG accounting.

In *weighting*, the results taken from the impact indicators are converted into numerical values. This can be done for each individual indicator or standardization result using weighting factors. However, it is also possible to aggregate results by impact categories. finally, a summary of all the results of the LCA can be expressed as a single indicator [50].

In this project, no impact category with grouping and weighting is assessed in more detail. However, results for the impact category Ecological Scarcity 2013 were additionally calculated, which can be found in Attachment A.3 Extensive LCIA.

### Methods of LCIAs

Table 3 shows frequently used impact categories[10].

Table 3: Examples of LCIA methods[11]

| | |
|---|---|
| IPCC 2013 | In the IPCC's First Assessment Report, the GWP was introduced, where it was also used to demonstrate the challenges of comparing components with different physical characteristics on the basis of a single metric. There are different time horizons, the most common is 100 years [62]. |
| Cumulative Energy Demand | The Cumulative Energy Demand Method is an approach that quantifies the energy content of all energy sources (renewable and non-renewable) [63]. It is an easy-to-understand indicator and is often used for communication with stakeholders. |
| Environmental Footprint | The Environmental Footprint Method is an initiative of the European Commission. It is a new and improved method that companies should use to measure the environmental performance of a product throughout its life cycle and includes many different impact categories [64]. |

[10] The terms LCIA methods and LCIA categories are used interchangeably in this work.
[11] For more information of LCIA methods recommended by ILCD see: https://eplca.jrc.ec.europa.eu/uploads/ILCD-Handbook-LCIA-Background-analysis-online-12March2010.pdf.

### 3.4 Interpretation

The interpretation, the fourth and final phase of an LCA, is used to derive conclusions, to explain limitations and to make recommendations [51]. The detailed and mostly complex results of the LCAs therefore need to be prepared, commented on, and summarized in such a way so that it is comprehensible to the target group of the respective study and support for decision-makers can be provided. The main components of the assessment phase are:

- identification of the significant parameters based on the results of the LCI and the LCIA,
- review that considers the sensitivity, completeness, and consistency analysis,
- conclusions, limitations, and recommendations [52].

## 4. Goal and scope

The main purpose of this LCA is to define the ecological impact of the VT system's transport performance over its entire life cycle. The assignment focuses on Switzerland, thus the use phase, the EOL phase as well as parts of the production phase take place in Switzerland.

The pod should differ only in dimensioning motor, battery, and electricity consumption. The tube differs with its main composition of concrete or steel and is built above ground. For the station, there are three cases with no, one or two launchers respectively. Recycling differs only in the amount of material. The specific battery data (Li-NMC) is provided by ecoinvent and premise.

Since no datasets on VT or Maglev systems are currently provided by LCI databases, the transport systems are compared, first only to each other and at the end, for rough classification, to a conventional aircraft and an aircraft powered by synthetic kerosene, as well as a train.

A sensitivity analysis is then carried out with a focus on the used electricity mix and assumed occupancy, as well as a Monte Carlo simulation regarding the GWP.

The functional unit is *1 person-kilometre* (pkm). Data from simulations of the ETF is used for energy consumption and direct emissions.

## 5. Life cycle inventory analysis

The LCI is based on the structure of ecoinvent to ensure the highest possible comparability with existing data and to allow various combinations of different scenarios. The focus is on material selection and construction phase of the system. The structure of the LCI is shown in Figure 17. The system is subdivided into a foreground and a background system. The foreground system includes the three main life cycle phases of manufacturing phase, use phase and the EOL of the product and represents all processes that are directly influenced by decisions within these three phases. In the background system, all inputs, and outputs to and from the foreground system are modelled, representing all processes that are directly influenced by decisions related to the foreground system.
When references to the VT system are made later in this study, without mentioning the prototype version, this is meant to include all of them.

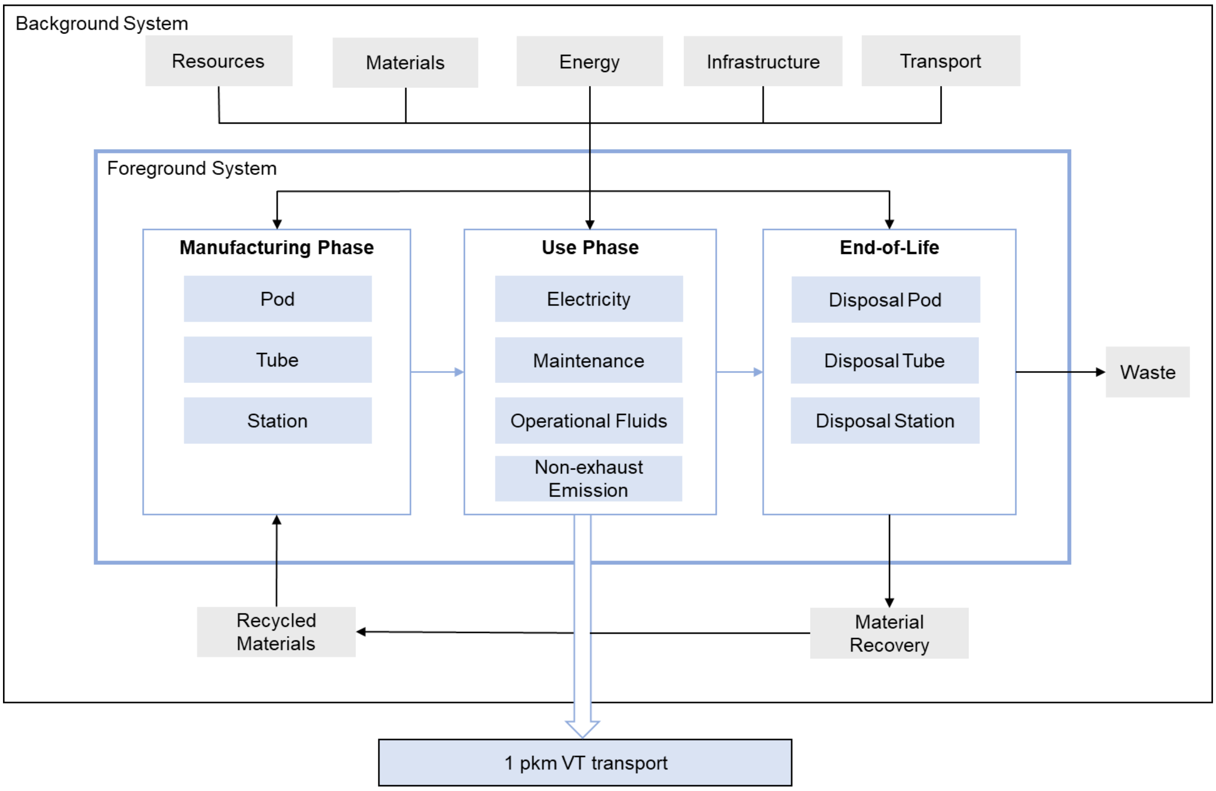


Figure 17: Structure of the LCI from the VT system, redesigned according to the eLCAr guideline. This diagram serves as a rough illustration only and does not represent all connections between the systems.

The scenarios differ only in the different weights of the pod, launcher and in the material selection of the tube thus also in the EOL. Two different propel systems are considered:

Self-propelled and propelled by one or two launchers[12]. There is therefore a total of four different scenarios (see Figure 18).

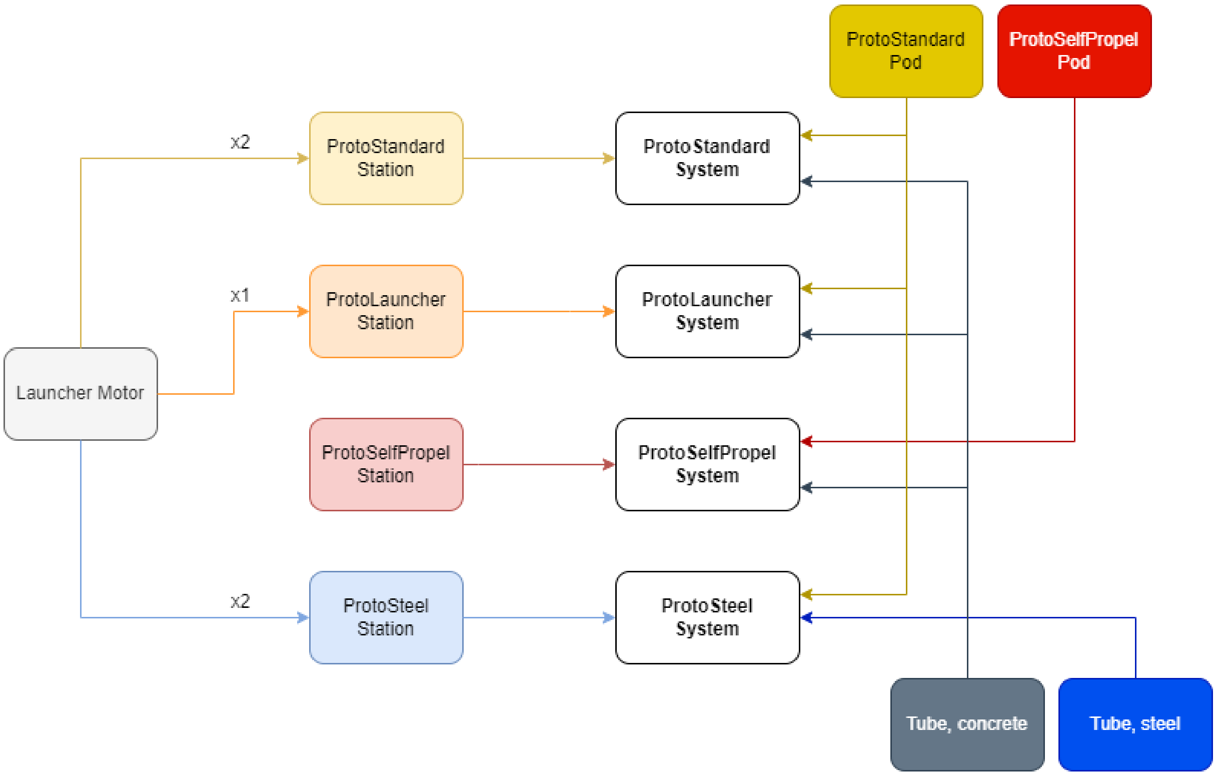


Figure 18: Overview of the different LCIs of the VT scenarios.

The overview is intended to represent the composition of the LCIs, but without EOL, as in this only the quantity in the different scenarios change. Table 4 should again serve as an explanation of the different scenarios.

Table 4: Explanation of the four different system scenarios

| System | Explanation |
|---|---|
| ProtoStandard | Reference case, with track-side acceleration and recuperation. |
| ProtoLauncher | The difference to the standard case is that there is only one track-side motor to launch the pod. |
| ProtoSelfPropel | Only pod-side acceleration and recuperation, meaning neither launcher nor recuperator on the track. |
| ProtoSteel | Analogous to the standard case, whereby the concrete tube is replaced by steel. |

[12] In practice, the second launcher is to perform the function of a recuperator.

Since, due to the prospective nature of this LCA, few precise details of the suppliers can be known at the moment, so-called *market activities*[13] have always been selected, which represent a corresponding cross-section of the origin of the respective product for a particular region and also contain average transport routes. If these market activities were not available, the corresponding transport routes were taken from similar market activities.

In the following subchapters, the phases of the life cycle are shown in more detail.

A detailed list of all the parameters chosen by the ETF is listed in detail in Attachment A.1 Extensive parameters of the VT system.

## 5.1 Manufacturing Phase

The manufacturing phase also includes the acquisition of raw materials, as well as the construction and is divided into three parts: pod, tube, and station. The exact datasets for this phase of the LCI are shown in Attachment A.2.1 Manufacturing Phase.

### 5.1.1 Pod

The pod can be roughly subdivided into fuselage, levitation motor, propulsion motor, battery pack, thermal management, and HVAC system. The reference flow of the pod was set to 1 «unit».

Table 5: Composition of the different versions of the Pod

| Material | ProtoStandard Pod [kg] | ProtoSelfPropel Pod [kg] |
|---|---|---|
| Fuselage | 9,800 | 9,800 |
| Levitation Motor | 496.8 | 756 |
| Propulsion Motor | 2,226 | 10,108 |
| Battery | 3,420 | 6,022 |
| Water | 2,856 | 5,506 |
| $LN_2$ | 221 | 336 |
| Sum | 19,020 | 32,528 |

A pod can theoretically carry 70 passengers and luggage (assumption: 100 kg per passenger). In order to make the LCA comparable with other transport systems, an

[13] For more information about markets in ecoinvent see: https://ecoinvent.org/the-ecoinvent-database/market-activities/.

occupancy rate of 80 % was assumed, just like for aircrafts, thus a further 5,600 kg transport weight was assumed.
The pod has a diameter of 3.4 metres, which allows six people to sit in a row (see Figure 19).

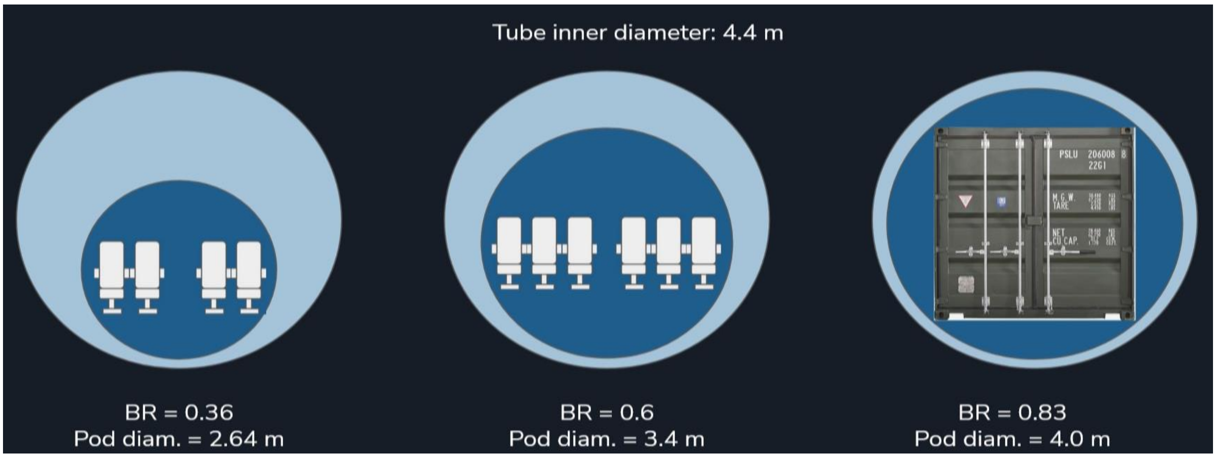


Figure 19: Cross-sections of the tube and the potential pod designs. In this project, only the middle case is considered; BR = blockage ratio.

The fuselage remains constant in both versions as the ETF currently uses a zero-dimensional model, which means that the volume of the technical components is not considered, only the weight It is assumed that most of the fuselage is used for the cabin for the passengers, only the ends and floors are used to accommodate the technical/propulsion equipment. So, it is not assumed that there will be a significant increase in volume due to the additional components, especially since the technology is very weight-dependent rather than volume-dependent.
A fleet size of 174 pods is assumed. A pod should be able to complete 110,000 launches in its lifetime. The target is 4,333.3 launches for each pod per year resulting in a lifetime of about 25.4 years. Under these assumptions, one pod has a total lifetime performance of 1,848 million pkm[14].
For the battery, 5,000 cycles were assumed, which in this context can fulfil the requirement for roughly 5,000 launches. Therefore, in order to serve the 110,000 launches of the pod, 22 batteries per pod are needed in its lifetime, which are accordingly modelled in the LCI.
The water and $LN_2$ used for cooling is modelled in the use phase of the LCI.

[14] As a comparison, a long-distance train in Switzerland achieves 929 million pkm and an aircraft for very short haul 7,249 million pkm according to ecoinvent. For more information see Table A 3.

#### 5.1.1.1 Fuselage

Since the fuselage of the pod is very similar to that of an aircraft, the smallest aircraft[15] from ecoinvent was taken as a template. This dataset does not contain any electronics or interior materials, which is why it is well suited as a basis.

Table 6: Material proportions of fuselage (pod) and aircraft; CFRP = Carbon fibre reinforced plastic

| Material | Fuselage (pod) [%] | Aircraft [%] |
|---|---|---|
| Aluminium | 20 | 57.2 |
| CFRP | 50 | 24.1 |
| Nickel | 5 | 2.4 |
| Steel | 10 | 11.6 |
| Titanium | 15 | 4.7 |
| Sum | 100 | 100 |

The production flows (energy, waste, etc.) were adopted and scaled according to the masses. However, the aircraft dataset contains a large proportion of kerosene that is used for test flights and was not included here. Furthermore, the EOL treatment is already in the dataset. It was assumed that the aircraft was roughly divided into its original materials as scrap and mainly landfilled. For the pod, on the other hand, it can be assumed that it will not be decommissioned before 2065, which means that a high recycling rate can be assumed. A cut-off was therefore made for the metals and a pyrolysis was modelled for the CFRP, which will be described in more detail later.

#### 5.1.1.2 Levitation Motor

The levitation motor is technically a superconducting coil with high voltage flowing through it, as described in chapter 2.2.3. These superconducting tapes have extremely high current densities even at 77 K [65] (vapour point of $LN_2$).

[15] Notten, P., aircraft production, passenger aircraft, very short haul, GLO, Allocation, cut-off by classification, ecoinvent database version 3.8

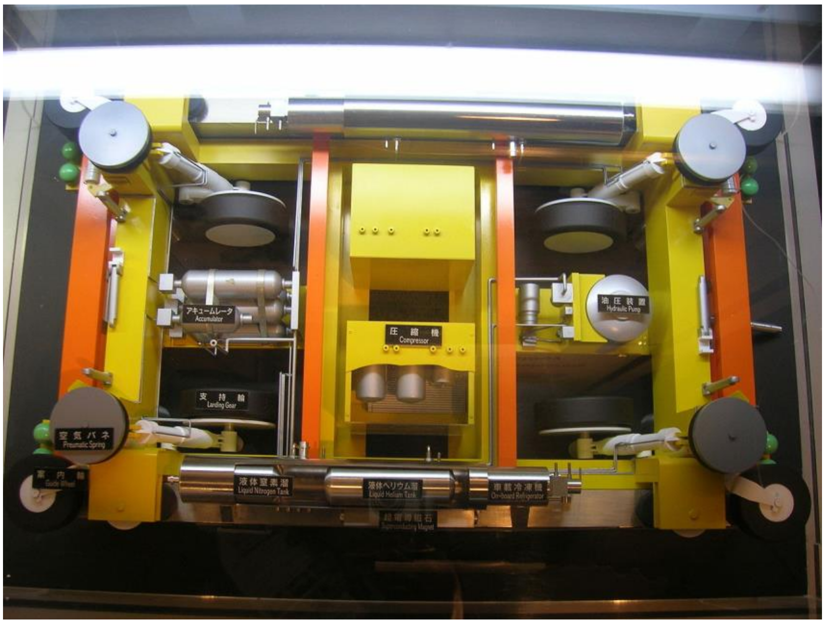

Figure 20: Superconducting magnet bogie from SCMaglev MLX01 (Japan) [66], which is only intended as an illustration here

The motor used can be roughly divided into the components in Table 7.

Table 7: Composition of the levitation motor; YBCO = Yttrium barium copper oxide

| Material | Levitation motor ProtoStandard [kg] | Levitation motor ProtoSelfPropel [kg] |
|---|---|---|
| Aluminium | 82.8 | 126 |
| Copper | 305.91 | 465.52 |
| YBCO | 20.39 | 31.03 |
| Silver | 6.12 | 9.31 |
| Hastelloy C276 | 81.58 | 124.14 |
| Sum | 496.8 | 756 |

The service life is assumed to be 100 years [67], which is a realistic estimate for permanent magnets.

This inventory was itself largely modelled with production flows, processing, and electronics such as a resistor being taken and scaled according to the individual masses from the production data of an electric motor[16] from ecoinvent.

Hastelloy C276 and YBCO were chosen because of their promising results in terms of high and constant superconducting performances in strong magnetic fields and high output at low cost in fusion power research [68].

[16] Habermacher, F., electric motor production, vehicle (electric powertrain), GLO, Allocation, cut-off by classification, ecoinvent database version 3.8

Since Hastelloy C276 and YBCO or similar are not available in ecoinvent, but use critical raw materials, they were also modelled.
The modelling of a flux pump, needed to charge the superconductor, was beyond the scope of this project. The energy required for lateral stabilisation is not included and is negligible [69] compared to levitation.

**Hastelloy C276**

Hastelloy C276 is a very good corrosion resistant nickel-molybdenum-chromium alloy [70]. A slightly rounded composition (see Table 8) was selected by the ETF.

Table 8: Composition of Hastelloy C276

| Material | Hastelloy C276 [%] |
|---|---|
| Nickel | 57 |
| Chromium | 16 |
| Molybdenum | 16 |
| Iron | 5 |
| Tungsten | 4 |
| Cobalt | 2 |
| Sum | 100 |

The production data for the iron-nickel-chromium alloy[17] in ecoinvent was used as a template. The raw materials were adjusted accordingly, and the remaining flows were adopted.

**YBCO Superconductor**

For the superconductor, there are several options to choose from and for this work, only YBCO will be considered for now. The only permanent magnet[18] in ecoinvent was used as a template. With the existing raw materials, which already exist in ecoinvent, the following reaction equation was assumed.

$$2\,Y_2O_3 + 8\,BaCO_3 + 12\,CuO + O_2 \rightarrow 4\,YBa_2Cu_3O_7 + 8\,CO_2$$

This results in the following mass balance in Table 9.

[17] Primas, A., iron-nickel-chromium alloy production, RER, Allocation, cut-off by classification, ecoinvent database version 3.8
[18] Del Duce, A., permanent magnet production, for electric motor, GLO, Allocation, cut-off by classification, ecoinvent database version 3.8

Table 9: Resulting mass balance of YBCO.

| Molecular Formula | Mol | Molar mass [g/mol] | Mass balance [w%] |
|---|---|---|---|
| YBCO | 4 | 666.19 | 1 |
| $CO_2$ | 8 | 44.01 | 0.132 |
| $Y_2O_3$ | 2 | 225.81 | 0.169 |
| $BaCO_3$ | 8 | 197.34 | 0.592 |
| CuO | 12 | 79.55 | 0.358 |
| $O_2$ | 1 | 32 | 0.012 |

The resulting masses were adjusted and replaced with the source materials of the existing dataset.

### 5.1.1.3 Propulsion Motor

Two different versions of the propulsion motor will be analysed, which are mostly composed of three materials (see Table 10).

Table 10: Composition of the from the different versions of the Propulsion Motor

| Material | ProtoStandard [kg] | ProtoSelfPropel [kg] |
|---|---|---|
| Copper | Confidential | Confidential |
| Silicon Steel | Confidential | Confidential |
| Epoxy Resin | Confidential | Confidential |
| Sum | 2,226 | 10,285 |

The standard propulsion motor is smaller with 2.85 MW peak power and is supported by one or two launcher motors during the launch. The self-propelled motor is designed to be larger, with 13.2 MW peak power, and does not require any support during launch.

Motors of this size can operate for up to 40 years [71]. As a conservative assumption, the lifetime of the motor is estimated to be 25 years.

As no process data or templates are available, the corresponding raw materials in ecoinvent were used. Furthermore, suitable process activities were used, which already include energy and waste.

**Silicon Steel**

Since silicone steel is not available in ecoinvent, but larger quantities are used for this LCA, this particular steel was re-modelled. Therefore, an LCA [72] was taken as a template in which silicon steel was modelled for Permanent Magnet Synchronous Motors (PMSM). For this LCA, however, the silicon content was adjusted to 3 % instead of 2 % and the aluminium content was changed from 0.4 % to 0 %.

#### 5.1.1.4 Battery

In order to maintain a constant maximum speed, the pod is powered by an on-board battery. The system therefore requires an additional battery after the launching process.

The number of batteries used depend on their availability in the market, the charging capacity, the cooling required and the location in the vehicle. The current assumption is simply the gross capacity for a full journey, considering a safety margin of 20 % and a depth of discharge of 85 % and an energy density of 375 Wh/kg. The ETF's preferred battery is the NMC 955 ($LiNi_{0.9}Mn_{0.05}Co_{0.05}O_2$), which is not yet being produced on a large scale but could dominate the transport market from 2040 [73]. Therefore, there are no sufficient LCIs yet, which is why the NMC 811 ($LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$), from ecoinvent was taken as the basis for this LCA.

In addition, premise uses new inventories of natural graphite [74] to partially replace the synthetic graphite used in the current ecoinvent inventory to represent a 50:50 split between natural and synthetic graphite [75], to better represent the graphite market and its original sources.

As this project is assumed to be commissioned in 2040, the cell-to-pack ratio is adjusted from the current 71.4 % in ecoinvent to 75 % according to current projections [76]. Furthermore, there is an error in ecoinvent 3.8 because the NMC811 battery contains NMC111 oxide in the cathode. This error was corrected in premise and adopted for this LCA.

Under the assumptions made in chapter 5.1.1 ($n_{Battery} = 22$) and here, 75,240 kg of battery per ProtoStandard Pod and 132,484 kg of battery per ProtoSelfPropel Pod are thus required over their entire lifetime.

### 5.1.1.5 Thermal Management

The vacuum environment prevents significant heat exchange with the outside of the pod, so on-board cooling must be provided. The following sources of heat must be covered by a thermal management system: inefficiencies of electrical devices, passenger heat, auxiliaries, and air friction heat.

Water/ice is intended to serve as a phase change material (PCM) for thermal management due to its suitable properties and thereby ideal economic and ecological criteria [77].

Since a more detailed consideration would be out of scope, as it would be of no major relevance for the LCA, only the water consumption is considered here, and the energy demand is addressed in the use phase.

### 5.1.1.6 HVAC System

The electricity consumption for the HVAC system is not included (it is included in the auxiliary systems, but not in a possible $CO_2$ scrubbing system). Electricity consumption for maintenance of cooling circuits or similar is not included and is not considered. Since no refrigerant with a high GWP is to be used, a more detailed consideration here would also be outside the scope. It should be noted that the other transport systems in ecoinvent also neglect HVAC.

### 5.1.2 Tube

The tube can be roughly subdivided into steel fibre reinforced concrete (SFRC), silicone joint, rail, liner, and valve. The reference flow for the tube was set to 1-metre and year (m*a), which includes both directions. The provision of tube is therefore seen as a permanent renewal rather than a one-off expenditure and EOL. This is common practice[19] in LCA [78] [79], as infrastructures do not usually reach a classic EOL, and thus very long-time horizons do not have to be considered and the maintenance is thereby also implicitly integrated.

The tube thickness and material composition are based on the upscaling of the so-called *GammaShellPipe*, which is a fully developed product for ETF's first test track in

[19] In the case of airports and ports, the unit ($m^2$*a) is used.

2023 [45] and the inner diameter of the modelled tube is 4.4 metres. The total length of the tube is assumed to be 300 km, which represents the route Zurich–Geneva.

Figure 21: Production of a test part for the tube [80].

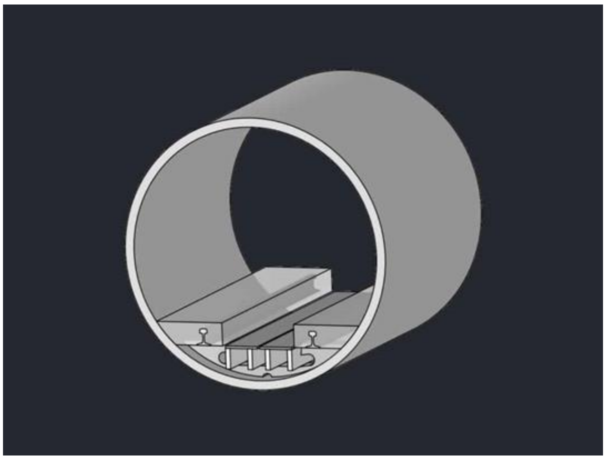

Figure 22: Conceptual design of a section of the tube [81].

The construction flows were taken from the railway track dataset from ecoinvent, they were partially adapted according to the land use. Diesel and electricity values were taken in the same way. It should be noted that the electricity used for the railway track is relatively high at 63.1 kWh per m*a. The largest share of this is due to the maintenance. However, the tube and especially its rails require much less maintenance, as the system is almost completely closed. Nevertheless, it was decided that these energy flows be adopted as they can be interpreted as energy required by the crane during construction. This is a conservative estimate as similar construction processes have shown a lower energy demand.

For land use (occupation and transformation), it can be assumed that only pillar cross-section uses land, as the tube itself will be at a height of approx. six metres. The area for pumps, safety exits, and transition ground can be neglected as they are not significant overall. The resulting area is:

$$\pi \times (0.75\, m)^2 = 1.77\, m^2$$

With a span of 40 m, this results in a land use of 0.0442 m²/m (unidirectional).

The exact composition of one metre tube is listed in Table 11.

Table 11: Composition of 1 metre concrete and steel tube (unidirectional)

| Material | Tube, concrete | Tube, steel |
|---|---|---|
| SFRC | 3.96 m³ | 0.532 m³ |
| Reinforcing steel | 136.1 kg | 2783.1 kg |
| Vacuum valve | 16 kg | 16 kg |
| Silicone joint | 1.125 kg | 1.125 kg |
| Aluminium rail | 71.8 kg | 71.8 kg |
| Liner | 45.6 kg | 0 kg |

The two tube variants differ only in the amount of SFRC, the reinforcing steel used and the liner. The individual components are examined in more detail in the following subchapters.

#### 5.1.2.1 Steel fibre reinforced concrete

The ETF has developed a concrete design [82] for vacuum transport infrastructures made of SFRC suitable for vacuum applications. This concrete is to be provided by the company *CREABETON*, which was also able to give precise information on the raw materials used (see Table 12).

Table 12: Composition of 1 m³ SFRC

| Material | SFRC [kg] |
|---|---|
| Cement | Confidential |
| Water | Confidential |
| Gravel | Confidential |
| Sand | Confidential |
| Confidential | Confidential |
| Confidential | Confidential |
| Confidential | Confidential |
| Long steel fibres | Confidential |
| Sum | Confidential |

Process-specific flows were added from the SFRC[20] dataset of ecoinvent and adapted to Switzerland as a geographical region. A total of 3.96 m³ per 1 metre (unidirectional) of concrete is to be used for sleeper, tube, and pillars. The lifetime was assumed to be 100 years, which is also assumed in other LCAs [78] for concrete but also for steel which are not exposed to extreme environmental conditions. It should be noted that

[20] Moraga, G., fibre-reinforced concrete production, steel, BR, Allocation, cut-off by classification, ecoinvent database version 3.8

the worst-case scenario of the ETF design is assumed here and ideally only half of the stated amount of concrete is used.

**Cement**

Since the concrete manufacturer also provided precise information on the cement used, a cement[21] dataset from ecoinvent was slightly adjusted.

**Steel fibres**

Ecoinvent uses the reinforcing steel[22] dataset for steel fibres, which represents a mixture of approx. 63 % unalloyed and 37 % alloyed steel and was adopted for this project.

#### 5.1.2.2 Silicone joint

Silicone joints are used to seal the individual concrete parts. 1.125 kg of silicone per 1 metre tube was specified and a lifetime of 30 years was assumed. The corresponding dataset from ecoinvent was used unchanged.

#### 5.1.2.3 Rail

The rail is based on the selected levitation principle and the thickness of the rail is conservatively selected according to a study [83] on a high-speed Maglev train.

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[21] Werner, F., cement production, alternative constituents 6-20%, CH, Allocation, cut-off by classification, ecoinvent database version 3.8

[22] Bourgault, G., market for reinforcing steel, GLO, Allocation, cut-off by classification, ecoinvent database version 3.8

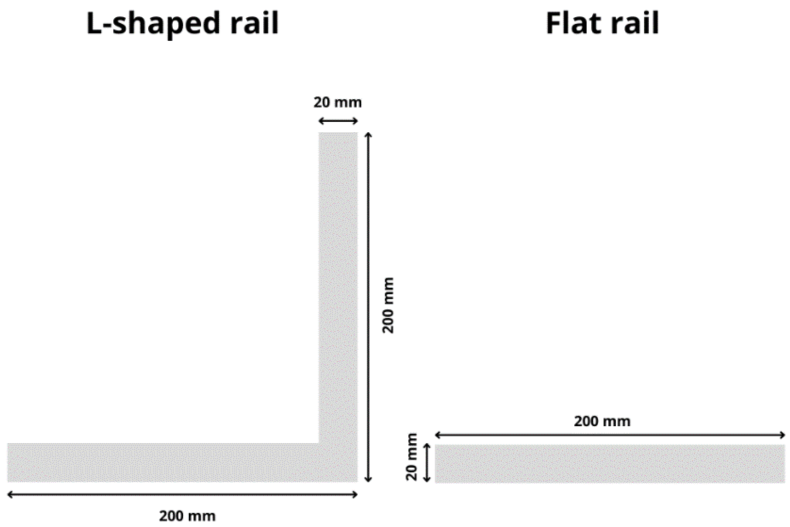

Figure 23: Cross section of the rails

Both flat and L-shaped rails are used on both sides of the track. All elements together result in an area of 240 cm², which will be made of aluminium. With a density of 2,670 kg/m³, this results in 64 kg of aluminium per 1 metre track. Since a double-sided LIM is used, an additional fin (which is the passive part on the pod) is needed on the rail side, which is the counterpart to the pod side fin during launch, resulting in another 7 kg per metre. It should be noted at this point that copper would technically be better for levitation as it is a better conductor, but it is much more expensive.

Wrought alloy aluminium was selected for the LCA and a representative processing activity was chosen to shape the aluminium into the desired form. The lifetime was assumed to be 50 years.

### 5.1.2.4 Liner

The liner thickness was selected in cooperation with the corresponding supplier for the ETF. It is based on flexible polyolefins [84] which are to be used as the insulating material. Two layers of this shall be used, resulting in

$$2 \times 4.8\, m \times \pi \times 1.5 \frac{kg}{m^2} = 45.6\, kg$$

of liner per 1 metre tube.

Confidential

Figure 24: Used liner from Sarnafil® [84]

The manufacturer states [85] that the minimum expected lifetime is 40 years. Another independent study has even shown [86] that liners for tunnels, for example, can have a service life of at least 50 years. As a conservative assumption, 40 years was set for this LCA.
The manufacturer did not provide sufficiently precise production data, which is why the dataset for packaging film (low density polyethylene) was used.

#### 5.1.2.5 Valve

A valve weighing 64 tonnes, which is mainly made of steel, is required every 4 km. This results in 16 kg of steel per 1 metre of tube for the valve.

Figure 25: Design of the ETF’s ultra-large vacuum valve [81].

A low-alloyed steel from ecoinvent was used and furthermore two processing activities were selected to replicate the manufacturing of the valves and a lifetime of 30 years [87] was assumed.

### 5.1.3 Station

The station includes the entrance hall where passengers arrive and pass through the checkpoints, the platforms where they wait to board, and the system of rails and switches connecting the launcher to the platforms. As with airports and railway stations, the latter element has the largest share of material and land consumption and was modelled under the assumption that the rails branch off with the standard 190-1/9 switch[23], the most commonly used railway switch for low speeds in Central Europe [88]. The number of platforms is set so that each individual platform is occupied by one pod during rush hour. This leads to stations being wider than conventional stations, but far shorter, as the pod length in this project is less than 100 m.

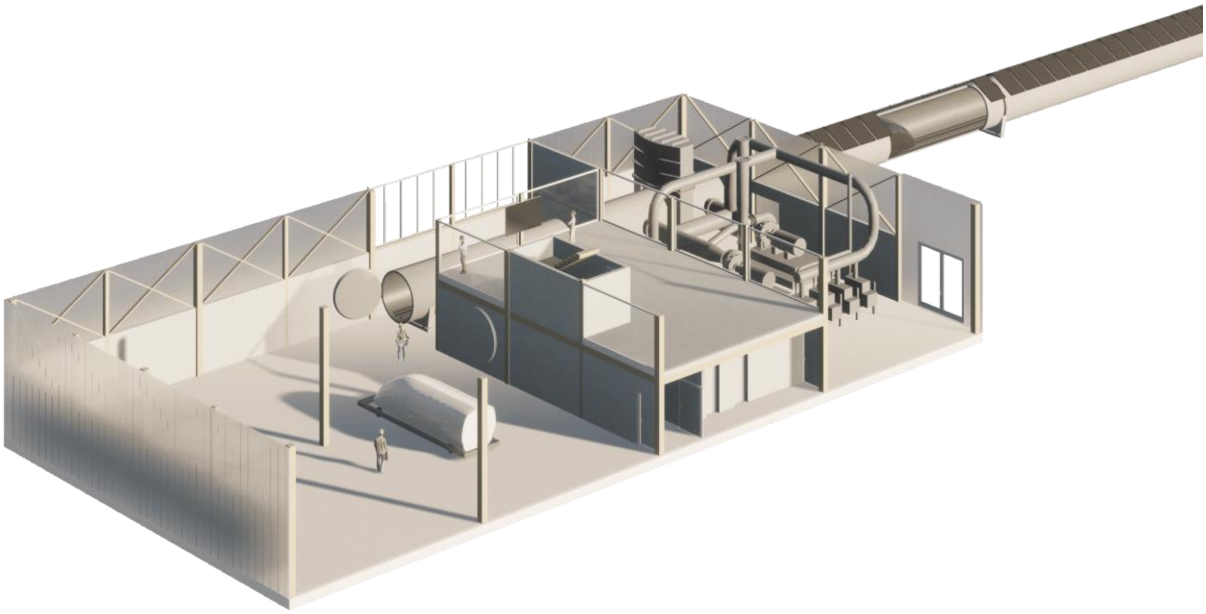

Figure 26: Conceptual design of the AlphaTube station from ETF [1].

For this LCI, the station can be roughly divided into a building, further tube for propulsion, a transformer, a supercapacitor, and a launcher motor. It was assumed that a building of 9,600 m² would be required. In addition, 30 parallel tracks, each

[23] The 190 in the notation stands for a curvature radius of 190 m, which is thus assumed to be the minimum curvature radius of the pods.

40 metres long and the switches required for them are to be built, which is why a further 25.65 km of tube is needed to allow passengers to board and accelerate. In addition to the building, a further 51,300 m² of land consumption was assumed.
In total, there are four different stations that only differ in the number of launchers and thus also only differ slightly in the size of the transformer and supercapacitor as the power peaks change accordingly (see Table 13).

Table 13: Composition of the different versions of the station

| Material | Unit | Proto-Standard | Proto-Launcher | Proto-SelfPropel | Proto-Steel |
|---|---|---|---|---|---|
| Building | m² | 9,600 | 9,600 | 9,600 | 9,600 |
| Tube | m | 25,650 | 25,650 | 25,650 | 25,650 |
| Launcher | unit | 2 | 1 | 0 | 2 |
| Transformer | kg | 158,000 | 172,000 | 206,500 | 158,000 |
| Supercapacitor | kg | 40,800 | 44,415 | 53,324 | 40,800 |

#### 5.1.3.1 Launcher Motor

This motor on the track side represents a load of several dozen MW to be distributed on a 10 to 20 km long launcher, depending on the assumed acceleration in a full-scale system. The motor consists of series-connected primary elements that are powered and switched in sequence to propel the pod. It is assumed that the launcher is passively cooled with a heat sink.

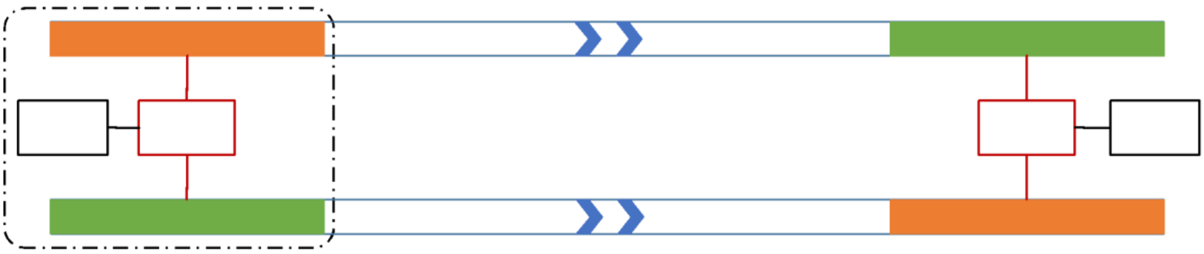

Figure 27: VT rail line with launcher in green and recuperator in orange [45].

In terms of material, the launcher motor is constructed much the same way as the propulsion motor (see chapter 5.1.1.3), only in larger dimensions (see Table 14). It has a peak power of 9.28 MW, weighs 14,628 tonnes, and a service life is also estimated to be about 25 years.

Table 14: Composition of one Launcher Motor

| Material | m [kg] |
|---|---|
| Copper | Confidential |
| Silicon Steel | Confidential |
| Epoxy Resin | Confidential |
| Sum | 14,628,000 |

The electric railway network was modelled using the Modified Nodal Analysis (MNA) by the ETF. In the simulation, the cable parameters were configured accordingly, the cable area was set to 400 mm², and the electrical resistance of copper was considered to be a value of 16.8 nΩm. With a launcher length of 31.2 km (very conservative assumption) assumed here, which is wired on both sides with cables, the following copper mass results are calculated.

$$V_{Copper} = 2 \times l_{Launcher} \times A_{Cross-section;\,Copper} = 2 \times 31.2\ km\ \times 400\ mm^2 = 24.96\ m^3$$

$$m_{Copper} = V_{Copper} \times \rho_{Copper} = 24.96\ m^3\ \times 8{,}900\ \frac{kg}{m^3} = 222{,}114\ kg$$

With a copper content of 66 % in the corresponding cable dataset from ecoinvent, this results in a further 336,582 kg of cable required for wiring.

#### 5.1.3.2 Supercapacitor

There are several challenges to overcome in the acceleration and deceleration ranges. Firstly, the loads change a lot: the load power of the system can be very large at the end of the acceleration range and at the beginning of the deceleration range. Secondly, during the morning and evening peaks, several pods are operating simultaneously in the launch and recuperator. The peak loads would be greater than the maximum power that can be supplied by the substation, resulting in financial losses for the extra power. The launch time delay between two pods is between 30 s and 840 s. A maximum of 8 × 2 pods will run simultaneously in the area with a time delay of 30 seconds. The power demand from the substations reaches a maximum peak power of 39.6 MW. However, during most of the day, the power demand will be below the maximum power. The ETF concluded in simulations [45] that an economical solution could be a supercapacitor, which already exists for such power peaks and is also used in this LCA.


Figure 28: Exemplary SC from ABB [89].

Currently, the model being adopted is ABB's Enviline™ ESS [89]. A total of two supercapacitors per station are to be used. One weighs 40.8 tonnes and has a service life of 1,000,000 cycles. About 59 cycles per working day are estimated, resulting in an expected lifetime of approx. 50 years.

In ecoinvent, there is only one dataset that represents all types of capacitors. It should be noted that supercapacitors are quite different from classical capacitors in terms of construction, e.g., an electrolyte is used in the supercapacitors. However, since no reproducible LCI for this could be found from other sources and the supercapacitor as a whole is not highly significant for the overall assessment of the LCA, the dataset from ecoinvent was used.

#### 5.1.3.3 Transformer

Two transformers are used per station. One transformer is to have a capacity of 158 MW, which, assuming that 1 tonne per 1 MW is needed [90], results in 158 tonnes without insulating oil. Depending on the size, a service life of 25 years (low voltage) to 65 years (high voltage) can be expected [91] [92]. Since this transformer can be classified in the medium to high voltage range, a service life of 50 years is assumed.

There is only one low-voltage and one high-voltage transformer from ecoinvent, which is why the high-voltage transformer was used here.

## 5.2 Use Phase

The use phase includes the operation of the VT system, thus the power consumption, operational fluids, and maintenance (see Figure 29).

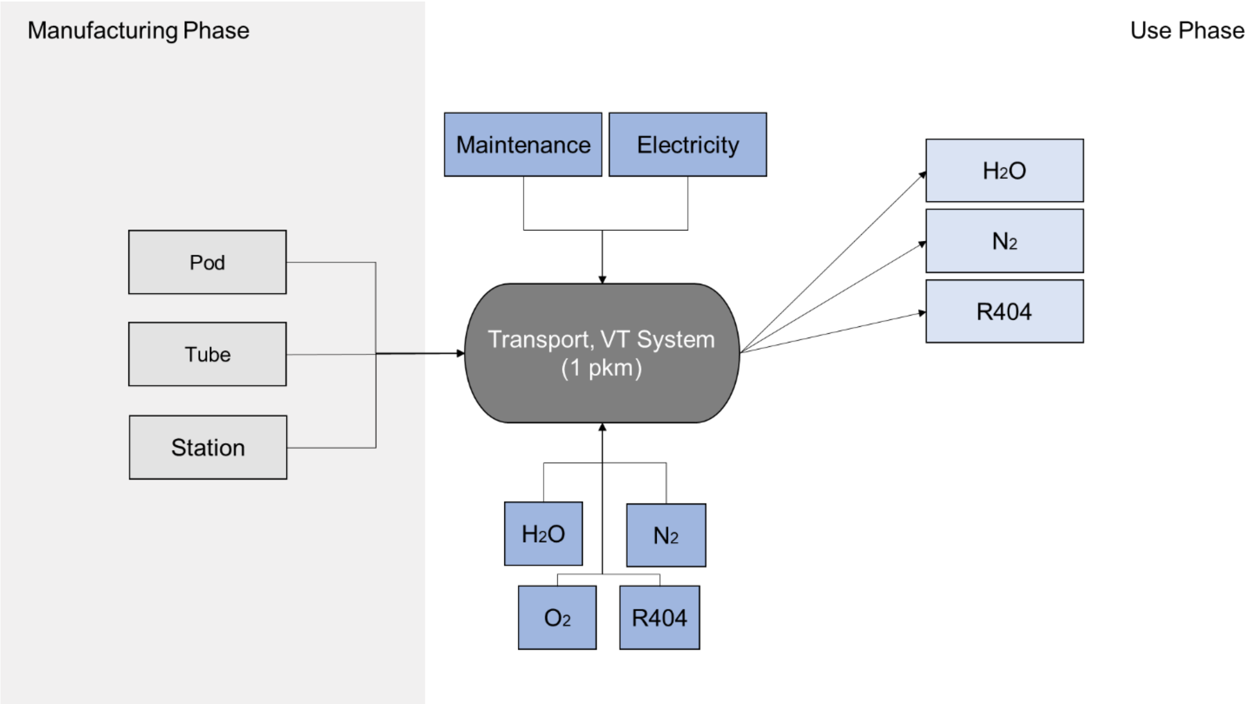


Figure 29: Scheme of the transport activity defined for 1 pkm.

It should be noted that the transport process itself can be considered emission-free. The emissions that arise come from sub-processes. For trains, SF6 emissions generally occur, which are caused by the insulating gas of the switchgear, these emissions would also arise in the case of the VT system. As an alternative, there is currently $g^3$ [93] from General Electric Company (GE) which has a GWP approx. 99 % lower than SF6, depending on the time horizon. The other alternative is from Siemens Energy, which uses a vacuum interrupter [94], which means that GHGs can be completely eliminated here. In view of these alternatives, which will replace SF6 in the future, the GHG was therefore omitted from the LCI. Furthermore, the pod uses landing wheels until it levitates from a speed of about 30 km/h, where minor abrasion may occur, which is, however, also negligible.

In LCIs for electric vehicles, according to eLCAr, the battery is allocated to the use phase, among other things because it does not have the same lifetime as the glider and powertrain. However, for this LCA, at the ETF's request, the battery is allocated to the pod, where it is also physically located, as it is to be compared directly with the LIM in the LCIA. Otherwise, as far as possible, a similar structure as in ecoinvent was applied in order to enable comparability with other transport systems.

A total of four scenarios are analysed.

A detailed overview of the mass and energy flows, as well as the exact datasets modelled from them for this phase of the LCI are shown in Attachment A.2.2 Use Phase.

### 5.2.1 Electricity

For the respective scenarios, corresponding energy flows were calculated by the ETF. The overall software was written in Python and the kinetics of the pod was simulated, but the applied aerodynamic drag was obtained from a computational fluid dynamic (CFD) model simulated with the software Ansys Fluent.

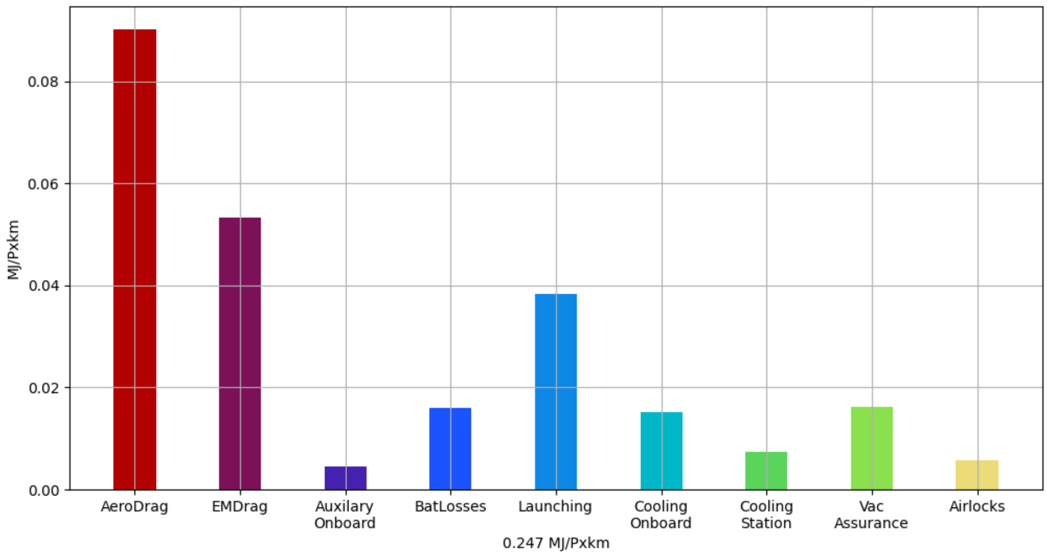


Figure 30: Breakdown of operating energy per pkm for the standard case at full occupancy.

Figure 30 shows the breakdown of the operating energy required for the parameters defined by the ETF (see Attachment A.1 Extensive parameters of the VT system). It is noteworthy that air drag is still the largest contributor, together with electromagnetic drag and the launcher. A summary of the energy consumption of the four different VT systems can be found in Table 15.

Table 15: Energy consumption for the different scenarios per pkm at full occupancy

| Flow | Unit | Proto-Standard | Proto-Launcher | Proto-SelfPropel | Proto-Steel |
|---|---|---|---|---|---|
| electricity | MJ | 0.247 | 0.268 | 0.318 | 0.247 |

The voltage system used will be of medium power with 9–16 kV, depending on which power electronics will have been developed by the time of construction. However, depending on local availability, the connection will be made to the high-voltage grid at 50–150 kV, which is why transformers have been added in the manufacturing phase. Additionally, a transformation from high voltage to medium voltage was modelled, which is associated with 0.62 % losses as in the Swiss electricity system in ecoinvent.

The Swiss Federal Railways electricity mix was selected for all scenarios, which consisted of 87.94 % hydropower, 10.76 % nuclear power and 1.3 % new renewables according to ecoinvent in the year 2017. This was mainly chosen to ensure a later comparison with the conventional train in Switzerland. It is difficult to estimate exactly what the electricity mix will look like in 2040 or beyond and to which voltage grid the VT system will be connected. Strictly speaking, it would also not be sufficient to take an electricity mix from one year, but an average value of this over the entire life of the VT system in order to obtain a truer assessment. However, due to the uncertainty of the prospective nature of this LCA, several prospective scenarios are analysed in the LCIA in each case and a sensitivity analysis of the electricity mix used is then further carried out (see chapter 7.1.1) so that existing uncertainties can be reduced.

### 5.2.2 Maintenance

Maintenance is very difficult to estimate and is not directly considered for aircraft in ecoinvent, which would have been the most comparable. The train datasets in ecoinvent include maintenance, but this cannot be applied due to the materials used. No more detailed information from aircraft manufacturers on repair could be found during the research, except that 10–20 % of the operational costs are due to aircraft maintenance [95], but this includes labour. In ecoinvent, datasets were found where a percentage of the original object cost was used as maintenance cost. In the case of a gas turbine, for example, 1 % of the turbine is used as maintenance flow, which can be interpreted as 1 % of the original materials and energy being required for maintenance. In the case of the pod, no major wear and tear is expected, as it levitates in a near-vacuum environment. Therefore, 3 % of the pod (without battery) was agreed upon as an assumption for maintenance. The battery itself is replaced regularly, so no further consideration is necessary here. For the tube, no further dataset is necessary for maintenance, as this is implicitly included in the reference flow unit m*a. In the case of the station, maintenance is partly in the background data.

### 5.2.3 Operational fluids

For the operation of the pod, water, $LN_2$, compressed oxygen and R404a are used, which can be summarised here under the term operational fluids.

**Water**

Ice, which melts during the trip, is used to cool the pod, and therefore takes on the function of a thermal battery. The melted water from the pod is extracted from the pod and goes to an ice maker [96] in the station to make ice again, which is then used again for the same or another pod.

**Liquid Nitrogen**

$LN_2$ is used to cool the superconducting coil to around 75 K. Some of it has to be refilled regularly and some $LN_2$ will remain liquid and won't need to be refilled on every trip.

**Compressed Oxygen**

As the pod is in an almost closed system, an oxygen supply for the passengers is necessary. Compressed oxygen bottles [97] with 50 litres under 200–300 bars are carried for this purpose. In ecoinvent, there is only oxygen in liquid form, which is, however, sufficient for consideration at this point.

**R404a**

R404a is a refrigerant that is used in the ice maker. The leakage value from a cooling process[24] was taken from ecoinvent.

Since the refrigerant R134a ($GWP_{100}$ = 1,430 $CO_2$-eq.) is used in this process and there is no biosphere flow for R404a ($GWP_{100}$ = 3,922 $CO_2$-eq.), the value was adjusted according to the higher GWP of R404a [98].

[24] Levova, T., operation, reefer, freezing, 40-foot, high-cube, R134a as refrigerant, GLO, Allocation, cut-off by classification, ecoinvent database version 3.8

## 5.3 End-of-Life

Like the Manufacturing Phase, the EOL can again be divided into the three components pod, tube and station. Full recycling was assumed for all metals used, which is why a cut-off was made for them. The exact datasets for this phase of the LCI are shown in Attachment A.2.3.

### 5.3.1 Pod

There is no recycling process for the CFRP in ecoinvent, as they do not yet have any major application in reality, which is why they are landfilled. Full recycling is expected by the EOL in approx. 2065 of the first pods. Therefore, a steam pyrolysis from another LCA [99] was re-modelled. Due to the uncertainty of how high the recycling share of carbon fibres will be in 2040 and the cut-off allocation, no credit was given at this point, which represents a very conservative approach.
For the battery, the EOL market activity was adopted from ecoinvent which represents a cross-section of hydrometallurgical (50 %) and pyrometallurgical (50 %) treatment. Recycling efficiencies of approx. 70 % are also achieved in the datasets. Here, too, it should be noted that recycling will become much more efficient after 2040, but due to the prospective uncertainty, no overly optimistic assumptions were made.
For the remaining material, such as epoxy resin from the motors, corresponding EOL market activities were used, which mostly represent a complete incineration.

### 5.3.2 Tube

According to the liner manufacturer, the liner can be recycled [100], which is why a cut-off was also made here. There is no suitable process in ecoinvent for the silicone joints, which is why the corresponding process for waste rubber is adopted, which reflects an incineration. For SFRC, the matching market activity that has a recycling share of 62 % was selected. Recycling here means that the concrete is crushed and then used as a replacement for the gravel in the new life cycle. Again, it should be noted that this is a very conservative assumption as a higher Circular Economy is expected in the future.

### 5.3.3 Station

For the building used, the EOL treatment is already in the background data. The launcher is treated in the same way as the propulsion motor, so that the metals are completely recycled, and the epoxy resin is incinerated. For the transformer and supercapacitor, the appropriate EOL treatment was selected for electronics, where they are shredded and then sorted by magnetic separation.

## 5.4 Allocation

No other products are created during the production of the VT systems, which simplifies the allocation of the environmental impact. However, the waste generated during production and at the EOL raises the question of how these impacts should be allocated. An often-used method is the *cut-off*[25] approach (see Figure 31), in which by-products (or waste) leave the system without being allocated any of the environmental burdens. As this allocation system model is the only one compatible with premise and other datasets other than ecoinvent, it is the one used in this study. It should be noted that for transport systems with a long service life, the EOL phase and thus the allocation method used is marginal anyway, as the main burden comes from the use phase [78] [101] [102].

[25] More information on all allocation models from ecoinvent are shown on the ecoinvent website: https://www.ecoinvent.org/database/system-models-in-ecoinvent-3/system-models-in-ecoinvent-3.html.

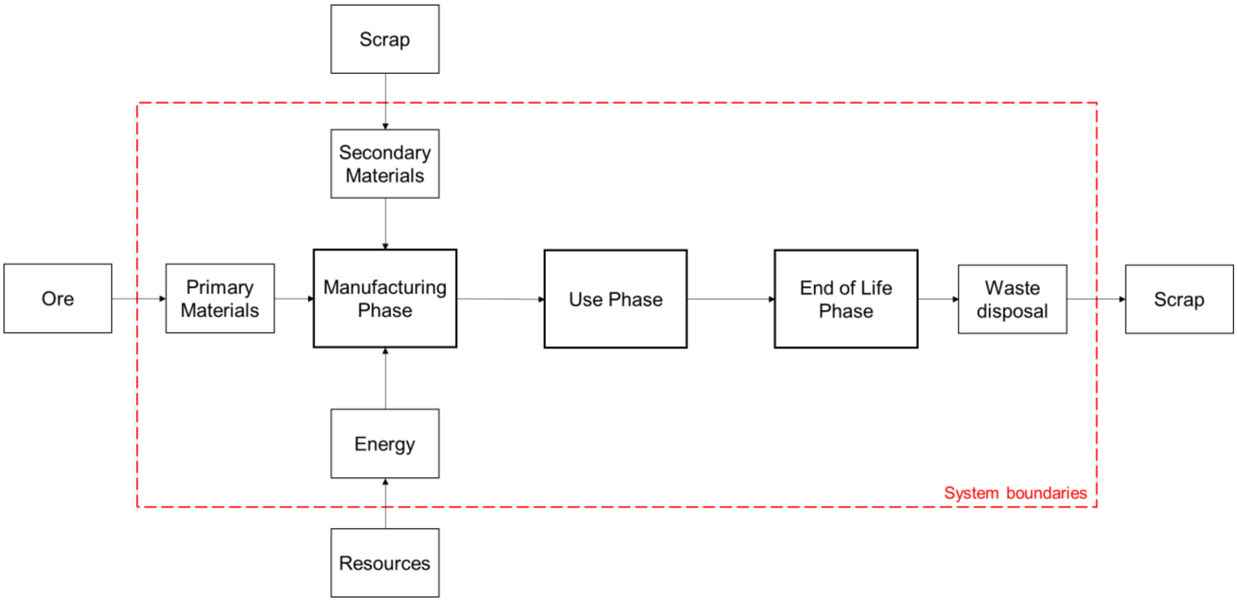

Figure 31: Scheme of the cut-off by classification system model.

## 6. Life cycle impact assessment

This chapter presents the results of the LCIA for the different transport scenarios. First, they are shown individually according to each LCIA method, then they are all compared to each other and finally, they are compared to existing transport systems from ecoinvent.

### 6.1 Life cycle impact assessment methods

The following methods, which are also recommended by ILCD and eLCAr, have been selected in collaboration with the ETF to assess the environmental impacts of the different VT scenarios in order to ensure maximum comparability with existing LCAs.

**IPCC 2013 – climate change, GWP 100a**

This method has already been described in detail above (see chapter 3.3). It is one of the most widespread methods and is of high priority for this LCA, too. The method calculates the GWP in kg $CO_2$-eq. based on current knowledge about climate change [62].

**Environmental Footprint 3.0**

The method of the Environmental Footprint (EF) is derived from the ILCD [64]. The first version of the EF was published in 2013 and has been continuously developed since then [103]. In 2018, the EF 2.0 was republished and later in the same year the EF 3.0 [64]. The EF 3.0[26] comprises of several different impact categories.
The chosen impact categories are described in more detail in Table 16.

[26] It should be noted that EF 3.1 was published in July 2022, which is not yet part of ecoinvent 3.8, but would not have brought any significant changes.

Table 16: Excerpt from the various EF impact categories [64] used for this LCA, with indicator and units.

| Impact category | Indicator | Unit | Robustness[27] |
|---|---|---|---|
| **Ozone depletion** | Ozone Depletion Potential (ODP) | kg CFC-11eq. | I |
| **Human toxicity, non-cancer effects*** | Comparative Toxic Unit for humans ($CTU_h$) | $CTU_h$ | II/III |
| **Particulate matter/Respiratory inorganics** | Human health effects associated with exposure to $PM_{2.5}$ | Disease incidences | I |
| **Acidification** | Accumulated Exceedance (AE) | mol H+ eq. | II |
| **Land use** | Soil quality index (Biotic production, Erosion resistance, Mechanical filtration, and Groundwater replenishment) | Dimensionless, aggregated index of: kg biotic production/($m^2$*a)[28] kg soil/($m^2$*a) $m^3$ water/($m^2$*a) $m^3$ groundwater/($m^2$*a) | III |
| **Water use** | User deprivation potential (deprivation weighted water consumption) | kg world eq. deprived | III |
| **Resource use, minerals, and metals** | Abiotic resource depletion (ADP ultimate reserves) | kg Sb eq. | III |

### Cumulative Energy Demand

Cumulative Energy Demand (CED) differs from other impact assessment methods because it does not quantify the direct environmental impacts of a product system [104]. Rather, it quantifies the primary energy consumption over the entire product life cycle of a product system. For this purpose, the *energy harvested* approach is used, which quantifies the total amount of energy sources provided for human use [63]. A distinction is made between renewable and non-renewable energy sources. Renewable energy sources include biomass, geothermal, solar, water and wind, while non-renewable energy sources include fossil fuels, nuclear, and primary forests. The reference unit of the characterisation factors is MJ.

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[27] According to ILCD [53] levels: “Level I” (recommended and satisfactory), “Level II” (recommended but in need of some improvements) or “Level III” (recommended, but to be applied with caution)

[28] This refers to occupation and transformation

## 6.2 Results

The effects are shown in relation to the functional unit (pkm) in each case. Furthermore, the impacts were again divided into typical processes/components of the transport systems, akin to ecoinvent vehicles. The way it is structured is explained in Table 17.

Table 17: Description of the structures of the separate processes

| Process | Sub-processes |
|---|---|
| Tube | Tube construction + maintenance +disposal |
| Station | Station construction + maintenance + disposal |
| Pod | Pod construction +maintenance + disposal |
| Electricity | Energy consumption (use-phase) |
| Operational fluids | Water + $LN_2$ + $O_2$ + R404a (use-phase) |

Four different scenarios are calculated for each VT system. One with the ecoinvent background data of today[29], and three different scenarios using premise to represent the year 2040 (see Table 18). This results in a total of 16 scenarios that are then compared for each impact category.

Table 18: Explanation of the coupled LCI scenarios [75] [60]; RCP = Representative Concentration Pathway

| RCP scenario | Explanation | Swiss scenario[30] | Explanation |
|---|---|---|---|
| RCP6.0 | Counter-factual scenario with no stringent climate policy implemented. | WWB | «Weiter wie bisher» (Continue as before) |
| RCP2.6 | Limit the global temperature increase to <2 °C by 2100, compared to pre-industrial levels. | ZERO Basis | Net zero by 2050 |
| RCP1.9 | Limit the global temperature increase to 1.5 °C by 2100, compared to pre-industrial levels. | ZERO Basis | Net zero by 2050 |

In order to better understand the differences to the prospective scenarios, it should be mentioned that premise mainly adjusts power plant, photovoltaic plants, wind turbine,

[29] It should be noted that ecoinvent can of course not reflect Today exactly. For example, electricity mixes from version 3.8 represent the period 2018–2019.
[30] For more information about the specific Swiss Scenarios see: https://www.bfe.admin.ch/bfe/en/home/policy/energy-perspectives-2050-plus.html/

cement production, and steel production efficiencies. Furthermore, it implements carbon capture technologies, synthetic fuels and adjusts the transport sector accordingly, and partially modifies hot pollutants.

All numerical results, including all impact models of the environmental footprint 3.0 that are not considered in this work, as well as the Ecological Scarcity 2013 method, which is widely used by Swiss federal authorities, can be found in Attachment A.3 Extensive LCIA.

### 6.2.1 IPCC 2013 – climate change, GWP100a

The assessment of the GWP of the scenarios is shown in Figure 32. The results are presented in kg $CO_2$-eq. per pkm.

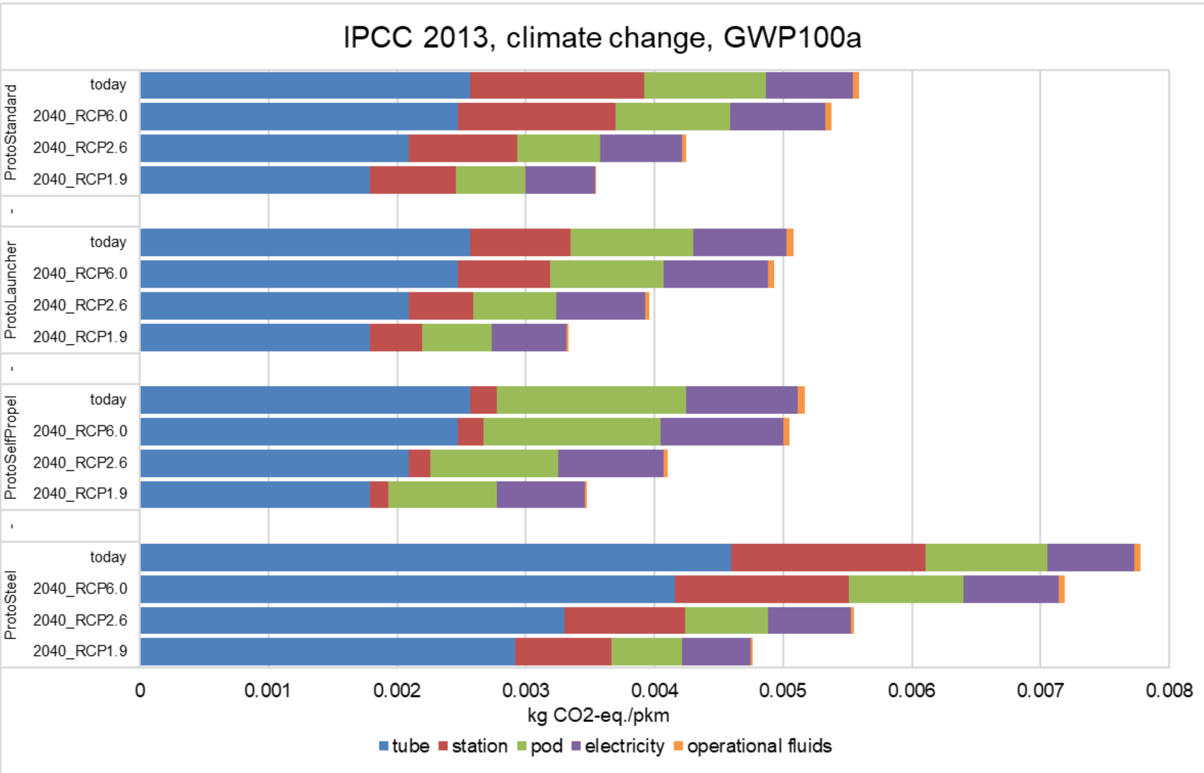


Figure 32: Environmental impact on GWP of the VT scenarios.

There are fundamental differences in the tube design between concrete and steel, with the latter accounting for almost half of the total GWP. By not using a recuperator (ProtoSelfPropel), significant amounts of emission-intensive metals are saved compared to the Standard case, without a significant increase in energy consumption during the operation.

The overall impacts of the design with pod-side acceleration and the design with a single launcher are quite similar, as the savings from not using the launcher are offset by the increased demand for LIM and battery capacity.
In the prospective scenarios, the relative distributions are more or less constant, with up to one third of GWP being reduced in absolute terms. The effect here would be significantly greater if a more GHG-intensive electricity mix were used.

In chapter 6.4, the subsystems are analysed in more detail regarding their GWP. Attachment A.4 Sankey Diagrams contains additional Sankey diagrams of all four construction designs with the background data of today.

### 6.2.2 Environmental Footprint 3.0

#### 6.2.3.1 Land use

The assessment of the land use of the scenarios is shown in Figure 33. The results are presented in 1/pkm, as the so-called soil quality index is dimensionless.

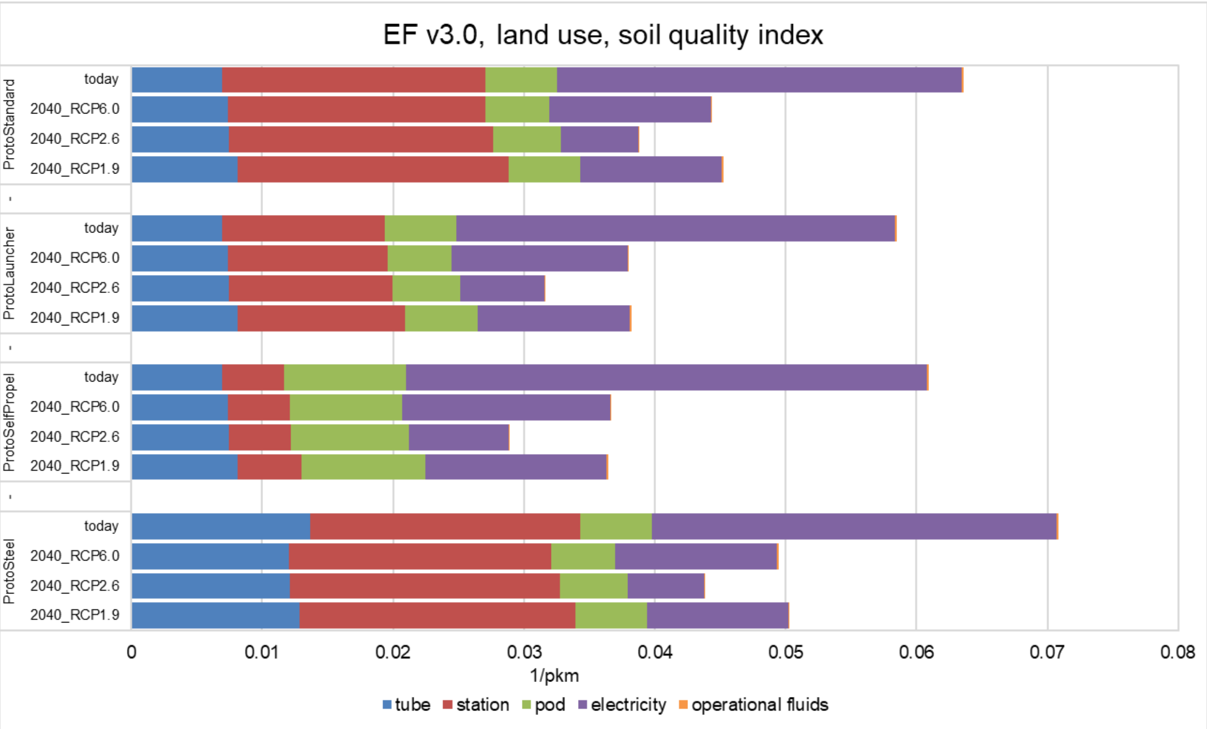


Figure 33: Impact on land use of the VT scenarios.

Electricity use in the non-prospective scenarios has the greatest impact on land use. This is almost entirely due to the wood chips used in the background system for electricity generation in Switzerland. In the prospective scenarios, this influence decreases because the IAM models assume even more efficient forest management and a large part of the biomass feedstock comes from residue, which does not require the allocation of further land use.

The station is still significant for all construction designs, with the exception of the ProtoSelfPropel scenario due to the non-existent launcher. 2/3 of the station's impact is due to the copper used, specifically the copper mines that are needed for their production. In almost all scenarios, the tube itself has a smaller impact than the stream and the station. About 1/3 of the impact of the tube itself is due to the SFRC. Only about 1 % of the total impact is due to the direct land use of the tube.

The pod has the least impact. Approximately 80 % of the pod's land use is due to the battery, as cell production is resource intensive. An exception here is the scenario without a launcher, as this requires more battery capacity.

Land use is lower in the prospective scenarios and decreases with more ambitious climate targets. RCP1.9 is an exception, as higher shares of $CO_2$ removal technologies are already present in the background. These are noticeable in indirect land consumption [105] as new plants will be necessary as well as a greater supply of energy.

Overall, the ProtoLauncher and the ProtoSelfPropel achieve the best results, mainly due to the lower copper consumption.

#### 6.2.3.2 Water use

The assessment of the water use of the scenarios is shown in Figure 34. The results are presented in kg world eq. deprived per pkm. It is the scarcity-adjusted water use, i.e., the relative amount of water available per area once the water needs of people and aquatic ecosystems are met [106].

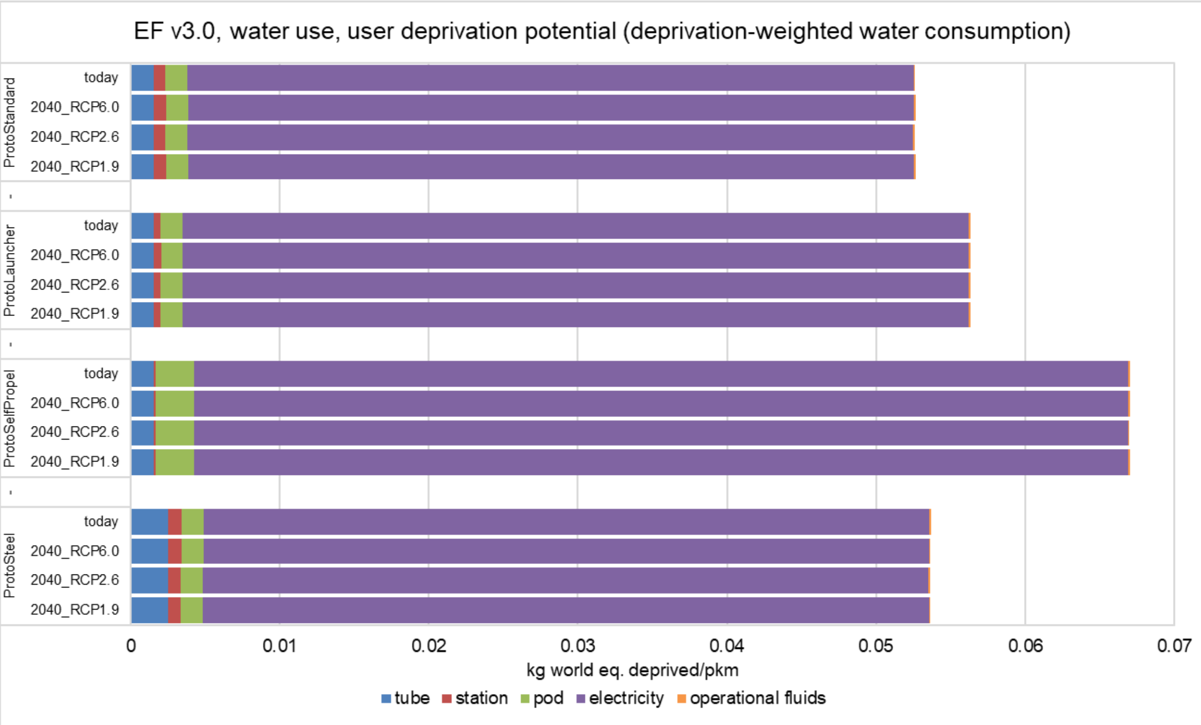


Figure 34: Impact on water use of the VT scenarios.

Since the largest share with approx. 90 % is accounted for by hydropower in Switzerland (reservoirs in the Alpine region), Figure 35 again shows an overview without electricity consumption in the use phase.

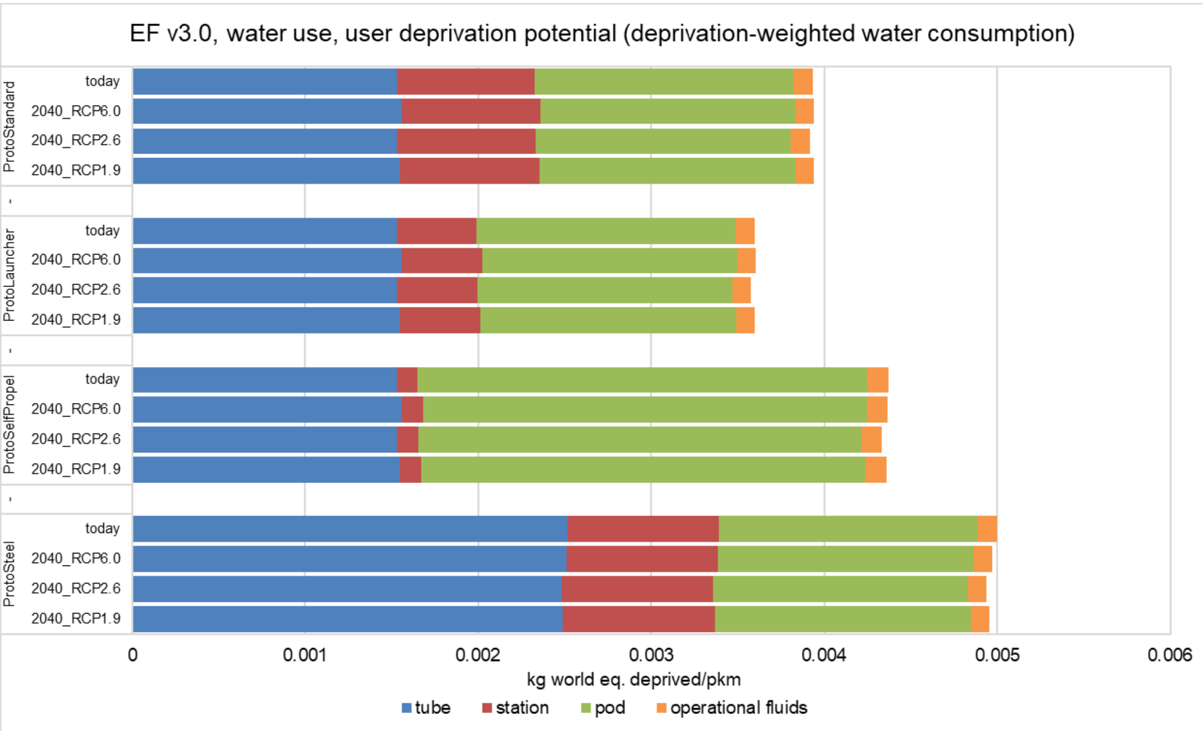


Figure 35: Impact on water use of the VT scenarios without electricity consumption in use phase.

Half of the tube's water footprint is due to electricity consumption and thus again to hydropower in Switzerland, with only 1/6 being due to the SFRC production itself.

In the case of the pod, around 90 % of this is due to battery cell production, mainly because of the water-intensive nickel sulphate and cobalt sulphate production

In the case of the station, half of its water consumption is due to the copper used or its production.

The direct water consumption of the VT system is negligible in relation to the indirect water consumption. Overall, ProtoStandard and ProtoSteel consume the least amount of water over their entire life cycle, this is because they have the lowest energy consumption in the use phase.

The water footprint does not change in the prospective scenarios because premise does not yet adjust the water consumption in the background system.

#### 6.2.3.3 Ozone depletion

The assessment of the ozone depletion of the scenarios is shown in Figure 36. The results are presented in kg CFC-11eq. per pkm. CFC-11 stands for trichlorofluoromethane and is a Class 1 ozone-depleting substance that damages the earth's protective ozone layer [107].

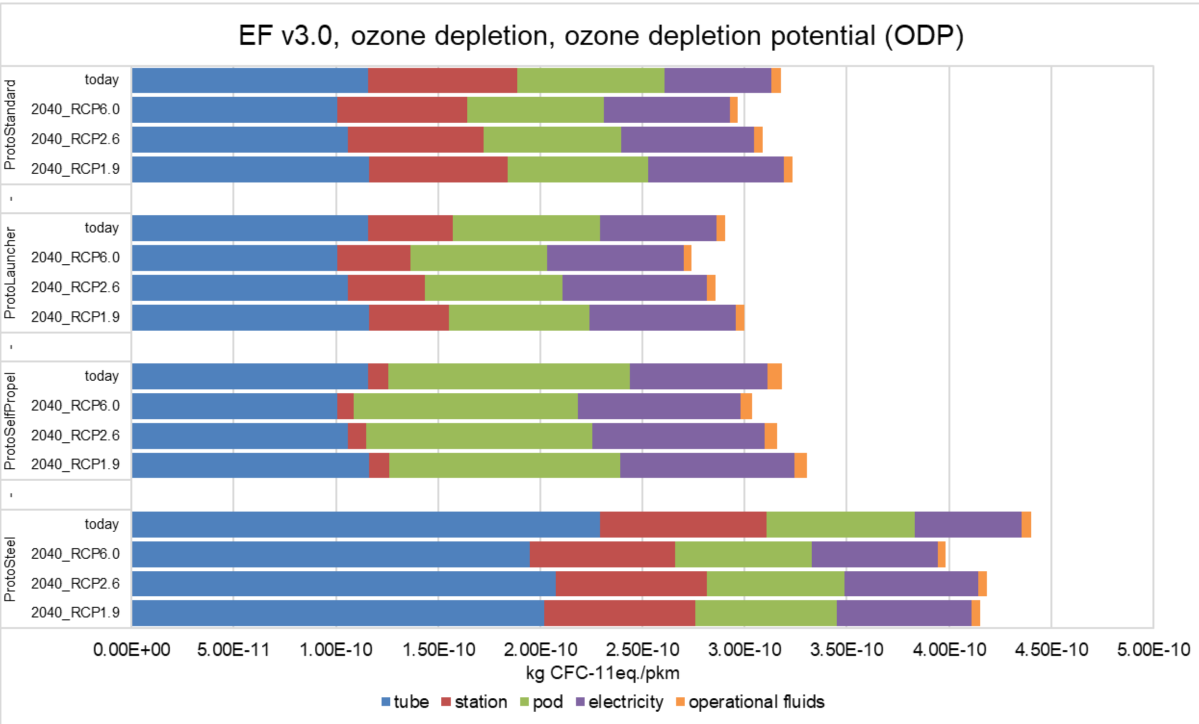


Figure 36: Impact on ozone depletion of the VT scenarios.

Most of the ozone-depleting emissions from the concrete tube come from aluminium production and SFRC production, one-third each from the tube. In the case of the steel tube, about 80 % is attributable to steel production and 20 % to aluminium production. The effects of station can be attributed to three equal parts, these being electric steel, copper, and the general manufacturing process of the launcher.

In the case of the pod, a total of 80 % is attributable to battery production.

And for electricity, one-third is caused by the incineration of wood chips, although this only accounts for approx. 1.3 % of the electricity mix used.

The refrigerant used for the ice machine has a total share of only 0.7 %.

The ozone depletion potential is higher for steel than for concrete, as higher ozone-depleting emissions are emitted during coking for the pig iron production. Therefore, the ProtoSteel achieves the worst results here whilst the other three scenarios achieve overall similar values to each other.

In the prospective scenarios, the ozone depletion potential increases slightly with lower RCP. This is mainly due to the higher $CO_2$ capture technology present in cement production. The steam heat required for the regeneration of the sorbent [108] is generated from natural gas, among other sources, and produces additional ozone-depleting emissions.

#### 6.2.3.4 Particulate matter formation

The assessment of the ozone depletion of the scenarios is shown in Figure 37. The results are presented in Disease incidences per pkm.

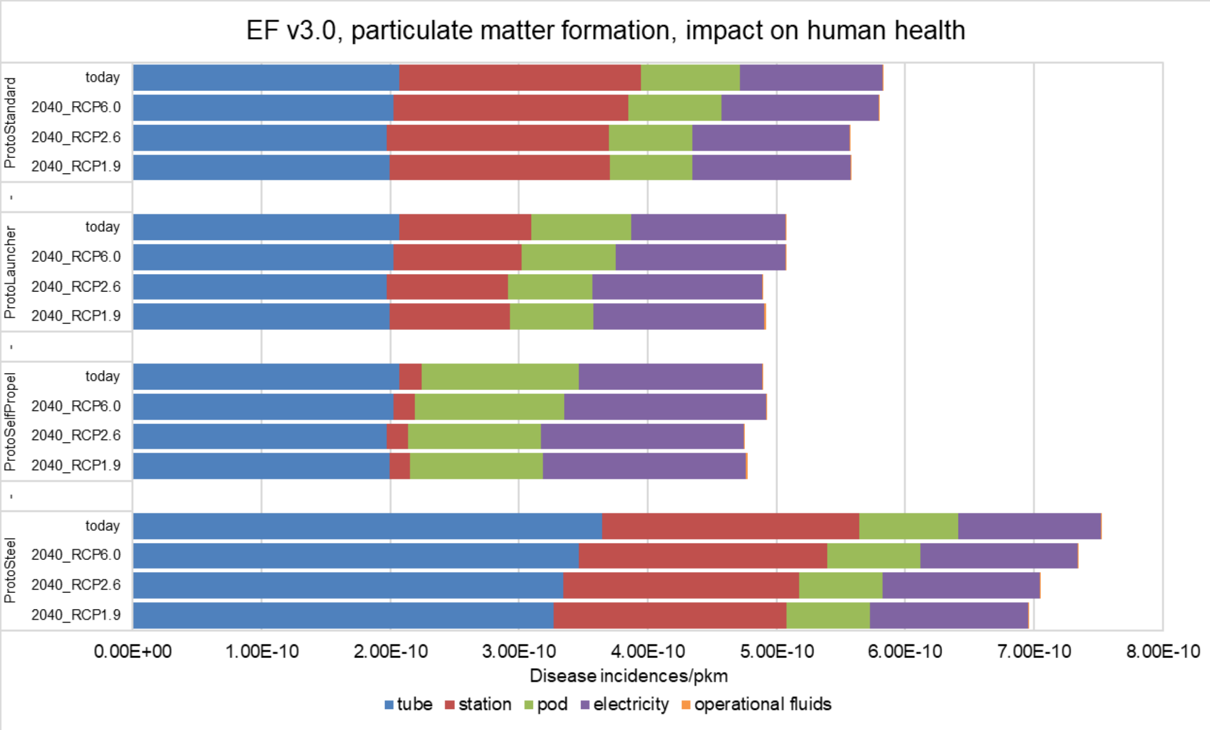

Figure 37: Impact on particulate matter formation (PMF) of the VT scenarios.

The distributions of impacts here are almost identical to those for land use. But here, about 75 % of the emissions from the stations are due to copper production, and 95 % of the pod's emissions are due to the battery.

The steel tube again performs poorly due to the share of coking for pig iron in the upstream that generates large quantities of particulate matter.

The slight reduction in the prospective scenarios comes mainly from the partial adjustments of hot pollutant emissions in premise [109]. But also, the adjustment of the prospective efficiency of the power plants and industry production as well as the higher share of renewables have an impact on the results.

#### 6.2.3.5 Acidification

The assessment of the acidification of the scenarios is shown in Figure 38. The results are presented in mol H+ eq. per pkm.

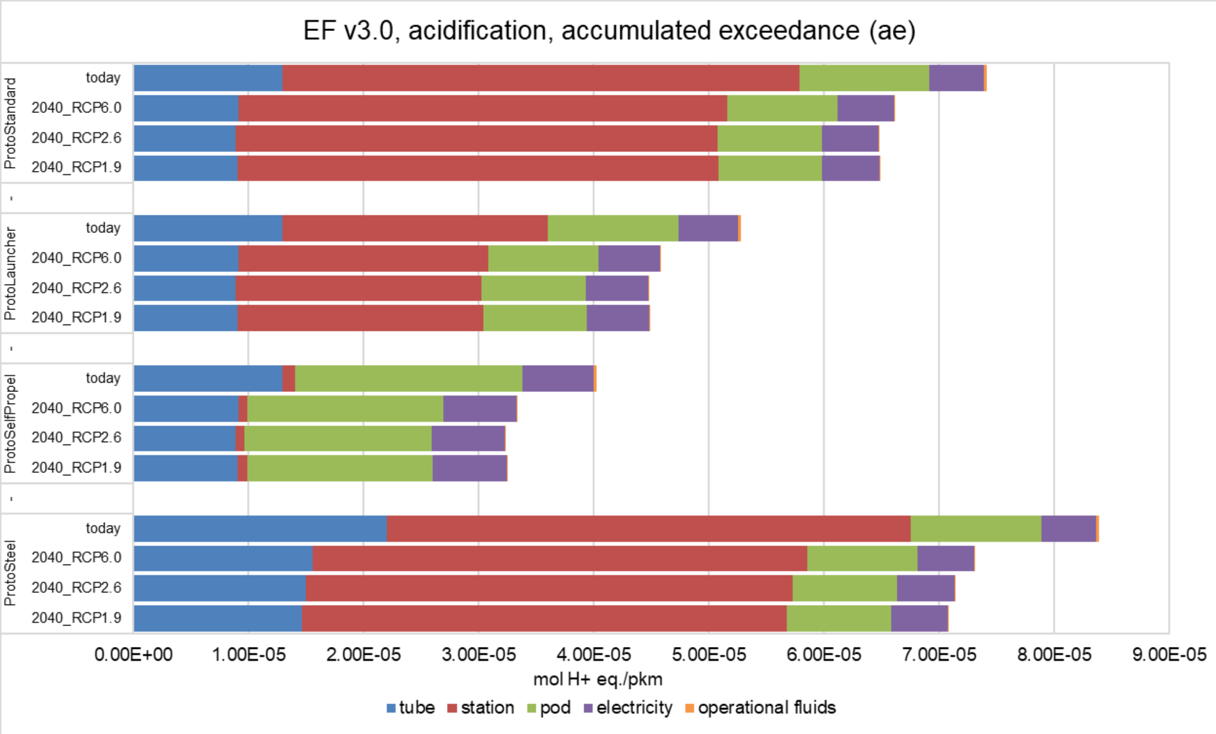


Figure 38: Impact on acidification of the VT scenarios.

Again, the distributions are roughly the same as for PMF, but that for acidification the production of copper is even more significant. A full 85% of the station is now attributable to copper production. This is because copper is mainly mined as copper sulphide, which releases high amounts of $SO_2$ into the environment during the smelting process.

In the case of the concrete tube, approx. 60 % is attributable to aluminium production and for the pods, 75 % is due to battery production. In the case of steel tube, more acidic emissions are caused by pig iron production, especially during sintering and coking. There is no significant factor that contributes to electricity in the use phase.

ProtoSelfPropel best

Overall, the ProtoSelfPropel achieves the best results here, as it does not require a copper-intensive launcher.

In the prospective scenarios, mainly less acidic emissions are emitted due to more efficient aluminium production in China. There, the higher efficiencies lead to fewer emissions in the background system.

### 6.2.3.6 Material resources: metals/minerals

The assessment of the ozone depletion of the scenarios is shown in Figure 39. The results are presented in kg antimony (Sb) eq. per pkm.

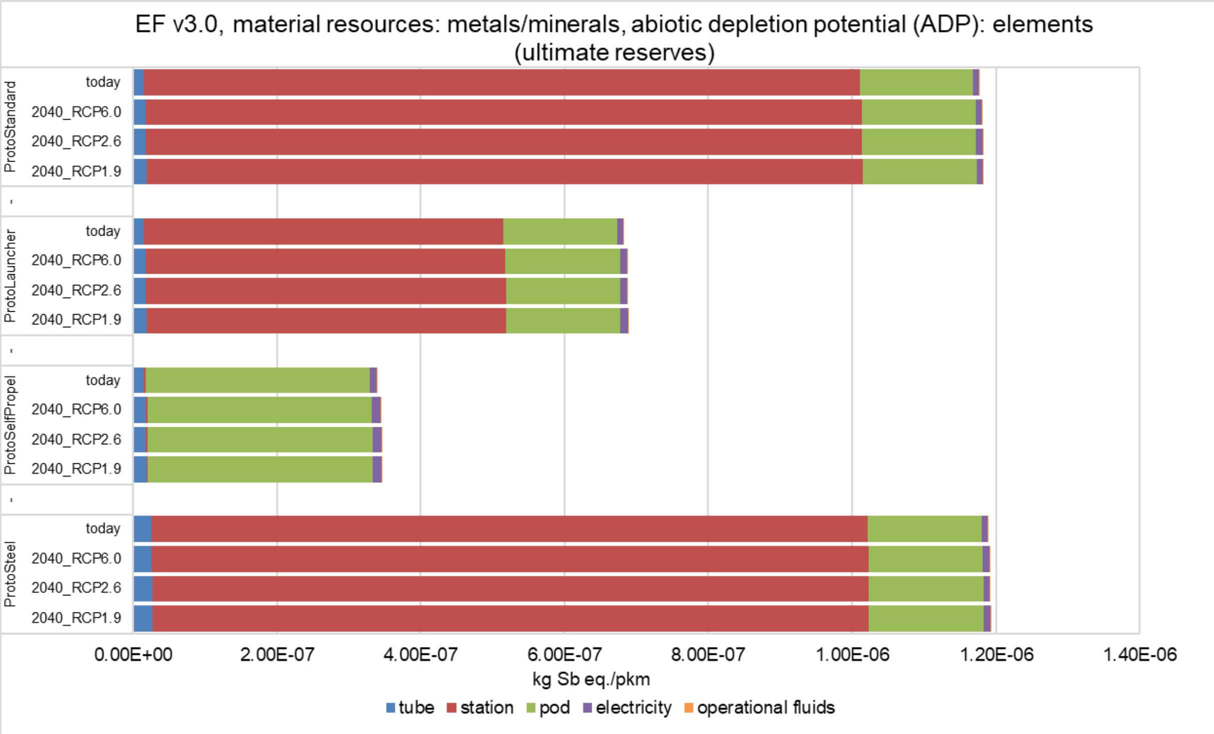


Figure 39: Impact on material resources of the VT scenarios

Copper alone accounts for about 90 % of the ADP at the stations because in this impact assessment method copper is weighted much higher than e.g., aluminium.

For the pods that are supported by launchers, about 90 % of the battery is responsible for the ADP. In the case of the ProtoSelfPropel, it is about 80 % because the larger motor with copper parts is more influential.

In the battery itself, again 50 % is due to the copper used and only about 10 % is due to nickel sulphate, 6 % for the cobalt sulphate and about 1 % for the lithium hydroxide. For the concrete tube, about 40 % is attributable to aluminium and 30 % SFRC. For the steel tube, it is about 70 % steel and 20 % aluminium. Overall, however, the tube and the power consumption can be neglected here, in relative terms.

The ProtoSelfPropel has the lowest ADP overall, due to the lower copper consumption. There are no differences here in the prospective scenarios, as premise does not yet adjust for recycling rates.

### 6.2.3.7 Human toxicity

The assessment of human toxicity of the scenarios is shown in Figure 40. The results are presented in $CTU_h$ per pkm. $CTU_h$ expresses the estimated increase in morbidity in the total human population per unit mass of the emitted chemical [110].

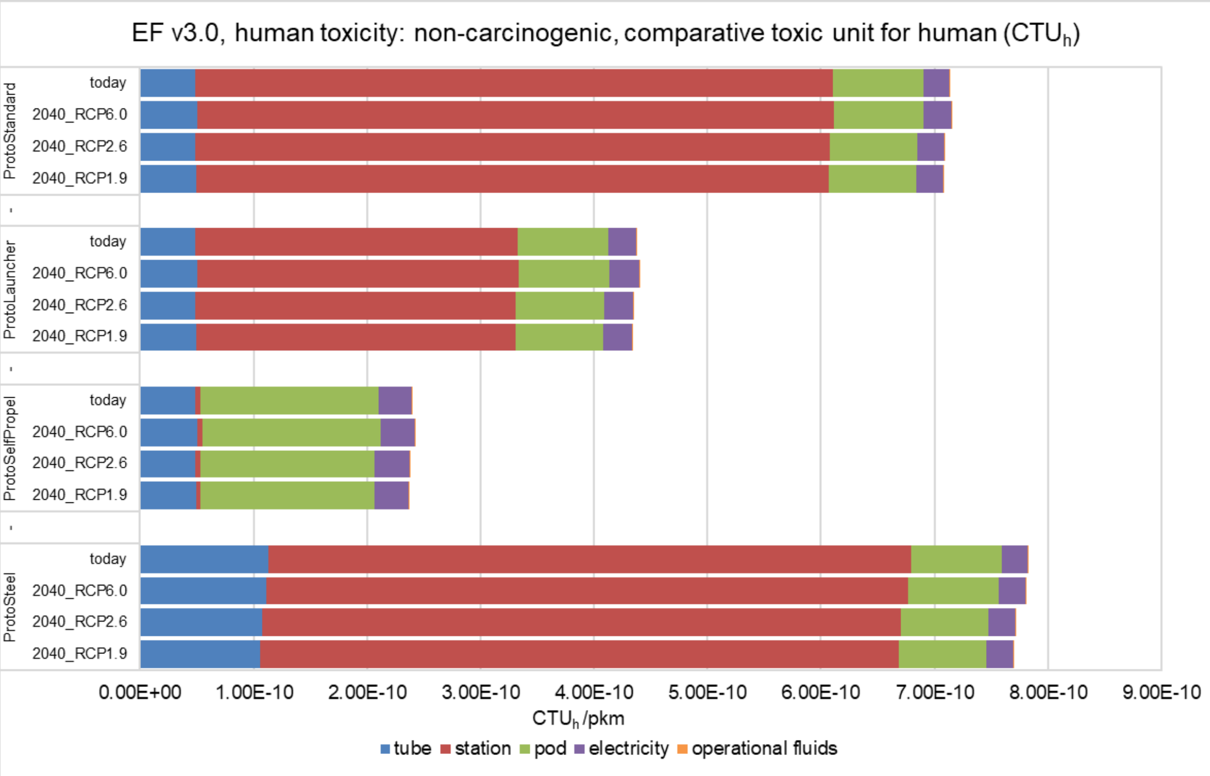


Figure 40: Impact on human toxicity of the VT scenarios

The effects here are due to the same factors as in the case of acidification (copper, battery cells and aluminium), which is why the diagrams look almost identical except for the unit. There are no major differences to the prospective scenarios, as premise does not make any direct changes regarding the toxic flows from this method. Although, as described, the efficiency of the power plants and industry are increasing, in the case of this assessment method the differences are hardly noticeable.

### 6.2.3 Cumulative Energy Demand

In the following subchapters, the CED is again divided into non-renewable and renewable as well as total and assessed. The assessment of the CED of the scenarios are shown in Figure 41–Figure 43. The results are presented in MJ per pkm.

### 6.2.3.1 Non-renewable

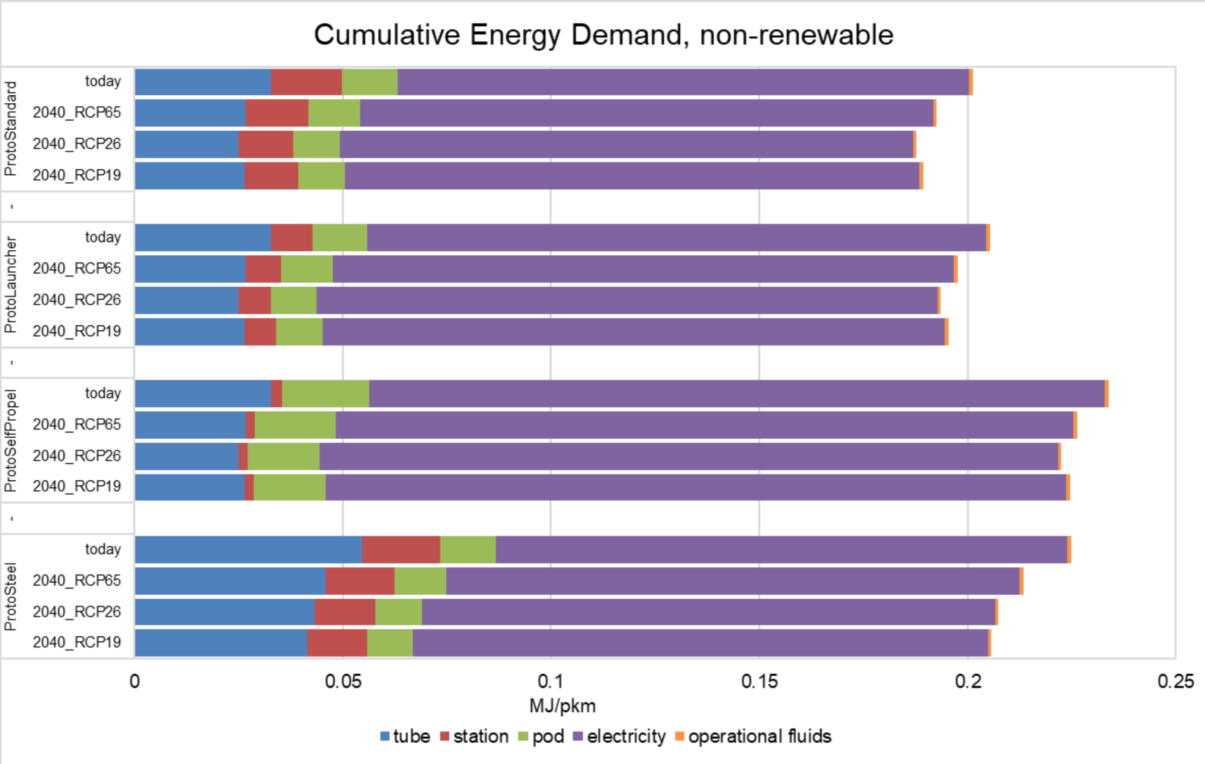


Figure 41: Non-renewable CED of the VT scenarios.

The largest share comes from the energy consumption in the use phase, which is due to the high proportion of nuclear energy. As previously mentioned, this remains the same in the use phase in all scenarios. There are no notable differences between the scenarios. However, it can be seen that in 2040 the share of fossil energy will have decreased. Overall, the ProtoSelfPropel has the highest total energy consumption due to its slightly higher energy consumption in the use phase.

#### 6.2.3.2 Renewable

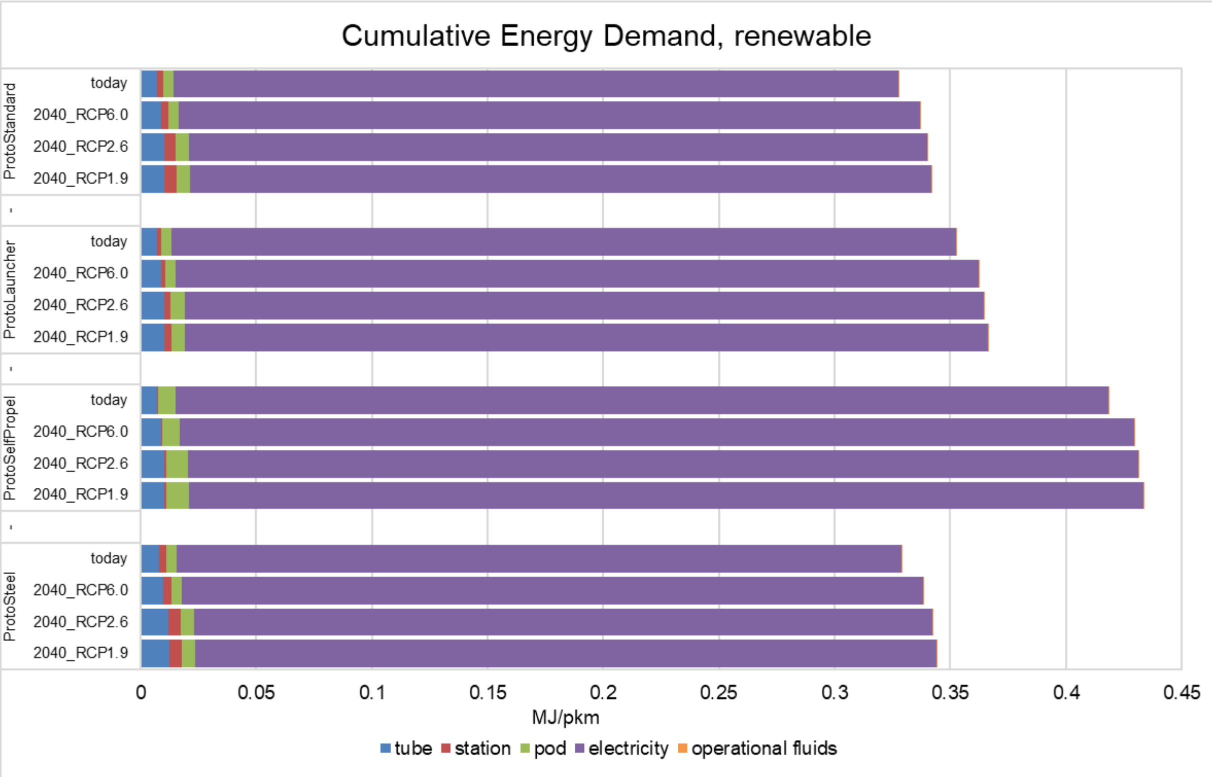


Figure 42: Renewable CED of the VT scenarios.

Here, the share in the use phase is even more significant due to the high share of renewables, especially hydropower, in the Swiss Federal Railway electricity mix. It can also be seen that in this case the share of renewable energies is increasing. However, this shift is somewhat limited due to the already fossil-free electricity mix used here.

#### 6.2.3.3 Total

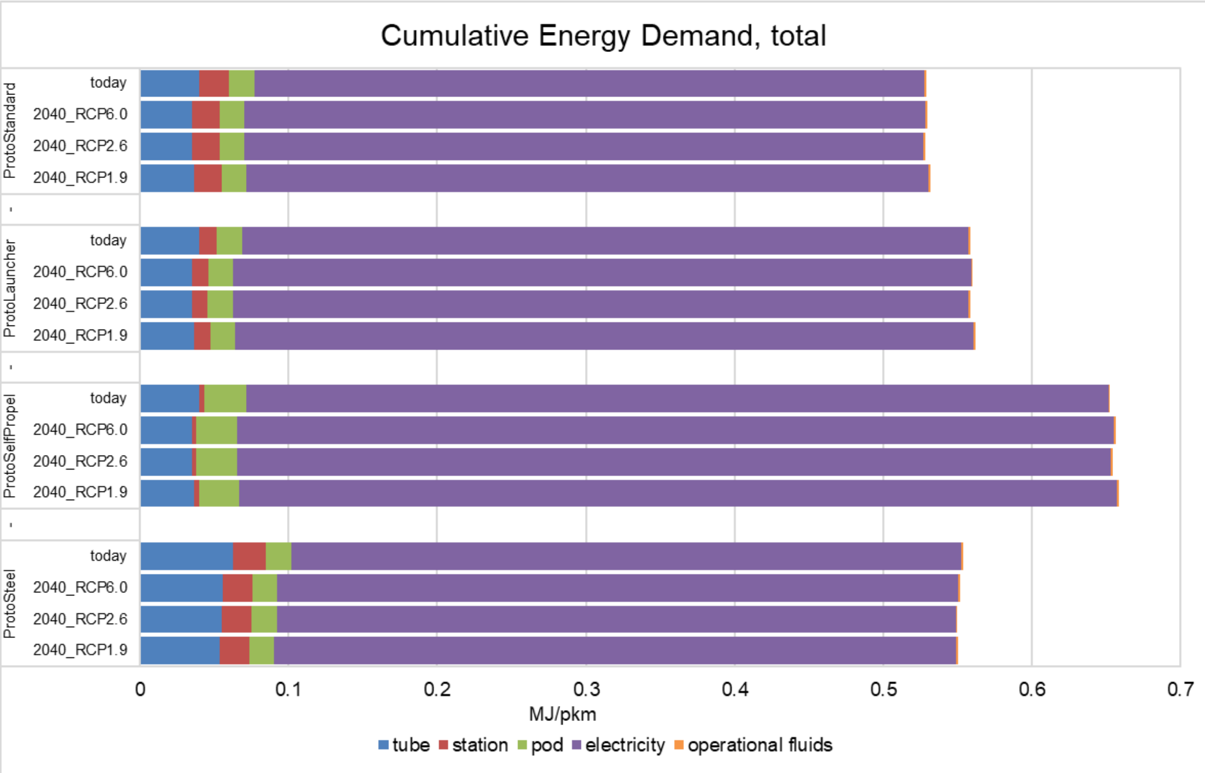


Figure 43: Total CED of the VT scenarios.

In the total CED, the ProtoStandard consumes the least energy, as it has the lowest energy consumption in the use phase due to its two launchers. The ProtoSteel achieves almost identical values but has slightly higher consumption due to the more energy-intensive steel tube. This is followed by the ProtoLauncher and ProtoSelfPropel, which in the same order also have higher energy consumption in the use phase. There are no differences worth mentioning in the different RCP scenarios, as the difference in non-renewable and renewable balances out and the higher future energy efficiencies in the background system are hardly noticeable due to the electricity mix used in the foreground system.

### 6.3 Comparison of life cycle impact assessment results

To summarise and provide a better overview, all impact assessment results were compared again (see Figure 44). For the different methods to be comparable with each other, all impacts of ProtoStandard were set at 100 % as a reference and the other scenarios were compared in relation to this reference. This is for comparability purposes only and is not intended to imply any weighting. Since there are no remarkable differences in the impacts of the prospective scenarios with regards to the differences of the current ones, it shall suffice at this point to compare the scenarios of today.

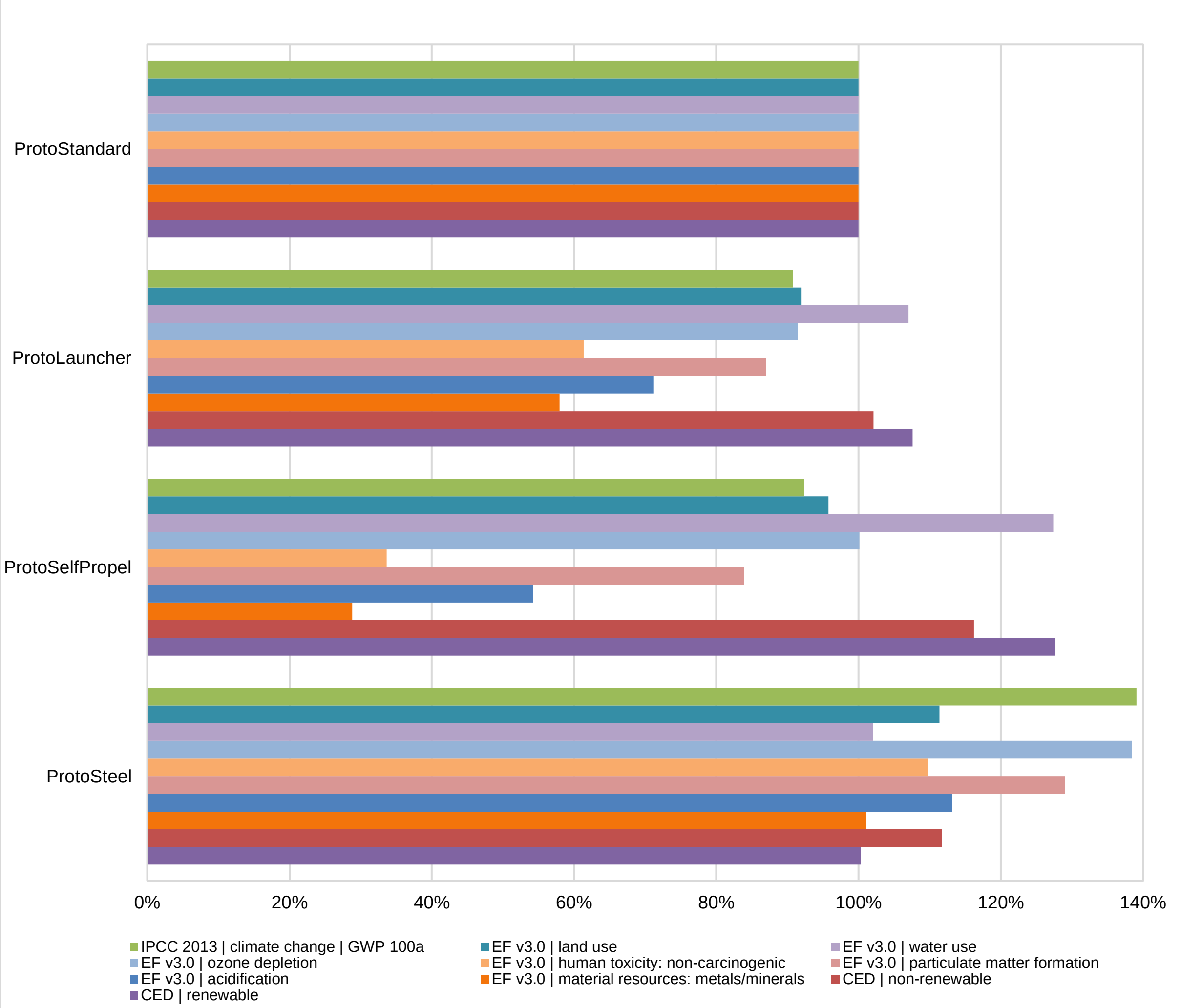


Figure 44: Comparison of the different impacts of the scenarios with the background data from today

It can be seen that no scenario has the lowest or highest impact in all methods. However, ProtoLauncher and ProtoSelfPropel have the lowest impacts in everything except for Water Use and CED. In contrast, the ProtoSteel has the highest impact in the remaining methods. The ProtoStandard has an average performance when compared to the other three scenarios in most impacts. It performs best in water consumption and CED.

Ultimately, it is not possible to say which scenario achieves the best results, but rather to provide guidance for individual weighting or prioritisation.

## 6.4 Acceleration on the track-side vs. pod-side

A pivotal question is whether acceleration is superior on the pod or on the track. The self-propelled pod must be equipped with both a more powerful LIM to accelerate to its maximum speed and a larger battery to provide the required energy. This results in a heavier pod that consumes additional energy (see chapter 6.2.3), especially for acceleration and levitation due to greater inertia and mass respectively. Other sources of additional energy consumption are the greater electromagnetic drag due to the greater lift required and thermal management due to the heat loss associated with the additional energy flow. It is therefore clear that the track-side version is more efficient from an operating energy point of view. However, this requires a large track-side motor that has to cover the entire distance the pod travels during acceleration; in contrast to the pod-side motor, which is just on board.

In order to make the effects of pod-side and track-side acceleration more visible, the environmental impacts of the four construction scenarios will be analysed in more detail (see Figure 45). Since the focus is on the relative impacts, the prospective scenarios do not need to be considered here. In addition, the GWP should suffice here, as this has the highest priority in this project. As a recap on the quantity of launchers in terms of system designs, Table 4 and Table 13 can be consulted.

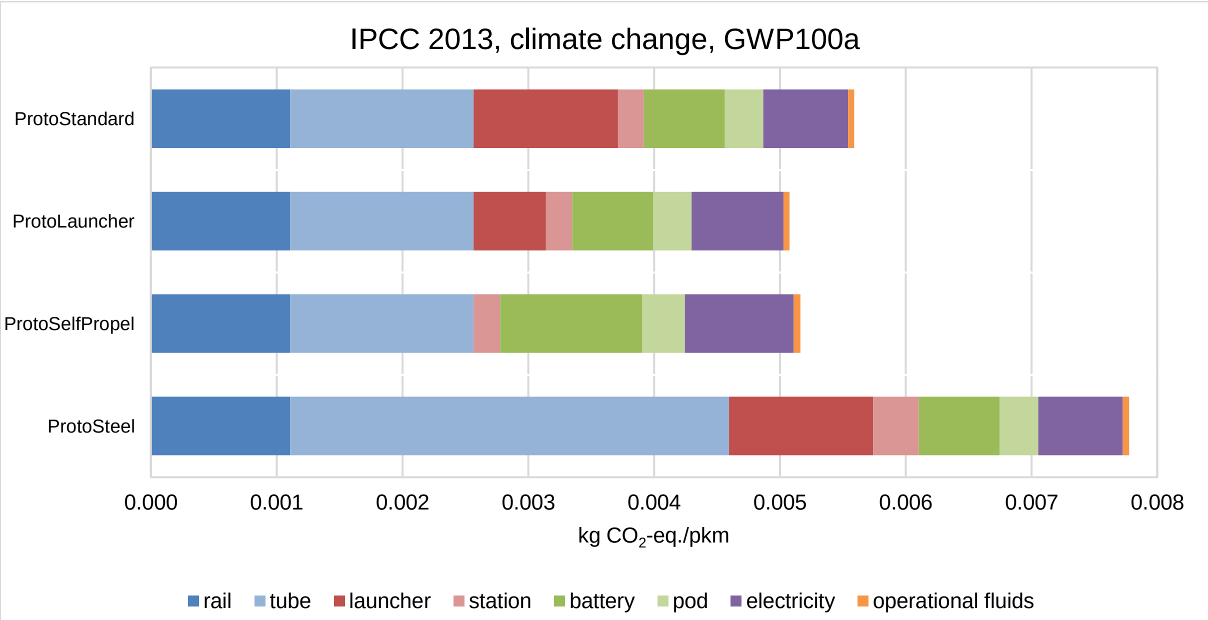


Figure 45: Impact on GWP of track-side vs. pod-side acceleration with the background data from today; the rail's share of the tube, the share of the rail on the tube, the share of the launcher on the station and the share of the battery on the pod can now be seen in the darker shade.

The overall impacts of the design with pod-side acceleration and the design with a single launcher are very similar because the savings from not using the launcher are offset by the increased demand for LIM and battery capacity. However, it should be noted again that the absolute difference would be greater with a more GHG-intensive electricity mix in the use phase, which was also indirectly shown in the CED assessment. Overall, under the current assumptions made here, the GWP optimum is therefore when using only one launcher and no recuperator.

## 6.5 Comparison of results in ecoinvent

This chapter aims to compare VT with railway and aviation transport. First, all impact categories are compared and then a detailed assessment of the GWP is made.

### 6.5.1 Relative comparison

For aviation, two comparisons are made: with conventional kerosene and with synthetic kerosene. The aircraft transport with the synthetic kerosene was modelled according to Treyer et al. [111] and the corresponding fuel itself was produced via Fischer-Tropsch synthesis and water electrolysis, the $CO_2$ comes from Direct Air Capture (DAC), and the heat demand is provided by heat pumps. The entire electricity demand for e-kerosene production is supplied by wind energy, while local electricity is used for all other modes of operation, assuming in particular the current consumption mix of the Swiss Federal Railways. All extraction and conversion processes performed ahead of the transport service are also assumed to use today's technology and energy mix. In addition, a short distance was selected as the flight, which is represented as a distance of 800–1500 km in ecoinvent. There is also a very short haul flight of <800 km, which would be more comparable to the typical Hyperloop distances of 300–1000 km, but for an impartial assessment, the more efficient short-haul aircrafts are used for comparison.
Figure 46 compares the ProtoStandard, the Swiss long-distance train and the two described aircraft in all methods used in this LCA. All impacts of ProtoStandard were again normalised to 100 % for reference. Figure 47 and Figure 48 represent the enlarged sections respectively.

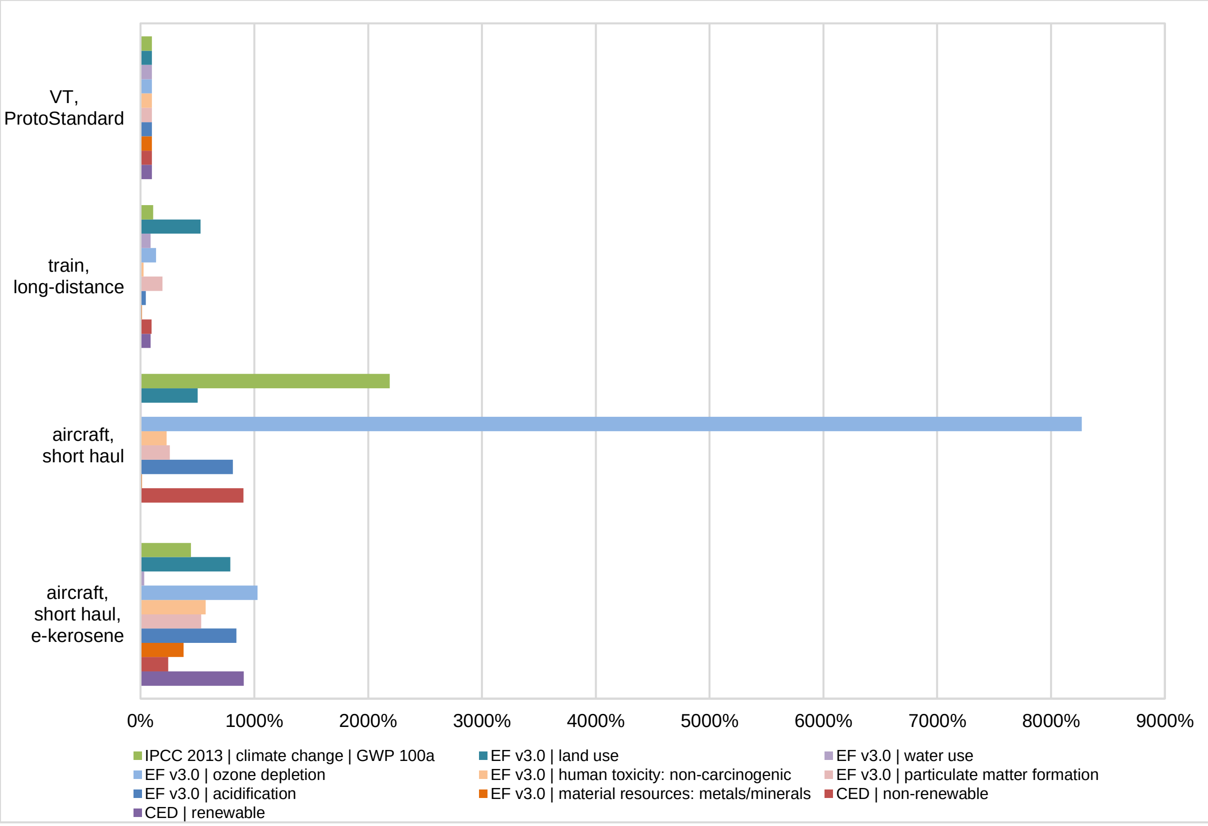


Figure 46: Comparison of the different impacts of several transport systems with the background data from today.

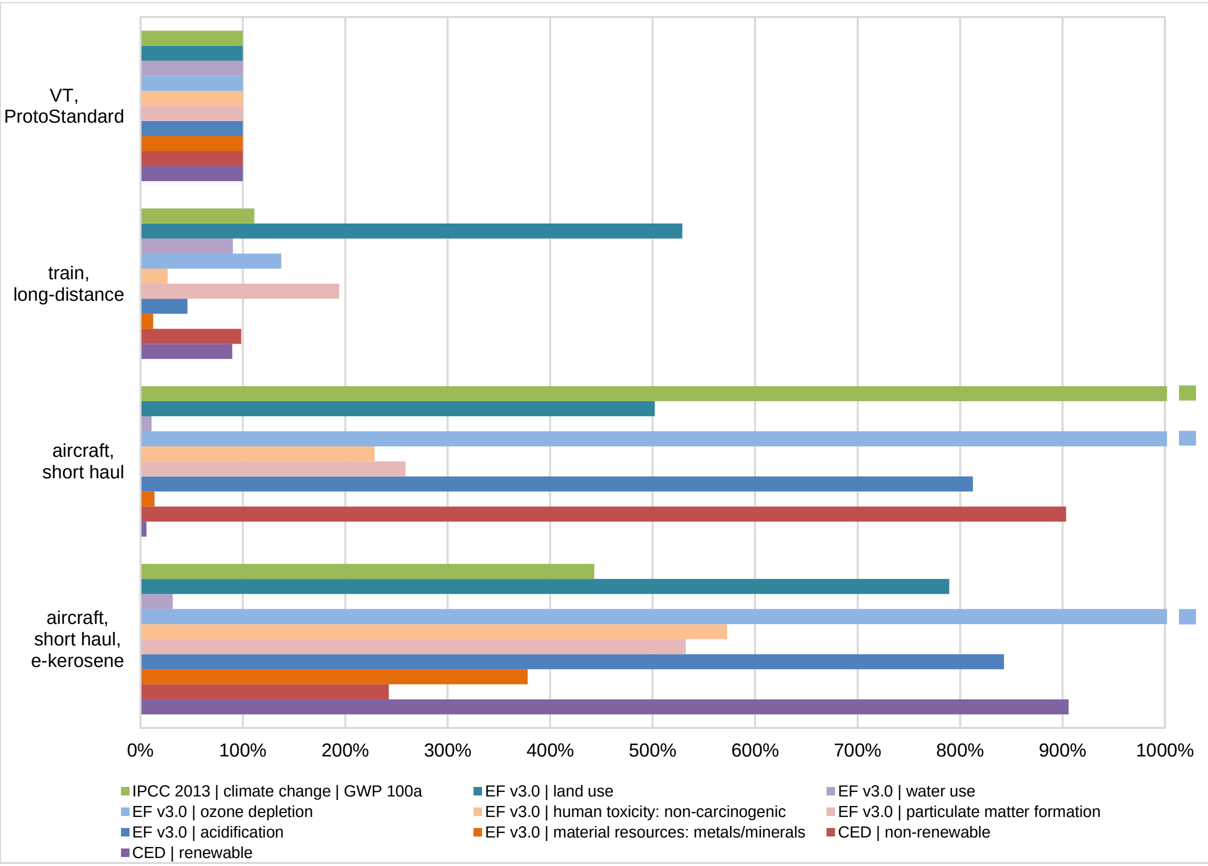


Figure 47: Comparison of the different impacts of several transport systems with the background data from today. Enlarged section between 0 and 1000 %.

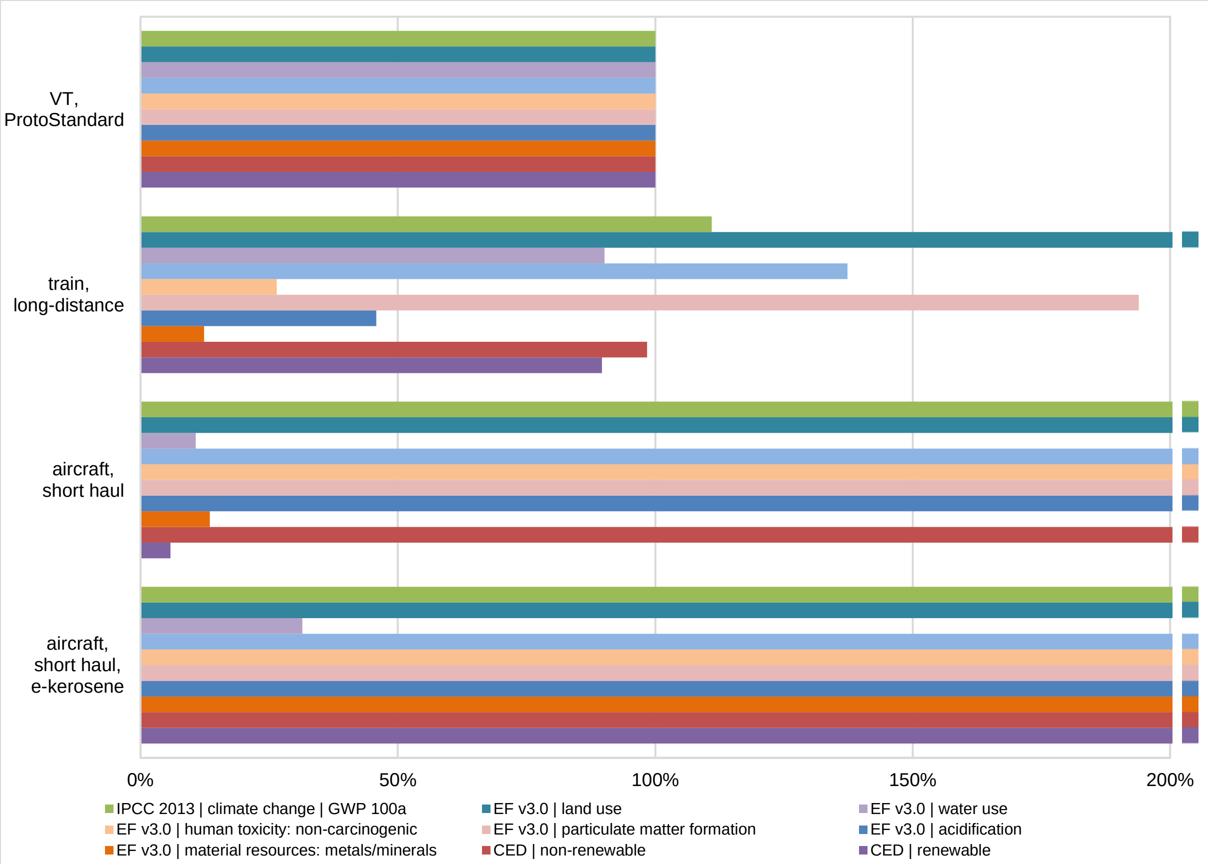


Figure 48: Comparison of the different impacts of several transport systems with the background data from today. Enlarged section between 0 and 200 %.

The conventional aircraft has the greatest environmental impact, particularly due to the combustion of fossil fuels while they are being operated. The use of fossil fuels combined with the very high energy demand results in the worst GWP and also to an apparently high ozone depletion potential due to petroleum production. Even land consumption is significantly higher for aircraft due to the land-intensive airport and onshore wells for petroleum or, in the case of synthetic kerosene, the wind power plants. In terms of water consumption, the ProtoStandard achieves worse results than the two aircraft, but this is almost exclusively due to Switzerland's water-intensive electricity mix. Furthermore, the conventional aircraft consumes significantly less metals and minerals than the copper-intensive VT system.

The train scores worse than the ProtoStandard in the categories GWP, land use, ozone depletion and PMF. In the case of land use, by a considerable factor of 5.3, as it mainly transits on the ground and for the PMF by a factor of 1.9, mainly due to the abrasion of the tracks. On the other hand, it achieves much better results in terms of human toxicity, acidification, and material resources, especially because it does not require as many critical metals as copper.

### 6.5.2 Breakdown of the GWP

For each transport mode, the GWP is broken down by emission source: Infrastructure (stations, airports, tubes, rails), vehicles (pods, aircrafts, trains), electricity during operation (and as feedstock for e-kerosene), fuel supply chain (production and distribution) and operation emissions ($CO_2$, $SF_6$, refrigerants, etc.)[31].
It should be noted that for some subsystems it is difficult to establish the same system boundaries as for other transport systems. For example, strictly speaking, the (wind) energy used here is also partly present in the fuel supply chain of e-kerosene. However, this is only intended to be a rough comparison of the partial life cycles and should suffice at this point.

The comparison of the GWP between VT and other modes of transport is shown in Figure 49.

[31] Non-$CO_2$ climate forcers like cirrus clouds are excluded from most LCI databases such as ecoinvent due to the large range of uncertainties that still exist today.

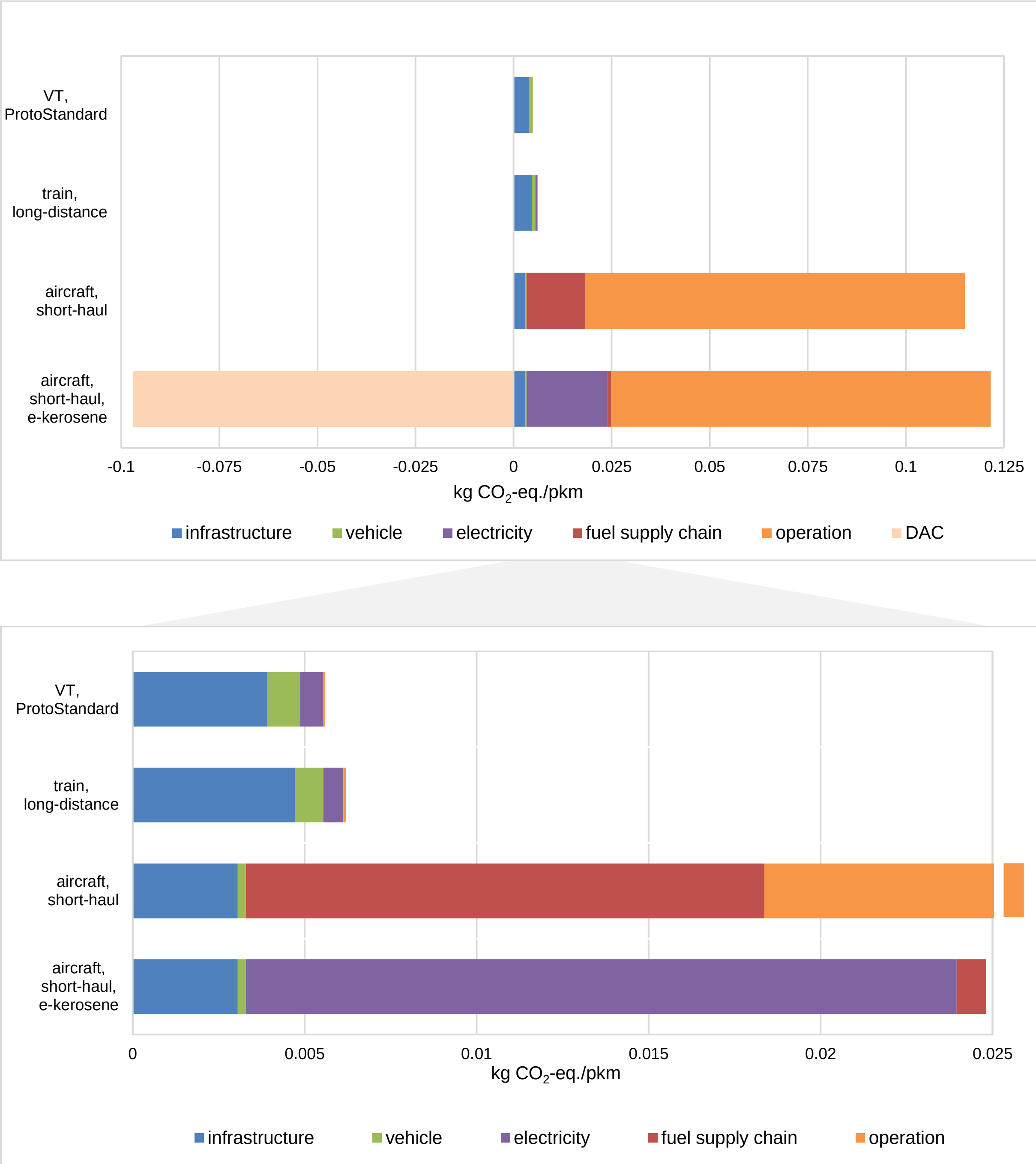


Figure 49: Impacts on the GWP of different transport systems with the background data from today. The bottom graph shows an enlarged section of the graph above between 0 and 25 g $CO_2$-eq./pkm. For e-kerosene aircraft, the $CO_2$-eq. absorbed by DAC can be subtracted from the $CO_2$ emitted during operation.

For clarity, the bottom graph of Figure 49 cancels out these two components of the life cycle.

The environmental impact of the aircraft itself is better than that of trains and the pod in the life cycle of the vehicles, mainly due to the large number of pkm that aircraft cover during their lifetime, which distributes the footprint among more passengers. The pod of the VT system particularly shows a significant footprint, and this is primarily due to the central role the electric batteries have in the pod life cycle. The train has an impact comparable to that of the pod. Although it does not require emission-intensive batteries, its lifetime pkm is lower than the expected lifetime pkm of the pod.

Aircraft powered by e-kerosene solve the fossil fuel problem, as the $CO_2$ emitted while in use is equal to the $CO_2$ absorbed by DAC to produce the fuel. Furthermore, due to the low conversion of electricity to fuel, the net electricity consumption of these aircraft is much higher for e-kerosene than for trains or VT systems. Even if all the electricity is generated from wind turbines, e-kerosene aircraft will be at a severe disadvantage in the total GWP[32].

The infrastructural footprint is surprisingly similar for all transport systems. In the case of air transport, airports still require large areas of land and consume a lot of energy for their ground operations. In addition to electricity and heating, airports also need to include maintenance and clearing operations. However, it should be noted again that in ecoinvent the maintenance of the aircraft is partly allocated to the airport. The difference between the railway and the VT infrastructure is primarily due to the assumed utilisation of the routes and the resulting lifetime pkm. The utilisation factor for long-distance trains in Switzerland is 28 %, while a utilisation of 80 % is assumed for the VT system. While the latter is decidedly optimistic, the higher modularity of the vehicles and the more frequent departures could allow for a timetable better adapted to demand and a higher load factor. Moreover, load factors of 80 % are typical for air transport [112] and are used in ecoinvent [113].

For a more appropriate comparison of the impact of the infrastructure, Figure 50 shows the GWP per m*a of railway track, concrete tube, and steel tube.

[32] It should be noted that the electric mix used by the Swiss Federal Railways employed by trains and the VT system is also extremely clean (7.8 $gCO_2$-eq/kWh), hence comparable with wind power (14 $gCO_2$-eq/kWh).

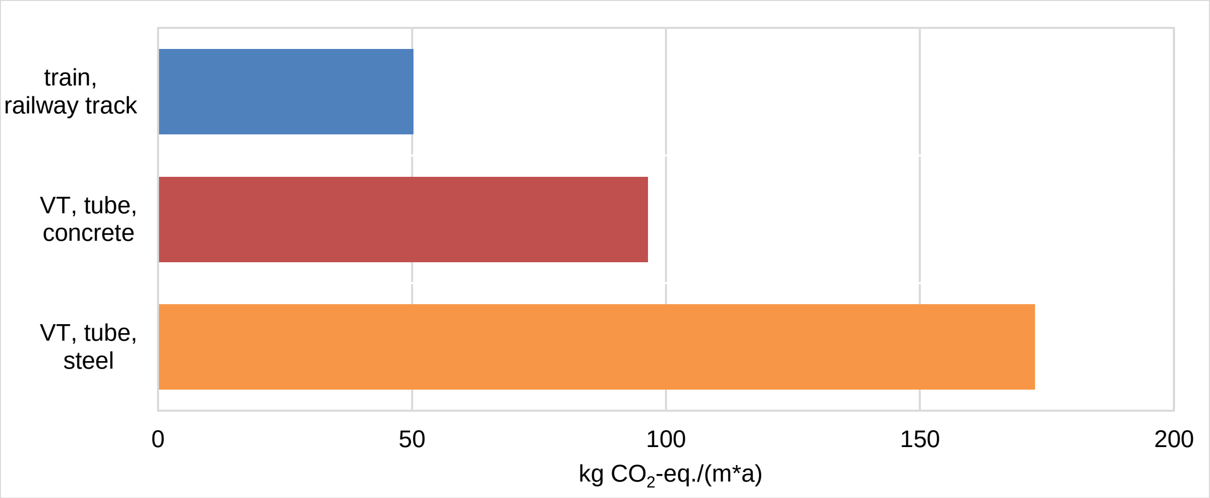

Figure 50: Environmental impact on GWP of railway track, concrete tube, and steel tube

The less material-intensive railway track has a significantly lower GWP than the VT tube per metre. Nevertheless, the difference is kept within limits, so that a more intensive use of the VT infrastructure pays off the environmental investment in the infrastructure, as can be seen in Figure 49. The differences in the environmental impacts of concrete and steel tube have already been discussed. However, it should be noted that detailed dynamic analyses of the material performance under the specific stresses first need to be carried out by the ETF before final conclusions can be drawn.

# 7. Interpretation

In this chapter, the LCA is concluded by the following interpretation of the results. Thereby, the components described in chapter 3.4.

## 7.1 Sensitivity analysis

The sensitivity of the selection of the material has already been shown indirectly through the different scenarios selected. However, the electricity consumption in the use phase has a particularly large influence on the whole life cycle. Therefore, this should be examined again in a best-case and worst-case scenario, which is also recommended by the eLCAr guidelines.
At the same time, this chapter should help to increase the comparability of the other transport systems and to examine them in more detail. The sensitivities should be sufficient for this subchapter on the basis of their GWP, as it has the highest priority in this project and especially in the case of the electricity mix, which has one of the highest sensitivities and is therefore well suited.

### 7.1.1 Electricity mix

For this purpose, a value was calculated with a low and a high GHG electricity mix and a linear function was derived from this (see Figure 51). For comparison with other transport systems, the ProtoStandard was compared with the Swiss long-distance train, conventional aircraft transports with different distances and the e-kerosene powered aircraft transport described in chapter 6.5. The aircraft with conventional fuel are independent of the foreground electricity mix here. Although electricity is used at the airport itself for maintenance etc., this is difficult to allocate and would also have only a marginal overall influence on the total life cycle. For reference, the GHG of the high-voltage electricity mixes for Switzerland, Europe and Swiss hydropower are also shown. It should be noted that the GHG balancing of country-specific electricity mixes is often discussed controversially [114] [115] [116], but only the values from ecoinvent were taken over for consistency, which should suffice for a rough classification.

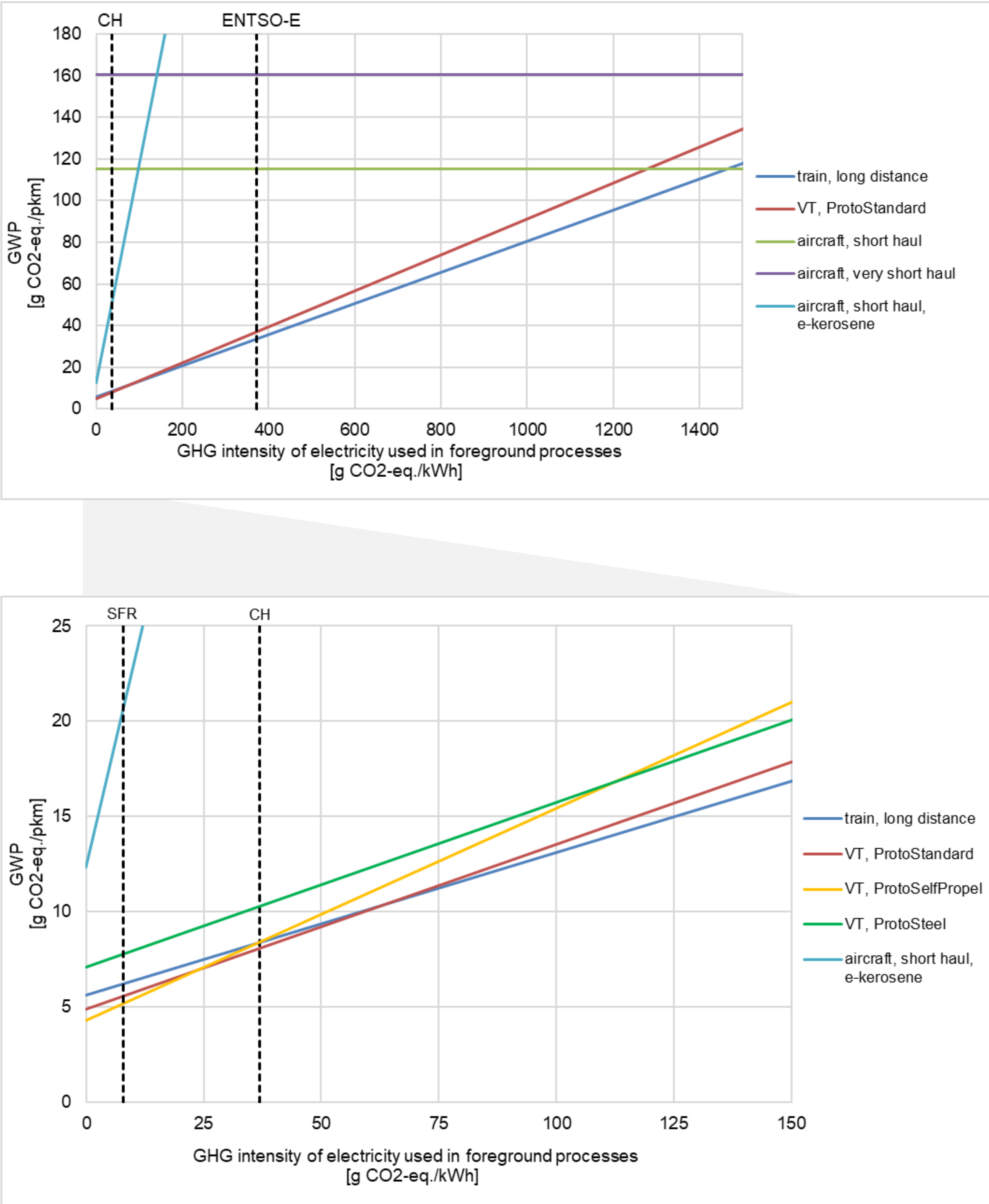


Figure 51: Performance on GWP100a of the 1 pkm in relation to the input electricity. The bottom graph is an enlarged version of the upper graph and contains two additional VT systems. CH = Switzerland; ENTSO-E = European Network of Transmission System Operators for Electricity; SFR = Swiss federal railways.

The VT system and train show similar trends due to their common dependency on electricity shown in Figure 49. Their higher efficiency compared to aviation is such that grid GHG intensities and more than 1250 g $CO_2$-eq./kWh (emissions from a lignite-fired power plant) are required to reach GWP parity. In the Swiss or European electricity mix, both VT and train dramatically outperform aviation. This is also true when synthetic jet fuel is used, as the low life cycle efficiency of e-kerosene has a multiplier effect on the GHG intensity of electricity.

Variations of the VT system have only a minor influence on the overall performance.

In the case of the Swiss electricity mix, the train and the ProtoSelfPropel achieve parity and, at over 60 g $CO_2$-eq./kWh, likewise with the ProtoStandard, thus achieving the lowest GWP compared to all transport systems. The ProtoSteel, on the other hand, always achieves worse values than to the train. The ProtoSelfPropel achieves the lowest GWP up to 25 g $CO_2$-eq./kWh and even reaches parity with the ProtoSteel at around 110 g $CO_2$-eq./kWh because of its lower energy efficiency.

Overall, shifting the acceleration from track-side to pod-side results in the cleanest system when electricity is provided at extremely low GHG intensity, but it quickly deteriorates at higher carbon intensities due to lower system efficiency. Figure 51 clearly shows that the impacts of electricity mixes can differ extremely and has a strong influence on the overall performance of the LCA.

### 7.1.2 Occupancy rate

As the transport systems are difficult to compare if they have different occupancy rates and this is crucial for the overall performance, this chapter aims to analyse the sensitivity of these.

In order to make a thorough comparison, however, one would have to determine a function depending on the mass for all transport systems, since the total mass changes depending on the load and therefore the overall performance. However, as this exceeds the scope of this paper, it is assumed here, for simplification, that the change in passenger weight has no influence on the overall performance of the transport systems. It should be noted, however, that the aircraft in particular is more negatively affected by passenger weight than the train [117] and the Hyperloop. Therefore, a simple scaling of the assessment of the GWP is shown in Figure 52.

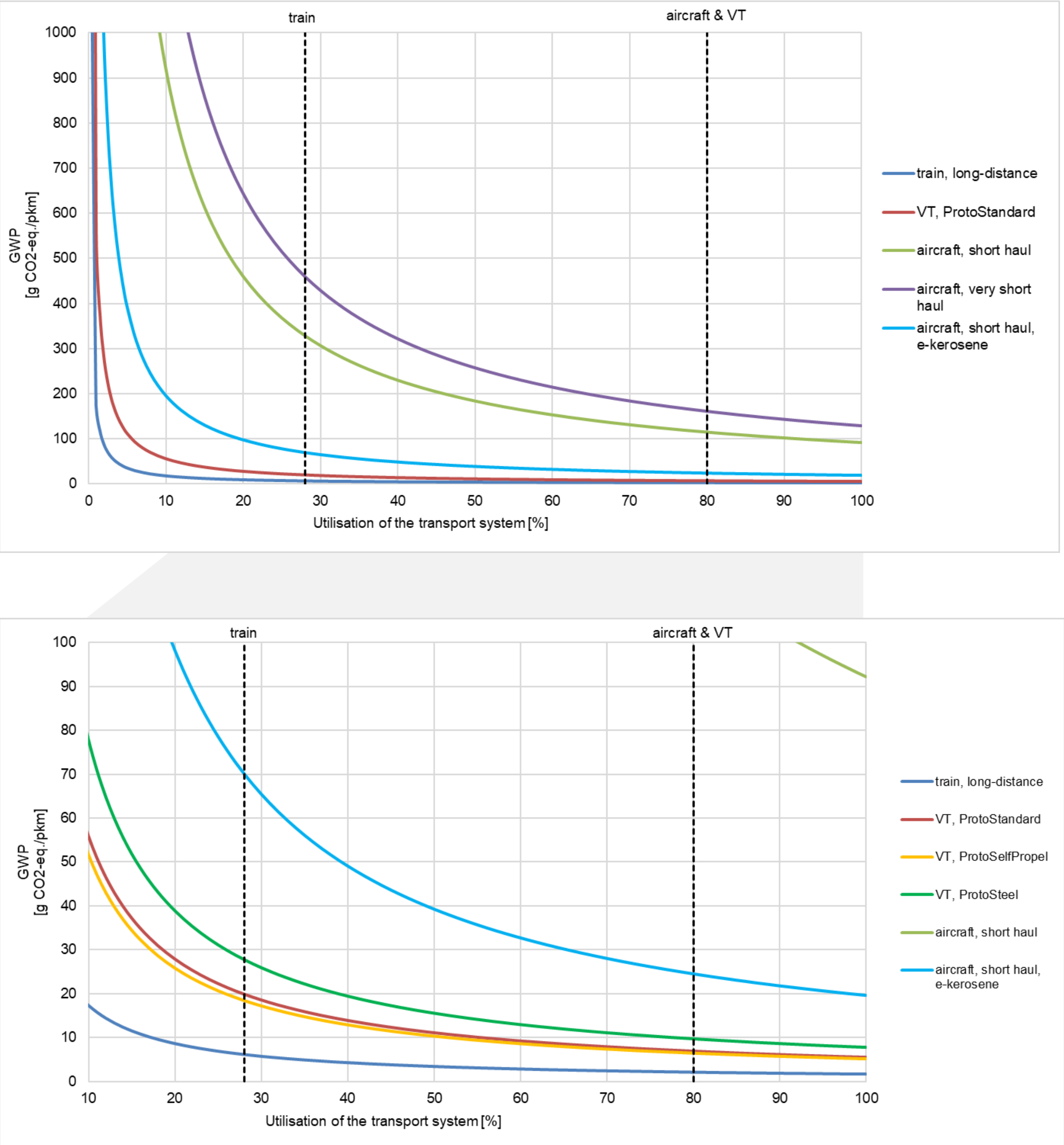

Figure 52: Comparison of the GWP100a of the different transport systems depending on the occupancy rate. The bottom graph is an enlarged version of the upper graph and contains two additional VT systems

If all transport systems have the same occupancy rate, then the train clearly has the lowest GWP. Even at a low load factor of about 25 %, the VT systems, apart from ProtoSteel, would still perform better than the fully occupied e-kerosene-powered aircraft. At full utilisation, the conventional aircraft performs several times worse than the train and VT system with a very low load of e.g., 10 %.

### 7.1.3 Monte Carlo Simulation

Using the ProtoStandard as an example, a Monte Carlo Simulation (MCS) is carried out in the Activity Browser (see Figure 53). Since the relative distributions in the other design scenarios are almost identical, the consideration of a VT system is sufficient here. Furthermore, the prospective scenarios do not need to be considered either, as no uncertainties have been linked to the premise data, as the data is, in principle, a projection.

It is very difficult to define concrete uncertainties for such a prospective system as this, as it is still in the design phase. It was therefore agreed with the ETF to assume a maximum deviation of ± 20 % of the individual components of the foreground system. Therefore, a lognormal distribution was assumed for each flow, with a sigma of 0.06, where the mean is the respective reported flow value. Lognormal distributions are easier to handle in the Activity Browser and ecoinvent uses them, in most cases, for their background system as well [118], mainly because it is not defined in the negative range [119], so that there are no accidental credits in an MCS.

The MCS was performed with 1,000 iterations and includes technosphere, biosphere and characterization factors, thus both background and foreground systems are fully considered. It can be debated whether 1,000 iterations are sufficient [120], but since this is only a rough analysis based on the many assumptions made, this should suffice here.

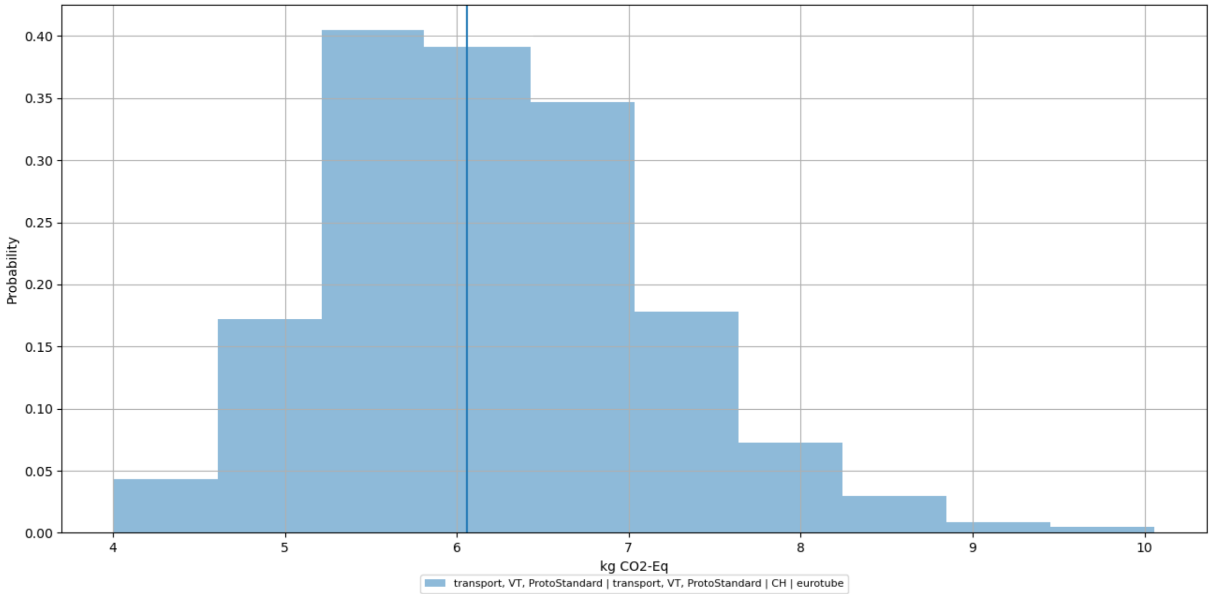


Figure 53: MCS of the GWP from the ProtoStandard with the background data of Today; blue line = average value

The mean value is above the median value (static value from LCIA), which is to be expected with a more lognormal distribution. The sigma has now increased due to the background data and the 2.5th (lower bound) percentile lies at about 4.6 g $CO_2$-eq./pkm and the 97.5th (upper bound) percentile lies at about 8.3 g $CO_2$-eq./pkm.
Overall, the MCS represents the expected lognormal distribution, which is, however, based on rough estimates, whereby the significance may be questioned. Nevertheless, it is worth mentioning that even the highest MCS values of the ProtoStandard are still much lower than the results of e-kerosene and especially fossil kerosene aircraft.

### 7.2 Significant parameters

The greatest influence on the LCA is the assumed utilisation or the transported lifetime passenger count of the VT systems, as shown in chapter 7.1.2, among others. Due to the assumptions made here, the high environmental investment costs are distributed over such a high number of passengers that they are amortised.
The second largest significant parameter is the chosen electricity mix. In the almost optimal scenario with the electricity mix from Swiss Federal Railways, only about 10 % of the total GWP is attributable to this mix. However, if the electricity mix from e.g., East India (almost exclusively coal-based) were used, about 95 % of the total GHG emissions would be attributable to it.

In many impact methods, especially the GWP, the tube as a subsystem has the highest impact under the assumptions made here. In particular, the aluminium used, and the clinker required for the cement have the greatest impact in the case of the concrete tube, for the steel tube on the other hand, it is mainly the pig iron for the steel used that has the greatest impact.

The influence of the station varies greatly depending on the method used. In the few methods used here, the effects are almost entirely due to the station's high copper demand. It can be shown that there are considerable differences in the dimension of the launcher or recuperator. The pod, with its battery, has a smaller impact in the overall life cycle in most LCIA methods and scenarios. The fuselage itself is almost negligible in relative terms. The exception here is the ProtoSelfPropel, which requires a higher battery capacity, therefore making the impact here higher. However, the greater influence in the overall life cycle pays off in all impact methods, as the impact of the launcher and recuperator is being more than compensated for.

What remains are the operational fluids, which are basically negligible in relation to the rest of the overall system in all methods.

## 7.3 Completeness and consistency

Every effort was made to obtain and process as much data as possible. Nevertheless, assumptions had to be made at several points, or alternative datasets had to be implemented because not all the desired processes could be realised, due to the prospective nature of the LCA.

Very accurate data could be obtained for the cement and concrete production, as the primary data were directly available here. The remaining materials were either scaled up accordingly from existing, but on a much smaller scale, subsystems or taken from the literature. The associated production flows were almost completely taken over by ecoinvent from similar systems and scaled where necessary. The exception is the Superconductor, Hastelloy C276, Silicon Steel and the recycling of CFRP, where secondary data other than ecoinvent was used, none of which showed a significant impact on the overall performance. In addition, the battery from premise was used, which, however, is in principle only a slight modification of the battery from ecoinvent.

In the EOL, simplifications had to be made that will probably not reflect reality in the future, as much higher recycling rates are to be expected compared to today. The appropriate recycling processes are not available in the databases and could only have been modelled under rough assumptions. In order to ensure comparability, it was decided to use the market activities from ecoinvent or to make a cut-off if only incineration or landfill processes were available in ecoinvent, as these are likely to be less common in 2065 and later to be able to meet the climate goals [121]. Especially in the case of aluminium, concrete, copper and steel, a higher assumed recycling rate would significantly improve the LCA results.

As described in chapter 5.2.1, the «right» choice of electricity mix is difficult to estimate and there is a small inconsistency between the electricity mix used and the EP2050+ in relation to nuclear power. However, several future scenarios were assessed, and a detailed sensitivity analysis was made with regard to the electricity mix. In addition, the nuclear share is to be compensated in the future mainly with photovoltaics in Switzerland, which is why there would be little change for most impact methods.

Furthermore, it was assumed, in this LCA, that the infrastructure would be used exclusively for passengers. However, it is planned to transport goods at night, as demand is lower at this time. This has not yet been considered and would reduce the environmental impact, as part of the infrastructure would also be allocated to the transport of goods, just as with trains and aircraft.

The crucial parts of the VT system were modelled. However, the thermal management and HVAC system were simplified. Moreover, the flux pump and the life support system were not considered. The life support system for the VT system has yet to be developed by the ETF, in principle the system used in submarines could be used. However, there would have been no significant impact on the overall performance if they had been considered, especially since at least all critical elements and energy flows were considered.

Allocation in the self-created models was fully avoided and, in case of doubt, decided to the disadvantage of the main product and documented in each case.

Overall, when assumptions were made, they were made with caution in all cases in order not to unfairly inflate the results.

## 7.4 Conclusions, limitations, and recommendations

Overall, informative results were achieved. Some points could be studied in more detail in further work.

The choice of the cut-off allocation in this LCA has been a very conservative assumption. It would be interesting to expand the disposal phase, in order to be able to depict the future under different scenarios. However, for a fair comparison, the EOL for trains and aircraft would have to be adjusted accordingly. Though, the impact of the EOL is still small relative to the current overall life cycle.

A limitation is the fact that only the cut-off system model was used to make all calculations. However, this is currently the only way to ensure compatibility with premise. Especially with regards to a deeper consideration of the EOL, a consideration of other system models would be interesting, and one could analyse the sensitivity of the results with more precision.

Within the framework of this work, an attempt was made to ensure a suitable comparison with other transport systems. However, even in the scenarios of today, some prospective assumptions have been made, such as the higher energy density of the battery. The prospective scenarios are, in turn, more comparable, as corresponding adjustments have also been made in the premise database. For the sake of completeness, one would have to adapt the VT systems with the background data of today to the current technology, which was outside the scope.

A direct comparison with other studies is difficult because there still is no LCA for other VT systems or Maglev trains. Nevertheless, the comparison was able to classify the impacts resulting from this LCA and to check them for plausibility. However, even if another system uses the functional unit pkm, it should still be questioned to what extent the system is comparable to other transport systems. This is because the functional unit makes no reference to the temporal dimension, which is why the comparison between train and VT systems is only of limited significance, which has also been shown in the different utilisation of the infrastructure. It could be possible to change the functional unit from pkm to pkm/h in order to make the different systems more comparable.

This work has only considered a point-to-point VT system. In a use case, a network with intermediate stations would be developed, which would also cause changes in the LCA.

The bill of materials for the current launcher is based on a design used in a 120-metre demonstration tube from the ETF. Therefore, an optimised design could significantly reduce material requirements and change the outcome of the comparison track-side and pod-side acceleration in terms of its environmental assessment.

Overall, mainly conservative assumptions were made with regard to the VT systems and yet it clearly outperforms the aircraft in almost all environmental impacts and is more comparable to a train. Since the main focus of this LCA is on GWP, the ProtoLauncher and ProtoSelfPropel can thus be called the most promising VT system, based on the results of this LCA.

# 8. Discussion

This chapter serves to summarise this thesis, to point out the limitations of LCA as a method and to provide an outlook for further research.

## 8.1 Limits of life cycle assessments

In this work, only LCA methodology has been used to quantify and compare the environmental impacts of VT systems. LCA is a good tool for environmental assessments, as its aim is to cover all relevant environmental issues and to prevent the displacement of environmental impacts outside the scope of analysis [22]. Nevertheless, there are some limitations of LCA as a method which should be considered.

Although the aim of LCA is to cover the entire product life cycle, the service sector in particular is underrepresented in LCA.

Furthermore, LCA focuses on environmental impact, but costs, social impacts, and accident risks are not considered.

There are environmental impacts that are very relevant for the assessment of transport technologies and have a high impact on human health, such as noise pollution [122], but do not yet exist as an LCIA method.

The spatial system boundaries are difficult to map with the existing data. Many inventories are only available for global averages, which is why the results can deviate in reality. Furthermore, there are temporal issues with the secondary data [123]. Some datasets in ecoinvent, for example, are 20 years old. Although these are adjusted to various current conditions such as the electricity mix, there are certainly limits to how far they can be adjusted manually to depict reality.

Premise provides a solid foundation for pLCAs and can account for incremental changes in efficiency, but it cannot predict potentially disruptive changes in technologies such as nuclear fusion [28] or breakthroughs in battery technology. Additionally, the results for some LCIA methods like human toxicity should be considered as highly uncertain. The IAM does not contain sufficient adjusted data for all existing LCIA methods. Furthermore, no adjustments to the recycling rates are currently integrated. And of course, IAMs cannot give an answer to how high the occupancy rates of e.g., aircraft and trains will be in the future, which is, however, relevant for a comparative LCA.

The VT system requires vast amounts of e.g., concrete, steel, and electricity[33] which are so high that they would significantly affect the supply of these. In Switzerland, for example, the share of hydropower in the electricity mix is dominant, but almost all potential for capacity expansion has already been exploited [61], which is why it is questionable whether Swiss hydropower can meet the additional demand for a nationwide VT network.

Many effects such as $CO_2$ uptake by cement-containing materials [124] or non-$CO_2$ climate forcers for which there are still high uncertainties are not yet included in LCI databases [125] but could influence the final results.

LCA cannot provide an answer to possible rebound effects. New transport technologies like VT could increase the demand for mobility and thus reduce environmental savings or even increase environmental impacts [126] [127] [128]. It should be mentioned, however, that the ETF is not intended to replace currently existing transport technologies, but mainly to provide a solution to the upcoming increased demand for mobility due to economic and population growth, so that the demand for short-haul flights in particular does not continue to rise [45].

## 8.2 Outlook

In order to be able to derive even more detailed results from the LCA, it would be interesting to expand the model by the following points.

Firstly, other key players in the VT field are investigating slightly different designs such as a compressor on the board [129] [130], allowing higher pressures, or photovoltaic panels on the tube to power the entire system [131] [132]. Integrating these ideas into the LCA to get more scenarios would be desirable.

Secondly, as already mentioned, the current LCA model does not yet represent a larger network where there would be changes in e.g., pod size (regional, intercity), fleet size, etc. and could therefore be expanded.

Thirdly, besides the levitation and propulsion systems considered here, there are other alternative solutions. In order to find the most ecological solution, these must also be considered as a whole system in an LCA and could be integrated in this work.

[33] Under the assumptions made here, this results in an energy consumption of 563 GWh/a per station, which is equivalent to approx. 1 % of Switzerland's final electricity consumption.

Fourthly, only the overground design has been considered so far. This is to be compared with the underground system, for which the necessary data is currently being collected.

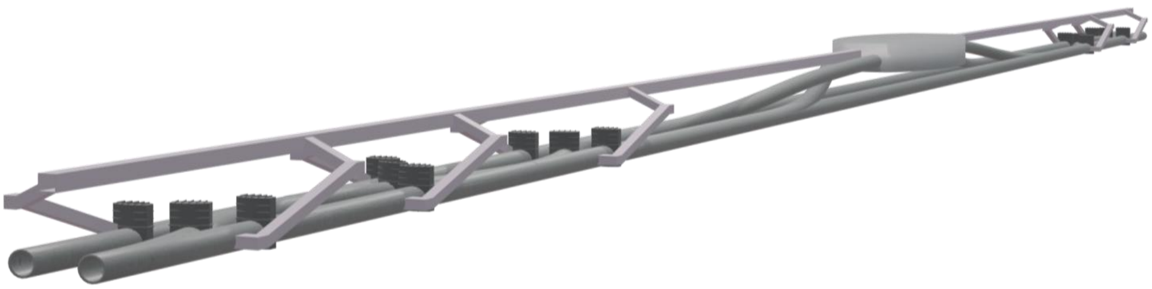

Figure 54: Underground system for VT with bypass system, valves, on/off ramps, and safety tunnel above the main track [45]

Fifthly, as it is a completely new infrastructure, the VT system will come at a considerable cost. Nevertheless, the life cycle costing (LCC) should be analysed, at the latest when political decision-makers and investors have to decide on a possible implementation. Recently, several studies [19] [131] [133] [134] have been carried out to analyse the cost-effectiveness of this transport system for passenger and freight transport. In order to analyse all areas of sustainability, a social life cycle assessment (S-LCA) would also be desirable.

Lastly, the ETF's VT model will be coupled with the LCA developed in this project using brightway. This shall increase the degree of parameterisation and simplify the application of the LCA.

## 8.3 Summary

In the LCA it was shown that VT has a high potential for reducing GHG and PM emissions as well as land use and ozone depletion. The critical phases in the life cycle were identified and particularly promising design options were derived.

If additional transport capacity is required, especially at higher velocities, the question is whether conventional transport systems can provide it or whether new and more sustainable alternatives should be considered.

It may therefore not only be possible to add a new mode of high-speed transport to the current network, but also to shift large parts of the emission-intensive short-haul flights to sustainable, entirely electric ground-based modes of transport.

Overall, the study shows that VT can indeed combine the speed of an aircraft with the environmental footprint and capacity of a train, filling a major gap in the future transport network and potentially help to meet climate targets in the transport sector.

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## A.1 Extensive parameters of the VT system

This part of the attachment contains the parameters set by the ETF. These are not directly part of the LCI, but the values from the LCI are derived from the parameters and assumptions defined here and therefore serve to provide a deeper understanding and transparency of the LCI.

Table A 1: Selected parameter values for the reference case from the ETF [45]

| System | Subsystem | Variable name | Description | Value | Unit |
|---|---|---|---|---|---|
| Traffic and Kinematics | | $v_t$ | Cruise speed | 250 | m/s |
| | | $a_{acc}$ | Acceleration of pod | 1 | $m/s^2$ |
| | | $a_{dec}$ | Deceleration of pod | 1 | $m/s^2$ |
| | | $px_h$ | Capacity of the line | 4685 | px/h |
| | | $l_{network}$ | Network length | 300 | km |
| | | $t_{taxi}$ | Time to manoeuvre in station | 300 | s |
| | | $t_{board}$ | Time for boarding/disembarking | 900 | s |
| Pod | General | $\rho_{fuselage}$ | Fuselage needed per passenger | 140 | kg |
| | | $d_{pod}$ | Outer pod diameter | 3.4 | m |
| | | $\lambda_{passengers}$ | Number of passengers per metre of cabin length | 5 | px/m |
| | | $n_{pod}$ | Passengers per pod | 70 | px |
| | | $m_{px}$ | Mass of passenger including luggage | 100 | kg |
| | | $P_{px}$ | Power emitted by presence of one human being | 100 | W |
| | | $P_{aux,px}$ | Auxiliary power needed onboard per person | 500 | W |

| | | | | | |
|---|---|---|---|---|---|
| | | $l_{mechanical}$ | Additional pod length on top of passenger cabin | 10 | m |
| | Propulsion | $\varepsilon_{prop}$ | Efficiency of the onboard propulsion | 0.9 | |
| | | $f_{motor}$ | Motor frequency. Scale factor to adjust power density of the onboard propulsion | 150 | Hz |
| | | $\eta_{drag}$ | How much of the mechanical drag energy is heating up the pod | 0.5 | |
| | Levitation | $r_{L2W}$ | Lift-to-Weight ratio of levitation system | 62 | |
| | Thermal management | $L_{TES}$ | Heat capacity of thermal battery | 334 | kJ |
| | | $\theta_{TES}$ | Safety margin of thermal battery | 1.2 | |
| | | $c_{fuselage}$ | Heat capacity of fuselage | 1000 | J/kg |
| | | $\Delta T_{fuselage}$ | Tolerable temperature increase of the fuselage | 30 | Kelvin |
| | Battery | $\rho_{Bat,cell}$ | Cell energy density of electrical battery | 500 | Wh/kg |
| | | $r_{c2p}$ | Cell-to-Pack mass ratio | 0.75 | |
| | | $\gamma_{Bat}$ | Usable range of battery | 0.85 | |
| | | $\rho_{discharge}$ | Discharge efficiency | 0.95 | |
| | | $\rho_{charge}$ | Charging efficiency | 0.95 | |
| | | $\theta_{Bat}$ | Safety margin of electrical battery | 1.2 | |
| Track | | $p$ | Pressure in tube | 10 | mbar |
| | | $d_{tube,out}$ | Outer tube diameter | 4.8 | m |
| | | $d_{tube,in}$ | Inner tube diameter | 4.4 | m |
| | | $\widehat{m}_{leakage}$ | Leakage per square metre, mass flow rate | 0.024 | slm/m$^2$ |
| | | $f_{pumpdown}$ | Number of annual full pumpdowns of the system | 1 | |

| | | | | | |
|---|---|---|---|---|---|
| | | | needed | | |
| Station | | $\varepsilon_{launcher}$ | Efficiency of the launcher | 0.9 | |
| | | $CoP_{PCM}$ | Coefficient of performance of thermal battery inverter | 3 | |
| | | $\varepsilon_{recuperator}$ | Efficiency of the recuperator | 0.9 | |

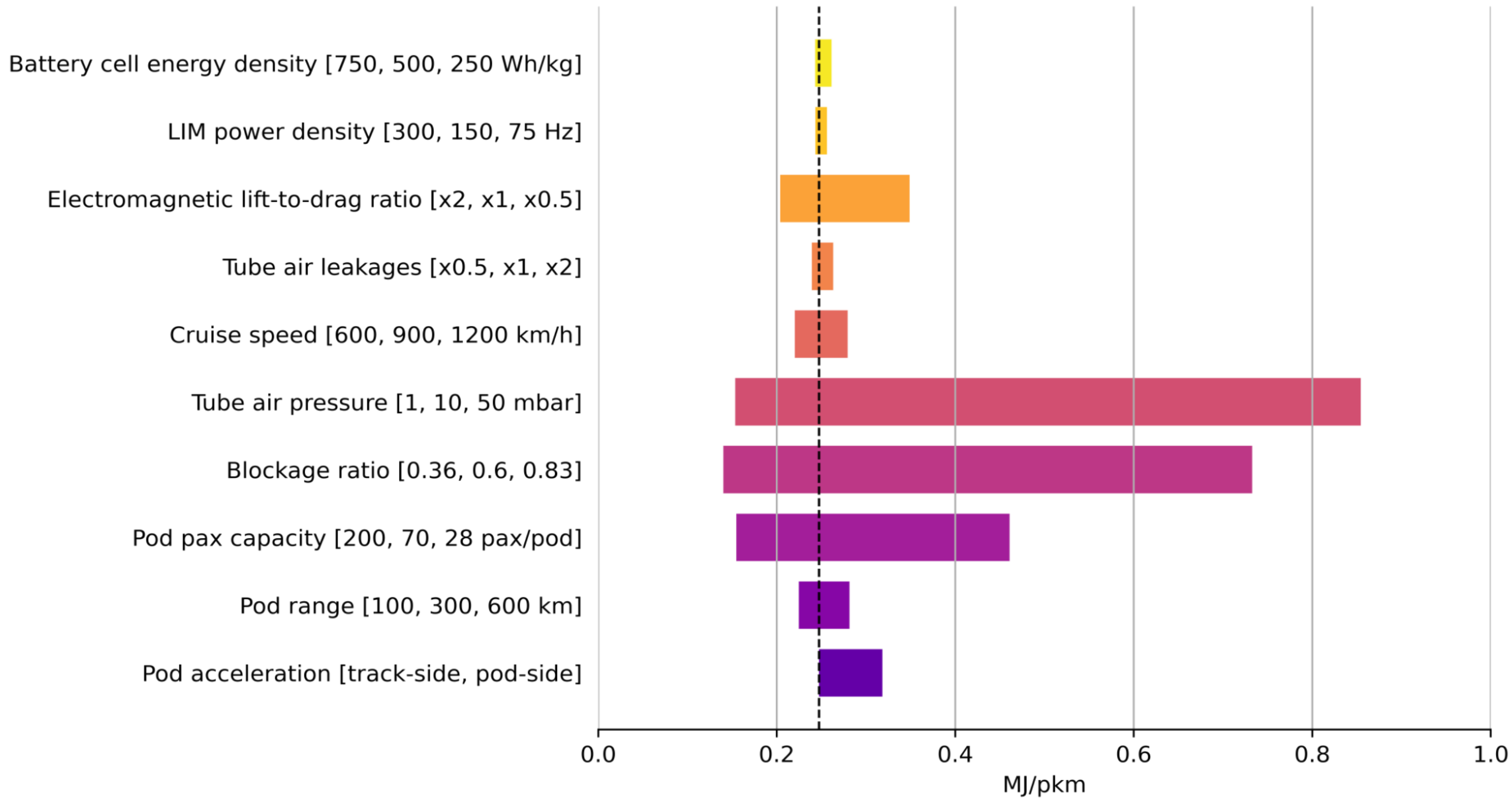


Figure A 1: Specific energy consumption of the VT system (in MJ/pkm) for different design settings of the ETF [45]. Each line examines a different dimension and the middle values, represented by the dashed line, indicate the reference case.

Table A 2: Launching frequencies of passenger and freight pods developed by the ETF [45]; red are the peak times

| Hour | Demand (pax/h) | Raw launching freq. (min) | Raw launching freq. (s) | Launching freq. (s) | Launches/h |
|---|---|---|---|---|---|
| 1 | Do not launch passenger pods, only freight | | | 105 | 35.8 |
| 2 | | | | 105 | 35.8 |
| 3 | | | | 105 | 35.8 |
| 4 | | | | 105 | 35.8 |
| 5 | 976 | 4.3 | 258 | 240 | 15 |
| 6 | 4179 | 1.0 | 60 | 60 | 60 |
| 7 | 6986 | 0.6 | 36 | 30 | 120 |
| 8 | 5560 | 0.8 | 45 | 45 | 80 |
| 9 | 4470 | 0.9 | 56 | 60 | 60 |
| 10 | 4075 | 1.0 | 62 | 60 | 60 |
| 11 | 4790 | 0.9 | 53 | 60 | 60 |
| 12 | 4771 | 0.9 | 53 | 60 | 60 |
| 13 | 4902 | 0.9 | 51 | 45 | 80 |
| 14 | 4403 | 1.0 | 57 | 60 | 60 |
| 15 | 5082 | 0.8 | 50 | 45 | 80 |
| 16 | 6911 | 0.6 | 36 | 30 | 120 |
| 17 | 8212 | 0.5 | 31 | 30 | 120 |
| 18 | 6654 | 0.6 | 38 | 45 | 80 |
| 19 | 4483 | 0.9 | 56 | 60 | 60 |
| 20 | 2928 | 1.4 | 86 | 90 | 40 |
| 21 | 2097 | 2.0 | 120 | 120 | 30 |
| 22 | 1605 | 2.6 | 157 | 180 | 20 |
| 23 | 942 | 4.5 | 268 | 240 | 15 |
| 24 | 302 | 13.9 | 836 | 840 | 4.3 |

Table A 3: Background information on the transport inventories from ecoinvent and the VT systems

| dataset | location | lifetime performance [pkm] | distance [km] | occupancy [%] |
|---|---|---|---|---|
| train, urban | CH | 4.029E+09 | no information | no information |
| train, regional | CH | 3.411E+08 | no information | 17 |
| train, long-distance | CH | 9.292E+08 | no information | 28 |
| train, high-speed | DE | 3.086E+09 | no information | 46 |
| aircraft, very short haul | GLO | 7.241E+09 | < 800 | 80 |
| aircraft, short haul | GLO | 8.598E+09 | 800 - 1500 | 80 |
| aircraft, medium haul | GLO | 1.116E+10 | 1500 - 4000 | 80 |
| aircraft, long haul | GLO | 4.350E+10 | > 4000 | 80 |
| VT, ProtoStandard | CH | 1.849E+09 | 300 | 80 |
| VT, ProtoLauncher | CH | 1.849E+09 | 300 | 80 |
| VT, ProtoSelfPropel | CH | 1.849E+09 | 300 | 80 |
| VT, ProtoSteel | CH | 1.849E+09 | 300 | 80 |

## A.2 Extensive LCI

This part of the attachment contains the full LCI used in Brightway and Activity Browser. Figure A 2 provides an overview of how the individual inventories are linked. The prospective inventories are not listed, as they only differ in the linkage to the prospective background databases. The listing is in alphabetical order of the LCIs. HVAC system, Boring and Crane were neglected as described. Thermal management, tube casting, pier and steel fibres are in the upstream/downstream of other processes.

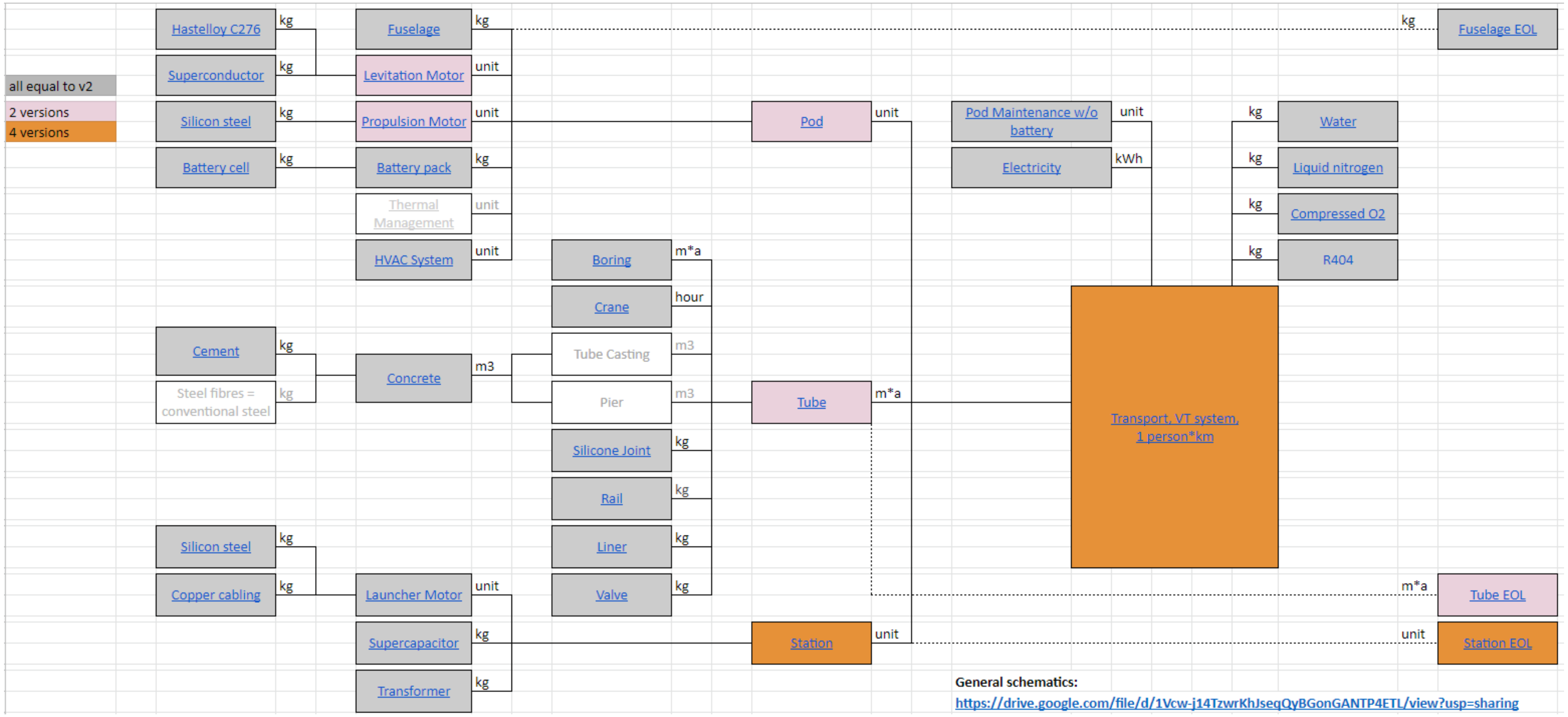


Figure A 2: Structural design of the LCIs of all scenarios, which were created in cooperation with the ETF.

## A.2.1 Manufacturing Phase

Table A 4: LCI of battery production, NMC811, Li-ion, rechargeable, prismatic

| **Activity** | **battery production, NMC811, Li-ion, rechargeable, prismatic** | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| production amount | 1 | | | | | |
| reference product | battery, Li-ion, NMC811, rechargeable, prismatic | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| battery production, NMC811, Li-ion, rechargeable, prismatic | 1.144 | eurotube | GLO | kilogram | production | battery, Li-ion, NMC811, rechargeable, prismatic |
| Battery cell, NMC-811 | 0.858 | batteries | GLO | kilogram | technosphere | Battery cell |
| battery management system production, for Li-ion battery | 0.02426 | cutoff38 | GLO | kilogram | technosphere | battery management system, for Li-ion battery |
| market for aluminium, wrought alloy | 0.14283 | cutoff38 | GLO | kilogram | technosphere | aluminium, wrought alloy |
| market for battery module packaging, Li-ion | 0.05718 | cutoff38 | GLO | kilogram | technosphere | battery module packaging, Li-ion |
| market for copper, anode | 0.001 | cutoff38 | GLO | kilogram | technosphere | copper, anode |
| market for electronic component, passive, unspecified | 0.00431 | cutoff38 | GLO | kilogram | technosphere | electronic component, passive, unspecified |
| market for ethylene glycol | 0.02302 | cutoff38 | GLO | kilogram | technosphere | ethylene glycol |
| market for glass fibre reinforced plastic, polyamide, injection moulded | 0.00033 | cutoff38 | GLO | kilogram | technosphere | glass fibre reinforced plastic, polyamide, injection moulded |
| market for impact extrusion of aluminium, 1 stroke | 0.141616 | cutoff38 | GLO | kilogram | technosphere | impact extrusion of aluminium, 1 stroke |
| market for injection moulding | 0.00405 | cutoff38 | GLO | kilogram | technosphere | injection moulding |

| | | | | | | |
|---|---|---|---|---|---|---|
| market for metal working factory | 1.48E-09 | cutoff38 | GLO | unit | technosphere | metal working factory |
| market for polyethylene, high density, granulate | 0.00405 | cutoff38 | GLO | kilogram | technosphere | polyethylene, high density, granulate |
| market for reinforcing steel | 0.00642 | cutoff38 | GLO | kilogram | technosphere | reinforcing steel |
| market for sheet rolling, aluminium | 0.001214 | cutoff38 | GLO | kilogram | technosphere | sheet rolling, aluminium |
| market for sheet rolling, copper | 0.001 | cutoff38 | GLO | kilogram | technosphere | sheet rolling, copper |
| market for sheet rolling, steel | 0.00642 | cutoff38 | GLO | kilogram | technosphere | sheet rolling, steel |
| market group for electricity, medium voltage | 0.00032 | cutoff38 | GLO | kilowatt hour | technosphere | electricity, medium voltage |
| market group for tap water | 0.02302 | cutoff38 | GLO | kilogram | technosphere | tap water |

Table A 5: LCI of cement production, alternative constituents 6-20%, eurotube

| **Activity** | **cement production, alternative constituents 6-20%, eurotube** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | 1 | | | | | |
| reference product | cement, alternative constituents 6-20%, eurotube | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| cement production, alternative constituents 6-20%, eurotube | 1 | eurotube | CH | kilogram | production | cement, alternative constituents 6-20%, eurotube |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | technosphere | Confidential |

| | | | | | | |
|---|---|---|---|---|---|---|
| Confidential | Confidential | cutoff38 | Confidential | Confidential | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | technosphere | Confidential |

Table A 6: LCI of electrical steel sheets

| **Activity** | **electrical steel sheets** | | | | | | |
|---|---|---|---|---|---|---|---|
| location | GLO | | | | | | |
| reference product | electrical steel sheets | | | | | | |
| type | process | | | | | | |
| unit | kilogram | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Carbon dioxide, fossil | 36 | biosphere3 | | kilogram | air | biosphere | |
| Nitrogen oxides | 0.1 | biosphere3 | | kilogram | air | biosphere | |
| Sulfur oxides | 0.006 | biosphere3 | | kilogram | air | biosphere | |
| electrical steel sheets | 1000 | eurotube | GLO | kilogram | | production | electrical steel sheets |
| heat production, propane, at industrial furnace >100kW | 588 | cutoff38 | RoW | megajoule | | technosphere | heat, district or industrial, other than natural gas |
| market for lubricating oil | 0.4 | cutoff38 | RER | kilogram | | technosphere | lubricating oil |
| market for phenolic resin | 1 | cutoff38 | RER | kilogram | | technosphere | phenolic resin |
| market for scrap steel | -114 | cutoff38 | CH | kilogram | | technosphere | scrap steel |
| market for sulfuric acid | 19 | cutoff38 | RER | kilogram | | technosphere | sulfuric acid |
| market group for electricity, medium voltage | 630 | cutoff38 | GLO | kilowatt hour | | technosphere | electricity, medium voltage |
| silicon steel, hot rolled | 1140 | eurotube | GLO | kilogram | | technosphere | silicon steel, hot rolled |
| treatment of sludge from steel rolling, residual material landfill | -3.3 | cutoff38 | CH | kilogram | | technosphere | sludge from steel rolling |

Table A 7: LCI of fibre-reinforced concrete production, steel, eurotube

| **Activity** | **fibre-reinforced concrete production, steel, eurotube** | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | fibre-reinforced concrete, steel, eurotube | | | | | | |
| type | process | | | | | | |
| unit | cubic meter | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Water, unspecified natural origin | Confidential | biosphere3 | | cubic meter | natural resource::in water | biosphere | |
| fibre-reinforced concrete production, steel, eurotube | 1 | eurotube | CH | cubic meter | | production | fibre-reinforced concrete, steel, eurotube |
| market for cement, alternative constituents 6-20%, eurotube | Confidential | eurotube | CH | kilogram | | technosphere | cement, alternative constituents 6-20%, eurotube |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | | technosphere | Confidential |
| market for concrete mixing factory | Confidential | cutoff38 | GLO | unit | | technosphere | concrete mixing factory |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | | technosphere | Confidential |
| market for gravel, crushed | Confidential | cutoff38 | CH | kilogram | | technosphere | gravel, crushed |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | | technosphere | Confidential |
| market for reinforcing steel | Confidential | cutoff38 | GLO | kilogram | | technosphere | reinforcing steel |
| market for sand | Confidential | cutoff38 | CH | kilogram | | technosphere | sand |
| market for scrap steel | Confidential | cutoff38 | CH | kilogram | | technosphere | scrap steel |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| market for steel, low-alloyed, hot rolled | Confidential | cutoff38 | GLO | kilogram | | technosphere | steel, low-alloyed, hot rolled |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | | technosphere | Confidential |
| market for tap water | Confidential | cutoff38 | CH | kilogram | | technosphere | tap water |
| market for waste concrete | Confidential | cutoff38 | CH | kilogram | | technosphere | waste concrete |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | | technosphere | Confidential |
| Confidential | Confidential | cutoff38 | Confidential | Confidential | | technosphere | Confidential |
| market for wastewater from concrete production | Confidential | cutoff38 | CH | cubic meter | | technosphere | wastewater from concrete production |

Table A 8: LCI of fuselage production

| **Activity** | **fuselage production** | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | fuselage | | | | | | |
| type | process | | | | | | |
| unit | kilogram | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| NMVOC, non-methane volatile organic compounds, unspecified origin | 0.026642 | biosphere3 | | kilogram | air | biosphere | |
| Water | 0.003683 | biosphere3 | | cubic meter | air | biosphere | |
| Water | 0.028993 | biosphere3 | | cubic meter | water | biosphere | |
| fuselage production | 1 | eurotube | CH | kilogram | | production | fuselage |
| market for aluminium, wrought alloy | 0.2 | cutoff38 | GLO | kilogram | | technosphere | aluminium, wrought alloy |
| market for carbon fibre reinforced plastic, injection moulded | 0.5 | cutoff38 | GLO | kilogram | | technosphere | carbon fibre reinforced plastic, injection moulded |
| market for nickel, class 1 | 0.05 | cutoff38 | GLO | kilogram | | technosphere | nickel, class 1 |
| market for steel, chromium steel 18/8 | 0.1 | cutoff38 | GLO | kilogram | | technosphere | steel, chromium steel 18/8 |
| market for titanium | 0.15 | cutoff38 | GLO | kilogram | | technosphere | titanium |
| market for wastewater, unpolluted | -0.00413 | cutoff38 | CH | cubic meter | | technosphere | wastewater, unpolluted |
| market group for electricity, medium voltage | 0.015019 | cutoff38 | GLO | kilowatt hour | | technosphere | electricity, medium voltage |
| market group for heat, district or industrial, natural gas | 49.62779 | cutoff38 | GLO | megajoule | | technosphere | heat, district or industrial, natural gas |
| market group for heat, district or industrial, other than natural gas | 1.465326 | cutoff38 | GLO | megajoule | | technosphere | heat, district or industrial, other than natural gas |
| market group for tap water | 36.82905 | cutoff38 | GLO | kilogram | | technosphere | tap water |
| waste CFRP | 0.5 | eurotube | CH | kilogram | | technosphere | waste CFRP |

Table A 9: LCI of hastelloy C276 production

| **Activity** | **hastelloy C276 production** | | | | | | |
|---|---|---|---|---|---|---|---|
| location | RER | | | | | | |
| production amount | 1 | | | | | | |
| reference product | hastelloy C276 | | | | | | |
| type | process | | | | | | |
| unit | kilogram | | | | | | |
| **Exchanges** | | | | | | | reference product |
| name | amount | database | location | unit | categories | | |
| Benzene | 2.28E-06 | biosphere3 | | kilogram | air | biosphere | |
| Benzene, hexachloro- | 2E-08 | biosphere3 | | kilogram | air | biosphere | |
| Cadmium | 3.65E-08 | biosphere3 | | kilogram | air | biosphere | |
| Carbon monoxide, fossil | 0.00232 | biosphere3 | | kilogram | air | biosphere | |
| Chromium | 1.25E-06 | biosphere3 | | kilogram | air | biosphere | |
| Copper | 2.3E-07 | biosphere3 | | kilogram | air | biosphere | |
| Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin | 4.54E-12 | biosphere3 | | kilogram | air | biosphere | |
| Hydrocarbons, aromatic | 0.000077 | biosphere3 | | kilogram | air | biosphere | |
| Hydrogen chloride | 5.2E-06 | biosphere3 | | kilogram | air | biosphere | |
| Hydrogen fluoride | 2.35E-06 | biosphere3 | | kilogram | air | biosphere | |
| Lead | 1.81E-06 | biosphere3 | | kilogram | air | biosphere | |
| Mercury | 2.24E-06 | biosphere3 | | kilogram | air | biosphere | |
| Nickel | 7E-07 | biosphere3 | | kilogram | air | biosphere | |
| Nitrogen oxides | 0.00018 | biosphere3 | | kilogram | air | biosphere | |
| PAH, polycyclic aromatic hydrocarbons | 3.72E-08 | biosphere3 | | kilogram | air | biosphere | |
| Particulates, < 2.5 um | 0.000166 | biosphere3 | | kilogram | air | biosphere | |
| Particulates, > 10 um | 5.86E-05 | biosphere3 | | kilogram | air | biosphere | |
| Particulates, > 2.5 um, and < 10um | 0.000166 | biosphere3 | | kilogram | air | biosphere | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Polychlorinated biphenyls | 2.32E-08 | biosphere3 | | kilogram | air | biosphere | |
| Sulfur dioxide | 0.000077 | biosphere3 | | kilogram | air | biosphere | |
| Zinc | 2.29E-05 | biosphere3 | | kilogram | air | biosphere | |
| hastelloy C276 production | 1 | eurotube | RER | kilogram | | production | hastelloy C276 |
| electric arc furnace converter construction | 4E-11 | cutoff38 | RER | unit | | technosphere | electric arc furnace converter |
| market for anode, for metal electrolysis | 0.003 | cutoff38 | GLO | kilogram | | technosphere | anode, for metal electrolysis |
| market for cobalt | 0.02 | cutoff38 | GLO | kilogram | | technosphere | cobalt |
| market for electric arc furnace dust | -0.0051 | cutoff38 | RER | kilogram | | technosphere | electric arc furnace dust |
| market for electric arc furnace slag | -0.0768 | cutoff38 | RER | kilogram | | technosphere | electric arc furnace slag |
| market for ferrochromium, high-carbon, 68% Cr | 0.235 | cutoff38 | GLO | kilogram | | technosphere | ferrochromium, high-carbon, 68% Cr |
| market for hard coal | 0.014 | cutoff38 | Europe, without Russia and Turkey | kilogram | | technosphere | hard coal |
| market for inert waste, for final disposal | -0.005 | cutoff38 | CH | kilogram | | technosphere | inert waste, for final disposal |
| market for iron scrap, sorted, pressed | 0.05 | cutoff38 | RER | kilogram | | technosphere | iron scrap, sorted, pressed |
| market for molybdenum | 0.16 | cutoff38 | GLO | kilogram | | technosphere | molybdenum |
| market for natural gas, high pressure | 0.00016 | cutoff38 | CH | cubic meter | | technosphere | natural gas, high pressure |
| market for nickel, class 1 | 0.57 | cutoff38 | GLO | kilogram | | technosphere | nickel, class 1 |
| market for oxygen, liquid | 0.0507 | cutoff38 | RER | kilogram | | technosphere | oxygen, liquid |
| market for quicklime, in pieces, loose | 0.055 | cutoff38 | CH | kilogram | | technosphere | quicklime, in pieces, loose |
| market for refractory, basic, packed | 0.0135 | cutoff38 | GLO | kilogram | | technosphere | refractory, basic, packed |
| market for tungsten concentrate | 0.0777 | cutoff38 | GLO | kilogram | | technosphere | tungsten concentrate |
| market group for electricity, medium voltage | 0.425 | cutoff38 | RER | kilowatt hour | | technosphere | electricity, medium voltage |
| market group for natural gas, high pressure | 0.02484 | cutoff38 | Europe without Switzerland | cubic meter | | technosphere | natural gas, high pressure |

Table A 10: LCI of launcher motor production, ProtoStandard

| **Activity** | **launcher motor production, ProtoStandard** | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| production amount | 1 | | | | | |
| reference product | launcher motor, ProtoStandard | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| launcher motor production, ProtoStandard | 1 | eurotube | GLO | unit | production | launcher motor, ProtoStandard |
| market for cable, unspecified | Confidential | cutoff38 | Confidential | kilogram | technosphere | cable, unspecified |
| market for copper, cathode | Confidential | cutoff38 | Confidential | kilogram | technosphere | copper, cathode |
| market for electrical steel sheets | Confidential | eurotube | Confidential | kilogram | technosphere | electrical steel sheets |
| market for epoxy resin, liquid | Confidential | cutoff38 | Confidential | kilogram | technosphere | epoxy resin, liquid |
| market for metal working, average for steel product manufacturing | Confidential | cutoff38 | Confidential | kilogram | technosphere | metal working, average for steel product manufacturing |
| market for waste plastic, industrial electronics | Confidential | cutoff38 | Confidential | kilogram | technosphere | waste plastic, industrial electronics |
| market for wire drawing, copper | Confidential | cutoff38 | Confidential | kilogram | technosphere | wire drawing, copper |

Table A 11: LCI of levitation motor production, ProtoSelfPropel

| **Activity** | **levitation motor production, ProtoSelfPropel** | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| production amount | 1 | | | | | |
| reference product | levitation motor, ProtoSelfPropel | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| levitation motor production, ProtoSelfPropel | 1 | eurotube | GLO | unit | production | levitation motor, ProtoSelfPropel |
| YBCO, superconductor production | 31.03 | eurotube | GLO | kilogram | technosphere | YBCO, superconductor |
| aluminium scrap, new, Recycled Content cut-off | -25.3 | cutoff38 | GLO | kilogram | technosphere | aluminium scrap, new |
| market for aluminium, wrought alloy | 126 | cutoff38 | GLO | kilogram | technosphere | aluminium, wrought alloy |
| market for copper, cathode | 465.52 | cutoff38 | GLO | kilogram | technosphere | copper, cathode |
| market for hastelloy C276 | 124.1379 | eurotube | GLO | kilogram | technosphere | hastelloy C276 |
| market for resistor, auxilliaries and energy use | 2.44 | cutoff38 | GLO | kilogram | technosphere | resistor, auxilliaries and energy use |
| market for selective coat, aluminium sheet, nickel pigmented aluminium oxide | 0.05 | cutoff38 | GLO | square meter | technosphere | selective coat, aluminium sheet, nickel pigmented aluminium oxide |
| market for sheet rolling, aluminium | 126 | cutoff38 | GLO | kilogram | technosphere | sheet rolling, aluminium |
| market for silver | 9.3103 | cutoff38 | GLO | kilogram | technosphere | silver |
| market for waste plastic, industrial electronics | -0.143 | cutoff38 | CH | kilogram | technosphere | waste plastic, industrial electronics |
| market for wire drawing, copper | 465.52 | cutoff38 | GLO | kilogram | technosphere | wire drawing, copper |

| | | | | | | |
|---|---|---|---|---|---|---|
| market group for electricity, low voltage | 0.115 | cutoff38 | GLO | kilowatt hour | technosphere | electricity, low voltage |
| market group for electricity, medium voltage | 378 | cutoff38 | GLO | kilowatt hour | technosphere | electricity, medium voltage |
| market group for heat, central or small-scale, other than natural gas | 309.532 | cutoff38 | GLO | megajoule | technosphere | heat, central or small-scale, other than natural gas |
| market group for heat, district or industrial, natural gas | 319.517 | cutoff38 | GLO | megajoule | technosphere | heat, district or industrial, natural gas |

Table A 12: LCI of levitation motor production, ProtoStandard

| Activity | levitation motor production, ProtoStandard | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| production amount | 1 | | | | | |
| reference product | levitation motor, ProtoStandard | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| levitation motor production, ProtoStandard | 1 | eurotube | GLO | unit | production | levitation motor, ProtoStandard |
| YBCO, superconductor production | 20.39 | eurotube | GLO | kilogram | technosphere | YBCO, superconductor |
| aluminium scrap, new, Recycled Content cut-off | -16.62 | cutoff38 | GLO | kilogram | technosphere | aluminium scrap, new |
| market for aluminium, wrought alloy | 82.8 | cutoff38 | GLO | kilogram | technosphere | aluminium, wrought alloy |
| market for copper, cathode | 305.91 | cutoff38 | GLO | kilogram | technosphere | copper, cathode |
| market for hastelloy C276 | 81.5764 | eurotube | GLO | kilogram | technosphere | hastelloy C276 |
| market for resistor, auxilliaries and energy use | 1.6 | cutoff38 | GLO | kilogram | technosphere | resistor, auxilliaries and energy use |
| market for selective coat, aluminium sheet, nickel pigmented aluminium oxide | 0.0359 | cutoff38 | GLO | square meter | technosphere | selective coat, aluminium sheet, nickel pigmented aluminium oxide |

| | | | | | | |
|---|---|---|---|---|---|---|
| market for sheet rolling, aluminium | 82.8 | cutoff38 | GLO | kilogram | technosphere | sheet rolling, aluminium |
| market for silver | 6.1182 | cutoff38 | GLO | kilogram | technosphere | silver |
| market for waste plastic, industrial electronics | -0.094 | cutoff38 | CH | kilogram | technosphere | waste plastic, industrial electronics |
| market for wire drawing, copper | 305.91 | cutoff38 | GLO | kilogram | technosphere | wire drawing, copper |
| market group for electricity, low voltage | 0.075 | cutoff38 | GLO | kilowatt hour | technosphere | electricity, low voltage |
| market group for electricity, medium voltage | 248.4 | cutoff38 | GLO | kilowatt hour | technosphere | electricity, medium voltage |
| market group for heat, central or small-scale, other than natural gas | 203.407 | cutoff38 | GLO | megajoule | technosphere | heat, central or small-scale, other than natural gas |
| market group for heat, district or industrial, natural gas | 209.968 | cutoff38 | GLO | megajoule | technosphere | heat, district or industrial, natural gas |

Table A 13: LCI of market for battery, Li-ion, NMC811, rechargeable, prismatic

| **Activity** | **market for battery, Li-ion, NMC811, rechargeable, prismatic** | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| production amount | 1 | | | | | |
| reference product | battery, Li-ion, NMC811, rechargeable, prismatic | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| market for battery, Li-ion, NMC811, rechargeable, prismatic | 1 | eurotube | GLO | kilogram | production | battery, Li-ion, NMC811, rechargeable, prismatic |
| battery production, NMC811, Li-ion, rechargeable, prismatic | 1 | eurotube | GLO | kilogram | technosphere | battery, Li-ion, NMC811, rechargeable, prismatic |
| market for transport, freight, aircraft, unspecified | 0.0623 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight, aircraft, unspecified |
| market for transport, freight, sea, container ship | 0.7368 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight, sea, container ship |
| market group for transport, freight train | 0.0153 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight train |
| market group for transport, freight, light commercial vehicle | 0.0096 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight, light commercial vehicle |
| market group for transport, freight, lorry, unspecified | 0.31 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight, lorry, unspecified |

Table A 14: LCI of market for cement, alternative constituents 6-20%, eurotube

| **Activity** | **market for cement, alternative constituents 6-20%, eurotube** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | 1 | | | | | |
| reference product | cement, alternative constituents 6-20%, eurotube | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| market for cement, alternative constituents 6-20%, eurotube | 1 | eurotube | CH | kilogram | production | cement, alternative constituents 6-20%, eurotube |
| cement production, alternative constituents 6-20%, eurotube | 1 | eurotube | CH | kilogram | technosphere | cement, alternative constituents 6-20%, eurotube |
| market for transport, freight train | 0.0037 | cutoff38 | CH | ton kilometer | technosphere | transport, freight train |
| market for transport, freight, lorry, unspecified | 0.0259 | cutoff38 | RER | ton kilometer | technosphere | transport, freight, lorry, unspecified |

Table A 15: LCI of market for electrical steel sheets

| **Activity** | **market for electrical steel sheets** | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| production amount | 1 | | | | | |
| reference product | electrical steel sheets | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| market for electrical steel sheets | 1 | eurotube | GLO | kilogram | production | electrical steel sheets |
| electrical steel sheets | 1 | eurotube | GLO | kilogram | technosphere | electrical steel sheets |
| market for transport, freight, sea, bulk carrier for dry goods | 0.4409 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight, sea, bulk carrier for dry goods |
| market group for transport, freight train | 0.1903 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight train |
| market group for transport, freight, inland waterways, barge | 0.0201 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight, inland waterways, barge |
| market group for transport, freight, lorry, unspecified | 0.2065 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight, lorry, unspecified |

Table A 16: LCI of market for fibre-reinforced concrete, steel, eurotube

| **Activity** | **market for fibre-reinforced concrete, steel, eurotube** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | 1 | | | | | |
| reference product | fibre-reinforced concrete, steel, eurotube | | | | | |
| type | process | | | | | |
| unit | cubic meter | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| market for fibre-reinforced concrete, steel, eurotube | 1 | eurotube | CH | cubic meter | production | fibre-reinforced concrete, steel, eurotube |
| fibre-reinforced concrete production, steel, eurotube | 1 | eurotube | CH | cubic meter | technosphere | fibre-reinforced concrete, steel, eurotube |
| market for transport, freight train | 8.806 | cutoff38 | CH | ton kilometer | technosphere | transport, freight train |
| market for transport, freight, lorry, unspecified | 61.642 | cutoff38 | RER | ton kilometer | technosphere | transport, freight, lorry, unspecified |

Table A 17: LCI of market for hastelloy C276

| **Activity** | **market for hastelloy C276** | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| production amount | 1 | | | | | |
| reference product | hastelloy C276 | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| market for hastelloy C276 | 1 | eurotube | GLO | kilogram | production | hastelloy C276 |
| hastelloy C276 production | 1 | eurotube | RER | kilogram | technosphere | hastelloy C276 |
| market for transport, freight, sea, bulk carrier for dry goods | 0.4409 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight, sea, bulk carrier for dry goods |
| market group for transport, freight train | 0.1903 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight train |
| market group for transport, freight, inland waterways, barge | 0.0201 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight, inland waterways, barge |
| market group for transport, freight, lorry, unspecified | 0.2065 | cutoff38 | GLO | ton kilometer | technosphere | transport, freight, lorry, unspecified |

Table A 18: LCI of pod production, ProtoSelfPropel

| **Activity** | **pod production, ProtoSelfPropel** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | 1 | | | | | |
| reference product | pod, ProtoSelfPropel | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| pod production, ProtoSelfPropel | 1 | eurotube | CH | unit | production | pod, ProtoSelfPropel |
| fuselage production | 9800 | eurotube | CH | kilogram | technosphere | fuselage |
| levitation motor production, ProtoSelfPropel | 0.25 | eurotube | GLO | unit | technosphere | levitation motor, ProtoSelfPropel |
| market for battery, Li-ion, NMC811, rechargeable, prismatic | 132484 | eurotube | GLO | kilogram | technosphere | battery, Li-ion, NMC811, rechargeable, prismatic |
| market for electricity, medium voltage | 41076 | cutoff38 | CH | kilowatt hour | technosphere | electricity, medium voltage |
| propulsion motor production, ProtoSelfPropel | 1 | eurotube | GLO | unit | technosphere | propulsion motor, ProtoSelfPropel |

Table A 19: LCI of pod production, ProtoSelfPropel, without battery

| **Activity** | **pod production, ProtoSelfPropel, without battery** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | 1 | | | | | |
| reference product | pod, ProtoSelfPropel, without battery | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| pod production, ProtoSelfPropel, without battery | 1 | eurotube | CH | unit | production | pod, ProtoSelfPropel, without battery |
| fuselage production | 9800 | eurotube | CH | kilogram | technosphere | fuselage |
| levitation motor production, ProtoSelfPropel | 0.25 | eurotube | GLO | unit | technosphere | levitation motor, ProtoSelfPropel |
| market for electricity, medium voltage | 41076 | cutoff38 | CH | kilowatt hour | technosphere | electricity, medium voltage |
| propulsion motor production, ProtoSelfPropel | 1 | eurotube | GLO | unit | technosphere | propulsion motor, ProtoSelfPropel |

Table A 20: LCI of pod production, ProtoStandard

| **Activity** | **pod production, ProtoStandard** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | 1 | | | | | |
| reference product | pod, ProtoStandard | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| pod production, ProtoStandard | 1 | eurotube | CH | unit | production | pod, ProtoStandard |
| fuselage production | 9800 | eurotube | CH | kilogram | technosphere | fuselage |
| levitation motor production, ProtoStandard | 0.25 | eurotube | GLO | unit | technosphere | levitation motor, ProtoStandard |
| market for battery, Li-ion, NMC811, rechargeable, prismatic | 75240 | eurotube | GLO | kilogram | technosphere | battery, Li-ion, NMC811, rechargeable, prismatic |
| market for electricity, medium voltage | 2885.4 | cutoff38 | CH | kilowatt hour | technosphere | electricity, medium voltage |
| propulsion motor production, ProtoStandard | 1 | eurotube | GLO | unit | technosphere | propulsion motor, ProtoStandard |

Table A 21: LCI of pod production, ProtoStandard, without battery

| **Activity** | **pod production, ProtoStandard, without battery** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | 1 | | | | | |
| reference product | pod, ProtoStandard, without battery | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| pod production, ProtoStandard, without battery | 1 | eurotube | CH | unit | production | pod, ProtoStandard, without battery |
| fuselage production | 9800 | eurotube | CH | kilogram | technosphere | fuselage |
| levitation motor production, ProtoStandard | 0.25 | eurotube | GLO | unit | technosphere | levitation motor, ProtoStandard |
| market for electricity, medium voltage | 2885.4 | cutoff38 | CH | kilowatt hour | technosphere | electricity, medium voltage |
| propulsion motor production, ProtoStandard | 1 | eurotube | GLO | unit | technosphere | propulsion motor, ProtoStandard |

Table A 22: LCI of propulsion motor production, ProtoSelfPropel

| **Activity** | **propulsion motor production, ProtoSelfPropel** | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| production amount | 1 | | | | | |
| reference product | propulsion motor, ProtoSelfPropel | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| propulsion motor production, ProtoSelfPropel | 1 | eurotube | GLO | unit | production | propulsion motor, ProtoSelfPropel |
| market for copper, cathode | Confidential | cutoff38 | Confidential | kilogram | technosphere | copper, cathode |
| market for electrical steel sheets | Confidential | eurotube | Confidential | kilogram | technosphere | electrical steel sheets |
| market for epoxy resin, liquid | Confidential | cutoff38 | Confidential | kilogram | technosphere | epoxy resin, liquid |
| market for metal working, average for steel product manufacturing | Confidential | cutoff38 | Confidential | kilogram | technosphere | metal working, average for steel product manufacturing |
| market for waste plastic, industrial electronics | Confidential | cutoff38 | Confidential | kilogram | technosphere | waste plastic, industrial electronics |
| market for wire drawing, copper | Confidential | cutoff38 | Confidential | kilogram | technosphere | wire drawing, copper |

Table A 23: LCI of propulsion motor production, ProtoStandard

| **Activity** | **propulsion motor production, ProtoStandard** | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| production amount | 1 | | | | | |
| reference product | propulsion motor, ProtoStandard | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| propulsion motor production, ProtoStandard | 1 | eurotube | GLO | unit | production | propulsion motor, ProtoStandard |
| market for copper, cathode | Confidential | cutoff38 | Confidential | kilogram | technosphere | copper, cathode |
| market for electrical steel sheets | Confidential | eurotube | Confidential | kilogram | technosphere | electrical steel sheets |
| market for epoxy resin, liquid | Confidential | cutoff38 | Confidential | kilogram | technosphere | epoxy resin, liquid |
| market for metal working, average for steel product manufacturing | Confidential | cutoff38 | Confidential | kilogram | technosphere | metal working, average for steel product manufacturing |
| market for waste plastic, industrial electronics | Confidential | cutoff38 | Confidential | kilogram | technosphere | waste plastic, industrial electronics |
| market for wire drawing, copper | Confidential | cutoff38 | Confidential | kilogram | technosphere | wire drawing, copper |

Table A 24: LCI of rail, aluminium

| Activity | rail, aluminium | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| reference product | rail, aluminium | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| rail, aluminium | 1 | eurotube | GLO | kilogram | production | rail, aluminium |
| market for aluminium, wrought alloy | 1 | cutoff38 | GLO | kilogram | technosphere | aluminium, wrought alloy |
| market for sheet rolling, aluminium | 1 | cutoff38 | GLO | kilogram | technosphere | sheet rolling, aluminium |

Table A 25: LCI of silicon steel

| Activity | silicon steel | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| reference product | silicon steel | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| silicon steel | 1000 | eurotube | GLO | kilogram | production | silicon steel |
| market for aluminium, primary, ingot | 0 | cutoff38 | IAI Area, EU27 & EFTA | kilogram | technosphere | aluminium, primary, ingot |
| market for ferrosilicon | 40.5 | cutoff38 | GLO | kilogram | technosphere | ferrosilicon |
| market for steel, unalloyed | 969.5 | cutoff38 | GLO | kilogram | technosphere | steel, unalloyed |

Table A 26: LCI of silicon steel, hot rolled

| **Activity** | **silicon steel, hot rolled** | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| reference product | silicon steel, hot rolled | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| silicon steel, hot rolled | 1 | eurotube | GLO | kilogram | production | silicon steel, hot rolled |
| market for hot rolling, steel | 1 | cutoff38 | GLO | kilogram | technosphere | hot rolling, steel |
| silicon steel | 1 | eurotube | GLO | kilogram | technosphere | silicon steel |

Table A 27: LCI of station construction, ProtoLauncher

| Activity | station construction, ProtoLauncher | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | station, ProtoLauncher | | | | | | |
| type | process | | | | | | |
| unit | unit | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Occupation, industrial area | 5130000 | biosphere3 | | square meter-year | natural resource::land | biosphere | |
| Occupation, traffic area, rail network | 10260000 | biosphere3 | | square meter-year | natural resource::land | biosphere | |
| Transformation, from unspecified | 153900 | biosphere3 | | square meter | natural resource::land | biosphere | |
| Transformation, to industrial area | 51300 | biosphere3 | | square meter | natural resource::land | biosphere | |
| Transformation, to traffic area, rail network | 102600 | biosphere3 | | square meter | natural resource::land | biosphere | |
| station construction, ProtoLauncher | 1 | eurotube | CH | unit | | production | station, ProtoLauncher |
| building construction, hall | 9600 | cutoff38 | CH | square meter | | technosphere | |
| launcher motor production, ProtoStandard | 4 | eurotube | GLO | unit | | technosphere | launcher motor, ProtoStandard |
| market for capacitor, auxilliaries and energy use | 88830 | cutoff38 | GLO | kilogram | | technosphere | capacitor, auxilliaries and energy use |
| market for transformer, high voltage use | 344000 | cutoff38 | GLO | kilogram | | technosphere | transformer, high voltage use |
| tube construction, concrete | 1282500 | eurotube | CH | meter-year | | technosphere | |
| used station, ProtoLauncher | -1 | eurotube | CH | unit | | technosphere | used station, ProtoLauncher |

Table A 28: LCI of station construction, ProtoSelfPropel

| **Activity** | **station construction, ProtoSelfPropel** | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | station, ProtoSelfPropel | | | | | | |
| type | process | | | | | | |
| unit | unit | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Occupation, industrial area | 5130000 | biosphere3 | | square meter-year | natural resource::land | biosphere | |
| Occupation, traffic area, rail network | 10260000 | biosphere3 | | square meter-year | natural resource::land | biosphere | |
| Transformation, from unspecified | 153900 | biosphere3 | | square meter | natural resource::land | biosphere | |
| Transformation, to industrial area | 51300 | biosphere3 | | square meter | natural resource::land | biosphere | |
| Transformation, to traffic area, rail network | 102600 | biosphere3 | | square meter | natural resource::land | biosphere | |
| station construction, ProtoSelfPropel | 1 | eurotube | CH | unit | | production | station, ProtoSelfPropel |
| building construction, hall | 9600 | cutoff38 | CH | square meter | | technosphere | building, hall |
| market for capacitor, auxilliaries and energy use | 106648 | cutoff38 | GLO | kilogram | | technosphere | capacitor, auxilliaries and energy use |
| market for transformer, high voltage use | 413000 | cutoff38 | GLO | kilogram | | technosphere | transformer, high voltage use |
| tube construction, concrete | 1282500 | eurotube | CH | meter-year | | technosphere | used station, ProtoSelfPropel |
| used station, ProtoSelfPropel | -1 | eurotube | CH | unit | | technosphere | used station, ProtoSelfPropel |

Table A 29: LCI of station construction, ProtoStandard

| Activity | station construction, ProtoStandard | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | station, ProtoStandard | | | | | | |
| type | process | | | | | | |
| unit | unit | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Occupation, industrial area | 5130000 | biosphere3 | | square meter-year | natural resource::land | biosphere | |
| Occupation, traffic area, rail network | 10260000 | biosphere3 | | square meter-year | natural resource::land | biosphere | |
| Transformation, from unspecified | 153900 | biosphere3 | | square meter | natural resource::land | biosphere | |
| Transformation, to industrial area | 51300 | biosphere3 | | square meter | natural resource::land | biosphere | |
| Transformation, to traffic area, rail network | 102600 | biosphere3 | | square meter | natural resource::land | biosphere | |
| station construction, ProtoStandard | 1 | eurotube | CH | unit | | production | station, ProtoStandard |
| building construction, hall | 9600 | cutoff38 | CH | square meter | | technosphere | building, hall |
| launcher motor production, ProtoStandard | 8 | eurotube | GLO | unit | | technosphere | launcher motor, ProtoStandard |
| market for capacitor, auxilliaries and energy use | 81600 | cutoff38 | GLO | kilogram | | technosphere | capacitor, auxilliaries and energy use |
| market for transformer, high voltage use | 316000 | cutoff38 | GLO | kilogram | | technosphere | transformer, high voltage use |
| tube construction, concrete | 1282500 | eurotube | CH | meter-year | | technosphere | tube, concrete |
| used station, ProtoStandard | -1 | eurotube | CH | unit | | technosphere | used station, ProtoStandard |

Table A 30: LCI of station construction, ProtoSteel

| **Activity** | **station construction, ProtoSteel** | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | station, ProtoSteel | | | | | | |
| type | process | | | | | | |
| unit | unit | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Occupation, industrial area | 5130000 | biosphere3 | | square meter-year | natural resource::land | biosphere | |
| Occupation, traffic area, rail network | 10260000 | biosphere3 | | square meter-year | natural resource::land | biosphere | |
| Transformation, from unspecified | 153900 | biosphere3 | | square meter | natural resource::land | biosphere | |
| Transformation, to industrial area | 51300 | biosphere3 | | square meter | natural resource::land | biosphere | |
| Transformation, to traffic area, rail network | 102600 | biosphere3 | | square meter | natural resource::land | biosphere | |
| station construction, ProtoSteel | 1 | eurotube | CH | unit | | production | station, ProtoSteel |
| building construction, hall | 9600 | cutoff38 | CH | square meter | | technosphere | building, hall |
| launcher motor production, ProtoStandard | 8 | eurotube | GLO | unit | | technosphere | launcher motor, ProtoStandard |
| market for capacitor, auxilliaries and energy use | 81600 | cutoff38 | GLO | kilogram | | technosphere | capacitor, auxilliaries and energy use |
| market for transformer, high voltage use | 316000 | cutoff38 | GLO | kilogram | | technosphere | transformer, high voltage use |
| tube construction, steel | 1282500 | eurotube | CH | meter-year | | technosphere | tube, steel |
| used station, ProtoSteel | -1 | eurotube | CH | unit | | technosphere | used station, ProtoSteel |

Table A 31: LCI of tube construction, concrete

| Activity | tube construction, concrete | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | tube, concrete | | | | | | |
| type | process | | | | | | |
| unit | meter-year | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Glyphosate | 5.38E-06 | biosphere3 | | kilogram | soil::industrial | biosphere | |
| Occupation, traffic area, rail network | 0.0884 | biosphere3 | | square meter-year | natural resource::land | biosphere | |
| Transformation, from unspecified | 0.000884 | biosphere3 | | square meter | natural resource::land | biosphere | |
| Transformation, to traffic area, rail network | 0.000884 | biosphere3 | | square meter | natural resource::land | biosphere | |
| tube construction, concrete | 1 | eurotube | CH | meter-year | | production | tube, concrete |
| excavation, skid-steer loader | 0.00922 | cutoff38 | RER | cubic meter | | technosphere | excavation, skid-steer loader |
| market for diesel, burned in building machine | 9.5 | cutoff38 | GLO | megajoule | | technosphere | diesel, burned in building machine |
| market for electricity, medium voltage | 63.09 | cutoff38 | CH | kilowatt hour | | technosphere | electricity, medium voltage |
| market for fibre-reinforced concrete, steel, eurotube | 0.0792 | eurotube | CH | cubic meter | | technosphere | fibre-reinforced concrete, steel, eurotube |
| market for glyphosate | 5.38E-06 | cutoff38 | GLO | kilogram | | technosphere | glyphosate |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| market for packaging film, low density polyethylene | 2.28 | cutoff38 | GLO | kilogram | | technosphere | packaging film, low density polyethylene |
| market for reinforcing steel | 2.722 | cutoff38 | GLO | kilogram | | technosphere | reinforcing steel |
| market for silicone product | 0.075 | cutoff38 | RER | kilogram | | technosphere | silicone product |
| rail, aluminium | 2.872 | eurotube | GLO | kilogram | | technosphere | rail, aluminium |
| treatment of used tube, concrete | -1 | eurotube | CH | meter-year | | technosphere | used tube, concrete |
| valve, vacuum | 1.067 | eurotube | GLO | kilogram | | technosphere | valve, vacuum |

Table A 32: LCI of tube construction, steel

| **Activity** | **tube construction, steel** | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | tube, steel | | | | | | |
| type | process | | | | | | |
| unit | meter-year | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Glyphosate | 5.38E-06 | biosphere3 | | kilogram | soil::industrial | biosphere | |
| Occupation, traffic area, rail network | 0.0884 | biosphere3 | | square meter-year | natural resource::land | biosphere | |
| Transformation, from unspecified | 0.000884 | biosphere3 | | square meter | natural resource::land | biosphere | |
| Transformation, to traffic area, rail network | 0.000884 | biosphere3 | | square meter | natural resource::land | biosphere | |
| tube construction, steel | 1 | eurotube | CH | meter-year | | production | tube, steel |
| excavation, skid-steer loader | 0.00922 | cutoff38 | RER | cubic meter | | technosphere | excavation, skid-steer loader |
| market for diesel, burned in building machine | 9.5 | cutoff38 | GLO | megajoule | | technosphere | diesel, burned in building machine |
| market for electricity, medium voltage | 63.09 | cutoff38 | CH | kilowatt hour | | technosphere | electricity, medium voltage |
| market for fibre-reinforced concrete, steel, eurotube | 1.06E-02 | eurotube | CH | cubic meter | | technosphere | fibre-reinforced concrete, steel, eurotube |
| market for glyphosate | 5.38E-06 | cutoff38 | GLO | kilogram | | technosphere | glyphosate |
| market for reinforcing steel | 55.662 | cutoff38 | GLO | kilogram | | technosphere | reinforcing steel |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| market for silicone product | 0.075 | cutoff38 | RER | kilogram | | technosphere | silicone product |
| rail, aluminium | 2.872 | eurotube | GLO | kilogram | | technosphere | rail, aluminium |
| treatment of used tube, steel | -1 | eurotube | CH | meter-year | | technosphere | used tube, steel |
| valve, vacuum | 1.067 | eurotube | GLO | kilogram | | technosphere | valve, vacuum |

Table A 33: LCI of valve, vacuum

| **Activity** | **valve, vacuum** | | | | | |
|---|---|---|---|---|---|---|
| location | GLO | | | | | |
| reference product | valve, vacuum | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| valve, vacuum | 1 | eurotube | GLO | kilogram | production | valve, vacuum |
| market for metal working, average for steel product manufacturing | 1 | cutoff38 | GLO | kilogram | technosphere | metal working, average for steel product manufacturing |
| market for sheet rolling, steel | 1 | cutoff38 | GLO | kilogram | technosphere | sheet rolling, steel |
| market for steel, low-alloyed, hot rolled | 1 | cutoff38 | GLO | kilogram | technosphere | steel, low-alloyed, hot rolled |

Table A 34: LCI of YBCO, superconductor production

| Activity | YBCO, superconductor production | | | | | | |
|---|---|---|---|---|---|---|---|
| location | GLO | | | | | | |
| production amount | 1 | | | | | | |
| reference product | YBCO, superconductor | | | | | | |
| type | process | | | | | | |
| unit | kilogram | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Benzo(a)pyrene | 1.3E-06 | biosphere3 | | kilogram | air | biosphere | |
| Carbon dioxide, fossil | 0.132 | biosphere3 | | kilogram | air | biosphere | |
| Carbon monoxide, fossil | 0.091708 | biosphere3 | | kilogram | air | biosphere | |
| Ethane, hexafluoro-, HFC-116 | 2.8E-05 | biosphere3 | | kilogram | air | biosphere | |
| Hydrogen fluoride | 0.000539 | biosphere3 | | kilogram | air | biosphere | |
| Methane, tetrafluoro-, R-14 | 0.000252 | biosphere3 | | kilogram | air | biosphere | |
| Nitrogen oxides | 6.39E-05 | biosphere3 | | kilogram | air | biosphere | |
| PAH, polycyclic aromatic hydrocarbons | 4.57E-05 | biosphere3 | | kilogram | air | biosphere | |
| Particulates, < 2.5 um | 0.002607 | biosphere3 | | kilogram | air | biosphere | |
| Particulates, > 2.5 um, and < 10um | 0.000609 | biosphere3 | | kilogram | air | biosphere | |
| Sulfur dioxide | 0.008831 | biosphere3 | | kilogram | air | biosphere | |
| YBCO, superconductor production | 1 | eurotube | GLO | kilogram | | production | YBCO, superconductor |
| market for aluminium electrolysis facility | 1.54E-10 | cutoff38 | GLO | unit | | technosphere | aluminium electrolysis facility |
| market for anode, for metal electrolysis | 0.44755 | cutoff38 | GLO | kilogram | | technosphere | anode, for metal electrolysis |
| market for barium carbonate | 0.592 | cutoff38 | GLO | kilogram | | technosphere | barium carbonate |
| market for cathode, for aluminium electrolysis | 0.018082 | cutoff38 | GLO | kilogram | | technosphere | cathode, for aluminium electrolysis |
| market for copper oxide | 0.358 | cutoff38 | GLO | kilogram | | technosphere | copper oxide |
| market for cryolite | 0.001598 | cutoff38 | GLO | kilogram | | technosphere | cryolite |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| market for filter dust from Al electrolysis | -0.002 | cutoff38 | GLO | kilogram | | technosphere | filter dust from Al electrolysis |
| market for refractory spent pot liner from Al electrolysis | -0.0019 | cutoff38 | GLO | kilogram | | technosphere | refractory spent pot liner from Al electrolysis |
| market for waste bitumen | -0.00039 | cutoff38 | Europe without Switzerland | kilogram | | technosphere | waste bitumen |
| market for waste bitumen | -1E-05 | cutoff38 | CH | kilogram | | technosphere | waste bitumen |
| market for waste bitumen | -0.0008 | cutoff38 | RoW | kilogram | | technosphere | waste bitumen |
| market for yttrium oxide | 0.169 | cutoff38 | GLO | kilogram | | technosphere | yttrium oxide |
| market group for electricity, medium voltage | 15.558 | cutoff38 | GLO | kilowatt hour | | technosphere | electricity, medium voltage |
| market group for heat, district or industrial, natural gas | 0.084 | cutoff38 | GLO | megajoule | | technosphere | heat, district or industrial, natural gas |
| market group for heat, district or industrial, other than natural gas | 0.089 | cutoff38 | GLO | megajoule | | technosphere | heat, district or industrial, other than natural gas |
| treatment of inert waste, inert material landfill | -0.005 | cutoff38 | CH | kilogram | | technosphere | inert waste, for final disposal |

## A.2.2 Use Phase

The data listed in this subchapter refers to a 100 % occupancy rate of the pod, which was subsequently adjusted to 80 %.

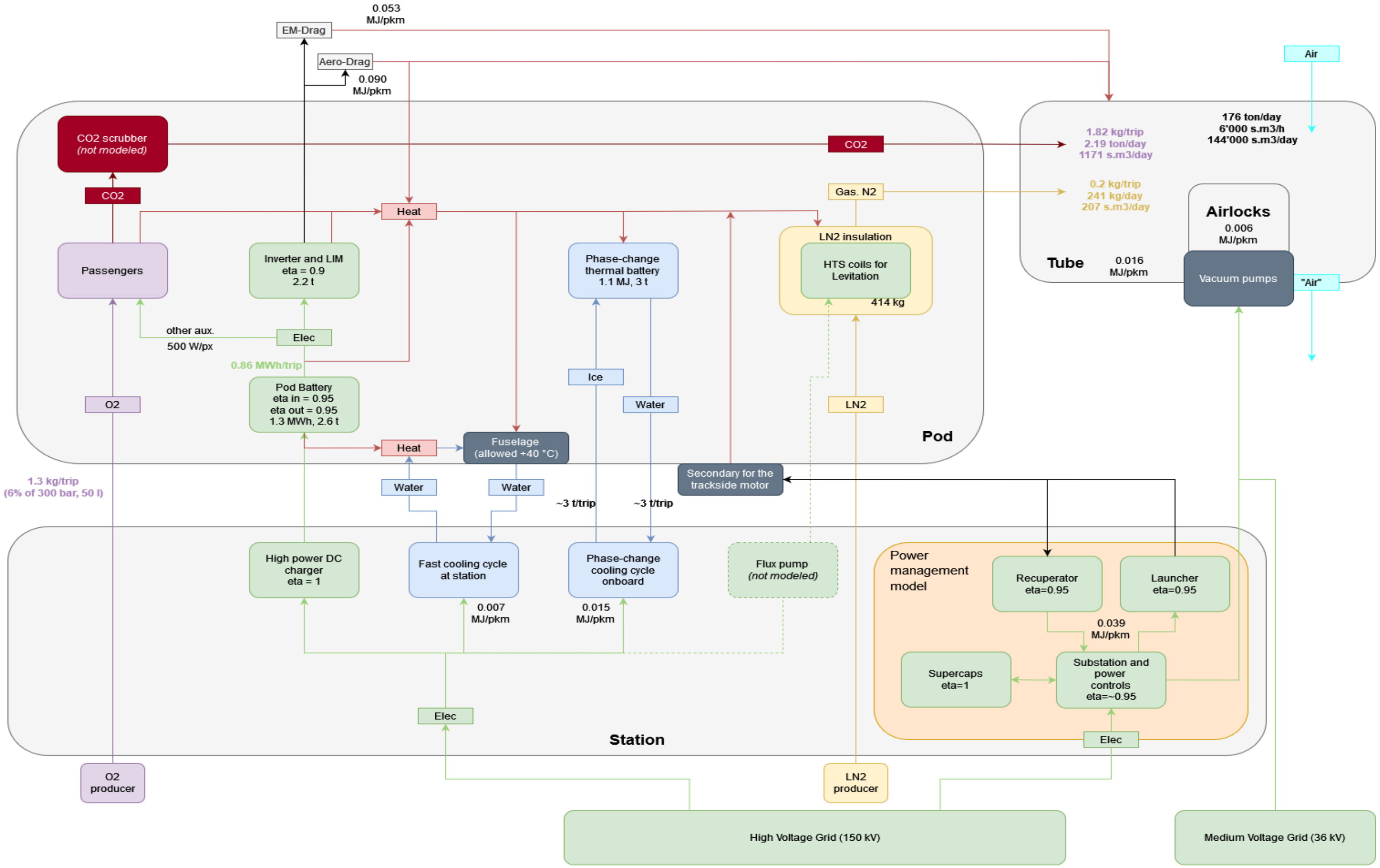


Figure A 3: Energy and mass flow of the ETF for the ProtoStandard [45].

Table A 35: LCI of electricity voltage transformation from high to medium voltage

| **Activity** | **electricity voltage transformation from high to medium voltage** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | 1 | | | | | |
| reference product | electricity, medium voltage | | | | | |
| type | process | | | | | |
| unit | kilowatt hour | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| electricity voltage transformation from high to medium voltage | 1 | eurotube | CH | kilowatt hour | production | electricity, medium voltage |
| market for electricity, high voltage, for Swiss Federal Railways | 1.0062 | cutoff38 | CH | kilowatt hour | technosphere | electricity, high voltage, for Swiss Federal Railways |

Table A 36: LCI of maintenance, pod, ProtoSelfPropel

| **Activity** | **maintenance, pod, ProtoSelfPropel** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | 1 | | | | | |
| reference product | maintenance, pod, ProtoSelfPropel | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| maintenance, pod, ProtoSelfPropel | 1 | eurotube | CH | unit | production | maintenance, pod, ProtoSelfPropel |
| pod production, ProtoSelfPropel, without battery | 0.03 | eurotube | CH | unit | technosphere | pod, ProtoSelfPropel, without battery |

Table A 37: LCI of maintenance, pod, ProtoStandard

| **Activity** | **maintenance, pod, ProtoStandard** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | 1 | | | | | |
| reference product | maintenance, pod, ProtoStandard | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| maintenance, pod, ProtoStandard | 1 | eurotube | CH | unit | production | maintenance, pod, ProtoStandard |
| pod production, ProtoStandard, without battery | 0.03 | eurotube | CH | unit | technosphere | pod, ProtoStandard, without battery |

Table A 38: LCI of transport, VT, ProtoLauncher

| **Activity** | **transport, VT, ProtoLauncher** | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | transport, VT, ProtoLauncher | | | | | | |
| type | process | | | | | | |
| unit | person kilometer | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | catego ries | type | reference product |
| Ethane, 1,1,1,2-tetrafluoro-, HFC-134a | 2.39E-09 | biosphere3 | | kilogram | air | biosphere | |
| Nitrogen | 9.5E-06 | biosphere3 | | kilogram | air | biosphere | |
| Water | 2.04E-07 | biosphere3 | | cubic meter | air | biosphere | |
| transport, VT, ProtoLauncher | 1 | eurotube | CH | person kilometer | | production | transport, VT, ProtoLauncher |
| electricity voltage transformation from high to medium voltage | 0.07441 | eurotube | CH | kilowatt hour | | technosphere | electricity, medium voltage |
| maintenance, pod, ProtoSelfPropel | 2.75E-10 | eurotube | CH | unit | | technosphere | maintenance, pod, ProtoSelfPropel |
| market for nitrogen, liquid | 9.5E-06 | cutoff38 | RER | kilogram | | technosphere | nitrogen, liquid |
| market for oxygen, liquid | 6.22E-05 | cutoff38 | RER | kilogram | | technosphere | oxygen, liquid |
| market for refrigerant R134a | 2.39E-09 | cutoff38 | GLO | kilogram | | technosphere | refrigerant R134a |
| market for tap water | 0.000204 | cutoff38 | CH | kilogram | | technosphere | tap water |
| pod production, ProtoStandard | 4.33E-10 | eurotube | CH | unit | | technosphere | pod, ProtoStandard |
| station construction, ProtoLauncher | 1.26E-12 | eurotube | CH | unit | | technosphere | station, ProtoLauncher |
| tube construction, concrete | 2.13E-05 | eurotube | CH | meter-year | | technosphere | tube, concrete |

Table A 39: LCI of transport, VT, ProtoSelfPropel

| Activity | transport, VT, ProtoSelfPropel | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | transport, VT, ProtoSelfPropel | | | | | | |
| type | process | | | | | | |
| unit | person kilometer | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Ethane, 1,1,1,2-tetrafluoro-, HFC-134a | 4.61E-09 | biosphere3 | | kilogram | air | biosphere | |
| Nitrogen | 1.45E-05 | biosphere3 | | kilogram | air | biosphere | |
| Water | 3.93E-07 | biosphere3 | | cubic meter | air | biosphere | |
| transport, VT, ProtoSelfPropel | 1 | eurotube | CH | person kilometer | | production | transport, VT, ProtoSelfPropel |
| electricity voltage transformation from high to medium voltage | 0.08842 | eurotube | CH | kilowatt hour | | technosphere | electricity, medium voltage |
| maintenance, pod, ProtoSelfPropel | 2.75E-10 | eurotube | CH | unit | | maintenance, pod, ProtoSelfPropel | maintenance, pod, ProtoSelfPropel |
| market for nitrogen, liquid | 1.45E-05 | cutoff38 | RER | kilogram | | technosphere | nitrogen, liquid |
| market for oxygen, liquid | 6.22E-05 | cutoff38 | RER | kilogram | | technosphere | oxygen, liquid |
| market for refrigerant R134a | 4.61E-09 | cutoff38 | GLO | kilogram | | technosphere | refrigerant R134a |
| market for tap water | 0.000393 | cutoff38 | CH | kilogram | | technosphere | tap water |
| pod production, ProtoSelfPropel | 4.33E-10 | eurotube | CH | unit | | technosphere | pod, ProtoSelfPropel |
| station construction, ProtoSelfPropel | 1.26E-12 | eurotube | CH | unit | | technosphere | station, ProtoSelfPropel |
| tube construction, concrete | 2.13E-05 | eurotube | CH | meter-year | | technosphere | tube, concrete |

Table A 40: LCI of transport, VT, ProtoStandard

| Activity | transport, VT, ProtoStandard | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | transport, VT, ProtoStandard | | | | | | |
| type | process | | | | | | |
| unit | person kilometer | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Ethane, 1,1,1,2-tetrafluoro-, HFC-134a | 2.39E-09 | biosphere3 | | kilogram | air | biosphere | |
| Nitrogen | 9.5E-06 | biosphere3 | | kilogram | air | biosphere | |
| Water | 2.04E-07 | biosphere3 | | cubic meter | air | biosphere | |
| transport, VT, ProtoStandard | 1 | eurotube | CH | person kilometer | | production | transport, VT, ProtoStandard |
| electricity voltage transformation from high to medium voltage | 0.0687 | eurotube | CH | kilowatt hour | | technosphere | electricity, medium voltage |
| maintenance, pod, ProtoStandard | 2.75E-10 | eurotube | CH | unit | | maintenance, pod, ProtoStandard | nitrogen, liquid |
| market for nitrogen, liquid | 9.5E-06 | cutoff38 | RER | kilogram | | technosphere | oxygen, liquid |
| market for oxygen, liquid | 6.22E-05 | cutoff38 | RER | kilogram | | technosphere | refrigerant R134a |
| market for refrigerant R134a | 2.39E-09 | cutoff38 | GLO | kilogram | | technosphere | tap water |
| market for tap water | 0.000204 | cutoff38 | CH | kilogram | | technosphere | pod, ProtoStandard |
| pod production, ProtoStandard | 4.33E-10 | eurotube | CH | unit | | technosphere | station, ProtoStandard |
| station construction, ProtoStandard | 1.26E-12 | eurotube | CH | unit | | technosphere | nitrogen, liquid |
| tube construction, concrete | 2.13E-05 | eurotube | CH | meter-year | | technosphere | tube, concrete |

Table A 41: LCI of transport, VT, ProtoSteel

| **Activity** | **transport, VT, ProtoSteel** | | | | | | |
|---|---|---|---|---|---|---|---|
| location | CH | | | | | | |
| production amount | 1 | | | | | | |
| reference product | transport, VT, ProtoSteel | | | | | | |
| type | process | | | | | | |
| unit | person kilometer | | | | | | |
| **Exchanges** | | | | | | | |
| name | amount | database | location | unit | categories | type | reference product |
| Ethane, 1,1,1,2-tetrafluoro-, HFC-134a | 2.39E-09 | biosphere3 | | kilogram | air | biosphere | |
| Nitrogen | 9.5E-06 | biosphere3 | | kilogram | air | biosphere | |
| Water | 2.04E-07 | biosphere3 | | cubic meter | air | biosphere | |
| transport, VT, ProtoSteel | 1 | eurotube | CH | person kilometer | | production | transport, VT, ProtoSteel |
| electricity voltage transformation from high to medium voltage | 0.0687 | eurotube | CH | kilowatt hour | | technosphere | electricity, medium voltage |
| maintenance, pod, ProtoSelfPropel | 2.75E-10 | eurotube | CH | unit | | technosphere | maintenance, pod, ProtoSelfPropel |
| market for nitrogen, liquid | 9.5E-06 | cutoff38 | RER | kilogram | | technosphere | nitrogen, liquid |
| market for oxygen, liquid | 6.22E-05 | cutoff38 | RER | kilogram | | technosphere | oxygen, liquid |
| market for refrigerant R134a | 2.39E-09 | cutoff38 | GLO | kilogram | | technosphere | refrigerant R134a |
| market for tap water | 0.000204 | cutoff38 | CH | kilogram | | technosphere | tap water |
| pod production, ProtoStandard | 4.33E-10 | eurotube | CH | unit | | technosphere | pod, ProtoStandard |
| station construction, ProtoSteel | 1.26E-12 | eurotube | CH | unit | | technosphere | station, ProtoSteel |
| tube construction, steel | 2.13E-05 | eurotube | CH | meter-year | | technosphere | tube, steel |

## A.2.3 End-of-Life

Table A 42: LCI of CFRP, steam thermolysis

| Activity | CFRP, steam thermolysis | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| reference product | CFRP, sized for recycling | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| CFRP, steam thermolysis | -1 | eurotube | CH | kilogram | production | CFRP, sized for recycling |
| market for aluminium, cast alloy | 0.0053 | cutoff38 | GLO | kilogram | technosphere | aluminium, cast alloy |
| market for electricity, medium voltage | 15 | cutoff38 | CH | kilowatt hour | technosphere | electricity, medium voltage |
| market for flat glass, uncoated | 0.0033 | cutoff38 | RER | kilogram | technosphere | flat glass, uncoated |
| market for nitrogen, liquid | 1.4 | cutoff38 | RER | kilogram | technosphere | nitrogen, liquid |
| market for steel, low-alloyed, hot rolled | 0.1267 | cutoff38 | GLO | kilogram | technosphere | steel, low-alloyed, hot rolled |
| market for stone wool | 0.0013 | cutoff38 | GLO | kilogram | technosphere | stone wool |
| market for tap water | 1.6 | cutoff38 | CH | kilogram | technosphere | tap water |

Table A 43: LCI of CFRP, waterjet cutting

| **Activity** | **CFRP, waterjet cutting** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| reference product | CFRP, sized for recycling | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| CFRP, waterjet cutting | 1 | eurotube | CH | kilogram | production | CFRP, sized for recycling |
| market for aluminium, cast alloy | 0.0031 | cutoff38 | GLO | kilogram | technosphere | aluminium, cast alloy |
| market for copper, cathode | 0.0016 | cutoff38 | GLO | kilogram | technosphere | copper, cathode |
| market for electricity, medium voltage | 4.9 | cutoff38 | CH | kilowatt hour | technosphere | electricity, medium voltage |
| market for steel, low-alloyed, hot rolled | 0.0267 | cutoff38 | GLO | kilogram | technosphere | steel, low-alloyed, hot rolled |
| market for tap water | 0.3972 | cutoff38 | CH | kilogram | technosphere | tap water |
| market for transport, freight, lorry, unspecified | 0.0287 | cutoff38 | RER | ton kilometer | technosphere | transport, freight, lorry, unspecified |
| waste CFRP | 1 | eurotube | CH | kilogram | technosphere | waste CFRP |

Table A 44: LCI of treatment of used tube, concrete

| **Activity** | **treatment of used tube, concrete** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | -1 | | | | | |
| reference product | used tube, concrete | | | | | |
| type | process | | | | | |
| unit | meter-year | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| treatment of used tube, concrete | -1 | eurotube | CH | meter-year | production | used tube, concrete |
| market for waste reinforced concrete | -184.14 | cutoff38 | CH | kilogram | technosphere | waste reinforced concrete |
| market for waste rubber, unspecified | -0.075 | cutoff38 | CH | kilogram | technosphere | waste rubber, unspecified |

Table A 45: LCI of treatment of used tube, steel

| **Activity** | **treatment of used tube, steel** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| production amount | -1 | | | | | |
| reference product | used tube, steel | | | | | |
| type | process | | | | | |
| unit | meter-year | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| treatment of used tube, steel | -1 | eurotube | CH | meter-year | production | used tube, steel |
| market for waste reinforced concrete | -0.025 | cutoff38 | CH | kilogram | technosphere | waste reinforced concrete |
| market for waste rubber, unspecified | -0.075 | cutoff38 | CH | kilogram | technosphere | waste rubber, unspecified |

Table A 46: LCI of used station, ProtoLauncher

| **Activity** | **used station, ProtoLauncher** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| reference product | used station, ProtoLauncher | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| used station, ProtoLauncher | -1 | eurotube | CH | unit | production | used station, ProtoLauncher |
| market for waste electric and electronic equipment | -432830 | cutoff38 | GLO | kilogram | technosphere | waste electric and electronic equipment |

Table A 47: LCI of used station, ProtoSelfPropel

| **Activity** | **used station, ProtoSelfPropel** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| reference product | used station, ProtoSelfPropel | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| used station, ProtoSelfPropel | -1 | eurotube | CH | unit | production | used station, ProtoSelfPropel |
| market for waste electric and electronic equipment | -519648 | cutoff38 | GLO | kilogram | technosphere | waste electric and electronic equipment |

Table A 48: LCI of used station, ProtoStandard

| **Activity** | **used station, ProtoStandard** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| reference product | used station, ProtoStandard | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| used station, ProtoStandard | -1 | eurotube | CH | unit | production | used station, ProtoStandard |
| market for waste electric and electronic equipment | -397600 | cutoff38 | GLO | kilogram | technosphere | waste electric and electronic equipment |

Table A 49: LCI of used station, ProtoSteel

| **Activity** | **used station, ProtoSteel** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| reference product | used station, ProtoSteel | | | | | |
| type | process | | | | | |
| unit | unit | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| used station, ProtoSteel | -1 | eurotube | CH | unit | production | used station, ProtoSteel |
| market for waste electric and electronic equipment | -397600 | cutoff38 | GLO | kilogram | technosphere | waste electric and electronic equipment |

Table A 50: LCI of waste CFRP

| **Activity** | **waste CFRP** | | | | | |
|---|---|---|---|---|---|---|
| location | CH | | | | | |
| reference product | waste CFRP | | | | | |
| type | process | | | | | |
| unit | kilogram | | | | | |
| **Exchanges** | | | | | | |
| name | amount | database | location | unit | type | reference product |
| waste CFRP | 1 | eurotube | CH | kilogram | production | waste CFRP |

### A.3 Extensive LCIA

This part of the Attachment contains the full LCIA values from the IPCC 2013 (GWP100a), EF 3.0, CED, and Ecological Scarcity 2013 methods in the form of tables. Since a structured overview is difficult due to the long names of the impact categories, each method is assigned a letter in the following list. The prospective scenarios are all marked with the year and the functional unit is 1 pkm for all systems.

a IPCC 2013 | climate change | GWP 100a

b EF v3.0 | acidification | accumulated exceedance (ae)

c EF v3.0 | climate change | global warming potential (GWP100)

d EF v3.0 | climate change: biogenic | global warming potential (GWP100)

e EF v3.0 | climate change: fossil | global warming potential (GWP100)

f EF v3.0 | climate change: land use and land use change | global warming potential (GWP100)

g EF v3.0 | ecotoxicity: freshwater | comparative toxic unit for ecosystems (CTUe)

h EF v3.0 | ecotoxicity: freshwater, inorganics | comparative toxic unit for ecosystems (CTUe)

i EF v3.0 | ecotoxicity: freshwater, metals | comparative toxic unit for ecosystems (CTUe)

j EF v3.0 | ecotoxicity: freshwater, organics | comparative toxic unit for ecosystems (CTUe)

k EF v3.0 | energy resources: non-renewable | abiotic depletion potential (ADP): fossil fuels

l EF v3.0 | eutrophication: freshwater | fraction of nutrients reaching freshwater end compartment (P)

m EF v3.0 | eutrophication: marine | fraction of nutrients reaching marine end compartment (N)

n EF v3.0 | eutrophication: terrestrial | accumulated exceedance (AE)

o EF v3.0 | human toxicity: carcinogenic | comparative toxic unit for human (CTUh)

| | |
|---|---|
| p | EF v3.0 \| human toxicity: carcinogenic, inorganics \| comparative toxic unit for human (CTUh) |
| q | EF v3.0 \| human toxicity: carcinogenic, metals \| comparative toxic unit for human (CTUh) |
| r | EF v3.0 \| human toxicity: carcinogenic, organics \| comparative toxic unit for human (CTUh) |
| s | EF v3.0 \| human toxicity: non-carcinogenic \| comparative toxic unit for human (CTUh) |
| t | EF v3.0 \| human toxicity: non-carcinogenic, inorganics \| comparative toxic unit for human (CTUh) |
| u | EF v3.0 \| human toxicity: non-carcinogenic, metals \| comparative toxic unit for human (CTUh) |
| v | EF v3.0 \| human toxicity: non-carcinogenic, organics \| comparative toxic unit for human (CTUh) |
| w | EF v3.0 \| ionising radiation: human health \| human exposure efficiency relative to u235 |
| x | EF v3.0 \| land use \| soil quality index |
| y | EF v3.0 \| material resources: metals/minerals \| abiotic depletion potential (ADP): elements (ultimate reserves) |
| z | EF v3.0 \| ozone depletion \| ozone depletion potential (ODP) |
| aa | EF v3.0 \| particulate matter formation \| impact on human health |
| ab | EF v3.0 \| photochemical ozone formation: human health \| tropospheric ozone concentration increase |
| ac | EF v3.0 \| water use \| user deprivation potential (deprivation-weighted water consumption) |
| ad | cumulative energy demand \| biomass \| renewable energy resources, biomass |
| ae | cumulative energy demand \| fossil \| non-renewable energy resources, fossil |
| af | cumulative energy demand \| geothermal \| renewable energy resources, geothermal, converted |
| ag | cumulative energy demand \| nuclear \| non-renewable energy resources, nuclear |
| ah | cumulative energy demand \| primary forest \| non-renewable energy resources, primary forest |
| ai | cumulative energy demand \| solar \| renewable energy resources, solar, converted |
| aj | cumulative energy demand \| water \| renewable energy resources, potential (in barrage water), converted |
| ak | cumulative energy demand \| wind \| renewable energy resources, kinetic (in wind), converted |

| | |
|---|---|
| al | ecological scarcity 2013 \| POP into water \| total |
| am | ecological scarcity 2013 \| carcinogenic substances into air \| total |
| an | ecological scarcity 2013 \| energy resources \| total |
| ao | ecological scarcity 2013 \| global warming \| total |
| ap | ecological scarcity 2013 \| heavy metals into air \| total |
| aq | ecological scarcity 2013 \| heavy metals into soil \| total |
| ar | ecological scarcity 2013 \| heavy metals into water \| total |
| as | ecological scarcity 2013 \| land use \| total |
| at | ecological scarcity 2013 \| main air pollutants and PM \| total |
| au | ecological scarcity 2013 \| mineral resources \| total |
| av | ecological scarcity 2013 \| non radioactive waste to deposit \| total |
| aw | ecological scarcity 2013 \| ozone layer depletion \| total |
| ax | ecological scarcity 2013 \| pesticides into soil \| total |
| ay | ecological scarcity 2013 \| radioactive substances into air \| total |
| az | ecological scarcity 2013 \| radioactive substances into water \| total |
| ba | ecological scarcity 2013 \| radioactive waste to deposit \| total |
| bb | ecological scarcity 2013 \| total \| total |
| bc | ecological scarcity 2013 \| water pollutants \| total |
| bd | ecological scarcity 2013 \| water resources \| total |

Table A 51: Extensive LCIA values

| Name | a | b | c | d | e | f | g | h | i |
|---|---|---|---|---|---|---|---|---|---|
| transport, VT, ProtoStandard | 5.6E-03 | 7.4E-05 | 5.7E-03 | 5.2E-05 | 5.6E-03 | 9.5E-06 | 5.8E-01 | 5.4E-02 | 5.2E-01 |
| transport, VT, ProtoLauncher | 5.1E-03 | 5.3E-05 | 5.1E-03 | 4.6E-05 | 5.1E-03 | 8.8E-06 | 3.9E-01 | 3.4E-02 | 3.5E-01 |
| transport, VT, ProtoSelfPropel | 5.2E-03 | 4.0E-05 | 5.2E-03 | 4.4E-05 | 5.2E-03 | 9.6E-06 | 2.6E-01 | 2.2E-02 | 2.4E-01 |
| transport, VT, ProtoSteel | 7.8E-03 | 8.4E-05 | 7.8E-03 | 5.4E-05 | 7.7E-03 | 1.2E-05 | 6.6E-01 | 6.0E-02 | 6.0E-01 |
| transport, VT, ProtoStandard, 2040_base | 5.4E-03 | 6.6E-05 | 5.4E-03 | 4.5E-05 | 5.4E-03 | 7.9E-06 | 5.7E-01 | 5.3E-02 | 5.1E-01 |
| transport, VT, ProtoLauncher, 2040_base | 4.9E-03 | 4.6E-05 | 5.0E-03 | 3.9E-05 | 4.9E-03 | 7.3E-06 | 3.8E-01 | 3.4E-02 | 3.5E-01 |
| transport, VT, ProtoSelfPropel, 2040_base | 5.1E-03 | 3.3E-05 | 5.1E-03 | 3.7E-05 | 5.1E-03 | 7.9E-06 | 2.6E-01 | 2.2E-02 | 2.3E-01 |
| transport, VT, ProtoSteel, 2040_base | 7.2E-03 | 7.3E-05 | 7.2E-03 | 4.6E-05 | 7.2E-03 | 8.6E-06 | 6.4E-01 | 5.8E-02 | 5.8E-01 |
| transport, VT, ProtoStandard, 2040_RCP26 | 4.2E-03 | 6.5E-05 | 4.3E-03 | 4.5E-05 | 4.3E-03 | -1.2E-05 | 5.6E-01 | 5.2E-02 | 5.0E-01 |
| transport, VT, ProtoLauncher, 2040_RCP26 | 4.0E-03 | 4.5E-05 | 4.0E-03 | 3.9E-05 | 4.0E-03 | -9.7E-06 | 3.7E-01 | 3.3E-02 | 3.4E-01 |
| transport, VT, ProtoSelfPropel, 2040_RCP26 | 4.1E-03 | 3.2E-05 | 4.2E-03 | 3.7E-05 | 4.1E-03 | -9.0E-06 | 2.5E-01 | 2.1E-02 | 2.2E-01 |
| transport, VT, ProtoSteel, 2040_RCP26 | 5.5E-03 | 7.1E-05 | 5.6E-03 | 4.6E-05 | 5.5E-03 | -1.7E-05 | 6.2E-01 | 5.6E-02 | 5.7E-01 |
| transport, VT, ProtoStandard, 2040_RCP19 | 3.5E-03 | 6.5E-05 | 3.6E-03 | 4.6E-05 | 3.7E-03 | -1.6E-04 | 5.5E-01 | 5.2E-02 | 5.0E-01 |
| transport, VT, ProtoLauncher, 2040_RCP19 | 3.3E-03 | 4.5E-05 | 3.4E-03 | 3.9E-05 | 3.5E-03 | -1.4E-04 | 3.7E-01 | 3.3E-02 | 3.4E-01 |
| transport, VT, ProtoSelfPropel, 2040_RCP19 | 3.5E-03 | 3.2E-05 | 3.5E-03 | 3.7E-05 | 3.6E-03 | -1.4E-04 | 2.4E-01 | 2.1E-02 | 2.2E-01 |
| transport, VT, ProtoSteel, 2040_RCP19 | 4.8E-03 | 7.1E-05 | 4.8E-03 | 4.6E-05 | 4.9E-03 | -2.1E-04 | 6.2E-01 | 5.6E-02 | 5.6E-01 |
| transport, passenger train, long-distance | 6.2E-03 | 3.4E-05 | 6.2E-03 | 4.0E-05 | 6.2E-03 | 1.1E-05 | 2.2E-01 | 1.7E-02 | 2.0E-01 |
| transport, passenger train, long-distance, 2040_base | 5.9E-03 | 2.8E-05 | 5.9E-03 | 2.5E-05 | 5.9E-03 | 9.4E-06 | 2.1E-01 | 1.6E-02 | 2.0E-01 |
| transport, passenger train, long-distance, 2040_RCP26 | 4.6E-03 | 2.7E-05 | 4.6E-03 | 2.5E-05 | 4.6E-03 | -8.0E-06 | 2.1E-01 | 1.5E-02 | 1.9E-01 |
| transport, passenger train, long-distance, 2040_RCP19 | 3.8E-03 | 2.7E-05 | 3.9E-03 | 2.5E-05 | 3.9E-03 | -1.2E-04 | 2.0E-01 | 1.5E-02 | 1.9E-01 |
| transport, passenger aircraft, short haul, e-kerosene | 2.5E-02 | 6.3E-04 | 2.5E-02 | 8.2E-05 | 2.5E-02 | 1.0E-04 | 2.6E+00 | 2.8E-01 | 2.3E+00 |
| transport, passenger aircraft, short haul | 1.2E-01 | 6.0E-04 | 1.2E-01 | 3.7E-05 | 1.2E-01 | 2.0E-05 | 1.1E+00 | 3.2E-01 | 6.6E-01 |

| Name | j | k | l | m | n | o | p | q | r |
|---|---|---|---|---|---|---|---|---|---|
| transport, VT, ProtoStandard | 1.3E-03 | 2.0E-01 | 5.2E-06 | 8.5E-06 | 9.6E-05 | 2.1E-11 | 0.0E+00 | 1.6E-11 | 4.8E-12 |
| transport, VT, ProtoLauncher | 1.1E-03 | 2.0E-01 | 3.5E-06 | 7.4E-06 | 8.1E-05 | 1.6E-11 | 0.0E+00 | 1.2E-11 | 4.1E-12 |
| transport, VT, ProtoSelfPropel | 1.1E-03 | 2.3E-01 | 2.3E-06 | 7.3E-06 | 7.7E-05 | 1.5E-11 | 0.0E+00 | 1.1E-11 | 3.6E-12 |
| transport, VT, ProtoSteel | 1.8E-03 | 2.2E-01 | 6.4E-06 | 1.1E-05 | 1.2E-04 | 4.0E-11 | 0.0E+00 | 2.4E-11 | 1.6E-11 |
| transport, VT, ProtoStandard, 2040_base | 1.3E-03 | 1.9E-01 | 5.0E-06 | 7.3E-06 | 8.3E-05 | 2.0E-11 | 0.0E+00 | 1.6E-11 | 4.5E-12 |
| transport, VT, ProtoLauncher, 2040_base | 1.1E-03 | 1.9E-01 | 3.3E-06 | 6.4E-06 | 7.0E-05 | 1.6E-11 | 0.0E+00 | 1.2E-11 | 3.8E-12 |
| transport, VT, ProtoSelfPropel, 2040_base | 1.1E-03 | 2.2E-01 | 2.2E-06 | 6.3E-06 | 6.6E-05 | 1.5E-11 | 0.0E+00 | 1.1E-11 | 3.3E-12 |
| transport, VT, ProtoSteel, 2040_base | 1.7E-03 | 2.1E-01 | 6.2E-06 | 9.1E-06 | 9.9E-05 | 3.8E-11 | 0.0E+00 | 2.3E-11 | 1.4E-11 |
| transport, VT, ProtoStandard, 2040_RCP26 | 1.3E-03 | 1.8E-01 | 4.5E-06 | 7.0E-06 | 8.1E-05 | 2.0E-11 | 0.0E+00 | 1.6E-11 | 4.3E-12 |
| transport, VT, ProtoLauncher, 2040_RCP26 | 1.1E-03 | 1.9E-01 | 2.9E-06 | 6.1E-06 | 6.8E-05 | 1.5E-11 | 0.0E+00 | 1.2E-11 | 3.6E-12 |
| transport, VT, ProtoSelfPropel, 2040_RCP26 | 1.1E-03 | 2.2E-01 | 1.7E-06 | 6.1E-06 | 6.5E-05 | 1.4E-11 | 0.0E+00 | 1.1E-11 | 3.2E-12 |
| transport, VT, ProtoSteel, 2040_RCP26 | 1.7E-03 | 2.0E-01 | 5.4E-06 | 8.6E-06 | 9.6E-05 | 3.6E-11 | 0.0E+00 | 2.3E-11 | 1.3E-11 |
| transport, VT, ProtoStandard, 2040_RCP19 | 1.3E-03 | 1.9E-01 | 4.3E-06 | 7.0E-06 | 8.1E-05 | 2.0E-11 | 0.0E+00 | 1.6E-11 | 3.9E-12 |
| transport, VT, ProtoLauncher, 2040_RCP19 | 1.1E-03 | 1.9E-01 | 2.7E-06 | 6.1E-06 | 6.8E-05 | 1.5E-11 | 0.0E+00 | 1.2E-11 | 3.3E-12 |
| transport, VT, ProtoSelfPropel, 2040_RCP19 | 1.1E-03 | 2.2E-01 | 1.6E-06 | 6.1E-06 | 6.5E-05 | 1.4E-11 | 0.0E+00 | 1.1E-11 | 3.0E-12 |
| transport, VT, ProtoSteel, 2040_RCP19 | 1.6E-03 | 2.0E-01 | 5.2E-06 | 8.5E-06 | 9.5E-05 | 3.4E-11 | 0.0E+00 | 2.3E-11 | 1.2E-11 |
| transport, passenger train, long-distance | 1.7E-03 | 1.9E-01 | 2.3E-06 | 8.3E-06 | 8.8E-05 | 2.3E-11 | 0.0E+00 | 1.1E-11 | 1.2E-11 |
| transport, passenger train, long-distance, 2040_base | 1.5E-03 | 1.7E-01 | 2.2E-06 | 7.1E-06 | 7.5E-05 | 2.1E-11 | 0.0E+00 | 1.1E-11 | 1.1E-11 |
| transport, passenger train, long-distance, 2040_RCP26 | 1.5E-03 | 1.7E-01 | 1.7E-06 | 6.8E-06 | 7.3E-05 | 2.1E-11 | 0.0E+00 | 1.1E-11 | 9.9E-12 |
| transport, passenger train, long-distance, 2040_RCP19 | 1.5E-03 | 1.7E-01 | 1.6E-06 | 6.8E-06 | 7.3E-05 | 1.9E-11 | 0.0E+00 | 1.0E-11 | 8.8E-12 |
| transport, passenger aircraft, short haul, e-kerosene | 1.6E-02 | 4.5E-01 | 2.5E-05 | 2.0E-04 | 2.2E-03 | 1.5E-10 | 0.0E+00 | 1.1E-10 | 4.2E-11 |
| transport, passenger aircraft, short haul | 1.0E-01 | 1.7E+00 | 5.6E-06 | 2.1E-04 | 2.3E-03 | 1.4E-11 | 0.0E+00 | 1.0E-11 | 3.9E-12 |

| Name | s | t | u | v | w | x | y | z | aa |
|---|---|---|---|---|---|---|---|---|---|
| transport, VT, ProtoStandard | 7.1E-10 | 3.9E-11 | 6.4E-10 | 3.1E-11 | 7.9E-03 | 6.4E-02 | 1.2E-06 | 3.2E-10 | 5.8E-10 |
| transport, VT, ProtoLauncher | 4.4E-10 | 3.5E-11 | 3.9E-10 | 1.8E-11 | 8.5E-03 | 5.8E-02 | 6.8E-07 | 2.9E-10 | 5.1E-10 |
| transport, VT, ProtoSelfPropel | 2.4E-10 | 4.0E-11 | 1.9E-10 | 7.6E-12 | 1.0E-02 | 6.1E-02 | 3.4E-07 | 3.2E-10 | 4.9E-10 |
| transport, VT, ProtoSteel | 7.8E-10 | 7.6E-11 | 6.8E-10 | 3.2E-11 | 8.0E-03 | 7.1E-02 | 1.2E-06 | 4.4E-10 | 7.5E-10 |
| transport, VT, ProtoStandard, 2040_base | 7.2E-10 | 3.6E-11 | 6.5E-10 | 3.1E-11 | 7.6E-03 | 4.4E-02 | 1.2E-06 | 3.0E-10 | 5.8E-10 |
| transport, VT, ProtoLauncher, 2040_base | 4.4E-10 | 3.3E-11 | 3.9E-10 | 1.8E-11 | 8.1E-03 | 3.8E-02 | 6.9E-07 | 2.7E-10 | 5.1E-10 |
| transport, VT, ProtoSelfPropel, 2040_base | 2.4E-10 | 3.7E-11 | 2.0E-10 | 7.5E-12 | 9.6E-03 | 3.7E-02 | 3.4E-07 | 3.0E-10 | 4.9E-10 |
| transport, VT, ProtoSteel, 2040_base | 7.8E-10 | 7.0E-11 | 6.8E-10 | 3.1E-11 | 7.7E-03 | 4.9E-02 | 1.2E-06 | 4.0E-10 | 7.3E-10 |
| transport, VT, ProtoStandard, 2040_RCP26 | 7.1E-10 | 3.5E-11 | 6.4E-10 | 3.1E-11 | 7.7E-03 | 3.9E-02 | 1.2E-06 | 3.1E-10 | 5.6E-10 |
| transport, VT, ProtoLauncher, 2040_RCP26 | 4.3E-10 | 3.2E-11 | 3.9E-10 | 1.7E-11 | 8.2E-03 | 3.2E-02 | 6.9E-07 | 2.9E-10 | 4.9E-10 |
| transport, VT, ProtoSelfPropel, 2040_RCP26 | 2.4E-10 | 3.7E-11 | 1.9E-10 | 7.4E-12 | 9.7E-03 | 2.9E-02 | 3.4E-07 | 3.2E-10 | 4.8E-10 |
| transport, VT, ProtoSteel, 2040_RCP26 | 7.7E-10 | 6.9E-11 | 6.7E-10 | 3.1E-11 | 7.8E-03 | 4.4E-02 | 1.2E-06 | 4.2E-10 | 7.1E-10 |
| transport, VT, ProtoStandard, 2040_RCP19 | 7.1E-10 | 3.5E-11 | 6.4E-10 | 3.1E-11 | 7.8E-03 | 4.5E-02 | 1.2E-06 | 3.2E-10 | 5.6E-10 |
| transport, VT, ProtoLauncher, 2040_RCP19 | 4.3E-10 | 3.2E-11 | 3.9E-10 | 1.7E-11 | 8.3E-03 | 3.8E-02 | 6.9E-07 | 3.0E-10 | 4.9E-10 |
| transport, VT, ProtoSelfPropel, 2040_RCP19 | 2.4E-10 | 3.7E-11 | 1.9E-10 | 7.4E-12 | 9.8E-03 | 3.6E-02 | 3.5E-07 | 3.3E-10 | 4.8E-10 |
| transport, VT, ProtoSteel, 2040_RCP19 | 7.7E-10 | 6.8E-11 | 6.7E-10 | 3.1E-11 | 8.0E-03 | 5.0E-02 | 1.2E-06 | 4.2E-10 | 7.0E-10 |
| transport, passenger train, long-distance | 1.9E-10 | 5.2E-11 | 1.3E-10 | 5.6E-12 | 7.7E-03 | 3.4E-01 | 1.5E-07 | 4.4E-10 | 1.1E-09 |
| transport, passenger train, long-distance, 2040_base | 2.0E-10 | 4.6E-11 | 1.5E-10 | 4.9E-12 | 6.6E-03 | 3.2E-01 | 1.6E-07 | 3.7E-10 | 1.2E-09 |
| transport, passenger train, long-distance, 2040_RCP26 | 1.9E-10 | 4.5E-11 | 1.4E-10 | 4.9E-12 | 6.6E-03 | 3.1E-01 | 1.6E-07 | 3.8E-10 | 1.2E-09 |
| transport, passenger train, long-distance, 2040_RCP19 | 1.9E-10 | 4.5E-11 | 1.4E-10 | 4.8E-12 | 6.7E-03 | 3.2E-01 | 1.6E-07 | 3.9E-10 | 1.2E-09 |
| transport, passenger aircraft, short haul, e-kerosene | 4.1E-09 | 3.2E-10 | 3.7E-09 | 1.2E-10 | 3.3E-03 | 5.0E-01 | 4.4E-06 | 3.3E-09 | 3.1E-09 |
| transport, passenger aircraft, short haul | 1.6E-09 | 2.6E-10 | 1.4E-09 | 1.3E-11 | 8.3E-03 | 3.2E-01 | 1.6E-07 | 2.6E-08 | 1.5E-09 |

| Name | ab | ac | ad | ae | af | ag | ah | ai | aj |
|---|---|---|---|---|---|---|---|---|---|
| transport, VT, ProtoStandard | 2.8E-05 | 5.3E-02 | 1.8E-02 | 5.9E-02 | 5.7E-05 | 1.4E-01 | 7.0E-06 | 4.8E-05 | 3.1E-01 |
| transport, VT, ProtoLauncher | 2.3E-05 | 5.6E-02 | 1.9E-02 | 5.3E-02 | 4.7E-05 | 1.5E-01 | 6.2E-06 | 3.7E-05 | 3.3E-01 |
| transport, VT, ProtoSelfPropel | 2.2E-05 | 6.7E-02 | 2.3E-02 | 5.4E-02 | 4.6E-05 | 1.8E-01 | 6.3E-06 | 2.7E-05 | 4.0E-01 |
| transport, VT, ProtoSteel | 4.0E-05 | 5.4E-02 | 1.8E-02 | 8.2E-02 | 7.6E-05 | 1.4E-01 | 1.4E-05 | 4.8E-05 | 3.1E-01 |
| transport, VT, ProtoStandard, 2040_base | 2.5E-05 | 5.3E-02 | 2.6E-02 | 5.6E-02 | 3.1E-04 | 1.4E-01 | 1.2E-06 | 1.6E-03 | 3.1E-01 |
| transport, VT, ProtoLauncher, 2040_base | 2.1E-05 | 5.6E-02 | 2.8E-02 | 5.1E-02 | 2.7E-04 | 1.5E-01 | 1.2E-06 | 1.6E-03 | 3.3E-01 |
| transport, VT, ProtoSelfPropel, 2040_base | 1.9E-05 | 6.7E-02 | 3.2E-02 | 5.2E-02 | 2.6E-04 | 1.7E-01 | 1.3E-06 | 1.6E-03 | 3.9E-01 |
| transport, VT, ProtoSteel, 2040_base | 3.5E-05 | 5.4E-02 | 2.6E-02 | 7.6E-02 | 3.9E-04 | 1.4E-01 | 1.4E-06 | 1.7E-03 | 3.1E-01 |
| transport, VT, ProtoStandard, 2040_RCP26 | 2.4E-05 | 5.3E-02 | 2.7E-02 | 5.0E-02 | 4.1E-04 | 1.4E-01 | 9.9E-07 | 2.8E-03 | 3.1E-01 |
| transport, VT, ProtoLauncher, 2040_RCP26 | 2.0E-05 | 5.6E-02 | 2.8E-02 | 4.6E-02 | 3.6E-04 | 1.5E-01 | 9.1E-07 | 2.7E-03 | 3.3E-01 |
| transport, VT, ProtoSelfPropel, 2040_RCP26 | 1.9E-05 | 6.7E-02 | 3.3E-02 | 4.7E-02 | 3.6E-04 | 1.8E-01 | 1.0E-06 | 2.8E-03 | 3.9E-01 |
| transport, VT, ProtoSteel, 2040_RCP26 | 3.4E-05 | 5.4E-02 | 2.8E-02 | 6.8E-02 | 4.8E-04 | 1.4E-01 | 1.1E-06 | 2.9E-03 | 3.1E-01 |
| transport, VT, ProtoStandard, 2040_RCP19 | 2.4E-05 | 5.3E-02 | 2.9E-02 | 4.9E-02 | 4.2E-04 | 1.4E-01 | 1.2E-06 | 3.1E-03 | 3.1E-01 |
| transport, VT, ProtoLauncher, 2040_RCP19 | 2.0E-05 | 5.6E-02 | 3.0E-02 | 4.5E-02 | 3.7E-04 | 1.5E-01 | 1.1E-06 | 2.9E-03 | 3.3E-01 |
| transport, VT, ProtoSelfPropel, 2040_RCP19 | 1.9E-05 | 6.7E-02 | 3.4E-02 | 4.7E-02 | 3.7E-04 | 1.8E-01 | 1.3E-06 | 3.0E-03 | 3.9E-01 |
| transport, VT, ProtoSteel, 2040_RCP19 | 3.2E-05 | 5.4E-02 | 2.9E-02 | 6.3E-02 | 4.9E-04 | 1.4E-01 | 1.3E-06 | 3.1E-03 | 3.1E-01 |
| transport, passenger train, long-distance | 3.0E-05 | 4.7E-02 | 1.6E-02 | 6.2E-02 | 4.2E-05 | 1.4E-01 | 1.7E-05 | 7.2E-06 | 2.8E-01 |
| transport, passenger train, long-distance, 2040_base | 2.6E-05 | 4.8E-02 | 2.4E-02 | 5.8E-02 | 3.3E-04 | 1.2E-01 | 7.1E-06 | 4.5E-03 | 2.7E-01 |
| transport, passenger train, long-distance, 2040_RCP26 | 2.5E-05 | 4.7E-02 | 2.4E-02 | 5.3E-02 | 6.3E-04 | 1.2E-01 | 6.8E-06 | 8.1E-03 | 2.7E-01 |
| transport, passenger train, long-distance, 2040_RCP19 | 2.5E-05 | 4.8E-02 | 2.6E-02 | 5.1E-02 | 6.6E-04 | 1.2E-01 | 7.1E-06 | 8.3E-03 | 2.7E-01 |
| transport, passenger aircraft, short haul, e-kerosene | 5.8E-04 | 1.7E-02 | 1.0E-02 | 4.4E-01 | 7.4E-04 | 4.9E-02 | 1.2E-04 | 3.2E-04 | 3.2E-02 |
| transport, passenger aircraft, short haul | 6.1E-04 | 5.6E-03 | 4.8E-03 | 1.8E+00 | 3.5E-04 | 2.6E-02 | 1.4E-05 | 4.3E-05 | 1.1E-02 |

| Name | ak | al | am | an | ao | ap | aq | ar | as |
|---|---|---|---|---|---|---|---|---|---|
| transport, VT, ProtoStandard | 7.5E-04 | 3.0E-02 | 1.0E+00 | 1.0E+00 | 2.5E+00 | 1.0E+01 | 8.2E-02 | 1.4E+00 | 1.2E-01 |
| transport, VT, ProtoLauncher | 6.8E-04 | 2.7E-02 | 9.1E-01 | 1.1E+00 | 2.3E+00 | 5.9E+00 | 8.4E-02 | 1.1E+00 | 1.1E-01 |
| transport, VT, ProtoSelfPropel | 7.3E-04 | 2.9E-02 | 8.8E-01 | 1.2E+00 | 2.3E+00 | 2.4E+00 | 9.9E-02 | 9.2E-01 | 1.1E-01 |
| transport, VT, ProtoSteel | 9.1E-04 | 3.9E-02 | 1.9E+00 | 1.1E+00 | 3.5E+00 | 1.1E+01 | 9.2E-02 | 2.6E+00 | 1.3E-01 |
| transport, VT, ProtoStandard, 2040_base | 1.6E-03 | 2.7E-02 | 1.1E+00 | 1.0E+00 | 2.4E+00 | 1.0E+01 | 8.4E-02 | 1.4E+00 | 8.6E-02 |
| transport, VT, ProtoLauncher, 2040_base | 1.5E-03 | 2.5E-02 | 9.7E-01 | 1.0E+00 | 2.2E+00 | 5.9E+00 | 8.7E-02 | 1.0E+00 | 7.2E-02 |
| transport, VT, ProtoSelfPropel, 2040_base | 1.6E-03 | 2.7E-02 | 9.4E-01 | 1.2E+00 | 2.3E+00 | 2.5E+00 | 1.0E-01 | 9.2E-01 | 6.8E-02 |
| transport, VT, ProtoSteel, 2040_base | 1.9E-03 | 3.5E-02 | 1.8E+00 | 1.1E+00 | 3.2E+00 | 1.1E+01 | 9.3E-02 | 2.5E+00 | 9.6E-02 |
| transport, VT, ProtoStandard, 2040_RCP26 | 1.8E-03 | 2.9E-02 | 1.1E+00 | 9.8E-01 | 1.9E+00 | 1.0E+01 | 8.8E-02 | 1.3E+00 | 7.6E-02 |
| transport, VT, ProtoLauncher, 2040_RCP26 | 1.6E-03 | 2.7E-02 | 9.6E-01 | 1.0E+00 | 1.8E+00 | 5.9E+00 | 9.0E-02 | 1.0E+00 | 6.0E-02 |
| transport, VT, ProtoSelfPropel, 2040_RCP26 | 1.7E-03 | 2.9E-02 | 9.4E-01 | 1.2E+00 | 1.9E+00 | 2.5E+00 | 1.1E-01 | 9.0E-01 | 5.4E-02 |
| transport, VT, ProtoSteel, 2040_RCP26 | 2.1E-03 | 3.7E-02 | 1.8E+00 | 1.1E+00 | 2.5E+00 | 1.1E+01 | 9.8E-02 | 2.4E+00 | 8.5E-02 |
| transport, VT, ProtoStandard, 2040_RCP19 | 2.1E-03 | 3.0E-02 | 1.0E+00 | 9.9E-01 | 1.6E+00 | 1.0E+01 | 8.8E-02 | 1.3E+00 | 8.5E-02 |
| transport, VT, ProtoLauncher, 2040_RCP19 | 1.8E-03 | 2.8E-02 | 9.4E-01 | 1.0E+00 | 1.5E+00 | 5.9E+00 | 9.0E-02 | 1.0E+00 | 7.0E-02 |
| transport, VT, ProtoSelfPropel, 2040_RCP19 | 1.9E-03 | 3.0E-02 | 9.2E-01 | 1.2E+00 | 1.6E+00 | 2.5E+00 | 1.1E-01 | 8.9E-01 | 6.5E-02 |
| transport, VT, ProtoSteel, 2040_RCP19 | 2.4E-03 | 3.6E-02 | 1.7E+00 | 1.0E+00 | 2.1E+00 | 1.1E+01 | 9.8E-02 | 2.4E+00 | 9.4E-02 |
| transport, passenger train, long-distance | 6.8E-04 | 4.6E-02 | 1.3E+00 | 9.7E-01 | 2.8E+00 | 1.5E+00 | 9.0E-02 | 1.5E+00 | 5.9E-01 |
| transport, passenger train, long-distance, 2040_base | 2.9E-03 | 3.8E-02 | 1.3E+00 | 9.1E-01 | 2.7E+00 | 1.6E+00 | 8.8E-02 | 1.5E+00 | 5.7E-01 |
| transport, passenger train, long-distance, 2040_RCP26 | 2.6E-03 | 4.1E-02 | 1.3E+00 | 9.0E-01 | 2.1E+00 | 1.6E+00 | 8.8E-02 | 1.4E+00 | 5.6E-01 |
| transport, passenger train, long-distance, 2040_RCP19 | 2.8E-03 | 4.2E-02 | 1.2E+00 | 9.0E-01 | 1.7E+00 | 1.6E+00 | 8.8E-02 | 1.4E+00 | 5.7E-01 |
| transport, passenger aircraft, short haul, e-kerosene | 2.9E+00 | 2.5E-01 | 1.4E+01 | 4.6E+00 | 1.1E+01 | 5.3E+01 | 1.8E-01 | 1.0E+01 | 7.3E-01 |
| transport, passenger aircraft, short haul | 3.1E-03 | 3.6E+00 | 1.1E+00 | 6.4E+00 | 5.6E+01 | 1.8E+01 | 4.5E-02 | 2.2E+00 | 2.6E-01 |

| Name | at | au | av | aw | ax | ay | az | ba | bb |
|---|---|---|---|---|---|---|---|---|---|
| transport, VT, ProtoStandard | 3.3E+00 | 1.5E+00 | 7.7E-02 | 1.9E-03 | 1.6E-03 | 6.3E-07 | 3.3E-02 | 3.0E+00 | 2.5E+01 |
| transport, VT, ProtoLauncher | 2.6E+00 | 1.3E+00 | 9.3E-03 | 1.8E-03 | 1.5E-03 | 6.8E-07 | 3.5E-02 | 3.1E+00 | 2.0E+01 |
| transport, VT, ProtoSelfPropel | 2.2E+00 | 1.4E+00 | -3.7E-02 | 2.0E-03 | 1.7E-03 | 7.9E-07 | 4.2E-02 | 3.7E+00 | 1.7E+01 |
| transport, VT, ProtoSteel | 4.6E+00 | 1.5E+00 | 2.4E-01 | 2.3E-03 | 2.3E-03 | 6.4E-07 | 3.3E-02 | 3.0E+00 | 3.0E+01 |
| transport, VT, ProtoStandard, 2040_base | 3.0E+00 | 1.5E+00 | 5.7E-02 | 1.8E-03 | 1.1E-03 | 6.0E-07 | 3.1E-02 | 2.8E+00 | 2.5E+01 |
| transport, VT, ProtoLauncher, 2040_base | 2.3E+00 | 1.3E+00 | -1.1E-02 | 1.7E-03 | 1.1E-03 | 6.5E-07 | 3.4E-02 | 3.0E+00 | 1.9E+01 |
| transport, VT, ProtoSelfPropel, 2040_base | 2.0E+00 | 1.4E+00 | -5.7E-02 | 2.0E-03 | 1.2E-03 | 7.7E-07 | 4.0E-02 | 3.6E+00 | 1.6E+01 |
| transport, VT, ProtoSteel, 2040_base | 4.1E+00 | 1.5E+00 | 2.3E-01 | 2.2E-03 | 1.2E-03 | 6.1E-07 | 3.2E-02 | 2.9E+00 | 2.9E+01 |
| transport, VT, ProtoStandard, 2040_RCP26 | 2.7E+00 | 1.5E+00 | 5.7E-02 | 1.9E-03 | 1.1E-03 | 6.1E-07 | 3.2E-02 | 2.9E+00 | 2.4E+01 |
| transport, VT, ProtoLauncher, 2040_RCP26 | 2.2E+00 | 1.3E+00 | -1.1E-02 | 1.8E-03 | 1.0E-03 | 6.5E-07 | 3.4E-02 | 3.1E+00 | 1.8E+01 |
| transport, VT, ProtoSelfPropel, 2040_RCP26 | 1.9E+00 | 1.4E+00 | -5.7E-02 | 2.0E-03 | 1.2E-03 | 7.7E-07 | 4.0E-02 | 3.6E+00 | 1.6E+01 |
| transport, VT, ProtoSteel, 2040_RCP26 | 3.8E+00 | 1.5E+00 | 2.3E-01 | 2.3E-03 | 1.2E-03 | 6.2E-07 | 3.2E-02 | 2.9E+00 | 2.8E+01 |
| transport, VT, ProtoStandard, 2040_RCP19 | 2.7E+00 | 1.5E+00 | 5.5E-02 | 2.0E-03 | 1.1E-03 | 6.2E-07 | 3.3E-02 | 2.9E+00 | 2.4E+01 |
| transport, VT, ProtoLauncher, 2040_RCP19 | 2.1E+00 | 1.3E+00 | -1.3E-02 | 1.8E-03 | 1.1E-03 | 6.6E-07 | 3.5E-02 | 3.1E+00 | 1.8E+01 |
| transport, VT, ProtoSelfPropel, 2040_RCP19 | 1.8E+00 | 1.4E+00 | -6.0E-02 | 2.1E-03 | 1.2E-03 | 7.8E-07 | 4.1E-02 | 3.7E+00 | 1.5E+01 |
| transport, VT, ProtoSteel, 2040_RCP19 | 3.7E+00 | 1.5E+00 | 2.3E-01 | 2.3E-03 | 1.2E-03 | 6.4E-07 | 3.3E-02 | 3.0E+00 | 2.7E+01 |
| transport, passenger train, long-distance | 4.2E+00 | 2.5E+00 | 1.3E-01 | 2.2E-03 | 2.5E-03 | 6.2E-07 | 3.0E-02 | 2.7E+00 | 1.9E+01 |
| transport, passenger train, long-distance, 2040_base | 4.0E+00 | 2.5E+00 | 1.1E-01 | 1.9E-03 | 1.8E-03 | 5.3E-07 | 2.7E-02 | 2.4E+00 | 1.9E+01 |
| transport, passenger train, long-distance, 2040_RCP26 | 3.8E+00 | 2.5E+00 | 1.1E-01 | 2.0E-03 | 1.8E-03 | 5.3E-07 | 2.7E-02 | 2.4E+00 | 1.8E+01 |
| transport, passenger train, long-distance, 2040_RCP19 | 3.8E+00 | 2.5E+00 | 1.1E-01 | 2.1E-03 | 1.9E-03 | 5.4E-07 | 2.7E-02 | 2.4E+00 | 1.7E+01 |
| transport, passenger aircraft, short haul, e-kerosene | 3.4E+01 | 5.5E+00 | 1.8E+00 | 2.3E-02 | 1.4E-02 | 2.6E-07 | 1.4E-02 | 1.3E+00 | 1.4E+02 |
| transport, passenger aircraft, short haul | 2.9E+01 | 7.2E-01 | 2.7E-01 | 1.5E-01 | 2.1E-03 | 6.7E-07 | 7.3E-03 | 6.6E-01 | 1.2E+02 |

| Name | bc | bd |
|---|---:|---:|
| transport, VT, ProtoStandard | 2.1E-01 | 7.5E-01 |
| transport, VT, ProtoLauncher | 2.0E-01 | 8.0E-01 |
| transport, VT, ProtoSelfPropel | 2.3E-01 | 9.5E-01 |
| transport, VT, ProtoSteel | 2.9E-01 | 7.6E-01 |
| transport, VT, ProtoStandard, 2040_base | 2.0E-01 | 7.5E-01 |
| transport, VT, ProtoLauncher, 2040_base | 1.9E-01 | 8.0E-01 |
| transport, VT, ProtoSelfPropel, 2040_base | 2.2E-01 | 9.5E-01 |
| transport, VT, ProtoSteel, 2040_base | 2.7E-01 | 7.6E-01 |
| transport, VT, ProtoStandard, 2040_RCP26 | 1.9E-01 | 7.5E-01 |
| transport, VT, ProtoLauncher, 2040_RCP26 | 1.8E-01 | 8.0E-01 |
| transport, VT, ProtoSelfPropel, 2040_RCP26 | 2.1E-01 | 9.5E-01 |
| transport, VT, ProtoSteel, 2040_RCP26 | 2.5E-01 | 7.6E-01 |
| transport, VT, ProtoStandard, 2040_RCP19 | 1.9E-01 | 7.5E-01 |
| transport, VT, ProtoLauncher, 2040_RCP19 | 1.8E-01 | 8.0E-01 |
| transport, VT, ProtoSelfPropel, 2040_RCP19 | 2.1E-01 | 9.5E-01 |
| transport, VT, ProtoSteel, 2040_RCP19 | 2.4E-01 | 7.6E-01 |
| transport, passenger train, long-distance | 2.2E-01 | 6.7E-01 |
| transport, passenger train, long-distance, 2040_base | 1.9E-01 | 6.8E-01 |
| transport, passenger train, long-distance, 2040_RCP26 | 1.8E-01 | 6.7E-01 |
| transport, passenger train, long-distance, 2040_RCP19 | 1.8E-01 | 6.8E-01 |
| transport, passenger aircraft, short haul, e-kerosene | 1.5E+00 | 2.3E-01 |
| transport, passenger aircraft, short haul | 6.8E+00 | 8.0E-02 |

## A.4 Sankey Diagrams

This section contains extracts from the Sankey diagrams in the Activity Browser with a cut-off below 5 % and a calculation depth of 250, using GWP100a and the background data from today as a reference.

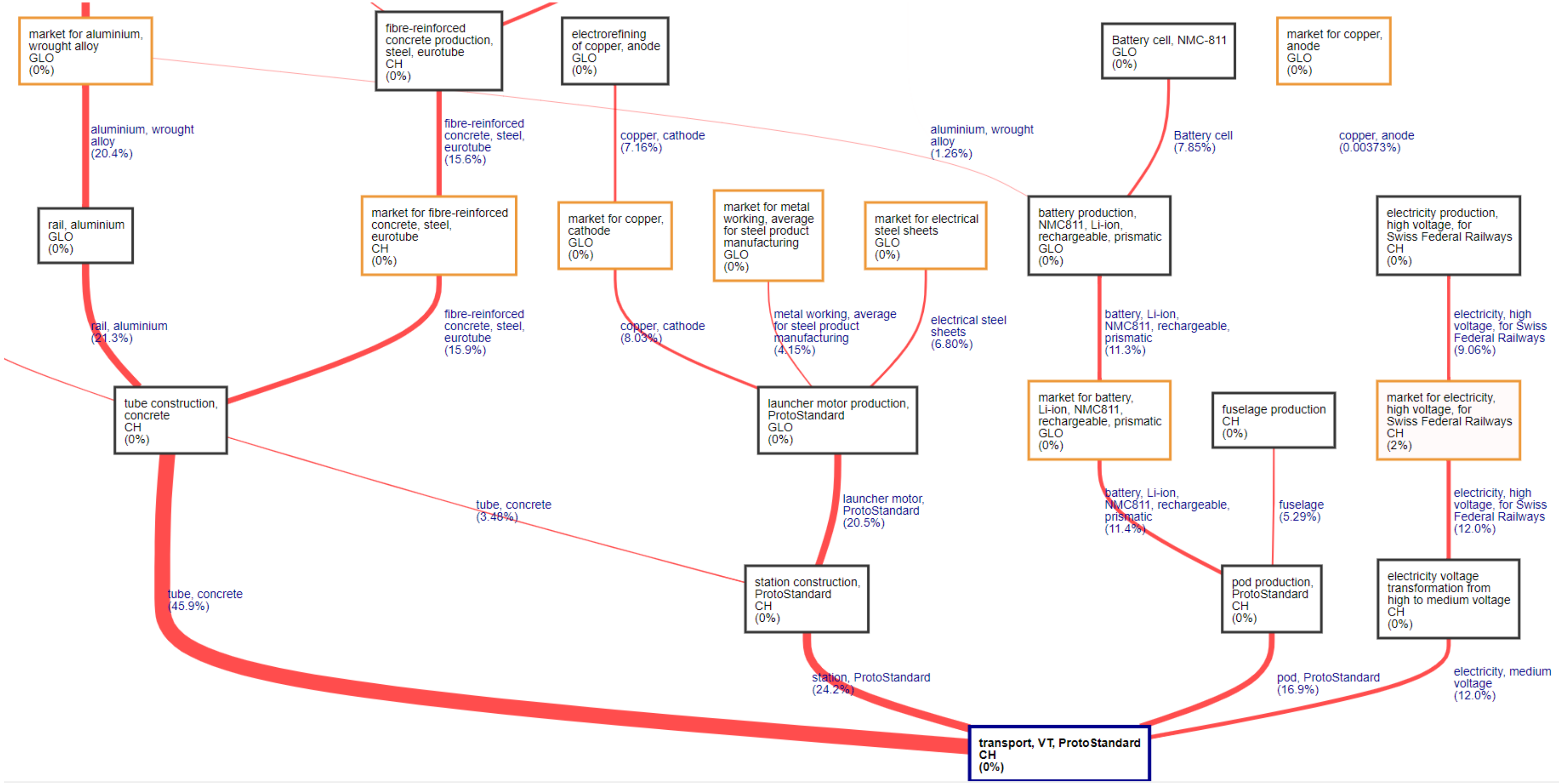


Figure A 4: Sankey diagram of the GWP100a of the ProtoStandard with today's background data.

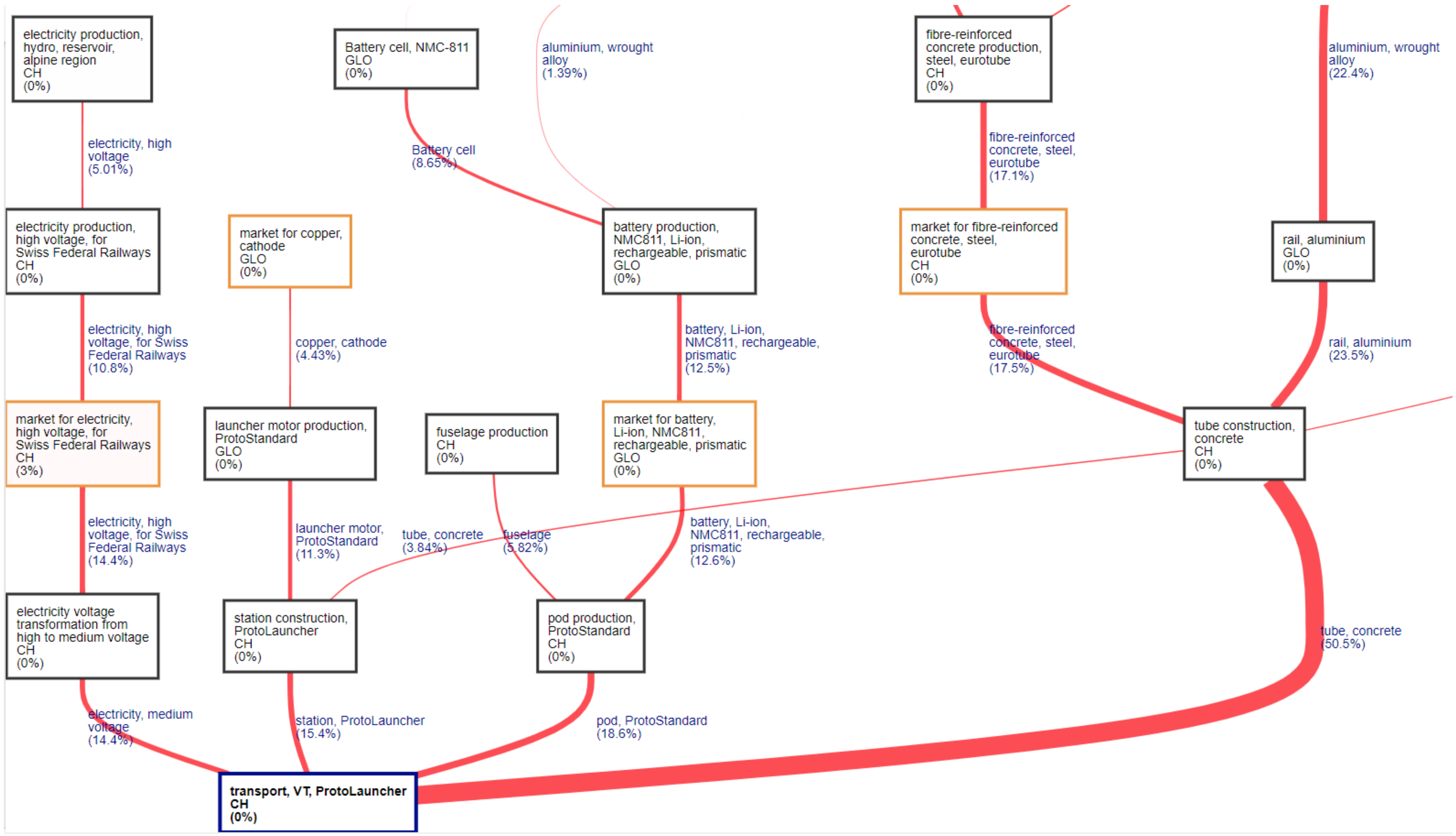


Figure A 5: Sankey diagram of the GWP100a of the ProtoLauncher with today's background data.

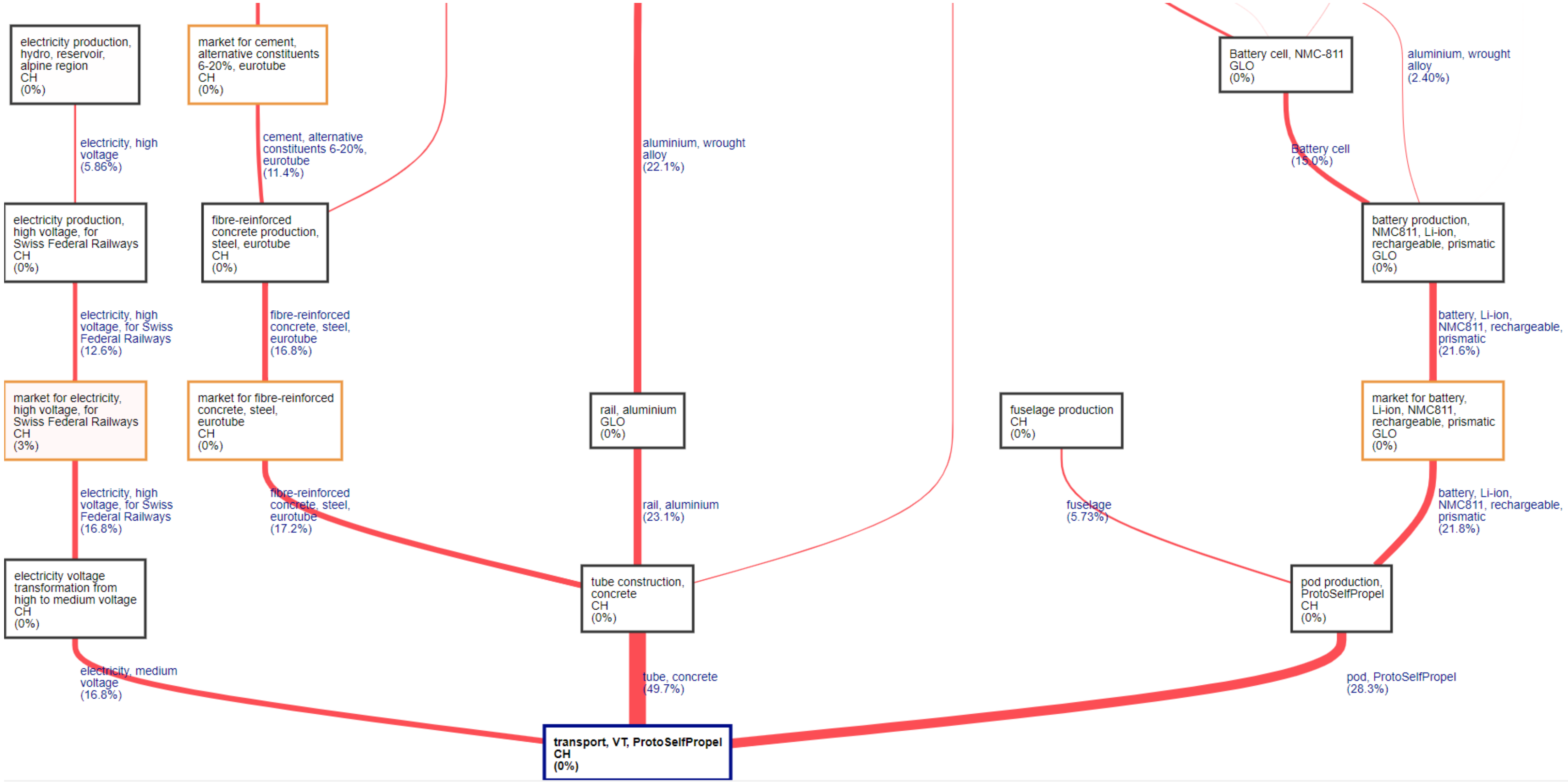


Figure A 6: Sankey diagram of the GWP100a of the ProtoSelfPropel with today's background data.

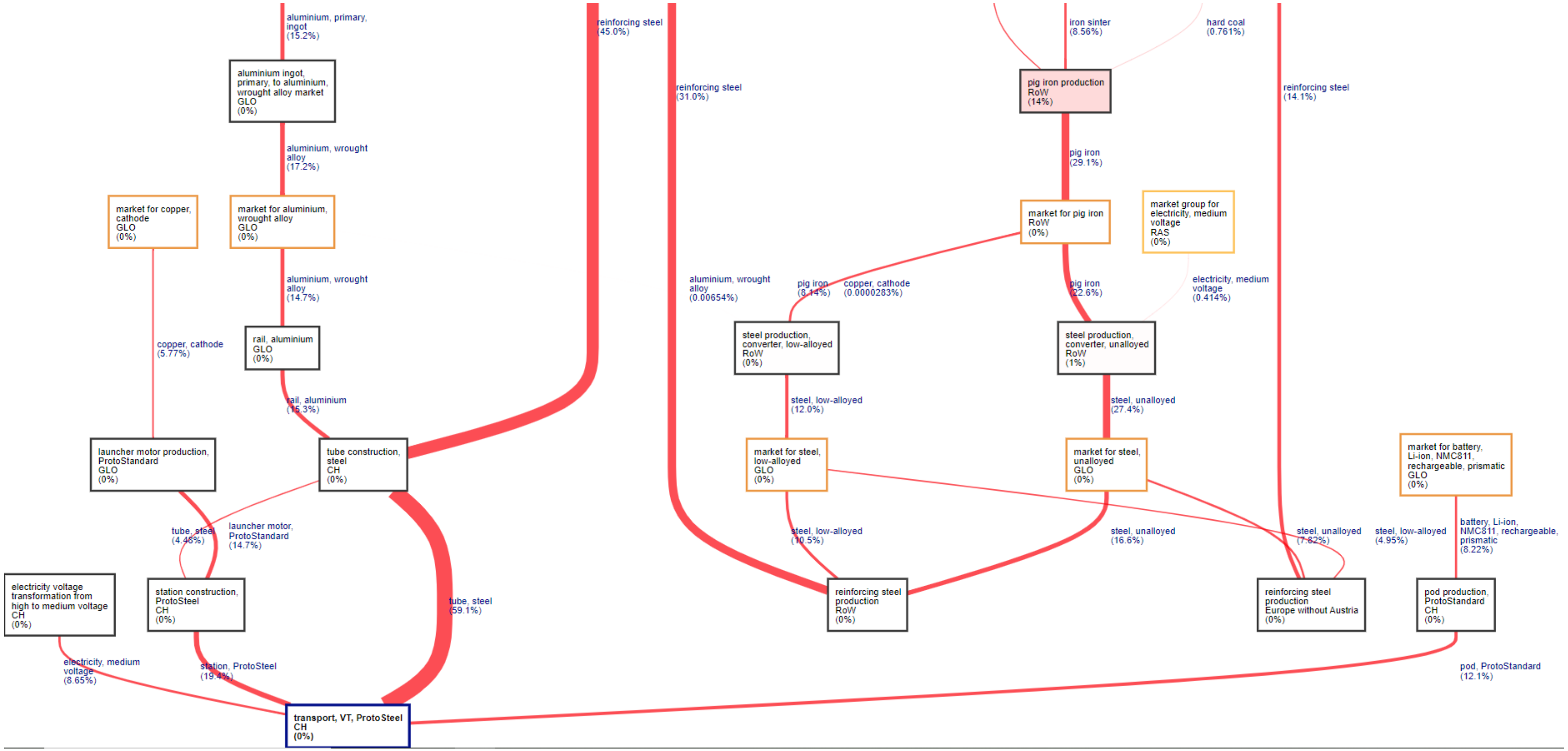


Figure A 7: Sankey diagram of the GWP100a of the ProtoSteel with today's background data.