# Master's Thesis

## Life cycle assessment of rail vehicle production based on manufacturing at the Siemens Mobility facility: Vienna Leberstraße

*Ökobilanz (LCA) der Schienenfahrzeugproduktion basierend auf der Fertigung im Siemens Mobility Werk: Wien Leberstraße*

Submitted in partial fulfillment of the requirements for the degree
Master of Science / Diplom-Ingenieur
under the supervision of

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Vienna, October 2019

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## *Declaration in Lieu of Oath*

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Vienna, October 2019

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# Abstract

This work presents a life cycle assessment (LCA) of the rail vehicle manufacturing at the Siemens Mobility production plant in Vienna, Austria. Addressing the global issue of environmental protection, the goal of the study is to make the environmental impact resulting from manufacturing transparent so it can be reduced. Following the international environmental standard ISO 14040, data for the LCA was collected over the manufacturing phases and the environmental impact was calculated using SimaPro. The results show that electrical energy and heating as well as transport of materials have the largest impact. The work suggests methods to reduce the resource consumption and therefore decrease the environmental impact of rail vehicle production.

***Keywords:*** life cycle assessment, rolling stock, efficiency

# Kurzfassung

Diese Arbeit umfasst eine Ökobilanz (LCA) der Schienenfahrzeugfertigung im Siemens Mobility Produktionswerk in Wien, Österreich. Sie hat das Ziel, die mit der Herstellung verbundenen Umweltauswirkungen transparent zu machen. Die daraus folgenden Erkenntnisse können dazu verwendet werden, die Umweltauswirkung zu reduzieren, was dem globalen Thema des Umweltschutzes einen Beitrag leistet. In Anlehnung an die internationale Umweltnorm ISO 14040 wurden über die Herstellungsphasen hinweg Daten für die Ökobilanz erhoben und die Umweltauswirkungen mit SimaPro berechnet. Die Ergebnisse zeigen, dass elektrische Energie sowie Gebäudeheizung und Transport von Hilfsmaterialien den größten Einfluss haben. Schließlich werden Vorschläge zur Reduzierung des Ressourcenverbrauchs und damit zur Verringerung der Umweltbelastung präsentiert.

***Keywords:*** Ökobilanz, Schienenfahrzeugbau, Effizienz

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# 1 Introduction and motivation

The demand for mobility solutions continues to rise as transportation of people and goods gains significance in today's society. Great importance is laid on the ability to move seamlessly within cities and to effortlessly travel to destinations hundreds to thousands of kilometers away.

Especially urban mobility is a growing concern as the global population increases and urbanisation continues. Roughly three quarters of the inhabitants in the present European Union States reside in cities [1], which poses a great load on the cities' transit infrastructure. With the goal of reducing problems derived from the use of private cars, such as traffic congestion and the negative environmental impacts, public transportation is encouraged [1]. According to the International Association of Public Transport, global annual metro ridership has increased by 20 % over the last six years, with metros in 178 cities carrying 168 million passengers per day [2]. Various other rail solutions such as regional, intercity and high-speed trains are available for travelling greater distances. Data from the International Union of Railways (UIC) reveals that the global number of passenger-kilometers travelled annually with rail vehicles has risen by over 50 % in the years 2004 to 2016 [3,4]. Figure 1 shows railway statistics over that time period.

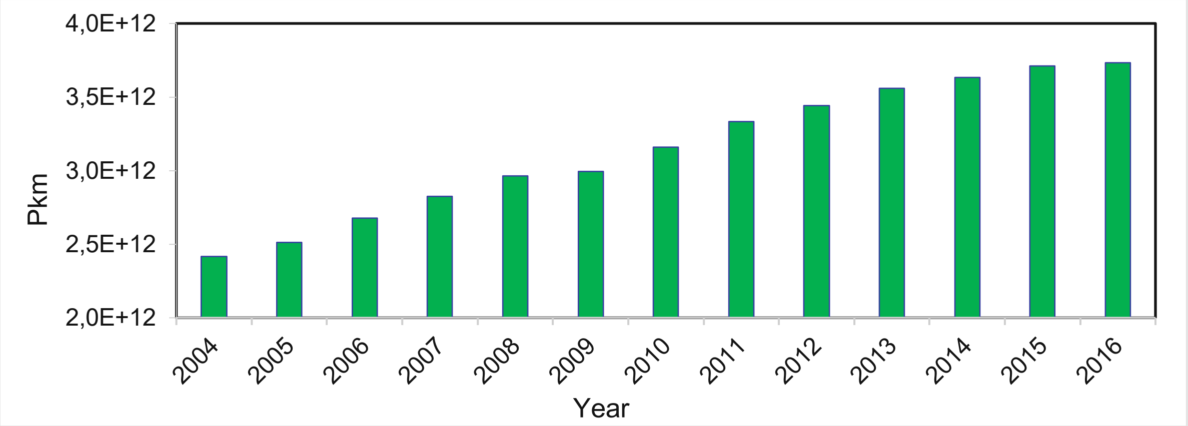

**Figure 1: Global annual number of passenger-kilometers travelled by rail in the years 2004 to 2016 [4].**

An increase in rail transportation capacity inherently demands for an increase in vehicle production. In general, unsustainable production of goods in recent centuries has led to severe depletion of resources, an increase in waste and global warming, and the release of toxins into the environment. Manufacturing of rolling stock is no exception.

Rail vehicles consist mainly of aluminum and steel, whereas the mobility industry consumes 42 % of primary aluminum produced per year [5]. Even though aluminum is one of the most abundant elements in the earth's crust, the extraction and refinement pose sustainability issues. First of all, it is very energy intensive to refine, and the production results in increased greenhouse gas emissions [5]. Second, Europe is increasingly dependent on aluminum imports from other parts of the world. Since 2010, the import of primary aluminum has increased to nearly 50 % of the total aluminum used [5]. This dependency on other countries poses political, economic and environmental sustainability issues. Imported goods have a longer way to travel and the refinement process results in higher environmental impacts than sourcing in the EU [5]. These concepts also apply to other materials used in rail vehicle production, and it should be clear that material waste of all kinds should be minimised in all manufacturing processes.

Energy consumption is not only a concern in the early stages of the life cycle of a rail vehicle, when the sourcing of raw materials is done, but also during manufacturing. In comparison to the energy consumed over the entire life cycle of the vehicle, the energy used for production is relatively small; seen absolute however, it is a considerable amount of energy that can be reduced. Reducing energy consumption during the manufacturing phase would lower the environmental impact.

In order to improve a system, it must first be evaluated. When interested in the environmental sustainability, the environmental impact of a product can be assessed using the methods described in a so-called life cycle assessment (LCA) in accordance with ISO 14040 [6]. Identifying the key drivers for various impacts is essential for subsequently improving the system and increasing efficiency and sustainability. For many companies, this is of interest in order to reduce costs, obtain non-mandatory certifications to improve their corporate image and to show the customer the environmental effects of the product [7]. Most large rail vehicle contracts are from state bodies, many of which demand a minimum recyclability rate and limited environmental impact. For these reasons, life cycle assessments are becoming common practice. Examples of studies that present a LCA of rail vehicles have been conducted by Stripple & Uppenberg, Del Pero et al. and Yeo et al. [8–10].

As part of a practical investigation, this study will evaluate the production of rail vehicles produced at the Siemens Mobility production facility in Vienna’s Leberstraße (SIE VIE LEB) with the goal of increasing efficiency and sustainability. Siemens Mobility is regarded as a leader in rail transportation and produces solutions for customers worldwide [11]. Its core business includes rail vehicles, rail automation and electrification solutions, turnkey systems, intelligent road traffic technology and related services. In fiscal year 2018 Siemens Mobility achieved a revenue of 8.8 billion euro [12].

The Siemens plant in Vienna Leberstrasse covers an area of 140 000 m² and is one of the world's largest production sites for metros, passenger coaches, trams and fully automated people movers [13]. The production palette of SIE VIE LEB is presented in Figure 2.

**Figure 2: Production palette at SIE VIE LEB [13].**

An aerial view of the facility as well as the contact information is visible in Figure 3.

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Leberstraße 34
1110 Vienna, Austria
Tel.: +43 517070
mobilityaustria.at@siemens.com

**Figure 3: Aerial view and contact information of Siemens Mobility Austria GmbH in Vienna.**

Audits are continuously conducted at Siemens in order to achieve environmental certifications part of environmental standard ISO 14001, as well as to meet quality standards in ISO 9001 and energy standards defined in ISO 50001. Previous studies at SIE VIE LEB relevant to the life cycle assessment include investigations into the upstream and downstream stages of a railway vehicle [14,15].

Results generated in the course of this thesis will complement the existing data, in order to complete a detailed LCA over the whole life cycle of a rail vehicle produced at SIE VIE LEB. Additionally, this information can be contributed to complete the product environmental declaration according to ISO 14025 Type III.

Figure 4 lists the major phases of the study and gives an overview how it is structured.

**Figure 4: Overview of the study.**

# 2 Relevant fundamentals

In the following sections relevant fundamentals will be briefly discussed in order to help the reader understand the study.

## 2.1 Product Life Cycle

The term *life cycle* describes all of the consecutive stages of a product's life, from the gathering of the necessary raw materials over production and usage, to its final disposal. It is common to distinguish between cradle-to-gate, gate-to-gate, cradle-to-grave, and cradle-to-cradle. In a cradle-to-gate assessment, the phase starting with the material extraction and ending with the finished product leaving the production facility gate is investigated, therefore representing only part of the life cycle. A gate-to-gate analysis only considers the value-adding processes of manufacturing. Cradle-to-grave additionally includes the use phase and end of life of a product, while cradle-to-cradle additionally evaluates the recycling of a product's materials.

The life cycle of a product can be further grouped into three major modules: upstream, core and downstream. The upstream module includes processes involved in raw material extraction and energy production, as well as their transport to the production site. The core processes are those belonging to the manufacturing of the selected product, and its transport to the customer. Downstream processes include use, maintenance and disposal of the product [16]. A simplified life cycle with its major modules is shown in Figure 5.

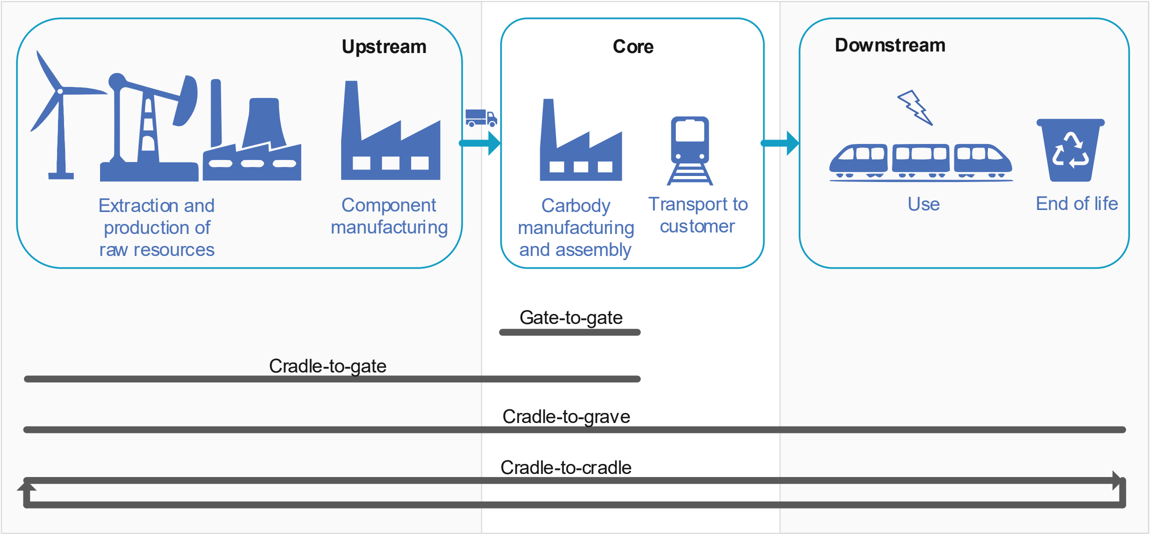


**Figure 5: Life cycle of a rail vehicle.**

## 2.2 Life Cycle Assessment

The Life Cycle Assessment (LCA) is a technique for the purpose of addressing environmental protection and the environmental impacts associated with products and services [6].

The principles and framework of the Life Cycle Assessment, along with its corresponding terms and definitions are defined in ISO 14040. It is part of the standards for environmental management (ISO 14000 series) and is used in accompaniment with ISO 14044 (LCA requirements and guidelines) [17] for assessing the interlinked stages of a product's life cycle, from its raw material acquisition to its disposal. The LCA is used to gain understanding of the environmental effects of the inputs and outputs during a product's life cycle, which can be used:

- to identify opportunities of improvement regarding environmental performance,
- to influence strategic planning, priority setting, product and process design,
- to aid the selection process of relevant environmental performance indicators,
- for marketing purposes (e.g. ecolabeling, environmental claims) [6].

### 2.2.1 LCA key components

As seen in Figure 6, an LCA comprises of 4 main phases:

a. the goal and scope definition phase,
b. the inventory analysis phase (LCI),
c. the impact assessment phase (LCIA),
d. the interpretation phase [6].

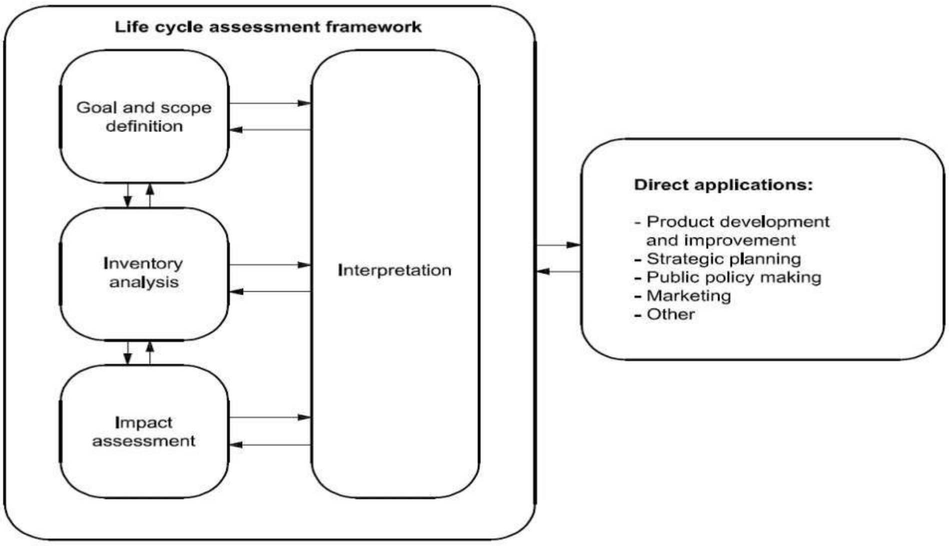


**Figure 6: Phases of a LCA defined in ISO 14040 [6].**

In the goal and scope definition phase, the system boundary and the level of detail of the LCA are described. Depending on the goal of the study, depth and breadth of the LCA will vary. The boundaries must be defined and documented. As this is an iterative process, the boundaries are adapted repeatedly in the course of the study. The ISO 14044 standard states that the purpose, reason and audience of the study shall be described, as well as whether the study will be made public. When defining the boundaries of the system, various concepts must be addressed, such as describing the product system, the functional unit, allocation methods, impact method, data quality requirements, study assumptions, limitations and type of critical review. The cut-off rules are discussed in this phase and describe which components will be left out of the study and why. For definitions of each term see ISO 14040 [6].

The LCI phase involves defining a model of the product life cycle with all of the environmental inputs and outputs. The collection of the data required to assess the life cycle of the product is presented in this phase. It deems as an inventory of inputs and outputs across the system border. In this phase, data is measured, calculated and estimated. Sources include meter readings, journals, books, reports, laboratory test results, calculations and databases from LCA software packages. Typically, the processes are represented using a flow-diagram, where the model of the process is described along with its inputs and outputs. Typical data listed includes energy inputs as well as material inputs and outputs. Products and waste are also listed, as well as emissions to air, water and ground and other environmental aspects.

To assist the developer in creating an LCA and simplify data collection and evaluation, commercially available software packages are considered standard practice. Examples of such packages are SimaPro, GaBi, Umberto NXT LCA, and OpenLCA [18]. These software packages are compatible with databases which include data for thousands of processes over different life cycle stages of numerous products. These are categorised in SimaPro in materials, processes, transport, waste treatment, and waste scenarios. For example, entries include the inputs and outputs related to generating 1 kWh electricity in Austria, or melting 1 kg of steel in Europe, or recycling 1 cardboard box in Switzerland. The ecoinvent v3 database, for example, can be purchased in addition to SimaPro and covers over 10 000 of such processes [19]. Using such data, the consideration of complex environmental aspects can be considered and gathered for handling in the LCIA.

The next phase is the Life Cycle Impact Assessment (LCIA). During the LCIA, the resulting impacts on the environment are derived from the individual inputs and outputs. The goal is to understand and evaluate the magnitude and significance of the potential impacts. The ISO 14040 standards define obligatory elements of the LCIA, which are classification and characterisation, and optional elements such as normalisation, ranking, grouping and weighting. In classification, each substance is assigned to an impact category. These include e.g. global warming potential, eutrophication potential, ozone layer depletion potential and acidification potential. A more detailed list is presented in Table 1. Once the substances have been assigned to impact categories, they can be summarised into an equivalent totals per category in the characterisation step using Intergovernmental Panel on Climate Change (IPCC) equivalency factors. Such factors are recorded in so-called LCA methods and determine the final impact category indicator result (ICIR). Examples and further explanations are discussed by Klöpffer [20]. Normalisation is an optional step following characterisation in order to compare environmental impacts. For this purpose, a normalised value is obtained by dividing the ICIR by a reference value.

**Table 1: Environmental impact categories addressed in this study [21].**

| Impact Category | Unit | Description |
|---|---|---|
| Global Warming Potential (GWP) | kg $CO_2$ equivalent | A measure of greenhouse gas emissions, such as $CO_2$ and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare. Global Warming Potential is calculated with a time horizon of 100 years. |
| Eutrophication Potential (EP) | kg $PO_4^{3-}$ equivalent | Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which are nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition. |
| Acidification Potential (AP) | kg $SO_2$ equivalent | A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion ($H^+$) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials. |
| Photochemical Ozone Creation Potential (POCP) | kg $C_2H_4$ equivalent | A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone $O_3$), produced by the reaction of Volatile Organic Compounds (VOC) and carbon monoxide in the presence of nitrogen oxides under the influence of Ultraviolet (UV) light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops. |
| Ozone Depletion Potential (ODP) | kg CFC-11 equivalent | A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UV-B ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants. |
| Abiotic depletion potential – Elements | kg Sb equivalent | A measure of the depletion of nonliving resources, more specifically in this case, natural elements. |
| Abiotic depletion potential – Fossil fuels | MJ net calorific value | A measure of the depletion of the finite reserves of fossil fuels. |

The interpretation of the results is the concluding section of the LCA, which includes a discussion of the results obtained during the previous phases. This involves consideration of the notable issues based on the results of the LCI and LCIA, and an evaluation that considers completeness, sensitivity and consistency checks. Uncertainty of the data is also typically addressed. This can include uncertainty from measuring equipment, uncertainty distributions of data in databases or uncertainty due to educated guesses. Limitations of the study are also important part of the section, as well as conclusions drawn from the results. Recommendations for improvement, based on the interpretation results are also typically included [17].

### 2.2.2 Product category rules

In addition to the standard ISO 14040, other documents such as the ones shown in Figure 7 can provide guidelines for preparing environmentally related product declarations. The hierarchy structure displays the overlapping documents related to quality management and environmental management systems. The Product Category Rules (PCR) complement given standards by providing specific rules for developing consistent environmental product declarations (EPD) in accordance to ISO 14025 [22]. By following a structured system such as the PCR, the EPD of various rolling stock vehicles are made comparable.

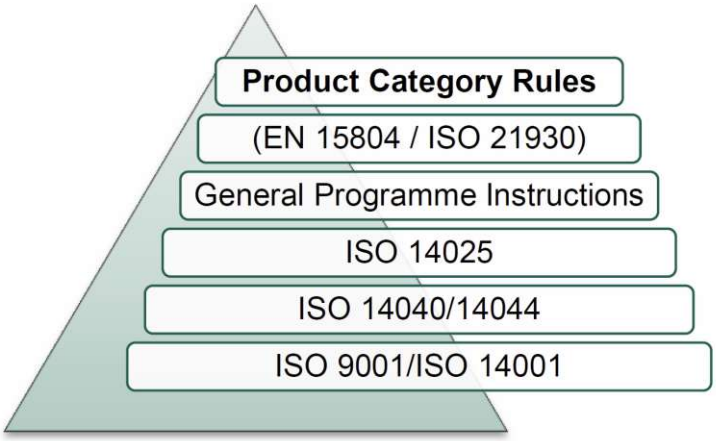


**Figure 7: Hierarchy of standards and other documents relevant for environmental declarations [16].**

The Product Category Rules for Rolling Stock (PCR RS) [16] is a document applicable for all types of rolling stock, e.g. locomotives, urban, regional and intercity trains, and distinguishes between passenger and cargo vehicles. It also includes a breakdown of rolling stock vehicles into product groups.

Chapter 4 of the PCR RS additionally provides a guideline for the recommended functional unit, rules for the system boundary, cut-off rules, allocation rules and data quality requirements. Recommended databases for generic data are listed as well as calculation rules and scenarios. Furthermore, the list of the relevant impact categories given in Table 1 is from the PCR RS.

Existing environmental product declarations for various rolling stock vehicles follow the PCR RS and can be found on the EPD website [23]. Examples online include EPD for the Sydney Metro Northwest from ALSTOM [24], Talent 2 locomotives, SPACIUM intercity trains and INNOVIA automated people movers by Bombardier [25–27] and the Sydney Growth trains from Downer [21].

## 2.3 Rolling stock manufacturing

The manufacturing of a rail vehicle involves various processes, a few of which will be highlighted here, to assist understanding of the methodologies during the life cycle assessment. Figure 8 shows an overview of the manufacturing phases and examples of the involved manufacturing processes. Initially, the vehicle body is manufactured and is sent to the surface treatment facility. Electrical assembly and mechanical assembly follow, before commissioning.

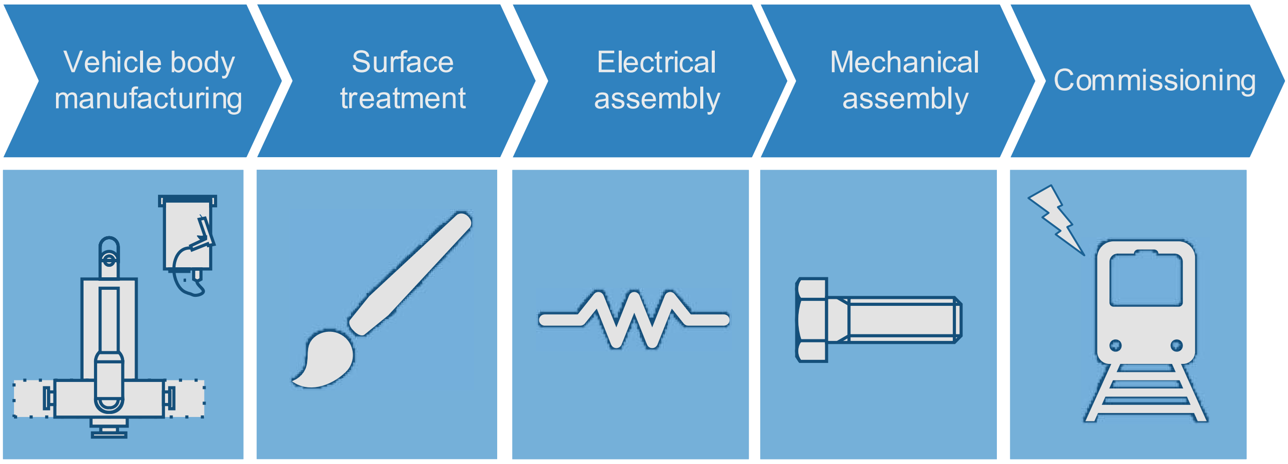


**Figure 8: Overview of the manufacturing phases at SIE VIE LEB.**

### 2.3.1 Components / product groups

Firstly, an overview of the components that make up a railway vehicle will be presented. The individual product groups that a railway vehicle is comprised of are described in DIN EN 15380-2 [28]. The designation begins with a breakdown into main product groups and then into subproduct group. Further designation at other lower levels is possible [28]. The code letters for main product groups (MPG) are listed below in Table 2.

All of the MPGs are supplied from off-site, with the exception of main product group *B: Vehicle body* which is manufactured on-site. Therefore, the most relevant main product group for this study is *B*. The assembly of the rail car takes place at the Siemens Vienna Leberstrasse facility. The main product groups can be further subcategorised into sub product groups (SPG). The SPG of MPG *B* and *C* are displayed in Table 2.

**Table 2: Main product group (MPG) and subproduct groups (SPG) designation [29].**

| MPG designation | Name of the MPG |
|---|---|
| B | Vehicle body |
| C | Vehicle fitting out |
| D | Interior appointments |
| E | Running gear |
| F | Power system, drive unit |
| G | Control apparatus for train operations |
| H | Auxiliary operating equipment |
| J | Monitoring and safety equipment |
| K | Lighting |
| L | Air conditioning |
| M | Ancillary operating equipment |
| N | Doors, entrances |
| P | Information facilities |
| Q | Pneumatic/hydraulic equipment |
| R | Brake |
| S | Vehicle linkage devices |
| T | Carrier systems, enclosures |
| U | Electrical wiring |

| Code letters | | Name |
|---|---|---|
| MPG | SPG | |
| **B** | A | **Vehicle body** |
| | B | Underframe |
| | C | Side walls |
| | D | Roof |
| | E | Head of vehicle |
| | F | End walls |
| | G | Weld-on/add-on parts |
| | H | Intermediate floor |
| | J | Partitions |
| **C** | A | **Vehicle fitting out** |
| | B | Window |
| | C | Floor |
| | D | Interior panelling |
| | E | Partitions |
| | F | External additions |
| | G | Vehicle paintwork |
| | H | Insulation |

## 2.3.2 Vehicle body manufacturing

As seen in Table 2, the main product group *B*, the vehicle body, consists of underframe, side walls, roof, head of vehicle, end walls, weld-on/add-on parts, intermediate floor, and partitions. How these components come together will be described below.

### 2.3.2.1 Vehicle body design

Nowadays, railway vehicle bodies are generally constructed using three different construction methods: differential, integral and hybrid construction. Figure 9 shows a comparison of differential and integral construction. In differential construction sheet metal is generally welded onto a frame structure to give the vehicle body its shape. It employs numerous semi-finished components of either steel or aluminum that are assembled in jigs. The material costs are generally lower, however the assembly costs higher due to greater labour time required to join numerous components [30]. The integral construction, on the other hand, utilises continuous casted hollow aluminum profiles, that are specially fabricated for the given project. The casted profiles are more expensive than the material used in differential construction, and their design is complex since the consideration of strength, repairability, profile fabrication, mass, and corrosion is challenging. A notable benefit of the aluminum integral construction, however, is the lower assembly costs, due to the fewer number of components and joining processes required. The hybrid construction method combines benefits of both methods into one. Various materials and various joining methods are employed. Both higher strength materials and lightweight profiles are used where needed. Additionally, the cross-section area of the carriage is variable, which is not the case with integral construction. Carriages can be modular designed, which poses benefits in repairability following a train accident [30].

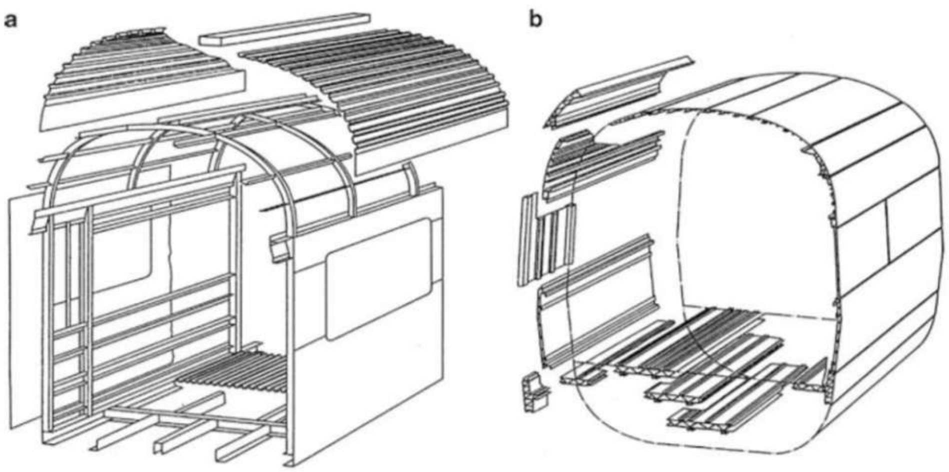


**Figure 9: Comparison of a) differential and b) integral construction [31].**

The construction method determines the material used, the design of the semi-finished components and manufacturing and assembly method. At SIE VIE LEB different body designs are selected based on customer specifications. Accordingly, different materials are employed during the production, typically steel or aluminum.

#### 2.3.2.2 Machining

Machining involves cutting processes that remove material from the workpiece and produces chips [32]. Common machining processes in the vehicle body manufacturing are trimming and end milling.

Trimming is used to cut profiles down to the required length for a specific project. This is necessary because the exact required length tolerances are expensive when they are met by the supplier. End milling employs a rotating cutting tool to remove a layer of material from the surface of the workpiece. Numerous layers are removed until the required volume has been taken off. Machining large components in an industrial setting takes place in computer numerical control (CNC) gantry machining centers.

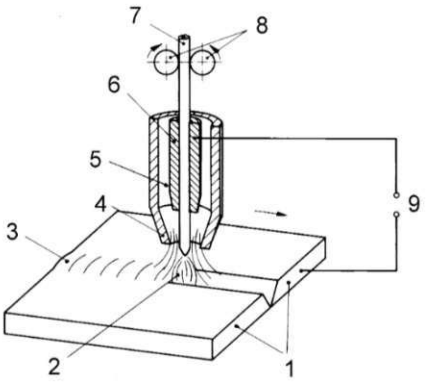
During machining, cutting fluids are used to reduce friction and wear as well as to cool the cutting zone, increasing tool life and improving surface finish. Furthermore, cutting fluid can reduce forces and therefore energy consumption, and flush away chips as well as protect against corrosion. Typical cutting fluids are oils and emulsions (semi-synthetic and synthetic) and can be applied by flooding, through a mist, with high-pressure systems, or through the cutting-tool itself [32]. A growing trend since the mid-1990s is near-dry machining (NDM) or minimum quantity lubrication (MQL), which tries to minimise the used metalworking fluids. NDM mitigates the environmental impact and the health hazards of using cutting fluids, as the air quality on the shop-floor is improved. Furthermore, costs are reduced due to the decrease in fluids that are bought and disposed of. NDM externally delivers a fine mist of an air-fluid mixture containing a small amount of oil, which is estimated at one ten-thousandth of the fluid required during flood cooling. Dry machining is also an alternative due to advances made in cutting tools [32]. However, dry machining is generally not recommended for aluminum alloys due to the formation of built-up edge (BUE), causing increased tool wear and lowered surface integrity [33].

#### 2.3.2.3 Welding

Welding is the most common method to join the metal profiles of the vehicle body. Engineering standards [34,35] and referenced literature [32] describe various metal welding techniques.

Typically, components are joined using gas metal arc welding (GMAW), alternatively known as metal shielding gas (MIG) welding. This process is preferred due to its speed, versatility and quality welds with aluminum. Since this is an important manufacturing process, GMAW will be briefly explained below.

In GMAW, an electrical discharge is used to provide enough heat to locally melt two or more workpieces and join them following cooling (see Figure 10). An electrical power supply is used, which provides the desired current and voltage to a wire electrode. The wire electrode is mechanically fed through wire rolls, which can be controlled by the welder’s trigger. When the wire electrode nears the workpiece, which is grounded within the welding device, an electric arc is created and melts the nearby metals and the electrode, which serves as a filler material. Both aluminum and steel components can be joined. To prevent contamination, typically a shielding gas such as argon is supplied through the nozzle.



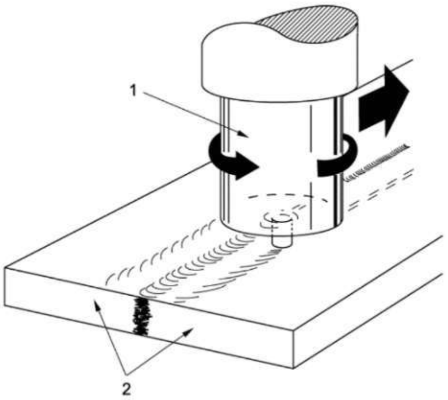
**Key**

| | | | |
|---|---|---|---|
| 1 | Workpiece | 6 | Contact tip |
| 2 | Arc | 7 | Wire electrode |
| 3 | Weld | 8 | Wire feed rolls |
| 4 | Nozzle | 9 | Power source |
| 5 | Shielding gas | | |

**Figure 10: Schematic overview of gas metal arc welding [34].**

GMAW is commonly a manual process, however, it can also be automated with a robot or gantry system. Automation is frequently selected for long straight welds where predictable parameters are used.

Another notable welding technique gaining popularity in rolling stock manufacturing is friction stir welding [30]. During friction stir welding (FSW), a rotating probe is plunged into the joint between the two workpiece surfaces, creating enough friction to soften and join them (see Figure 11). The high contact pressure causes frictional heating which raises the temperature locally enough to soften and stir together the workpieces. No additional shielding gas, MIG wire or surface cleaning is required [32]. A challenge of FSW is, however, the tighter tolerances required to achieve an accurate gap between workpieces. Due to the required high forces needed, FSW is most commonly done on large CNC centers and is limited to softer metals such as aluminum. Three dimensional curves are possible with FSW, however require more complex planning than straight welds, largely due to the necessary supports to withstand the high forces.



**Key**

| | | | |
|---|---|---|---|
| 1 | Rotating tool | 2 | Workpiece |

**Figure 11: Schematic overview of friction stir welding [34].**

In a study by Pfefferkorn et al. [36], the energy consumption and environmental impact between GMAW and FSW was compared. Results show that the latter results in lower energy consumption and lower environmental impacts. Pfefferkorn et al. also make note of the health hazards posed by welding processes. It has been shown that FSW results in fewer hazardous gas particulates, in comparison to GMAW.

#### 2.3.2.4 Dye penetration inspection

Following welding, the work is checked using dye penetrant inspection techniques. This is a simple and widespread method to check for surface-breaking defects such as welding surface faults like hairline cracks or surface porosity. It is based on capillary effects, in which a low surface tension fluid penetrates its way into surface discontinuities. First, the surface must be pre-cleaned using solvents. Then the penetrant is applied and allowed to soak in for roughly 30 minutes. The excess penetrant dye is then removed, using chemical removers such as emulsifiers. Then a developer is applied, which draws the dye from the defects to form a visible indication of the surface defect. Any section where the dye has bleed-out is inspected under high lighting conditions (1100 lux) and defects are recorded. Finally, the substances are removed from the surface in post-cleaning. For further information, references such as that from Gourd [37] can be addressed, as well as ISO 3059, ISO 3452-1 or ISO 23277.

#### 2.3.2.5 Finishing

Another important step during vehicle body manufacturing is finishing. This involves cleaning up welds, drilling, tapping threads, grinding, and welding on small parts by hand. Power tools are typically used to complete these tasks that can be powered electrically or by compressed air.

Compressed air is considered to be an expensive, energy-intensive and inefficient form of energy [38,39]. The infrastructure is also more expensive to install in comparison to electrically powered tools and requires compressors and lines of tubing. However, compressed air power tools offer the benefit that they can offer a longer lifespan, easier and fewer repairs and are often lighter. They are also are considered safer and better suitable than electric tools in wet conditions and areas where danger of explosion exists. Ways to reduce energy consumption in compressed air systems can be found in a study by Fraunhofer [40].

### 2.3.3 Surface treatment

The surface of the vehicle body is treated to provide protection and meet requirements both of the railway industry and the customer [30]. Corrosion protection and aesthetics are respective examples. The DIN EN ISO 12944-4 series focuses on methods for corrosion protection of steel structures by protective paint systems [41–44]. Depending on the car body material, joining methods, and field of application, different methods for surface treatment are preferred. Figure 12 shows an overview of the surface treatment processes typically applied in rolling stock manufacturing.

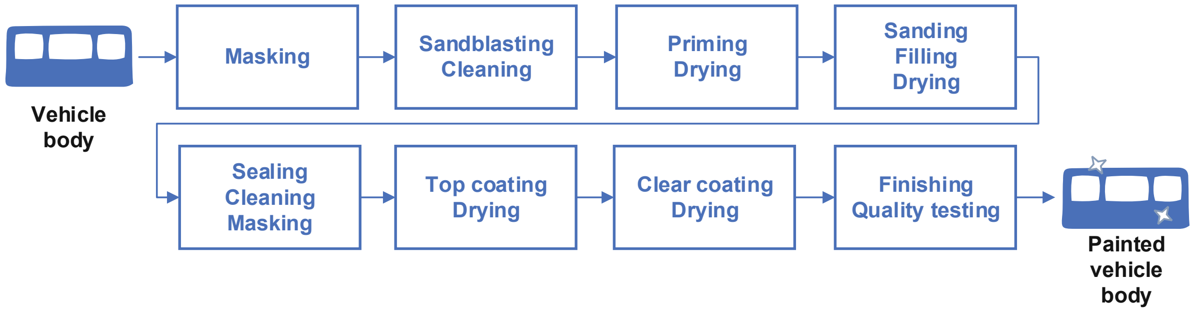


**Figure 12: Example processes for surface treatment of a rail vehicle.**

## 2.3.4 Assembly

Assembly follows surface treatment and involves the steps required to mount components to the car body. These include flooring, seats, various channels, cabling, HVAC systems, and so on. Lastly, the complete body is placed on the bogies.

The assembly processes are dominated by physical labour with manual tools. Electric drills are used to mount equipment, while compressed air and hydraulic tools are commonly used to lift heavy objects. To transport components within the assembly hall, forklifts and various flatbed rail vehicle transporters are employed.

Following mechanical and electrical assembly, the finished vehicle is transferred to commissioning where it is brought into service.

# 3 LCA of the core module

The following life cycle assessment of the core module has been carried out according to ISO 14040 and ISO 14044 [6,17]. Additional documentation such as the Product Category Rules for Rolling Stock (PCR RS) [16] and corporate documentation has also been taken into consideration. Following the goal and scope definition, methods for data measurements are presented, along with a review of the collected data. Finally, impact assessment and the data interpretation are presented.

## 3.1 Goal and Scope definition

The goal and scope are used to guide the work of the study and to set context of the LCA. For clarity, the keywords relevant for each point of consideration in ISO 14044 are marked in bold. The corresponding definitions can be found below.

### 3.1.1 Goal

As environmental sustainability is of growing importance, Siemens seeks opportunities for environmental improvement across the entire product life cycle. The study will assess the environmental impact resulting from the production (core module) of one generic rail-vehicle. The **intended application** of the LCA is to increase transparency and also to complement the existing upstream and downstream life cycle data belonging to Siemens Mobility. With the resulting completed set of data, a complete life cycle assessment of a Siemens rail vehicle can be conducted. Additionally, this information will be used to complete an environmental product declaration Type III according to ISO 14025.

The **intended audience** of the core module LCA is Siemens. The data collected will be internally used by engineers in environmental protection. Indirectly, the results will be displayed in the environmental product declarations and available to customers.

The **reason** for an LCA of the core module is to identify opportunities to improve environmental sustainability of the manufacturing processes. Furthermore, with a complete LCA of all modules, internal strategic planning regarding environmental decisions can be made. This data will be used to complete the Siemens Generic LCA-Model, which serves as a template for conducting internal life cycle assessments. Through customisation of this generic model, the environmental impacts of current and future vehicles, regardless of model, can be assessed, compared and improved.

### 3.1.2 Scope

The **product system** studied in this LCA is the manufacturing of one generic rail vehicle at the Siemens Mobility production facility Leberstraße (SIE VIE LEB) in Vienna, Austria. The term generic rail vehicle is further discussed in the assumptions below. The **function of the product system** is to produce one generic vehicle.

The **functional unit** of the LCA is one generic rail vehicle that leaves the production facility following static commissioning at SIE VIE LEB. The resource flows and environmental impacts are evaluated per functional unit, therefore in this case per vehicle produced.

In order to assess the environmental impacts from the production of one vehicle, the **system boundary** must be defined. The boundary must include the processes required to transform the raw materials into a finished product. A list from the PCR RS of recommended processes to include and exclude is displayed in Table 3. Since the transport of the vehicle to the customer is strongly project specific, it is excluded from this study and will be assessed for each order individually. The adjusted system boundary is marked in red in Figure 13.

**Table 3: Processes relevant for the core module according to the PCR RS [16]. Note that transportation of the rail vehicle to the customer is not included in this study and has therefore been crossed out.**

| | **Processes relevant for core module** |
|---|---|
| **Included** | Production and use of electricity, heat, and steam fuel used for the vehicle assembly.<br>Production and use of known auxiliary materials (welding, mounting equipment, etc. which are not included in upstream module) used for the vehicle assembly.<br>~~Transportation of the rail vehicle from the assembly facility to the location of its use (to the customer)~~<br>Waste generated and treatment of waste from the assembly processes on the Rolling Stock manufacturer site |
| **Excluded** | Building, maintenance, dismantling and disposal of rail vehicle assembly/ manufacturing facilities<br>Packaging of rail vehicle<br>Business travel of personnel<br>Travel to and from work by personnel<br>Research and development activities. (Engineering activities)<br>Waste generated and treatment of waste from suppliers packaging on the Rolling Stock manufacturer site<br>If waste from supplier packaging can't be separated from other waste from the assembly/manufacturing site the waste generated form supplier packaging can be included in the LCA if not adding significant to the result of the EPD. |

Note that components purchased from external suppliers, such as those for fitting out, power systems and running gear are not included in this scope, since they are not produced at SIE VIE LEB. Furthermore, all material that stays on and within the vehicle when it leaves the facility is not considered part of the scope boundary. This study is restricted to the materials consumed and produced solely for manufacturing such as energy, shielding gases during welding and waste.

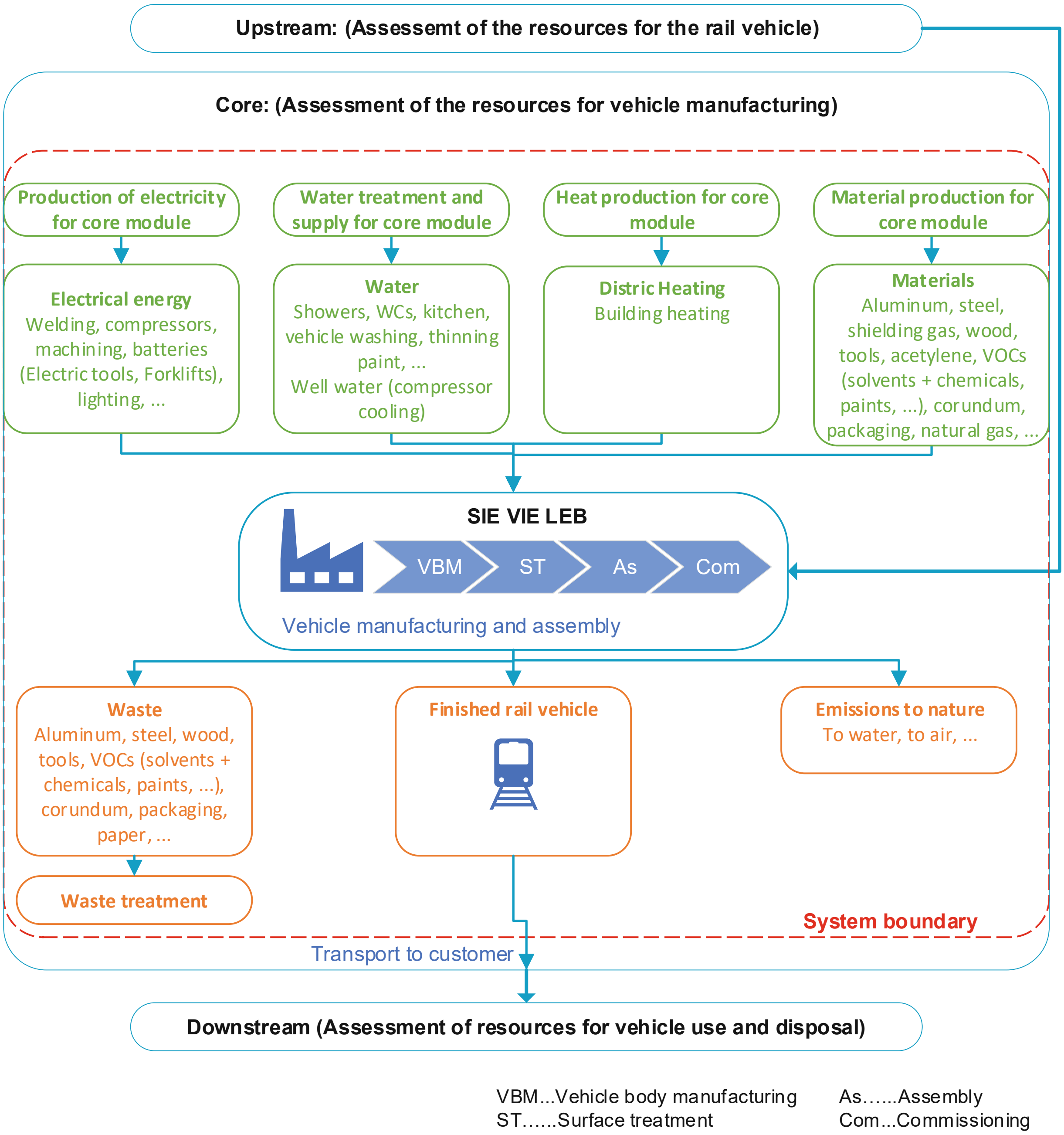


**Figure 13: Product system boundary of the LCA.**

Regarding the **time boundary** of the study, the data directly measured for the LCI is taken at discrete moments in time spanning from May 2019 to September 2019. The collected internal data however has been averaged over the last five fiscal years.

As far as data is available, it is entered in the LCI, as in the case of energy, natural gas, district heating, water, chemical gases and waste. In these cases, no specific data was **cut-off**. Corresponding to the PCR RS, the substances included in the Railway Industry Substance List [45] shall be included in the LCA as far as possible.

**Allocation procedures** are required to allot the inputs and outputs to products and processes within and outside of the scope. Since production as well as research and engineering are accomplished at SIE VIE LEB, the resource use must be split into relevant manufacturing flows and flows not relevant for manufacturing. Furthermore, waste is produced as a by-product in addition to the generic rail-vehicle and must be allocated to various disposal processes. Using a closed loop disposal method, a fraction of the waste of certain processes remains in the system and is counted as a credit towards the input from the technosphere. Modelling the waste as a credit accounts for the fact that a part of the waste gets recycled and saves extraction and production of raw materials. The allocation is graphically represented in Figure 14.

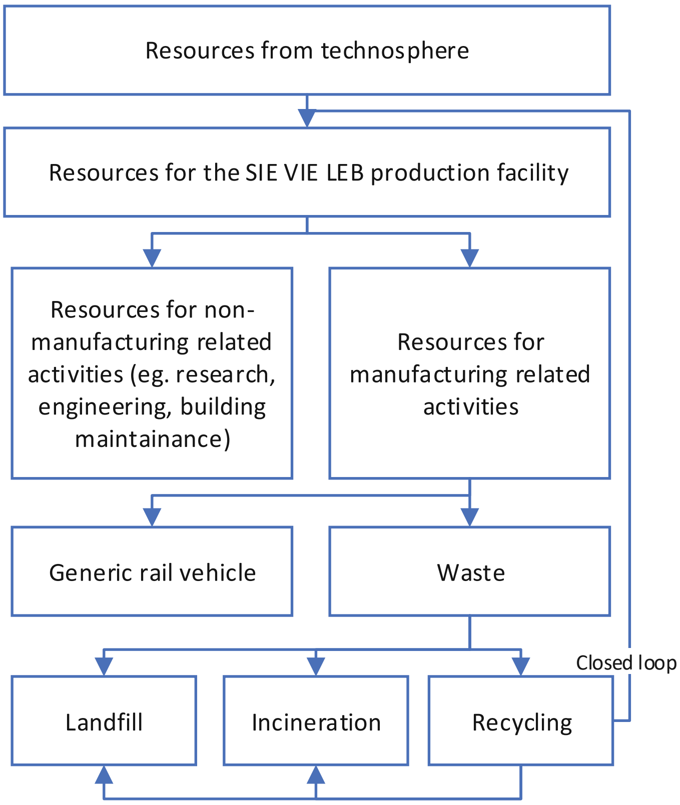


**Figure 14: Allocation procedure with a closed loop recycling method used in the LCA.**

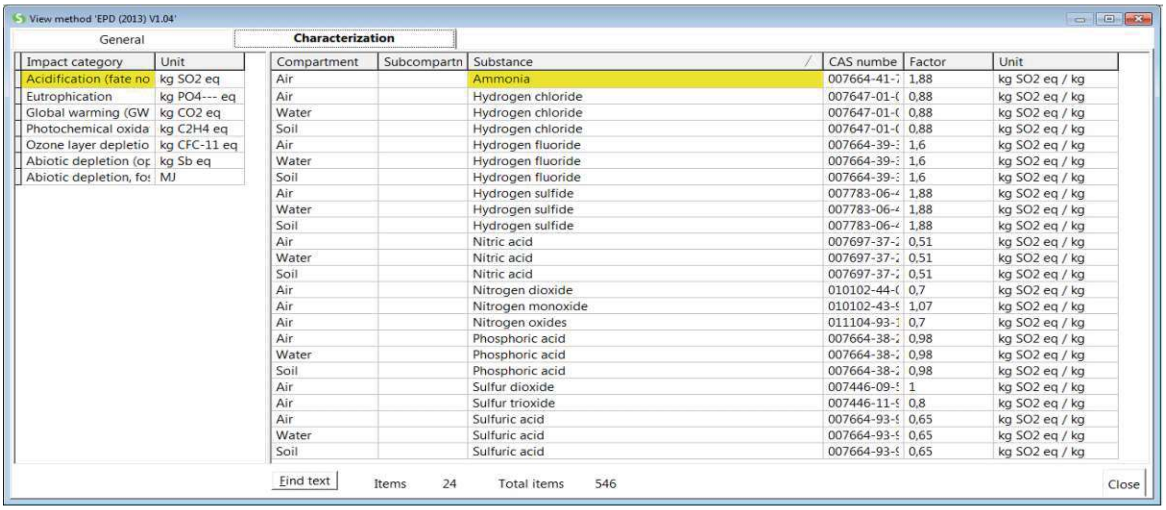
The **method** used for the LCIA is EPD (2013) v.1.04. The relevant characterisation models and factors for the impact categories are available at [23] and have been defined in this method for use in SimaPro.

The types of impacts selected are those found in the PCR RS and are summarised in Table 4.

**Table 4: Indicators describing potential environmental impacts from the PCR RS [16].**

| Impact Category | Unit |
|---|---|
| Global Warming Potential (GWP) | kg $CO_2$ equivalent |
| Ozone Depletion Potential (ODP) | kg CFC-11 equivalent |
| Acidification Potential (AP) | kg $SO_2$ equivalent |
| Eutrophication Potential (EP) | kg $PO_4^{3-}$ equivalent |
| Formation potential of tropospheric ozone (POCP or POFP) | kg $C_2H_4$ equivalent |
| Abiotic depletion potential – Elements | kg Sb equivalent |
| Abiotic depletion potential – Fossil fuels | MJ net calorific value |

An example of the characterisation factors in the method, EPD (2013) v.1.04, are shown in Figure 15.



| Impact category | Unit |
|---|---|
| Acidification (fate no | kg SO2 eq |
| Eutrophication | kg PO4--- eq |
| Global warming (GW | kg CO2 eq |
| Photochemical oxida | kg C2H4 eq |
| Ozone layer depletio | kg CFC-11 eq |
| Abiotic depletion (op | kg Sb eq |
| Abiotic depletion, fo: | MJ |

| Compartment | Subcompartn | Substance | CAS numbe | Factor | Unit |
|---|---|---|---|---|---|
| Air | | Ammonia | 007664-41- | 1,88 | kg SO2 eq / kg |
| Air | | Hydrogen chloride | 007647-01- | 0,88 | kg SO2 eq / kg |
| Water | | Hydrogen chloride | 007647-01- | 0,88 | kg SO2 eq / kg |
| Soil | | Hydrogen chloride | 007647-01- | 0,88 | kg SO2 eq / kg |
| Air | | Hydrogen fluoride | 007664-39- | 1,6 | kg SO2 eq / kg |
| Water | | Hydrogen fluoride | 007664-39- | 1,6 | kg SO2 eq / kg |
| Soil | | Hydrogen fluoride | 007664-39- | 1,6 | kg SO2 eq / kg |
| Air | | Hydrogen sulfide | 007783-06- | 1,88 | kg SO2 eq / kg |
| Water | | Hydrogen sulfide | 007783-06- | 1,88 | kg SO2 eq / kg |
| Soil | | Hydrogen sulfide | 007783-06- | 1,88 | kg SO2 eq / kg |
| Air | | Nitric acid | 007697-37- | 0,51 | kg SO2 eq / kg |
| Water | | Nitric acid | 007697-37- | 0,51 | kg SO2 eq / kg |
| Soil | | Nitric acid | 007697-37- | 0,51 | kg SO2 eq / kg |
| Air | | Nitrogen dioxide | 010102-44- | 0,7 | kg SO2 eq / kg |
| Air | | Nitrogen monoxide | 010102-43- | 1,07 | kg SO2 eq / kg |
| Air | | Nitrogen oxides | 011104-93- | 0,7 | kg SO2 eq / kg |
| Air | | Phosphoric acid | 007664-38- | 0,98 | kg SO2 eq / kg |
| Water | | Phosphoric acid | 007664-38- | 0,98 | kg SO2 eq / kg |
| Soil | | Phosphoric acid | 007664-38- | 0,98 | kg SO2 eq / kg |
| Air | | Sulfur dioxide | 007446-09- | 1 | kg SO2 eq / kg |
| Air | | Sulfur trioxide | 007446-11- | 0,8 | kg SO2 eq / kg |
| Air | | Sulfuric acid | 007664-93- | 0,65 | kg SO2 eq / kg |
| Water | | Sulfuric acid | 007664-93- | 0,65 | kg SO2 eq / kg |
| Soil | | Sulfuric acid | 007664-93- | 0,65 | kg SO2 eq / kg |

Items 24 Total items 546

**Figure 15: Example of characterisation factors in the EPD (2013) v.1.04 method listed in SimaPro.**

When building the LCI, different data sources with varying grades of data quality have been considered. Unless otherwise stated, data from annual reports and internal sources has been taken over a five-year average from fiscal years 2014 to 2018. This represents a recent representation of the production. When using generic data from the ecoinvent database, instead of direct measurements, the data quality is reduced, however in some cases unavoidable.

A number of **assumptions** must be made in an LCA and are discussed here along with the **limitations** of the study.

To ensure validity of the results for all rolling stock manufactured at Siemens, the data shall be averaged for all vehicles produced at this location. These include metros, VAL, Locomotives, regional trains, and light rail vehicles. Of course, the differences in vehicles and further customer-specific requirements result in different resources required for the production. Furthermore, data measurements taken at the facility are indeed from the production of a specific vehicle model. It shall be assumed, however, that the difference in the resulting environmental impacts due to manufacturing between varying models is negligible. This is a required assumption to build the Siemens generic LCA-model. As an example, it may here be assumed that welding and painting a steel locomotive is deemed equivalent to welding and painting an aluminum metro. This statement has been iteratively revised, following measurements and questionnaires with on-site technicians. It is also further discussed below. As a result of this assumption, it is not considered of importance which train model is selected for data measurements.

Resource flow data collected from internal documentation, such as annual energy consumption, has been averaged over five fiscal years. It is assumed that the averaged values are representative of the resource flows each year. The real resource flows however can vary greatly within one year and over fiscal years. This may influence the resulting environmental impacts.

District heat and natural gas consumption are dependent on outdoor temperatures. Therefore, more heating resources may be consumed in a very cold year than what this LCA model may predict.

Based on internal documentation, it may be assumed that a generic rail vehicle body has roughly 1000 m of welds. This has an effect on the estimated energy consumed to join a vehicle.

The waste treatment model has been developed using a closed loop recycling process. The recyclability and recoverability calculation method from the European Rail Industry (UNIFE) Sustainable Transport Committee sets the standard for the waste treatment in this study and the recycling factors can be found in the UNIFE document [46]. It should be noted that a high recoverability factor is taken from the report. As a result, the recycled quotas are returned to the manufacturing process as a credit and relatively little material leaves the system boundary; but rather stays in the system in a closed loop. This concept is necessary for a simplified waste treatment model and is further discussed in ISO 14044 [17,20].

An additional assumption is the distance travelled to transport materials to SIE VIE LEB and waste to the waste treatment facility. 250 km total travel distance by a EURO5 certified lorry is assumed.

Since the purpose of this report deems for internal use, the optional **critical review** of the LCA by an external expert review panel will not be conducted.

## 3.2 Life cycle inventory Analysis (LCI)

As stated in ISO 14040, the inventory analysis involves collection and calculation of data to quantify relevant inputs and outputs of a product system. The following section therefore further describes the product system and presents the data collection methods, as well as inputs and outputs at SIE VIE LEB. Due to data privacy protection, absolute values are not presented.

### 3.2.1 Production facility layout

Figure 16 depicts the SIE VIE LEB facility layout. The office spaces are marked in red, the vehicle body manufacturing in green, auxiliary spaces in yellow, surface treatment in orange, and assembly and commissioning in blue. With over 5000 $m^2$ and 500 desk places, building 100 is the largest office building on the facility grounds, followed by building 330 with roughly 200 places. Since the work of these offices is focused on engineering, the resource use of offices 100, 330, 382, and 381 is excluded from this study.

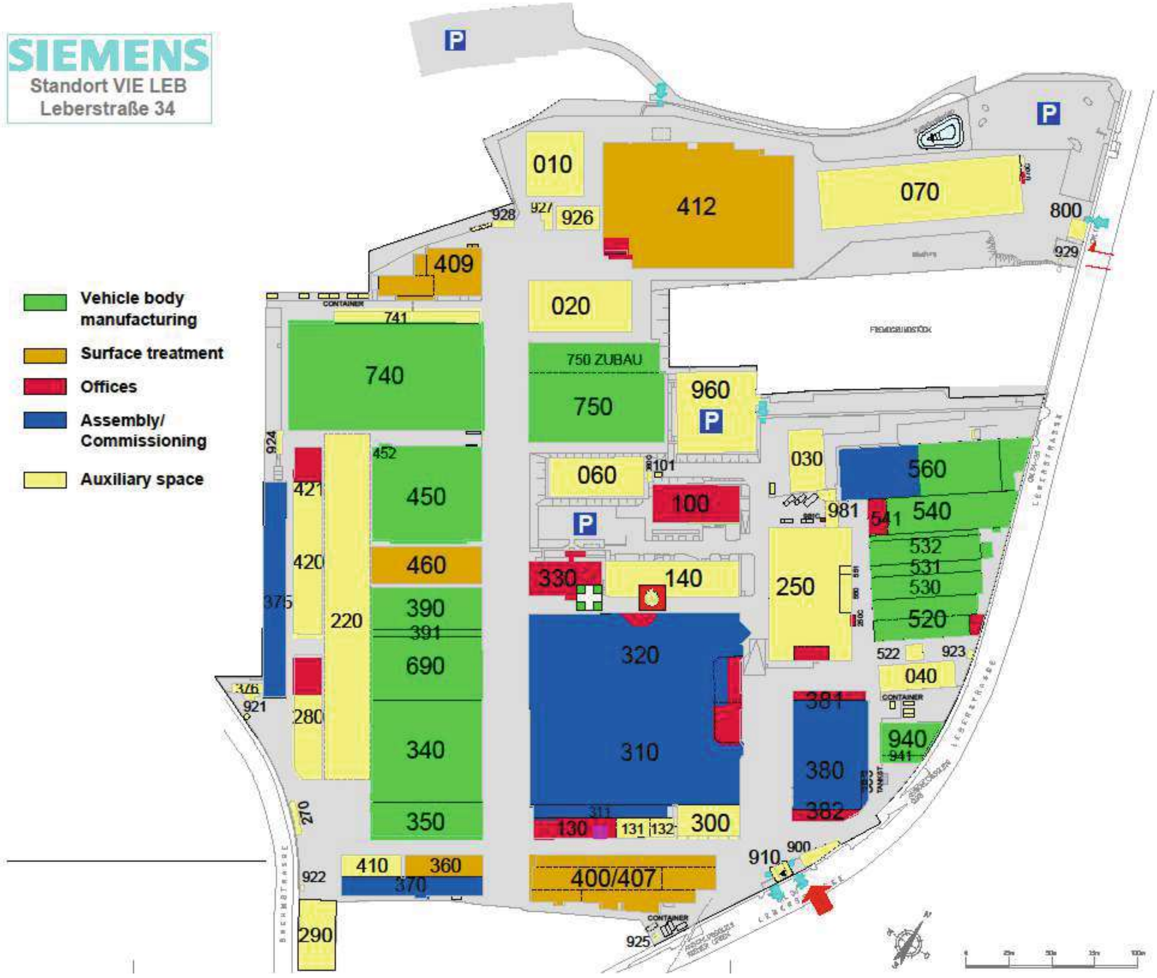


Figure 16: Siemens Mobility Vienna Leberstraße production facility map.

### 3.2.2 Production flow overview

A simplified illustration of the main production phases of a railway vehicle is presented in Figure 17. The vehicle body manufacturing and surface treatment accounts for the majority of manufacturing processes at SIE VIE LEB. The manufacturing time is roughly 6 months from material delivery to the end of static commissioning.

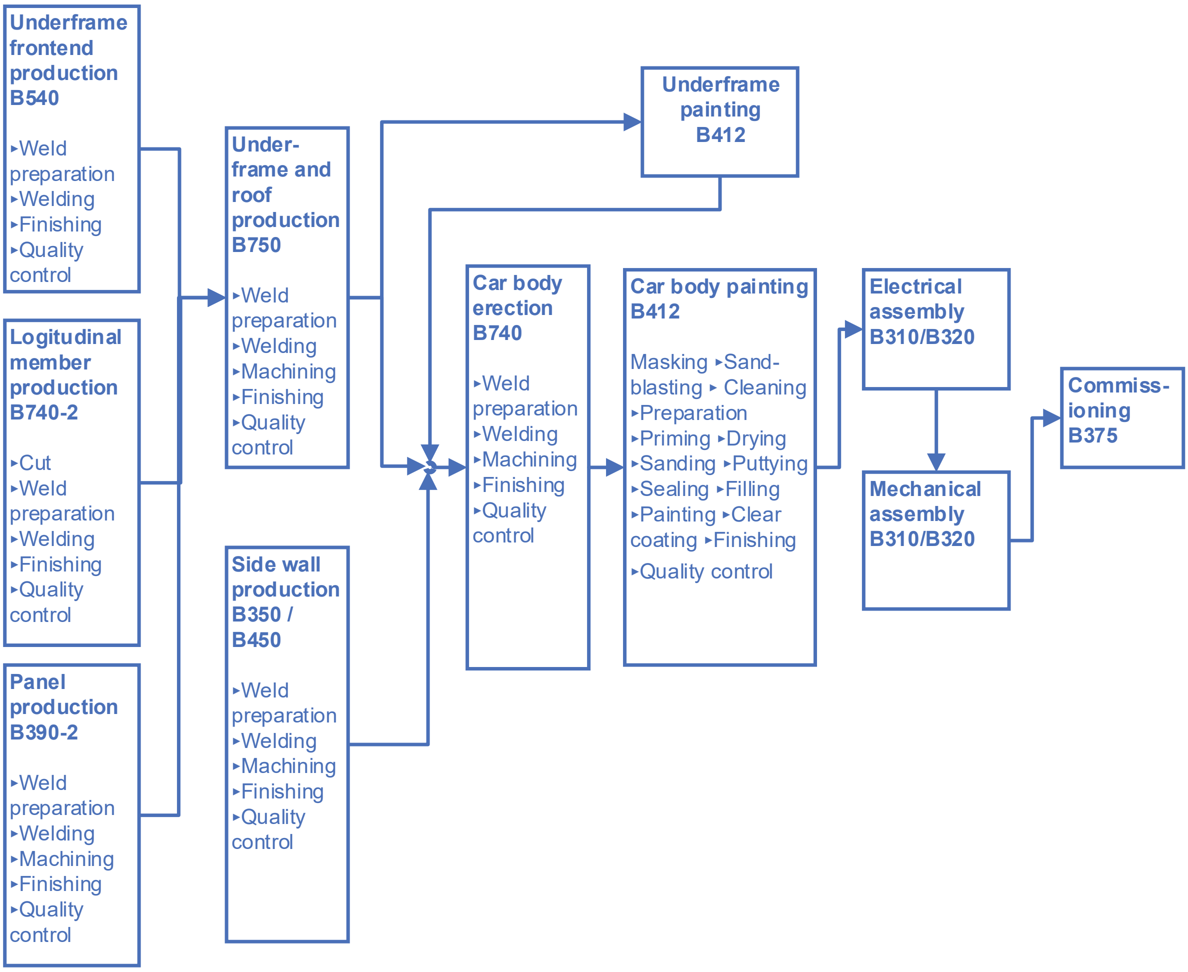


**Figure 17: Process diagram describing manufacturing of a railway vehicle.**

Vehicles of both aluminum integral and steel differential construction are manufactured at SIE VIE LEB. The raw metal components arrive at the facility and are transferred to the corresponding production hall for processing. Initially, the underframe frontend, longitudinal members and panels are manufactured by joining the delivered components. These components are then welded together in hall 750 and result in the underframe and roof. The side walls are produced in parallel. For all manufacturing steps, jigs are required to hold the components in place. These are externally manufactured and consist of steel supports and clamps as shown in Figure 18. The bottom of the underframe then receives a separate surface treatment and is joined afterwards with the mentioned components to complete the vehicle body. The vehicle body then receives surface treatment, and proceeds to mechanical and electrical assembly. Finally, the vehicle undergoes static commissioning.

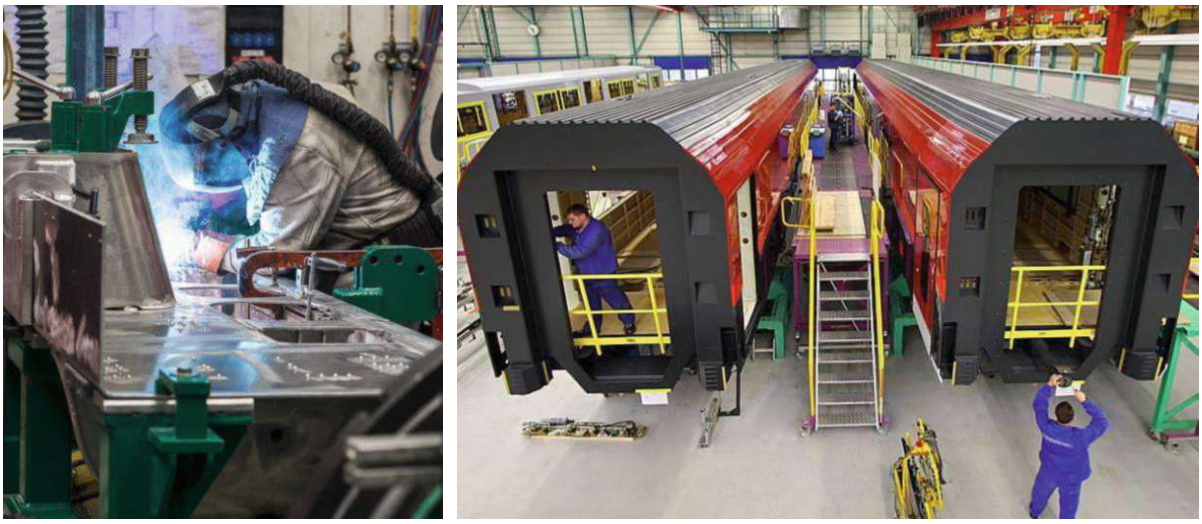

a) b)

**Figure 18: a) GMAW of a rail vehicle component mounted in a jig. b) Assembly of rail vehicle [13].**

During each process, resources are consumed, and waste and emissions are produced. Waste products accumulated at various stations and collected on a regular basis by waste treatment companies. The amount of each waste type collected each year is summarised in internal reports into waste categories such as scrap wire or cardboard. These categories are defined in ÖNORM S 2100 “Abfallkatalog” and the waste catalogue ordinance [47].

### 3.2.3 SimaPro model

In order to model the complex product system with numerous inputs and outputs, the software tool SimaPro was selected. The scheme follows that of the Siemens generic LCA model and divides the rail vehicle life cycle into the following phases and subprocesses.

- Rolling stock
    - Upstream
    - Core
        - Manufacturing
            - Vehicle body manufacturing
            - Surface treatment
            - Assembly
            - Commissioning
            - Transport of materials to and from SIE VIE LEB
        - Transport to customer
    - Downstream

The manufacturing phases are further divided into individual processes such as welding and machining. Figure 19 displays the graphic user interface of SimaPro with the above-mentioned rolling stock life cycle model. Using this method, one can trace the environmental impacts of each process, or cumulatively the impacts of the phases such as car body manufacturing or surface treatment.

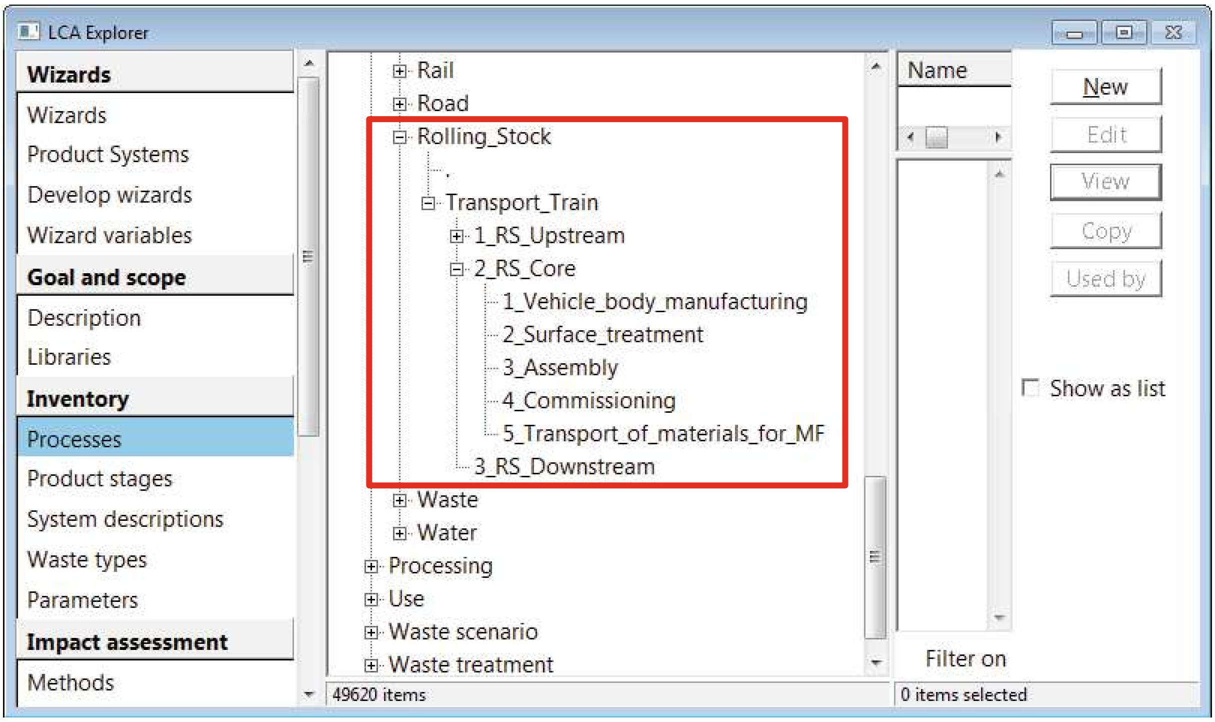


**Figure 19: Overview of Siemens generic LCA model for rolling stock in SimaPro.**

The individual flows (material, energy, district heat and others) are summarised in the following sections, along with the methods to measure their values. The data that is collected for the life cycle inventory (LCI) is entered for each process in SimaPro.

### 3.2.4 Material flows

Various material inputs into the VIE LEB production facility have been collected from internal reports. The Siemens Environmental and Technical Safety Information Systems (SESIS) reports include data regarding hazardous chemicals, waste, and resource use. Additional documentation such as procurement data, Volatile Organic Compound (VOC) data, and recycling data has also been used for the LCI. Through expert interviews, the inputs could be linked to specific manufacturing phases and processes. The questionnaire form used—a modified version of the one recommended in ISO 14044—can be found in the annex. Table 5 shows a summary of the noteworthy materials that flow to and from the plant.

**Table 5: Noteworthy material flows required for production.**

| Materials | |
|---|---|
| Acetylene/Ethin | Paint |
| Alu | Paper |
| Aluminum cans | Plastic |
| Cardboard | Plastic film (LDPE) |
| Chemical rests | Plastic with hazardous materials |
| Cleaners | Process water |
| Coloured glass | R134a (CH2FCF3) |
| Construction waste | R22 |
| Consumer batteries | R404A |
| Copper | R407C |
| Corundum | R410A |
| Diesel | R507A |
| Electronics WEE | Refrigerators |
| Flat glass | Residual waste |
| Glue rests | Spray cans |
| Industrial waste | Steel |
| Inert waste | Styrofoam (EPS) |
| Lacquer and paint | Technical $CO_2$ Emission |
| Lamps | VOC-contaminated materials |
| Lead-batteries | VOC-Water-Mix |
| Mineral wool | Waste water |
| Oil water mix | White glass |
| Oil-contaminated materials | Wood rest |
| Old oil | … |

To link the resources to individual phases and processes, each was analysed as described in the following chapters. Note that materials that stay on the vehicle, such as GMAW wire, are not taken into account, since they belong to the rail vehicle and are already considered in the upstream module.

### 3.2.4.1 Vehicle body manufacturing

The major processes involved in VBM are machining, welding, finishing, and quality inspection.

Machining involves removal of excess metal and therefore produces metal chips as waste. The metallic waste is well documented and was estimated in kilograms per vehicle. Minimal lubrication is used on all machining centers, which results in no collected containers of machining fluid. The lubricant is wiped off and collected in the waste category contaminated consumables.

Welding typically consumes electrodes, shielding gas and produces emissions to air, which are hazardous to the workers nearby. Aluminum vehicle components are joined mostly using GMAW and FSW. Steel differential constructions are typically joined with both GMAW and spot welding. When welding aluminum, acetylene is commonly consumed by a burner to pre-heat the working material to roughly 90 °C. The amount of consumed acetylene per vehicle has been estimated from the average purchased amount over the last 5 fiscal years. Since the emissions to air due to welding and burning of acetylene is difficult to measure, generic data has been adopted from the ecoinvent database.

To estimate the amount of argon (99.99 % Ar) shielding gas used during welding, two different methods were used. First, the average flow rate was determined from technical welding specifications and from worker interviews. The average flow rate lies by 18 liters per minute. Based on measurements and interviews, the average travel speed is 30 cm min$^{-1}$. As a result, an estimate of 60000 l per vehicle was calculated. Second, the amount of shielding gas purchased in each fiscal year was averaged and divided by the number of rail vehicles produced in that time, to result in 66000 l per vehicle. The higher value 66000 l per vehicle was accepted for the LCI. Other gases such as oxygen, carbon dioxide and nitrogen have been evaluated using the second method and also entered in the SimaPro inventory.

The mass of copper electrodes, for example for spot welding, and tools such as steel end mills consumed per vehicle has been estimated based on expert interviews and was entered in the LCI. Note that GMAW wire remains on the vehicle and was therefore not considered an auxiliary material, but rather belongs to the vehicle mass. The amount of chemicals used for weld quality inspection has been collected from purchase order reports. Since they are cleaned up and disposed of in special hazardous waste containers, the waste output has been collected in the list of VOC contaminated materials.

#### 3.2.4.2 Surface treatment

Surface treatment involves the use of various solvents, cleaners and paints. The use of these chemicals is well documented due to regulations, and an average mass of each, consumed per vehicle, was calculated using internal reports.

Due to an investment in a fully automated and highly efficient painting facility in 2013, the amount of materials used and wasted was greatly reduced. The system uses water-thinnable paints and fillers based on polyurethane or epoxy primer, which are stored in 200 l containers in paint supply rooms. These fluids are pumped to the mixing stations in two main painting booths with each two robots. A pigging system pushes the unused paint back into the storage containers ensuring that the paint in the supply line is not wasted. Therefore, only 1.5 l are lost instead of up to 15 l per robot and color change. The paint is applied to the rail vehicle via a robot-mounted rotary atomizer. Rotary bells spin up to 60000 rpm and spray the paint which is directed by external electrostatic charging. The application efficiency achieved is around 70 %. The rotating plates must be changed roughly 3 times per year per robot. Since these components have a low mass and are recycled within the system boundary, the environmental impacts are negligible. As a result, the rotating plates have not been entered in the LCI.

Sandblasting is done manually, and implements corundum, technical aluminum oxide, to remove the surface layer of the workpiece. The process results in metallic chips, which are continuously removed using a magnet separator. The corundum is cleaned and reused up to five times, before it is collected by a recycling company and used as an input in other industries.

Masking, as seen on the vehicle body during surface treatment in Figure 20, is disposed of as plastic contaminated with VOCs. The picture also depicts two robots with the rotary atomic atomizers in the painting booth.

**Figure 20: Fully automated painting process in the surface treatment facility.**

Between each process of puttying, filling, painting, and varnishing, the vehicle is left in special booths to dry. Natural gas burners are used to heat and hold the booth temperature at around 60 °C. Other than the cafeteria kitchen, this is the only process that consumes natural gas at SIE VIE LEB. Based on consumption reports, and by subtracting the cafeteria use, a natural gas consumption of 9176 kWh per vehicle has been determined. The natural gas consumption has been normalised and plotted with the average monthly outside temperature recorded by the city of Vienna [48]. Over fiscal years 2014 to 2018, 2017 had the fewest number of total delivered vehicles. Since the amount of consumed natural gas is dependant on the number of produced vehicles, this could explain the decrease in consumption around that time. Otherwise, there is a correlation between the temperature and natural gas used. The emissions to air resulting from natural gas combustion can be found in the ecoinvent database and have been used in the LCI.

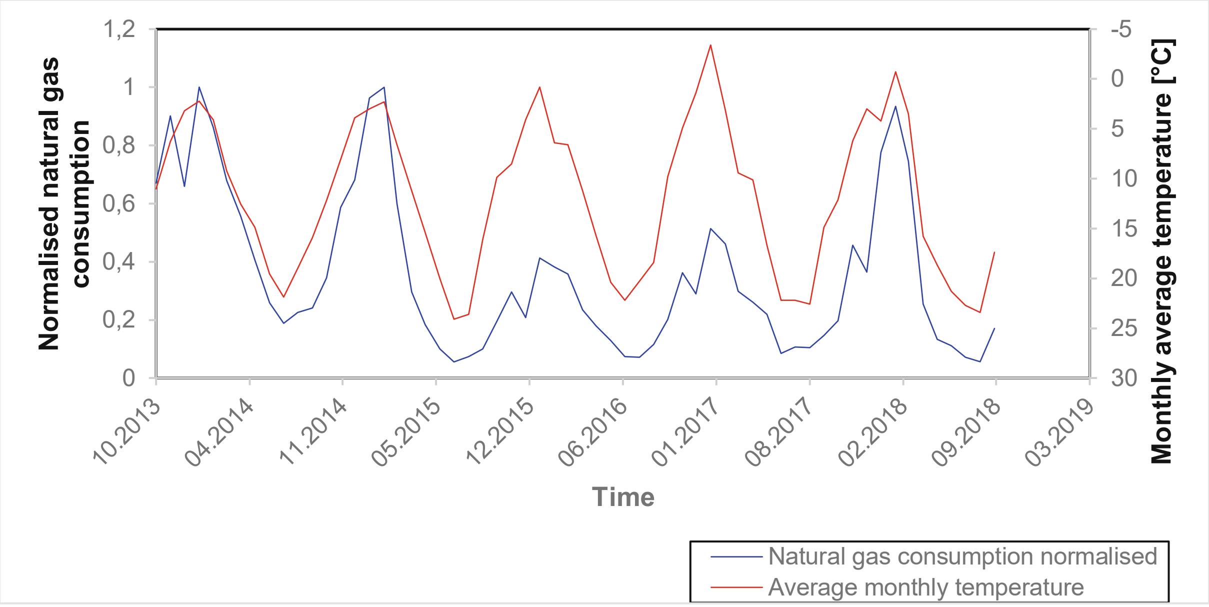


**Figure 21: Normalised curve of the natural gas consumption plotted with the average monthly outdoor temperatures.**

### 3.2.4.3 Electrical and mechanical assembly

In comparison to the above-mentioned manufacturing phases, electrical and mechanical assembly employ fewer materials. Nonetheless, notable chemical inputs include bolt adhesives, chemical cleaners and glues. Notable outputs include wire scraps, excess interior material such as flooring, insulation and waste glue products. These are collected in waste bins and collected by a waste treatment company. The corresponding amounts have been recorded in interview and by addressing internal reports such as the SESIS. Packaging is discussed in section 3.2.4.5.

### 3.2.4.4 Commissioning

Commissioning does not employ significant amounts of environmentally relevant materials.

### 3.2.4.5 Multi-phase material flows

Some materials are consumed at numerous production phases and are therefore discussed only once—in this section. Packaging, paper, aluminum canisters, diesel for internal transport, and various waste products flow in and out of the facility and are not distinctly related to one process. In this case, all flow amounts over fiscal years 2014 to 2018 were averaged and used to determine an average value per vehicle. Based on observances at the production facility, this value was then allocated to each production phase, in order to enter the values in the LCI in SimaPro.

Based on previous internal investigations at SIE VIE LEB, some 100 000 trips are made by internal transport per month. This is accomplished by both diesel and electric forklifts, self-propelled transporters and trucks. The diesel fueled vehicles are supplied by on-site filling stations. As part of the “Smarter Together” program in 2016, six diesel forklifts were replaced by electric forklifts [49]. Internal studies showed according savings of 11200 l diesel per year. For this reason, the amount of fossil fuel for internal transport has been averaged over the last two fiscal years, to represent the situation with fewer diesel vehicles.

According to the PCR RS, vehicle packaging to and from the facility is not included in the study. Other packaging however including that of wood, cardboard and organic materials are entered in the LCI. Since these materials are considered 98 % recyclable, and a closed-loop system has been selected, only 2 % is lead to waste while the remainder is returned within the system as a credit.

As mentioned in the scope definition, some processes at SIE VIE LEB do not count towards manufacturing, and the resources consumed must therefore be subtracted from total annual amounts. As an example, the total amount of recycled paper has been taken from the SESIS reports. The share of paper used for research and engineering-related office work was calculated and subtracted. According to [50], the average Austrian uses 264 kg of paper per year. By subtracting this amount, multiplied by the number of office workers involved in non-manufacturing related tasks, a rough estimate of the amount of consumed paper due to manufacturing can be achieved. Data related to office spaces and the number of workers in each building was obtained from internal documentation.

### 3.2.5 Energy flows

Energy consumption was determined using various methods, depending on the manufacturing process. Where applicable, energy consumption data was collected from available energy meters. Since the energy meter infrastructure in the plant is not very comprehensive, solely an overview of energy consumption of numerous buildings grouped together is available. This data proved itself useful for making comparisons with scaled data from temporary measurements. In most cases, a given energy meter counts for both production halls and office buildings. This poses the challenge of separating the energy consumption relevant for office space and for core production, since only manufacturing processes are included in this LCA. For this reason, and to better understand the energy consumption on a process-level, more detailed analysis was conducted. This involved installing a power analyser and energy logger at numerous stations, as well as calculating energy demand based on known documentation. Additionally, data was extracted from an energy monitoring system (EMS) installed as part of a sustainability project, and was compared with data in the ecoinvent database.

When calculating the environmental impacts due to electrical energy consumption, the electricity mix as seen in Table 6 has been selected. This represents an average mix supplied to SIE VIE LEB over the last five fiscal years. Since this mix does not exist in SimaPro, its has been manually defined using the following method. The standard Austria medium-voltage electricity mix was selected in the ecoinvent database, which contains references to a standard Austria high-voltage mix. This process is linked to high-voltage energy production sources such as hydropower, wind power and natural gas combustion, as well to imported electricity mixes from Germany, Czech republic and Italy. The entries in SimaPro were manually overridden until the desired custom electricity mix was achieved.

| Electricity production source | |
|---|---:|
| Hydro | 47% |
| Wind | 10% |
| Biomass | 4% |
| Biogas | 1% |
| Other green energy | 1% |
| Coal | 10% |
| Natural gas | 27% |

**Table 6: Averaged electrical energy mix used for the LCI.**

A Chauvin Arnoux PEL 103 Power and Energy Logger was used to record power and energy consumption at seven locations. Figure 22 shows the connection for the power meter used with a three-phase four-wire system supplied by a Y-circuit.

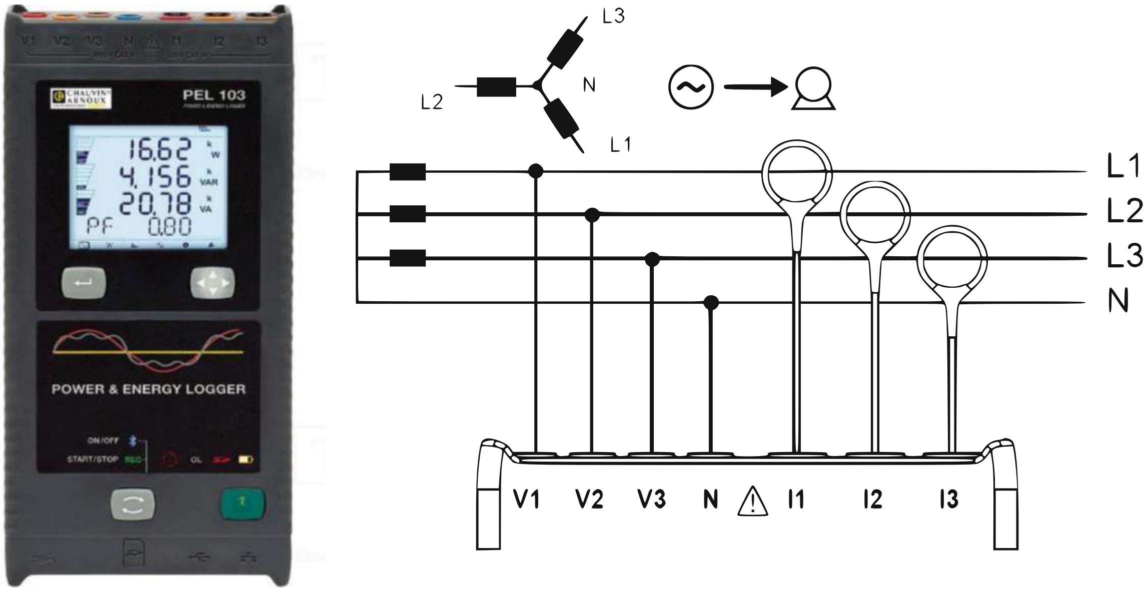


**Figure 22: Chauvin Arnoux PEL 103 power logger (left) and example layout for three-phase four-wire systems in Y-configuration (right) [51].**

The device was configured using the Chauvin Arnoux PEL software, so that various measured values could be logged to an SD-card for analysing. Bluetooth capability allowed for wireless check-ups to view the measurements live.

The device was then installed with the help of technicians to gain information concerning the consumption of each manufacturing phase as described below.

#### 3.2.5.1 Vehicle body manufacturing

As described in section 3.2.2, vehicle body manufacturing is divided into the following major process groups: machining, welding, finishing, and quality inspection.

Machining at SIE VIE LEB takes place on three large HAGEmatic gantry machining centers, designed for machining large aluminum and steel components [52]. The machines are capable of milling, drilling, threading and friction stir welding. An example of a HAGEmatic machining center milling an aluminum sidewall is displayed in Figure 23. The center has two working areas, allowing for more effectively used time. While components are being mounted in the jigs at working area 1, machining can take place at working area 2, and vice versa. This allows for continuous use of the machine and higher productivity.

**Figure 23: HAGEmatic machining an aluminum sidewall [52].**

To record the consumed energy, the power logger was installed at the switchboard as seen in Figure 25. MiniFlex MA103 current transformers (CT) were chosen, due to their flexibility and large diameter. The direction of the CT pointed towards the load and were connected correctly with safety banana plugs to phases L1, L2 and L3 of the PEL 103. The corresponding voltage lines were clamped into the switchboard, both supplying power to the device and allowing for power measurements. The energy consumption during milling on the HAGEmatic center in hall “750 Zubau” was recorded over a time period of 200 hours or roughly 8 days. During this time, the aluminum longitudinal members for a metro Nurnberg underframe as well as roof attachment plates were machined. The energy consumption was internally calculated by the power analyser and shown on the front display and values were wireless checked using a PC to ensure the equipment was functioning as expected. The data was then transferred to the PC using the PEL software and saved to a spreadsheet file for further analysis. The resulting load curve is shown in Figure 24. The machining center draws an average power of 13.6 kW during operation. The consumption on the weekend, when there was no production, is 1.8 kW, which resulted in an energy consumption of 100 kWh over 30 hours. Based on the machining time per component, the energy consumption data and the number of vehicles produced per year, the energy consumption of 240 kWh to machine one vehicle body was estimated.

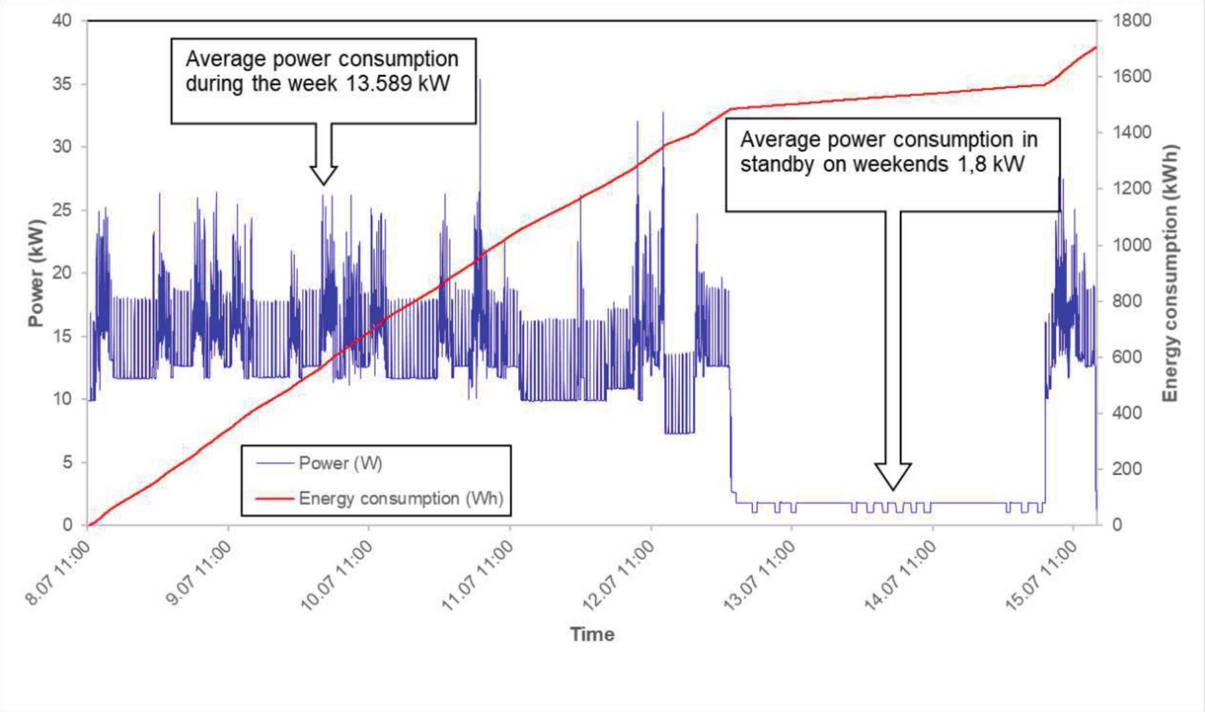


**Figure 24: Load curve from machining on the HAGEmatic machining center in hall 750-Zubau.**

Regarding welding, various literature values were studied prior to conducting the energy measurements. The ecoinvent v3 database includes the process arc welding of aluminum “Welding, arc, aluminium {GLO}| market for | Cut-off, U” with an input from technosphere of 0.05 kWh per welded meter. Documented however in this entry is also the comment: “*Based on rather rough estimates. Not to be used if welding is of importance in the system considered”* [53]. Due to this reason, and since the energy consumption of welding is assumed to be significant, further investigations followed. Previous measurements conducted in 2014 showed that the energy consumption per meter was roughly 0.3 kWh [54]. When considering the work by Pfefferkorn et al. [36], and dividing the test’s total energy consumption by the length of weld, a value of 0.33 kWh $m^{-1}$ was calculated. To obtain a more representative value for welding at SIE VIE LEB, four different measurements were conducted: at a gantry welding robot, a hand welding station for the front-end of the underframe, and two measurements at the on-site welding trainee school.

The gantry welding robot with two welding heads in production hall 750 is used to weld the underframe and roof components of various aluminum vehicles. The gantry system as well as the two welding devices and cooling systems are supplied by one switchboard, in which the power logger was installed (see Figure 25).

**Figure 25: Energy logger PEL 103 installed in the gantry switchboard of the welding robot.**

The period of measurement was organised so that welding an entire aluminum roof and underbody was recorded from start to finish. This consisted of welding the outside left and right sides of the roof and then, after flipping the roof using a rotating crane system, welding the left and right sides of the inside. The same process was applied for the underbody. The load profile of automated side-wall welding can be seen in Figure 26. The welding robot shows an average power consumption of 11.6 kW while welding and 1.1 kW during active standby. The total process of welding a roof and underbody as described resulted in an energy consumption of 35 kWh. It may be noted that the gantry robot stood still for a long time showing 60 W power consumption. This falls into the category of non-value adding energy consumption and should ideally be diminished.

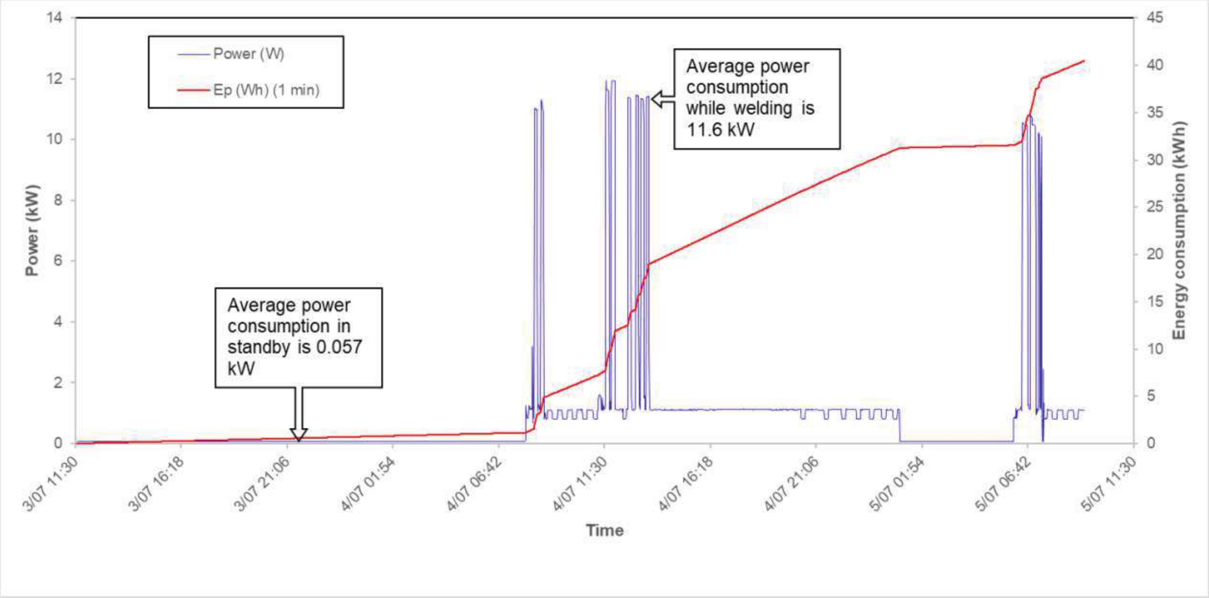


**Figure 26: Load curve from welding on two-headed gantry welding robot in hall 750-Zubau.**

Numerous components are also welded by hand using portable Fronius Transpuls Synergie 4000 industrial gas metal arc welding stations. These are connected to industrial 5-pole 16 A electrical sockets. To measure the energy consumption during welding, a 16 A cable adapter was installed along with the power logger. The welding technician was explained to weld the underframe frontend as usual from start to finish according to technical diagrams. From these documents, the length of weld was determined to be 32 m. The load curve is shown in Figure 27.

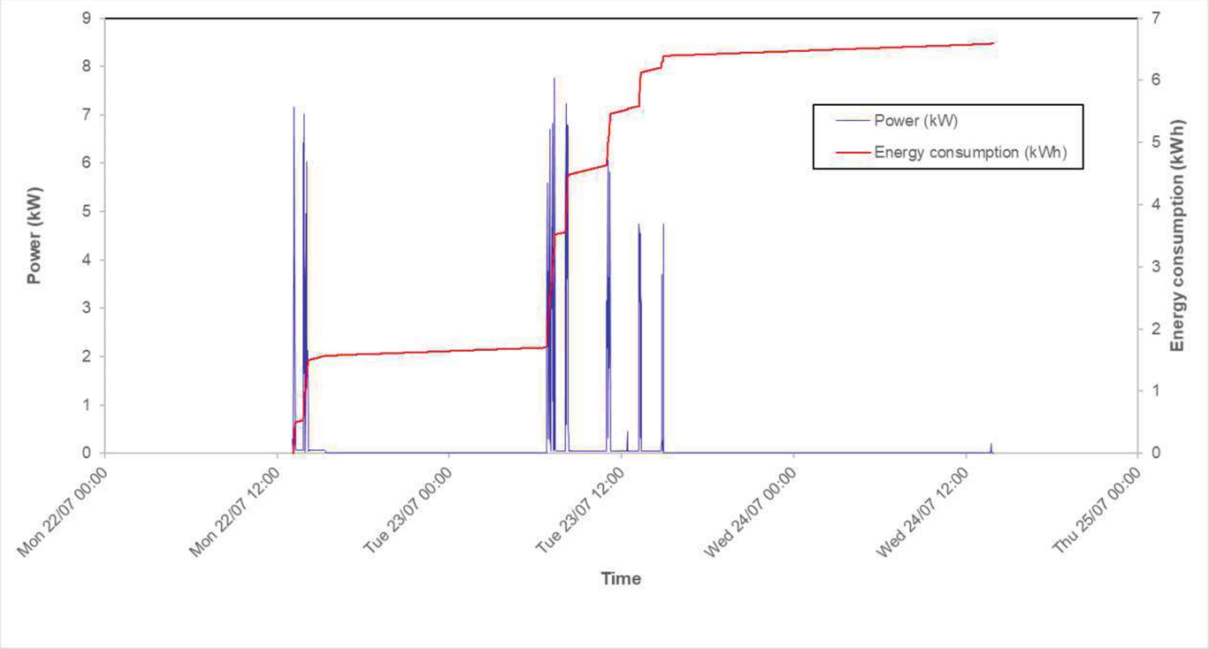


**Figure 27: Load curve from welding one underframe frontend by hand in B560.**

Three further measurements at hand welding stations were conducted to increase the reliability of the obtained specific energy consumption value. A Fronius Transpuls Synergie 4000 with a Fronius FK-4000-R cooler was again used for all welds. Welders at the training facility were asked to weld standardised 30 cm fillet welds with 3 layers. One welder joined two aluminum workpieces with a thickness of 8 mm in horizontal vertical (PB) and then vertical up (PF) positions, and the other one steel workpiece with a thickness of 8 mm in PB. For more information on the positions see the standard DIN EN ISO 6947. The test parameters and the resulting load curves are shown in Figure 28 and Figure 29.

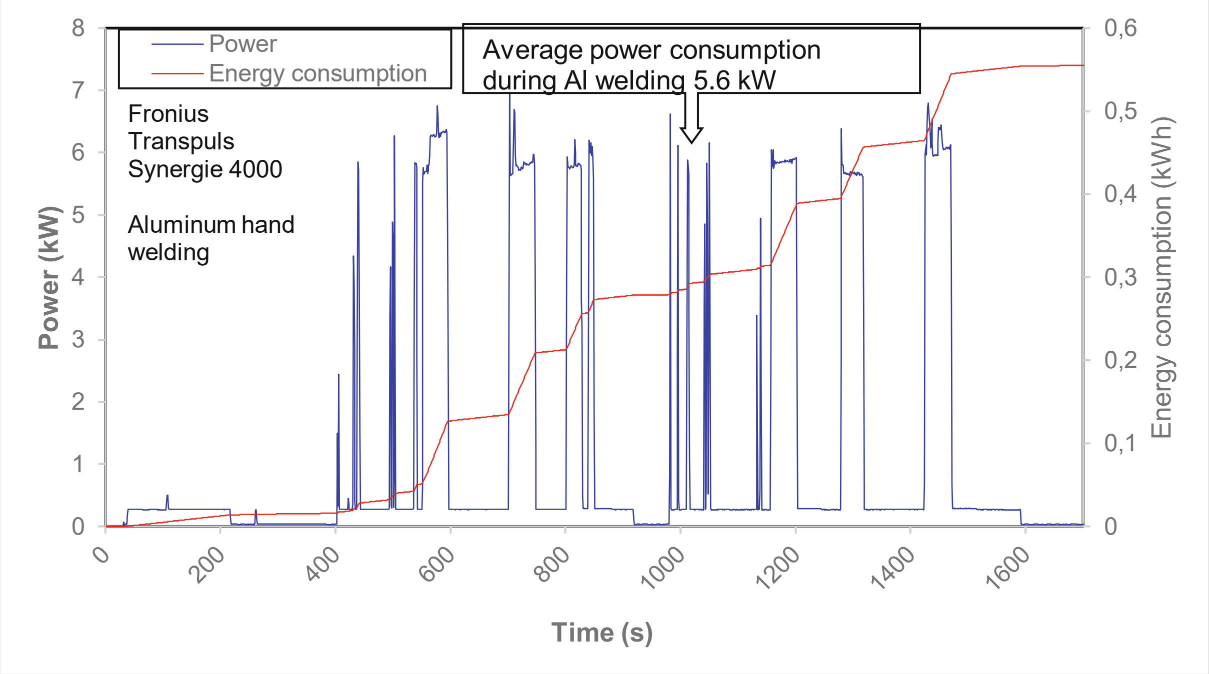


**Figure 28: Load curve from welding aluminum test workpieces by hand at the welding school.**

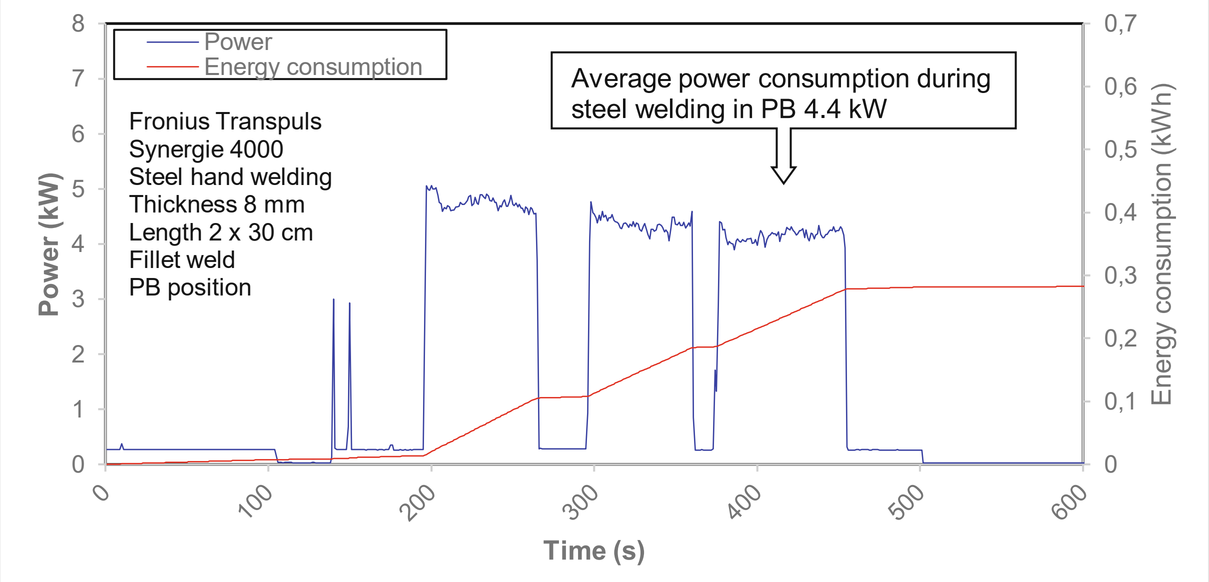


**Figure 29: Load curve from welding steel test workpiece by hand at the welding school.**

One may see that during aluminum hand welding the average power consumption is 5.6 kW and during steel welding 4.4 kW. That of the gantry robot is roughly double with 11.6 kW. The main reason for this is that the gantry robot has two welding heads. The final results of all welding measurements were further analysed. The energy consumed during the measured time period was divided by the length of weld determined from technical documents. The average consumption when welding the steel workpieces is 0.32 kWh $m^{-1}$, while the consumption to weld one meter aluminum is 0.33 kWh.

This corresponds to the values calculated in literature mentioned above and a value of 0.33 kWh $m^{-1}$ will be taken instead of the generic value in ecoinvent. Note that the tests have revealed that the energy consumption does not differ greatly when welding the two different materials. For this reason, the assumption made in section 3.1.2, that the environmental impacts from manufacturing a steel vehicle are similar to those from manufacturing an aluminum vehicle will be kept for the model.

In the course of a research project, an energy management system (EMS) was implemented in building 750 in 2014. As seen in Figure 30, the system includes two Sentron PAC power meters to measure electrical energy consumption, as well as two compressed air flow meters and two air pressure sensors. The measured values are monitored by an industrial PC in real-time and logged for further processing. With the Sentron Powermanager software, the saved values were exported to spreadsheet files and analysed to model a more accurate representation of the energy consumption of hall 750 and for comparison with other similar production halls at SIE VIE LEB. The power consumption and power profile are shown in Figure 31. Since the results appear unrealistically low (average power of 13 kW during the day), the results will not be considered for this study. Future attempts to rebuild the system are recommended.

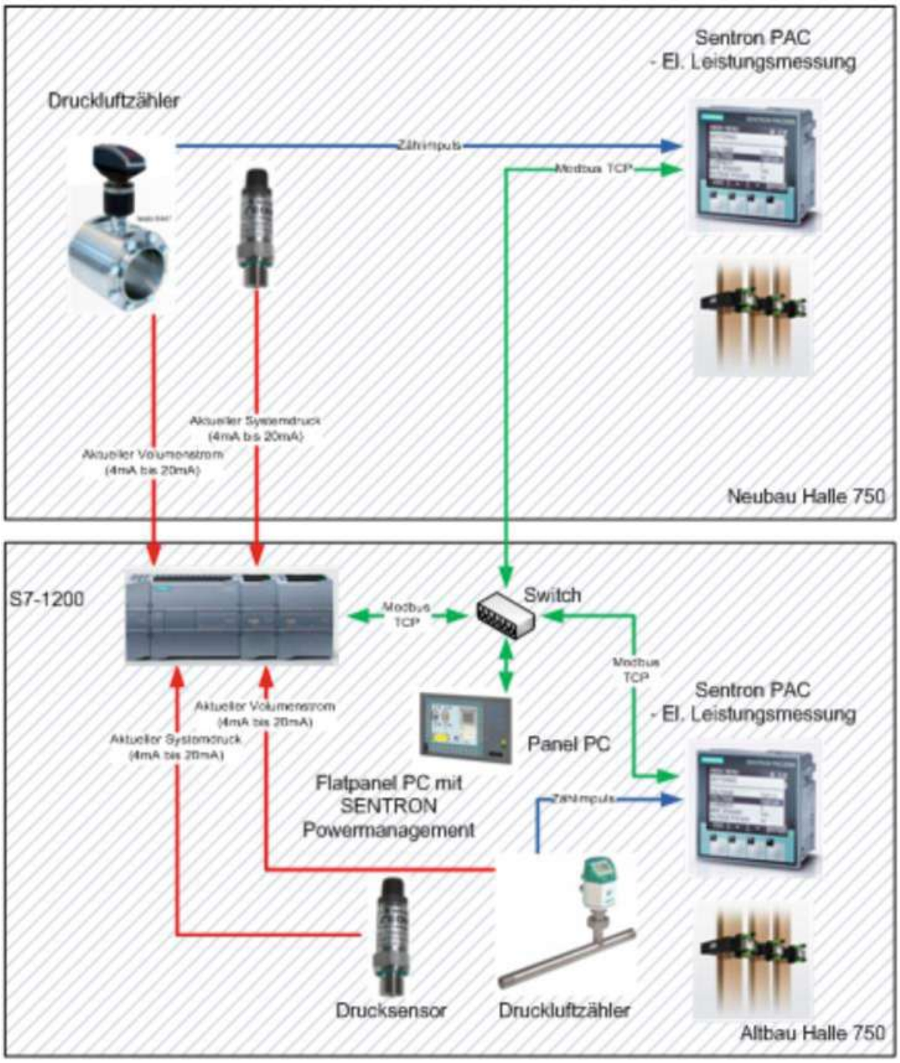


**Figure 30: Energy management system installed in hall 750.**

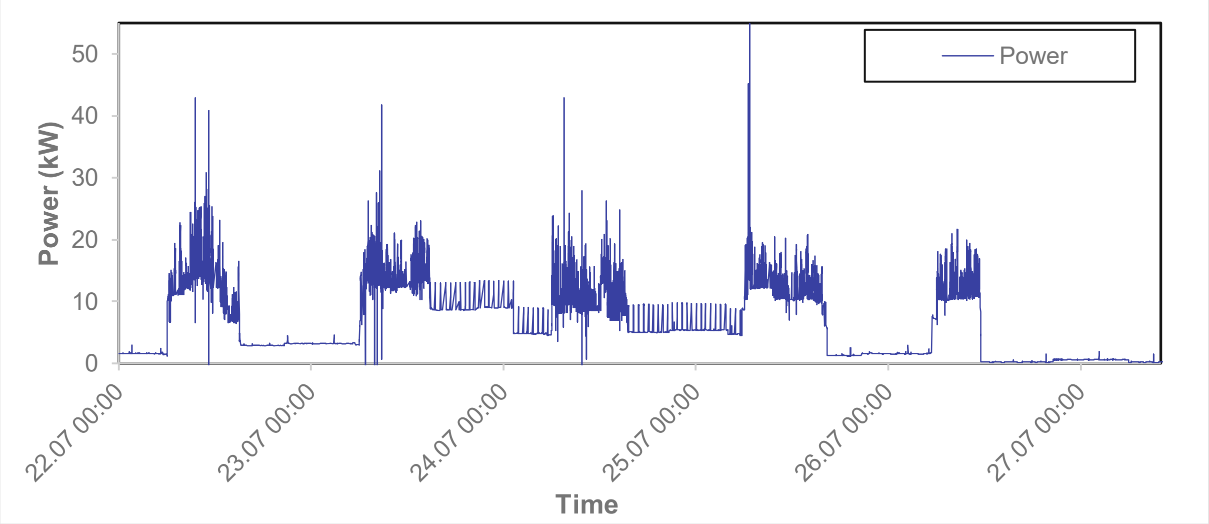


**Figure 31: Power curve resulting from EMS in hall 750.**

The three air compressors in building 132 for VBM have energy meters installed and their data was obtained from internal reports. Other energy meters record consumption of buildings 540, 541 and 560. The energy consumption was averaged over fiscal years 2016 to 2018 and divided by the total number of vehicles produced per year. Based on the discussed measurements, and the estimated production activity in each hall, the energy consumption for the remaining vehicle body manufacturing phase was determined.

#### 3.2.5.2 Surface treatment

The energy consumption for the surface treatment facility is logged by energy meters. The power consumption of the three compressors in building 412 is recorded separately. This data was directly adopted for the LCI. In order to get a more detailed breakdown of the energy consumed by the ventilation systems, a one-week measurement in building 412 was conducted. The power logger was installed in the power room of building 412 where the energy consumption of the ventilation system, filters and climate control are supplied. The load curve in Figure 32 shows the according consumption behavior.

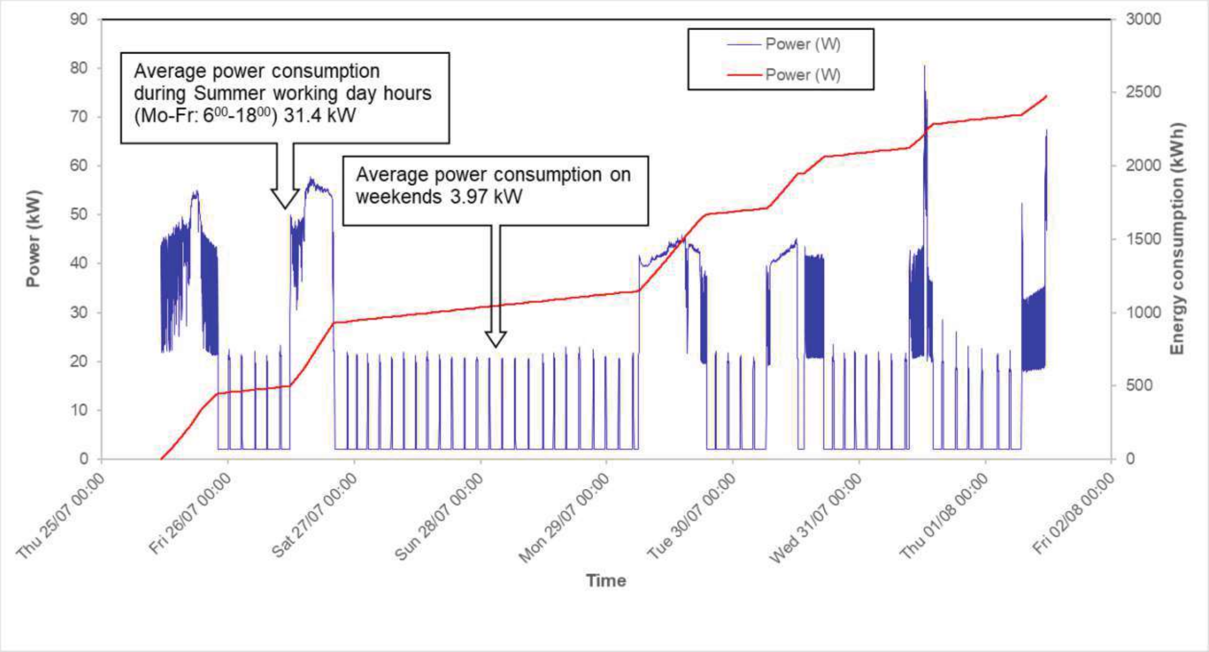


**Figure 32: Load curve from ventilation and climate control system in building 412.**

During painting, a selective air suction system is active, that only extracts air where and when overspray occurs. This reduces the amount of ventilated air and energy consumption.

The ventilation system is intermittently activated on the weekend even though no value adding activity took place during this time. It may also be noted that the power consumption is much higher than other processes measured, indicating that ventilation is one of the most energy intensive processes. Each production hall has its own ventilation system, and the energy consumption of each system was estimated by scaling the obtained values using the surface area of each building.

### 3.2.5.3 Electrical and mechanical assembly

Due to the large surface area in the assembly halls, and high requirements for quality lighting, a large portion of energy is consumed by lamps. The amount of energy consumed by lighting has been estimated using calculations as defined in the DIN 12464 standards [55]. Data regarding the number of lights and lamp model was obtained from Siemens Building Services (SGS) and was used to calculate the energy consumption. This value was 1230 kWh per vehicle per year in the assembly halls 320 and 310. Similar calculations were also conducted for the remaining buildings at SIE VIE LEB, to get an estimate of the electricity consumption due to lighting.

### 3.2.5.4 Commissioning

Static commissioning conducted at VIE LEB requires electrical energy for powering the trains. All components are powered and statically tested in standstill. The process can range up to a month, depending on parameters such as the length of the train, the components that are tested, and to what extent they should be tested. Using a MATLAB simulation tool that was designed to model the energy consumption during the use phase of the vehicle, the energy consumed during train standstill was estimated. The active power value calculated during standby was multiplied by an average time that vehicles need for static commissioning. This value was scaled down to one rail vehicle and entered in the LCI.

### 3.2.5.5 Multi-phase energy consumption

Other processes that draw energy over numerous product phases are internal transport, lighting and ventilation, whereas some have already been discussed in previous sections.

Regarding internal transport at SIE VIE LEB, numerous electric vehicles are used on site and include electric forklifts and small electric trucks. Based on the given energy consumption for each vehicle, number of vehicles and the number of operational hours per year, the energy consumption for internal transport has been estimated and entered in the LCI.

Non-manufacturing related electricity consumption for office lighting, cooling and on-site servers has been estimated and excluded in the LCI. This accounts for roughly 28 % of the energy consumption at SIE VIE LEB. Vehicle body manufacturing and surface treatment are each responsible for roughly one quarter of the consumption. Assembly consumes 14 % of the total energy and commissioning roughly 5 %. Figure 33 portrays the fractions of energy required for each manufacturing phase.

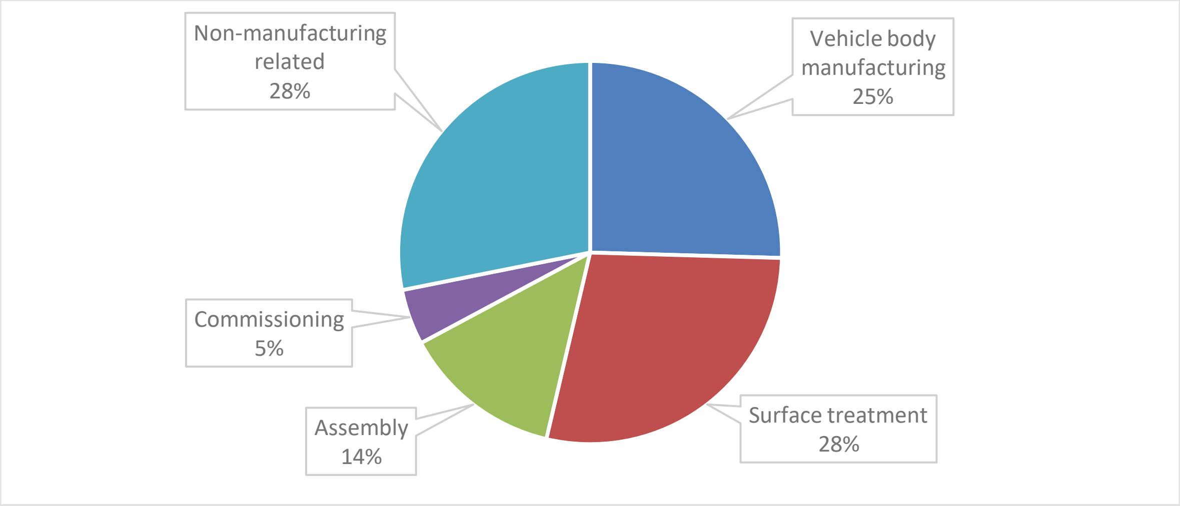


**Figure 33: Shares of electrical energy required for the manufacturing phases.**

### 3.2.6 District heat flows

The plant receives district heating to heat production halls during colder months. Figure 34 shows a normalised curve of the heating demand, in relation to the average monthly outdoor temperature in Vienna over the fiscal years 2014 to 2018 [48].

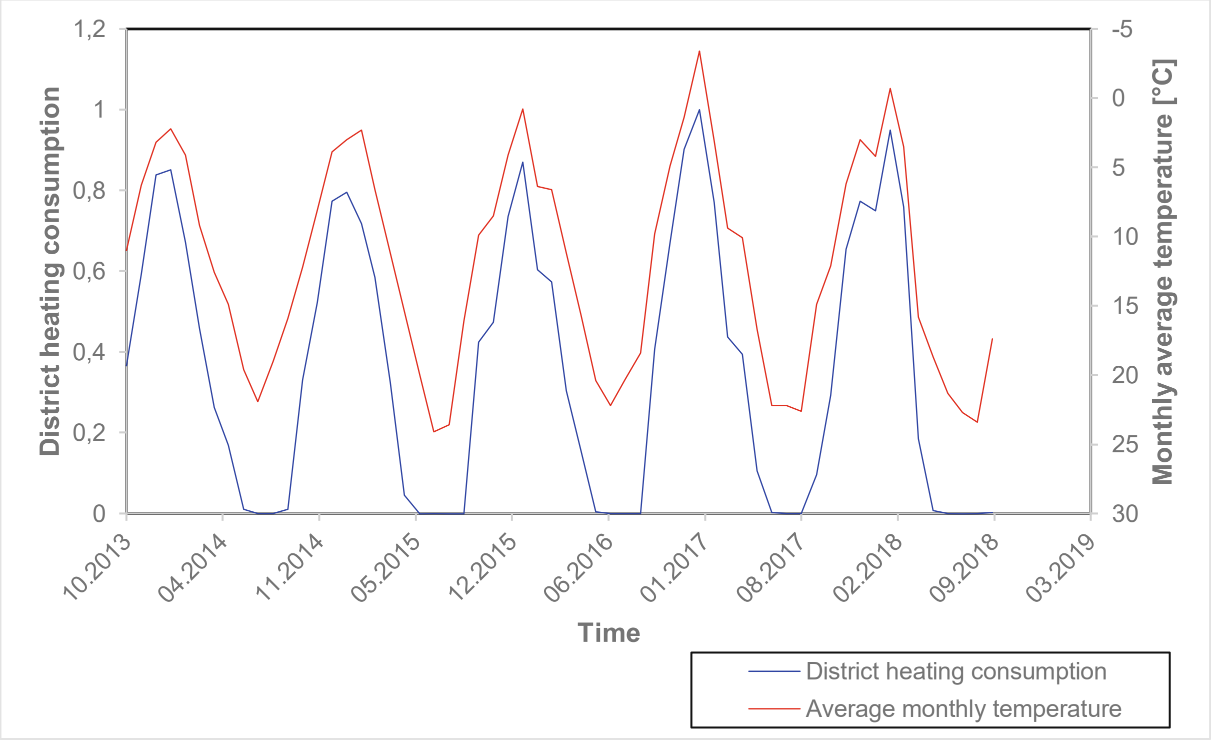


**Figure 34: Normalised curve of the district heat consumption plotted with the average monthly outdoor temperatures.**

The district heat flow meters at SIE VIE LEB do not measure the heat flows per building, but rather roughly by groups of buildings. Thus, the share of heat not relevant for manufacturing was subtracted. In order to achieve this, a model to estimate the monthly district heat consumption relevant for production was created based on weighting factors that take the surface area of the heated buildings into account. An estimated 80 kWh $m^{-2}$ was multiplied by the office surface area to obtain the office heat consumption. Using data from the existing meters, for known halls, a heating factor in kWh $m^{-2}$ was calculated and multiplied by the area of halls with similar height and manufacturing activities. Using this method, the heat use of similar buildings was estimated. In the case of surface treatment existing meters measured the heat use accurately. The heat consumption of each manufacturing phase was modelled and entered in the LCI. An overview of this model can be seen in Figure 35. Roughly 60 % of heating is consumed by vehicle body manufacturing and 23 % use required to heat the assembly halls. Surface treatment cabins are heated with natural gas and therefore ST requires only 3 % of the total district heat. Commissioning accounts for 3 % and non-manufacturing related heating requires 12 % of total demand. Corresponding with the main activity at SIE VIE LEB, it is not surprising to see vehicle body manufacturing consume the most district heat.

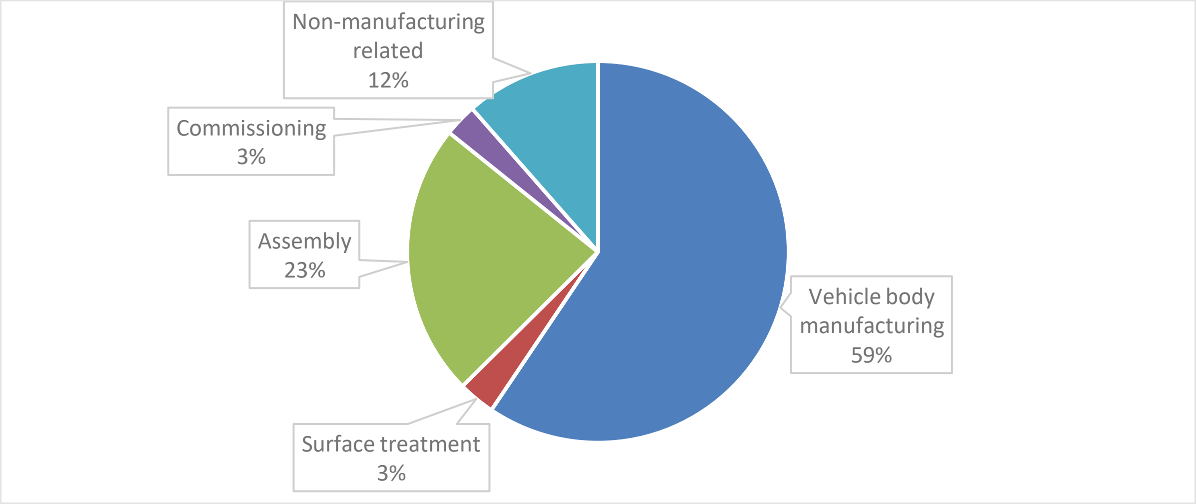


**Figure 35: Shares of district heat required for the manufacturing phases.**

### 3.2.7 Water flows

Water meters measure the water consumption at SIE VIE LEB, which—except from the use in non-manufacturing related offices—is included in the study. Therefore, the water use from buildings 330 and 100 was subtracted from the total water use. Little water is consumed during the manufacturing process. Most of the water is consumed by showers and washrooms by over 1500 workers on site. The water consumption by manufacturing workers has been considered in the study. Water contaminated from the surface treatment processes is collected in basins and picked up by recycling companies. These annual inputs and outputs were divided by the average number of vehicles produced each year. Based on the number of workers involved in each manufacturing phase, the water flows were allocated accordingly and entered in the SimaPro.

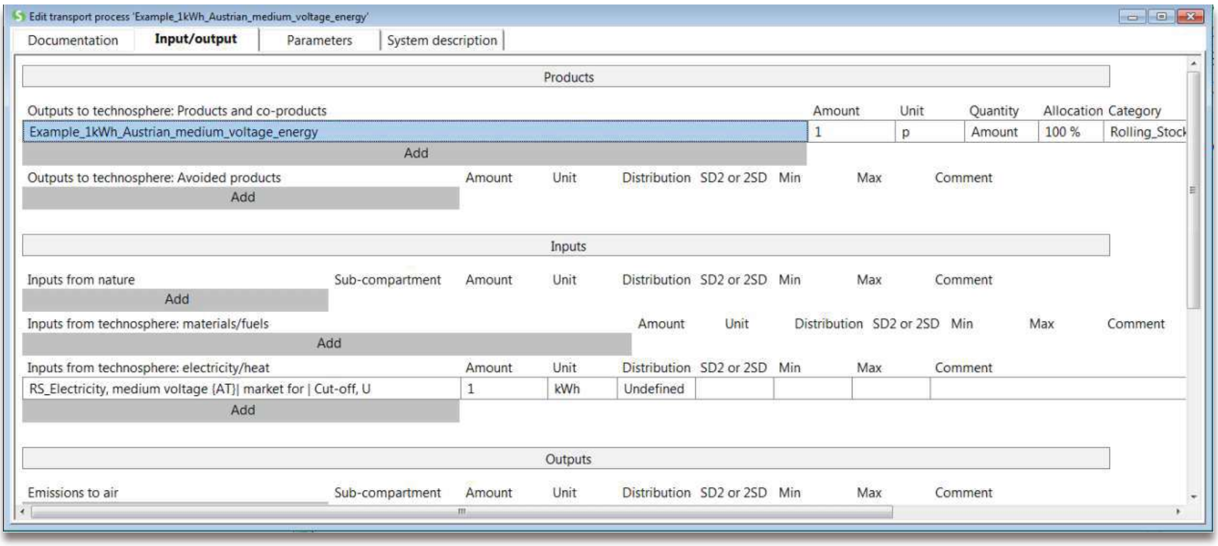
It may also be mentioned that water is pumped from an on-site well to cool the air compressors in building 132. Since the water is returned to nature the way it was extracted, the environmental impacts are negligible, and it is excluded from the LCI. Since this however results in wasted thermal energy that could be used in the system, it will be further discussed in the chapter 4.

## 3.3 Life cycle impact assessment (LCIA)

The LCIA is focused on evaluating the significance of potential environmental impacts using the results from the LCI [6]. This involves connecting inputs to and from nature with the selected environmental impact categories. By selecting the method EPD (2013) v.1.04 in SimaPro, the impact categories and corresponding characterisation factors (CF) are defined in the LCA model. By running the LCIA calculation, the category indicator results are computed and available in the graphic user interface.

For clarification, a short example will be discussed to explain the calculation process in SimaPro. For example, 1 kWh electrical energy from the medium-voltage Austrian power grid is consumed and is entered in the LCI as input from the technosphere (see Figure 36). When the user clicks “calculate”, SimaPro determines the processes and all relevant quantities of inputs and outputs to nature required to produce 1 kWh energy under these conditions, which are defined in the ecoinvent database. Such processes include production of energy in countries like Germany, Italy and Czech Republic, through the use of natural gas, biogas, lignite, hard coal, and renewable sources. In “classification”, the inputs and outputs quantified during the computation are classified into the defined categories, for example global warming. Figure 37 shows the results of the calculation, listing the substances resulting from 1 kWh electrical energy consumption, classified according to their global warming potential. In this example, an electrical power consumption of 1 kWh under these conditions would result in 285 g $CO_2$, 0.761 g $CH_4$ and 0.0172 g $N_2O$, among others. These are relevant for the category global warming and are therefore multiplied by the characterisation factors defined in the EPD method in order achieve a $CO_2$ equivalent value. With the respective characterisation indicators 1 kg $CO_2$/kg $CO_2$, 28 kg $CO_2$/kg CH4 and 265 kg $CO_2$/kg N2O, this characterisation calculation is as follows:

$$
\begin{aligned}
CO_2\ category\ indicator\ result &= \sum (CF\ for\ in/output_i * LCI\ in/output_i) \\
&= 1 * m_{CO2} + 28 * m_{CH4} + 265 * m_{N2O} + \sum \mathrm{CF_i} * \mathrm{m_i} \\
&= (1 * 285\ g) + (25 * 21.3\ g) + (265 * 4.55\ g) + \cdots \\
&= 315\ g\ CO_2\ equivalent
\end{aligned}
$$



Edit transport process 'Example_1kWh_Austrian_medium_voltage_energy'

Products

| Outputs to technosphere: Products and co-products | Amount | Unit | Quantity | Allocation | Category |
|---|---|---|---|---|---|
| Example_1kWh_Austrian_medium_voltage_energy | 1 | p | Amount | 100 % | Rolling_Stock |

Outputs to technosphere: Avoided products — Amount, Unit, Distribution, SD2 or 2SD, Min, Max, Comment

Inputs

Inputs from nature — Sub-compartment, Amount, Unit, Distribution, SD2 or 2SD, Min, Max, Comment

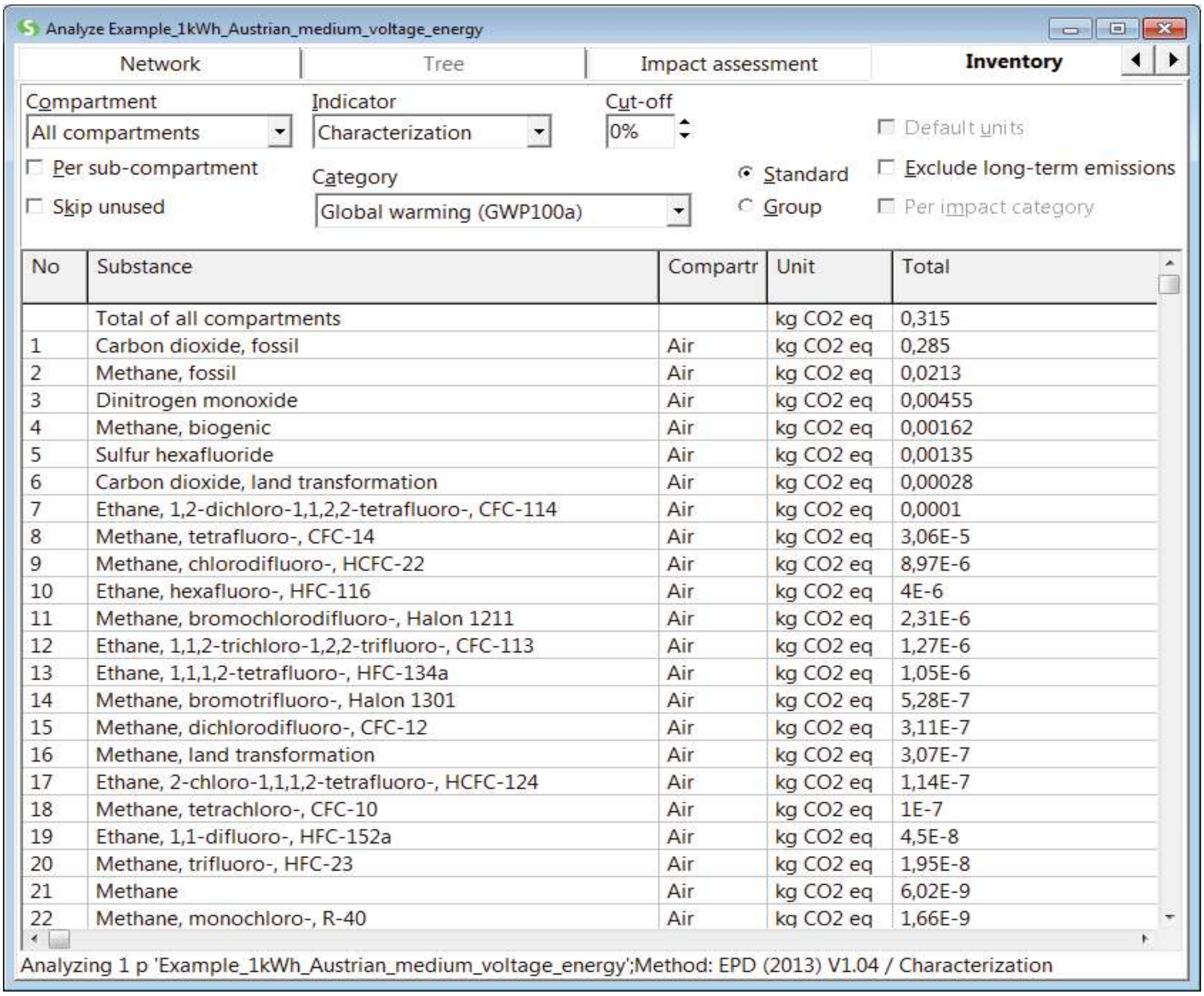
Inputs from technosphere: materials/fuels — Amount, Unit, Distribution, SD2 or 2SD, Min, Max, Comment

| Inputs from technosphere: electricity/heat | Amount | Unit | Distribution | SD2 or 2SD | Min | Max | Comment |
|---|---|---|---|---|---|---|---|
| RS_Electricity, medium voltage {AT}\| market for \| Cut-off, U | 1 | kWh | Undefined | | | | |

Outputs

Emissions to air — Sub-compartment, Amount, Unit, Distribution, SD2 or 2SD, Min, Max, Comment

**Figure 36: Example resource flow in SimaPro consisting of 1 kWh electrical energy.**



Analyze Example_1kWh_Austrian_medium_voltage_energy

Compartment: All compartments
☐ Per sub-compartment
☐ Skip unused
Indicator: Characterization
Category: Global warming (GWP100a)
Cut-off: 0%
● Standard
○ Group
☐ Default units
☐ Exclude long-term emissions
☐ Per impact category

| No | Substance | Compartr | Unit | Total |
|---|---|---|---|---|
| | Total of all compartments | | kg CO2 eq | 0,315 |
| 1 | Carbon dioxide, fossil | Air | kg CO2 eq | 0,285 |
| 2 | Methane, fossil | Air | kg CO2 eq | 0,0213 |
| 3 | Dinitrogen monoxide | Air | kg CO2 eq | 0,00455 |
| 4 | Methane, biogenic | Air | kg CO2 eq | 0,00162 |
| 5 | Sulfur hexafluoride | Air | kg CO2 eq | 0,00135 |
| 6 | Carbon dioxide, land transformation | Air | kg CO2 eq | 0,00028 |
| 7 | Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114 | Air | kg CO2 eq | 0,0001 |
| 8 | Methane, tetrafluoro-, CFC-14 | Air | kg CO2 eq | 3,06E-5 |
| 9 | Methane, chlorodifluoro-, HCFC-22 | Air | kg CO2 eq | 8,97E-6 |
| 10 | Ethane, hexafluoro-, HFC-116 | Air | kg CO2 eq | 4E-6 |
| 11 | Methane, bromochlorodifluoro-, Halon 1211 | Air | kg CO2 eq | 2,31E-6 |
| 12 | Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113 | Air | kg CO2 eq | 1,27E-6 |
| 13 | Ethane, 1,1,1,2-tetrafluoro-, HFC-134a | Air | kg CO2 eq | 1,05E-6 |
| 14 | Methane, bromotrifluoro-, Halon 1301 | Air | kg CO2 eq | 5,28E-7 |
| 15 | Methane, dichlorodifluoro-, CFC-12 | Air | kg CO2 eq | 3,11E-7 |
| 16 | Methane, land transformation | Air | kg CO2 eq | 3,07E-7 |
| 17 | Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124 | Air | kg CO2 eq | 1,14E-7 |
| 18 | Methane, tetrachloro-, CFC-10 | Air | kg CO2 eq | 1E-7 |
| 19 | Ethane, 1,1-difluoro-, HFC-152a | Air | kg CO2 eq | 4,5E-8 |
| 20 | Methane, trifluoro-, HFC-23 | Air | kg CO2 eq | 1,95E-8 |
| 21 | Methane | Air | kg CO2 eq | 6,02E-9 |
| 22 | Methane, monochloro-, R-40 | Air | kg CO2 eq | 1,66E-9 |

Analyzing 1 p 'Example_1kWh_Austrian_medium_voltage_energy';Method: EPD (2013) V1.04 / Characterization

**Figure 37: Example of a life cycle inventory following characterisation in the impact category global warming, related to production of 1 kWh medium-voltage electrical energy in Austria.**

The above-described calculations have been done for all inputs and outputs in the life cycle inventory for each impact category defined in Table 1. The calculated category indicator result of each process is displayed in Figure 38 as a percent of the total results per impact category. In the legend many processes display the name “{GLO}| market for | Cut-off, U”. This represents global data from the ecoinvent database and will not further be discussed. The markings in the legend indicate the main contributors to each category. A discussion of each impact can be found in the following sections. In all categories, electrical energy consumption contributes significantly to the total environmental impacts. As assumed in the scope definition, the effects due to steel and aluminum waste are nearly negligible. This is mostly due to the closed loop recycling method, which will be further discussed in section 3.4.

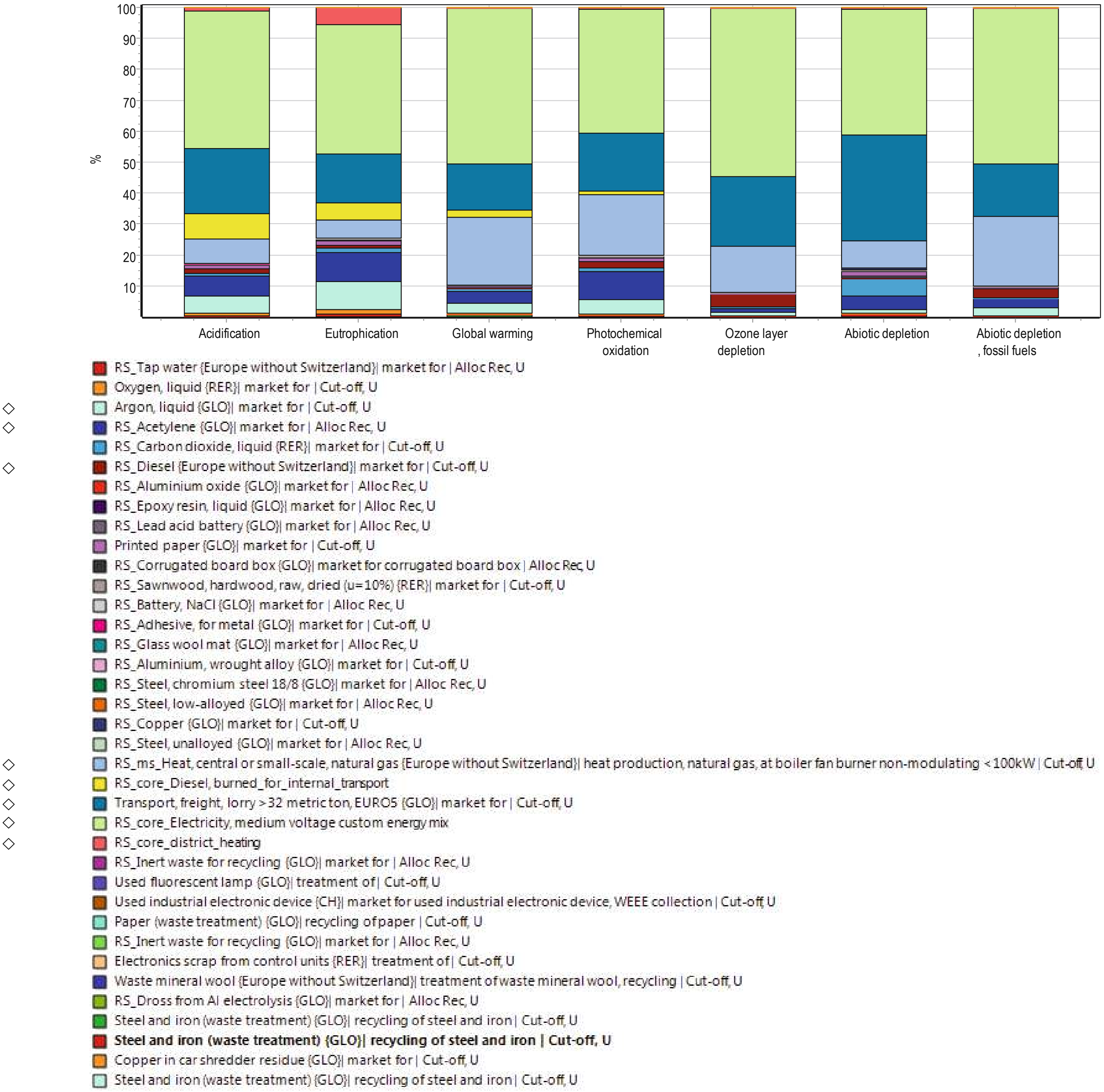


**Figure 38: Environmental impact indicator results of the seven analysed impact categories.**

To further understand the environmental impacts due to each manufacturing phase, the indicator results were grouped accordingly (see Figure 39). In all categories, the surface treatment phase causes the largest amount of environmental impact. This is due to the high electrical energy consumption, as well as the combustion of natural gas to heat the drying cabins. VBM contributes roughly one quarter less to each impact category than ST. The environmental impact due to assembly and non-manufacturing related activities is roughly half of that due to surface treatment. The commissioning phase consumes few resources and therefore contributes the least to each environmental impact.

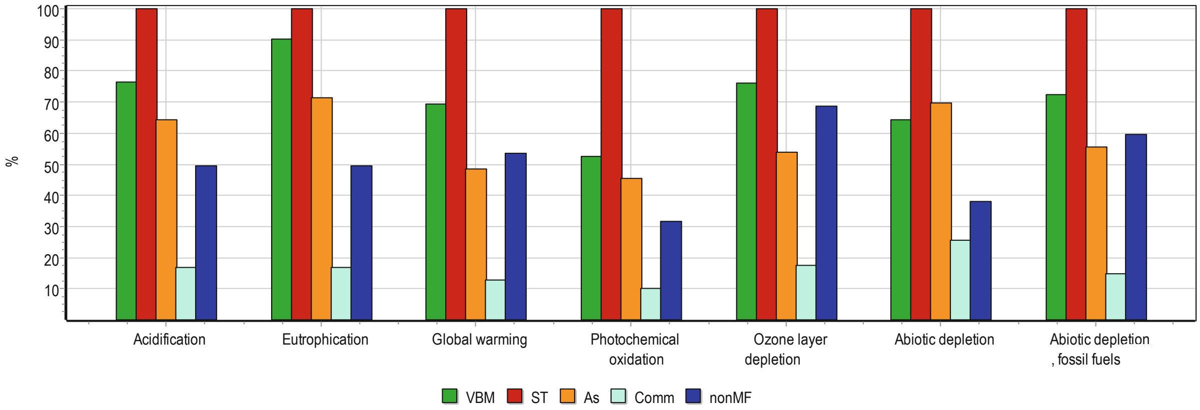


**Figure 39: LCIA profile displaying a comparison of environmental impact results grouped into manufacturing phases.**

### 3.3.1 Global warming potential (GWP)

The total category indicator result of GWP is 11.58 metric tonnes $CO_2$-equivalent (t $CO_2$-eq.) per manufactured generic rail vehicle. The simplified network diagram in Figure 40 displays to what extent each process contributes to the overall global warming potential. Thicker lines represent a greater contribution to the overall environmental impact category. For increased readability, processes that contribute less than 2.4 % percent are not displayed; they are, however, considered in the calculations. As seen in Figure 39, the process that contributes the most to global warming is surface treatment. The resource that contributes the most to GWP is electricity. In total, lighting for manufacturing processes accounts for 13 % of the total GWP due to the high electrical energy consumption. All electrical energy required for compressed air generation accounts for roughly 9 % of total GWP. Note that due to the closed-loop recycling method, most of the environmental impacts due to material sourcing are very low. This is discussed in section 3.4. The transport of materials to and from the facility is, however, taken into account and results in 1.73 t $CO_2$-eq. per rail vehicle. The combustion of diesel, acetylene and natural gas result in 3.2 t $CO_2$-eq. per rail vehicle. Natural gas is only used to heat the drying cabins during surface treatment.

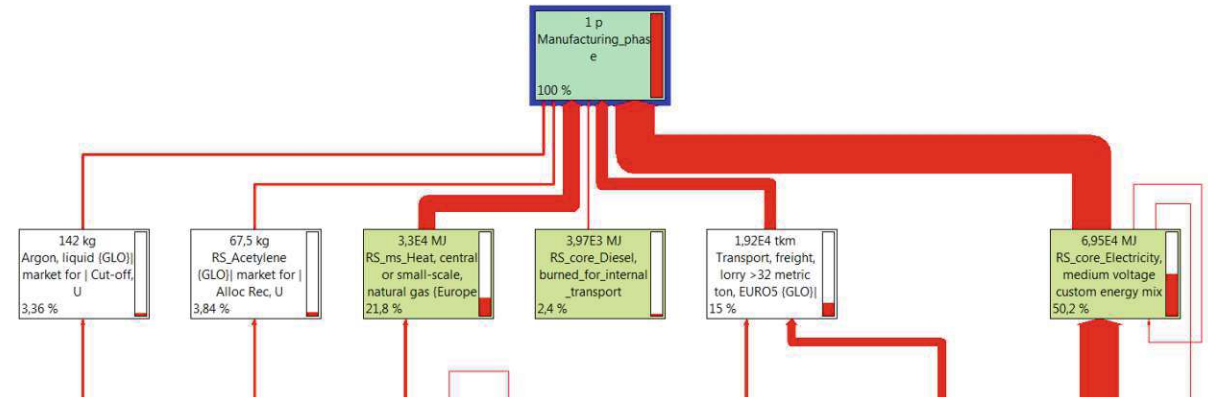


**Figure 40: Network diagram of the global warming potential (only processes contributing greater than 2.4 % to this impact category are displayed).**

To further investigate the situation and relate individual processes to the GWP, a simple calculation using $CO_2$-eq. factors was conducted for electrical energy, heat and natural gas consumption. This was done outside of SimaPro and does not consider data from the ecoinvent database. Instead, $CO_2$-eq. factors from the local electricity provider [56], as well as Austrian Institute for Construction Technology OIB-Standard 6 [57] were multiplied by the energy consumption per vehicle. Diesel, acetylene, and other materials not listed above were not considered. The results were visualised in a Sankey-diagram (see Figure 41). The results imply that district heating does in fact influence GWP, which is not considered in the SimaPro model. This circumstance is further discussed in section 3.4.8.

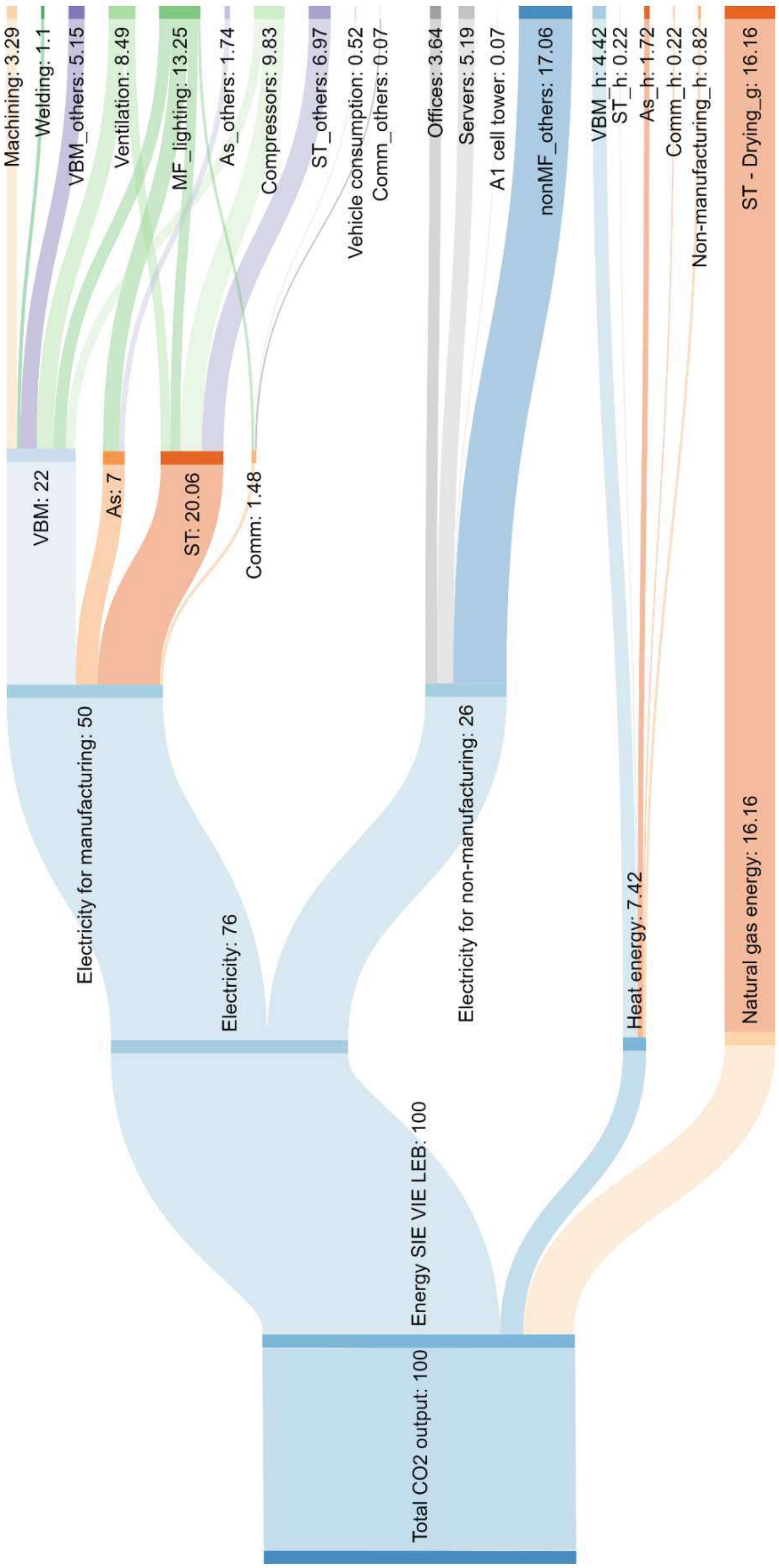


**Figure 41: Sankey diagram displaying sources of total $CO_2$-eq. emissions according to emission factors.**

## 3.3.2 Eutrophication potential (EP)

Analog to GWP, eutrophication potential has been calculated and is shown in Figure 42. The total category indicator result of EP is 8.08 kg $PO_4^{3-}$-eq. In this case, the electrical energy consumption accounts for 42 % of the total EP. Acetylene and argon use contribute 9 %, while transport of materials to and from the facility contribute 16 % to the total EP. By expanding the network diagram seen in Figure 42, it is possible to analyse where the large contribution towards EP from electricity can be sourced to. The model reveals that over 20 % of the EP is caused due to the sourcing of lignite. This has negative effects on local waters. Sourcing of biogas accounts for 10 % of the total EP.

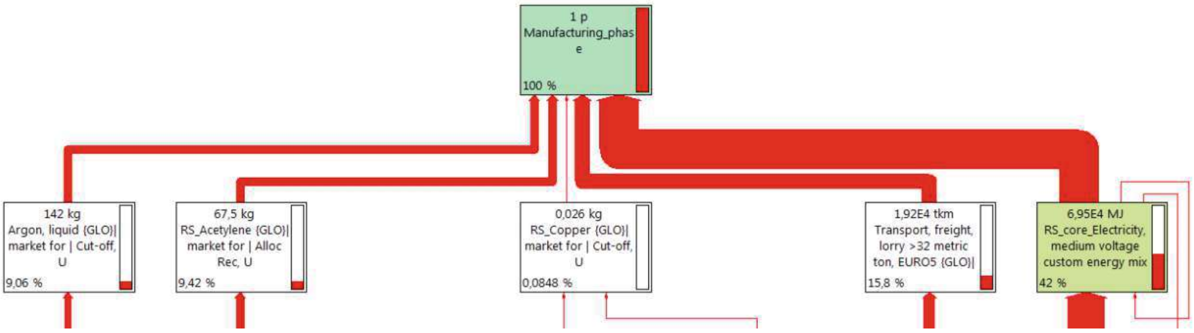


**Figure 42: Network diagram of the eutrophication potential. Only processes contributing greater than 7 % to this impact category are displayed.**

## 3.3.3 Acidification potential (AP)

The total category indicator result of AP is 30.3 kg $SO_2$-eq. per rail vehicle. As seen in the simplified network diagram in Figure 43, electrical energy consumption accounts for 45 % of the total AP. Natural gas combustion and transport of materials to and from the facility contribute 8 % and 21 % respectively. In this case, argon and acetylene use each contribute roughly 6 % to this environmental impact category.

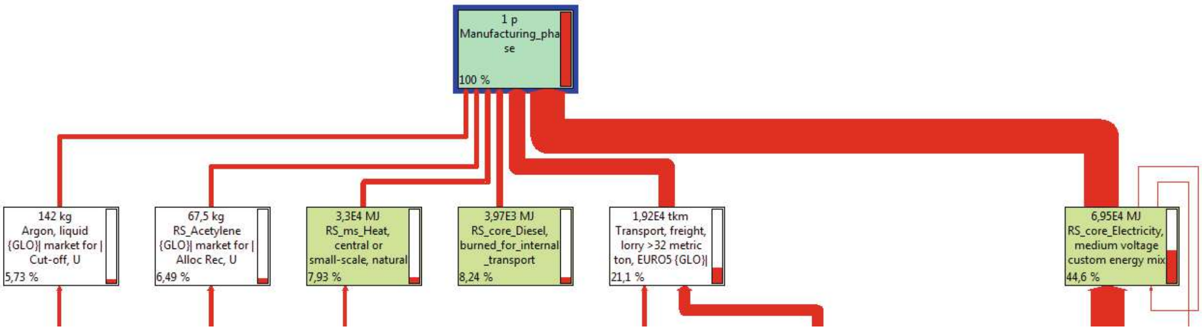


**Figure 43: Network diagram of the acidification potential. Only processes contributing greater than 4.6 % to this impact category are displayed.**

### 3.3.4 Photochemical ozone creation potential (POCP)

The total category indicator result of POCP is 1.5 kg $C_2H_4$-eq. Figure 44 displays the processes that cause photochemical ozone creation. When considering POCP, electrical energy consumption accounts for roughly 40 %. Combustion of natural gas for drying results in 25 %, and transport of materials to and from SIE VIE LEB result in the 19 %. Argon and acetylene use result in 4 % and 9 % respectively.

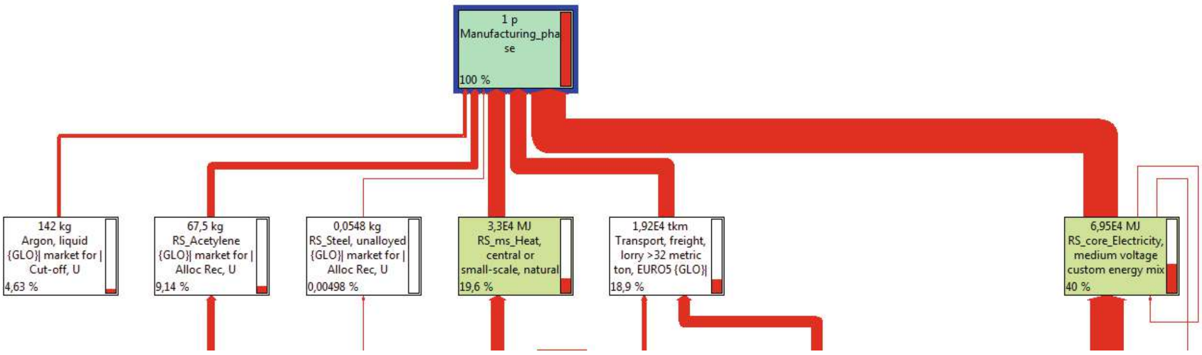


**Figure 44: Network diagram of the photochemical ozone creation potential. Only processes contributing greater than 4.6 % to this impact category are displayed.**

### 3.3.5 Ozone depletion potential (ODP)

The total category indicator result of ODP is 1.44 g CFC-11-eq. As seen in the simplified network diagram in Figure 45, electrical energy consumption accounts for 54 % of the total ODP. Natural gas combustion and transport of materials to and from the facility contribute 15 % and 23 % respectively. In this case, argon and acetylene use are less significant than in the other categories while diesel combustion contributes 4 % to ODP.

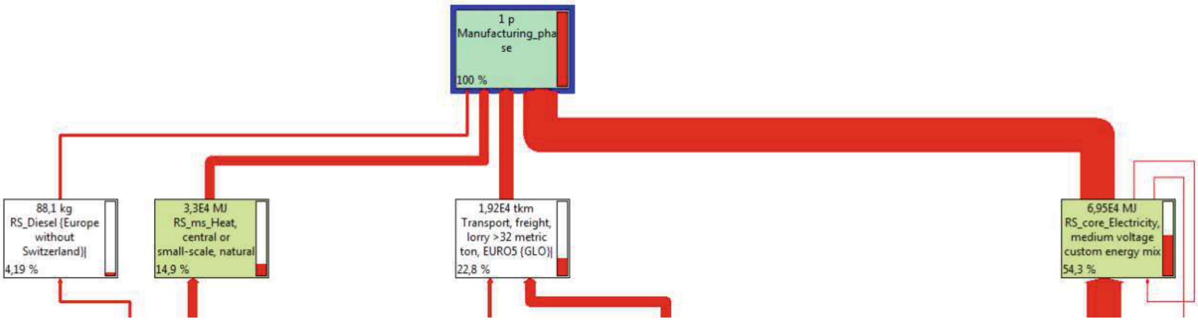


**Figure 45: Network diagram of the ozone depletion potential. Only processes contributing greater than 1.8 % to this impact category are displayed.**

### 3.3.6 Abiotic depletion potential of elements (ADP)

Abiotic depletion potential is divided into two environmental impact categories: depletion of elements and depletion of fossil fuels. The total category indicator result of ADP of elements is 9.59 g Sb-eq. As seen in the simplified network diagram in

Figure 46, electrical energy consumption accounts for 41 % of the total ADP of elements. Natural gas combustion and transport of materials to and from the facility contribute 9 % and 23 % respectively. In contrast to the other network diagrams, here the transmission of electricity has a large effect on the total impact category. The transmission requires copper, which leads to a high ADP result.

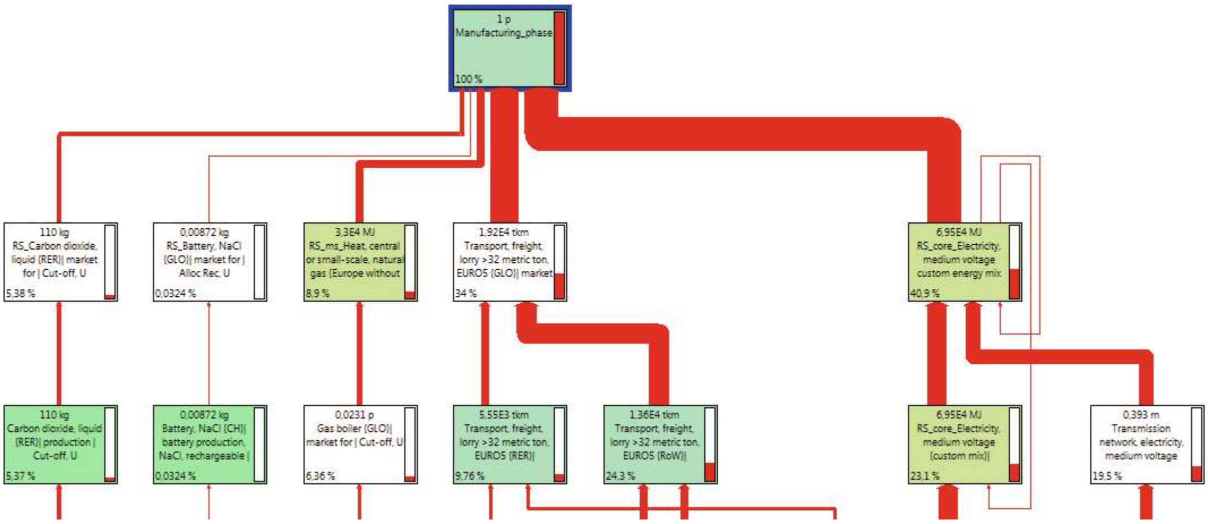


**Figure 46: Network diagram of the abiotic depletion potential of elements. Only processes contributing greater than 5 % to this impact category are displayed.**

### 3.3.7 Abiotic depletion potential of fossil fuels (ADP)

The total category indicator result of ADP of fossil fuels is 160000 MJ-net calorific value. As seen in the simplified network diagram in Figure 47, electrical energy consumption accounts for 51 % of the total ADP of elements. Natural gas combustion and transport of materials to and from the facility contribute 23 % and 17 % respectively. Diesel and acetylene use each result in roughly 3 % of fossil fuel depletion.

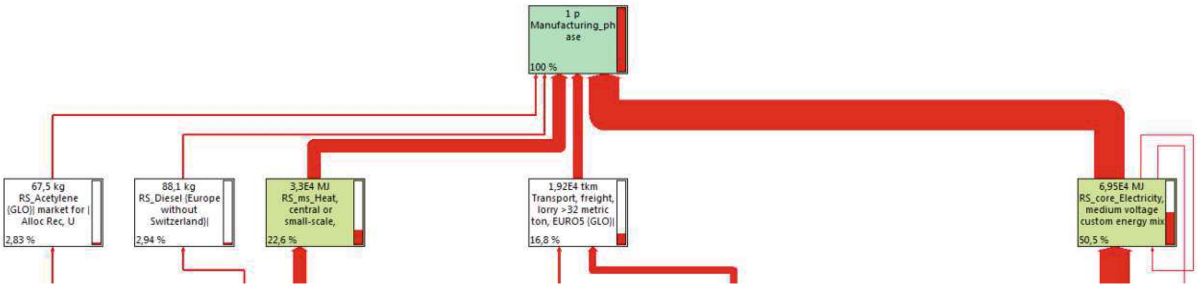


**Figure 47: Network diagram of the abiotic depletion potential of fossil fuels. Only processes contributing greater than 2.8 % to this impact category are displayed.**

### 3.3.8 LCIA data summary

Table 7 displays an overview of resulting category indicators resulting from the core module during production of a generic rail vehicle. The results will be discussed in the following section.

**Table 7: Overview of the environmental impacts in each category following characterisation.**

| Impact category | Unit | Total |
|---|---|---|
| Acidification | kg $SO_2$-eq. | 30.3 |
| Eutrophication | kg $PO_4^{3-}$-eq. | 8.08 |
| Global warming | kg $CO_2$-eq. | 11600 |
| Photochemical oxidation | kg $C_2H_4$-eq. | 1.50 |
| Ozone layer depletion | g CFC-11-eq. | 1,44 |
| Abiotic depletion, elements | g Sb-eq. | 9.59 |
| Abiotic depletion, fossil fuels | MJ | 160000 |

## 3.4 Interpretation of the LCI and LCIA results

According to ISO 14044, the discussion includes an identification of the significant issues based on the results of the LCI and LCIA, an evaluation that considers completeness, sensitivity and consistency checks, as well as conclusions, limitations, and recommendations [17].

The results of the LCIA expose that the electrical energy consumption, various combustion processes and material transport have a large environmental impact in all examined categories. As these account for the largest portion of impacts, they will be further discussed. In many cases, sensitivity analysis was conducted, to gain insight how each process shapes the total results. Sensitivity analysis is a technique to determine how changes in data and methodology affect the LCIA results [17]. For example, a small change of one quantity may cause in large fluctuations in the impact indicator outcomes. Additional calculations with possible improvements were also conducted and the results discussed below.

### 3.4.1 Electrical energy

In most cases, the upstream processes required for the consumed electricity account for roughly half of all impact results. This is due to the use of non-renewable energy carriers for electricity generation and is therefore largely dependant on the selected electricity mix.

To further investigate this issue, a sensitivity analysis was conducted to compare the effect of different electricity mixes. Four additional scenarios were defined and can be seen in Table 8. These scenarios include overriding the average mix with a green electricity mix, an electricity mix with 68 % renewable and 33 % non-renewable energy, a mostly non-renewable mix, and a mix with 100 % hydropower.

**Table 8: Various electricity mix scenarios used for sensitivity analysis.**

| Electricity production source | Average mix at SIE VIE LEB | Green mix available at provider | Austria mix available at provider | Non-renewable mix | 100 % hydropower mix |
|---|---|---|---|---|---|
| Hydro | 47% | 84% | 52% | 6% | 100% |
| Wind | 10% | 10% | 12% | 9% | 0% |
| Biomass | 4% | 4% | 3% | 4% | 0% |
| Biogas | 1% | 1% | 0% | 2% | 0% |
| Other renewables | 1% | 1% | 1% | 1% | 0% |
| Coal | 10% | 0% | 10% | 20% | 0% |
| Natural gas | 27% | 0% | 22% | 58% | 0% |

To assist the sensitivity analysis, the SimaPro model was parametrised, which allows for easier changes of variables. Instead of entering a fixed value, a string was entered, which had a corresponding value saved in the parameters section of the model. The parameters were linked to a spreadsheet file and were loaded each time the calculations were run. Figure 48 shows the environmental impacts of the vehicle manufacturing using these four additional electricity mixes. The non-renewable electricity mix causes roughly 30 % more impacts, except in the category ADP of elements; in this category, the mixes score similarly. According to this calculation using the ecoinvent database, the hydropower mix causes the least amount of environmental impacts, followed by the green mix. As a result of this sensitivity analysis, changing from the averaged SIE VIE LEB electricity mix to the green mix would decrease the environmental impacts in all categories. Since electrical energy consumption is the largest overall contributor to environmental impacts, this change in electricity mix is encouraged.

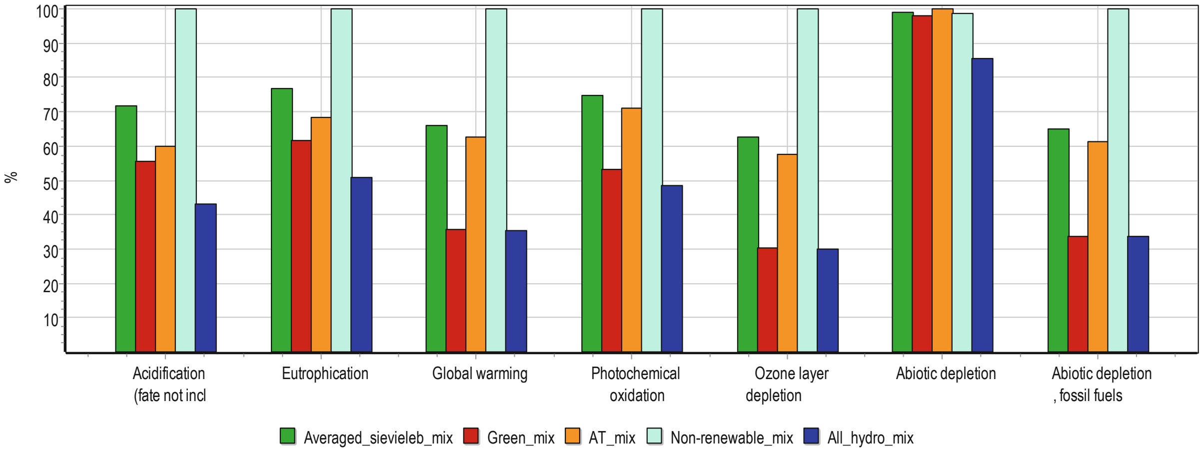


**Figure 48: LCIA profile comparing environmental impact results of various electricity mix scenarios.**

Table 9 shows the results of the calculation using the green mix in comparison to the that of the actual mix. The reduction of environmental impacts is significant; in three categories roughly 50 %.

**Table 9: Comparison of environmental impact results of original scenario with averaged SIE VIE LEB electricity mix, with a green electricity mix.**

| Impact category | Unit | Total – averaged SIEVIELEB mix | Total – green mix | Reduction |
|---|---|---|---|---|
| Acidification | kg $SO_2$-eq. | 30.3 | 23.4 | -23% |
| Eutrophication | kg $PO_4^{3-}$-eq. | 8.08 | 6.50 | -20% |
| Global warming | kg $CO_2$-eq. | 11600 | 6240 | -46% |
| Photochemical oxidation | kg $C_2H_4$-eq. | 1.50 | 1.07 | -29% |
| Ozone layer depletion | g CFC-11-eq. | 1.44 | 0.700 | -51% |
| Abiotic depletion, elements | g Sb-eq. | 9.59 | 9.50 | -1% |
| Abiotic depletion, fossil fuels | MJ | 160000 | 83000 | -48% |

### 3.4.2 Natural gas

Natural gas consumption accounts for 6 to 23 % of the total environmental impacts. All natural gas combustion is related to drying during surface treatment. To reduce the amount of natural gas consumed, various other drying technologies could be considered. Brock et al. [58] discusses numerous methods for forced drying, many of which do not rely on fossil fuel combustion—infrared drying, ultraviolet drying and pulsed radiation drying are just a few to mention. Infrared radiation is commonly used in the automotive industry due to its quick drying times, fast system reaction times, reduced space requirement and relatively low cost. Since it solely relies on electrical energy, natural gas combustion would be eliminated. Disadvantages of typical electrical heating systems are that electrical energy is more costly, and typically only more environmentally friendly if green electricity is procured. From an exergetic point of view, there is an enormous waste of exergy when electrical resistive heaters are used for space heating [59,60]. To obtain a rough estimate of the environmental impacts of an electrically powered instead of a gas-fired drying system, a further calculation was considered. In the additional scenario, the 9176 kWh natural gas were replaced with 9176 kWh of electrical energy.

The results are displayed in Table 10. When the same amount of energy is applied electrically instead of using gas, an increase in environmental impacts is observed. This is the case as the actual electricity mix is used, in which environmental impacts are caused by non-renewable primary energy carriers.

**Table 10: Comparison of environmental impact results from original scenario and drying scenario with natural gas energy 100 % replaced with electrical energy.**

| Impact category | Unit | Total – base scenario | Total –electrical heating and no gas scenario | Increase |
|---|---|---|---|---|
| Acidification | kg $SO_2$-eq. | 30.3 | 34.4 | 13% |
| Eutrophication | kg $PO_4^{3-}$-eq. | 8.08 | 9.24 | 14% |
| Global warming | kg $CO_2$-eq. | 11600 | 11800 | 2% |
| Photochemical oxidation | kg $C_2H_4$-eq. | 1.50 | 1.49 | 0% |
| Ozone layer depletion | g CFC-11-eq. | 1.44 | 1.60 | 11% |
| Abiotic depletion, elements | g Sb-eq. | 9.59 | 10.6 | 11% |
| Abiotic depletion, fossil fuels | MJ | 160000 | 162000 | 2% |

An additional alternate solution may be to use a heat pump to raise the exergetic efficiency. With this technology, less energy must be applied to increase the temperature from a reference temperature to the temperature required for drying, $T_d$, in comparison to use of gas-fired heaters. As a worst case, setting the reference temperature equal to the average annual temperature for Vienna $T_U = 10\ °C$, and $T_d\ = 90°C$, then the theoretical amount of mechanical energy that needs to be applied using a Carnot heat cycle is approximated one fifth of the energy required for the drying process, $Q_d$ (see equation 1).The elimination of natural gas use and an addition of 20 % of $Q_d$ as electrical energy has been calculated in SimaPro. The results of the described scenario are summarised in Table 11. A decrease in GWP, POP and ADP of fossil fuels can be observed. This concept will be further discussed in section 4. Note that use of process heat to increase the reference temperature would further increase the COP. As an example, the use of waste heat while cooling the air compressors should be considered.

$$COP = \frac{T_d}{T_d - T_U} = \frac{363.15K}{363.15K - 283.15K} \approx 5 \leq \frac{Q_d}{W} \quad (1)$$

$COP$… coefficient of performance
$T_d$… temperature required for drying
$T_U$… outside temperature
$Q_d$… energy required for the drying process
$W$… energy required to be added to the system

**Table 11: Comparison of environmental impact results from original scenario and theoretical drying scenario with a heat pump.**

| Impact category | Unit | Total – base scenario | Total –heat pump and no gas scenario | Reduction |
|---|---|---|---|---|
| Acidification | kg $SO_2$-eq. | 30.3 | 29.3 | -3% |
| Eutrophication | kg $PO_4^{3-}$-eq. | 8.08 | 7.96 | -1% |
| Global warming | kg $CO_2$-eq. | 11600 | 9670 | -17% |
| Photochemical oxidation | kg $C_2H_4$-eq. | 1.5 | 1.27 | -15% |
| Ozone layer depletion | g CFC-11-eq. | 1.44 | 1.31 | -9% |
| Abiotic depletion, elements | g Sb-eq. | 9.59 | 9.15 | -5% |
| Abiotic depletion, fossil fuels | MJ | 160000 | 132000 | -17% |

Another effort to reduce gas consumption is the use of better insulation in the drying halls since heat loss leads to higher gas demand. In the current situation, heat loss to the rooms above the drying halls was noticed. Furthermore, modernisation of the burners may result in more efficient heating and less gas waste.

### 3.4.3 Transport of materials to and from SIE VIE LEB

The transportation of resources to and from the production facility accounts for a significant environmental impact in each category. The total mass of materials within the project scope was multiplied with a factor of 250 km distance to get from material supplier plants to SIE VIE LEB, and from there to recycling facilities. Examples of such materials are corundum, metal waste, paint waste, paper waste and wood. It has been defined that the means of transportation is using freight lorries over 32 metric tonnes, with EURO5 certification. The environmental impacts therefore mostly arise from diesel and gasoline combustion. In reality, transport distance of materials to Leberstraße 34 varies and is dependant on the resource itself. When leaving SIE VIE LEB, many materials are transported to Vienna's *Abfallbehandlungsanlage* 14 km away, where they are sorted and pretreated. The PCR RS recommends a distance of 500 km, when distances are unknown, however internal documentation shows that most often, the distance is shorter.

To further investigate the effects of transport, a sensitivity analysis was conducted, in which the transportation distance as well as EURO certification was adjusted. In the first alternative scenario, the transport distance with the same lorries as in the base scenario travelled a distance of 500 km instead of 250 km. The results of this case are shown in Table 12. Doubling the travelling distance significantly increased the environmental impacts, with increases ranging from 15 to 34 %. This reveals that the travel distance of the resources should be kept to a minimum thus resources and ideally sourced and recycled locally.

**Table 12: Comparison of environmental impact results from original scenario and scenario with 500 km travel with 32 tonne EURO5 lorries.**

| Impact category | Unit | Total – base scenario | Total –500 km transport | Increase |
|---|---|---|---|---|
| Acidification | kg $SO_2$-eq. | 30.3 | 36.7 | 21% |
| Eutrophication | kg $PO_4^{3-}$-eq. | 8.08 | 9.36 | 16% |
| Global warming | kg $CO_2$-eq. | 11600 | 13300 | 15% |
| Photochemical oxidation | kg $C_2H_4$-eq. | 1.50 | 1.78 | 19% |
| Ozone layer depletion | g CFC-11-eq. | 1.44 | 1.77 | 23% |
| Abiotic depletion, elements | g Sb-eq. | 9.59 | 12.9 | 34% |
| Abiotic depletion, fossil fuels | MJ | 160000 | 186000 | 17% |

In the second alternative scenario, EURO6 lorries were selected instead of EURO5, leading only to a slight reduction of environmental impacts (see Table 13).

**Table 13: Comparison of environmental impact results from original scenario and scenario with 250 km travel with 32 tonne EURO6 lorries.**

| Impact category | Unit | Total – base scenario | Total –EURO6 lorry | Reduction |
|---|---|---|---|---|
| Acidification | kg $SO_2$-eq. | 30.3 | 28.5 | -6% |
| Eutrophication | kg $PO_4^{3-}$-eq. | 8.08 | 7.74 | -4% |
| Global warming | kg $CO_2$-eq. | 11600 | 11500 | -1% |
| Photochemical oxidation | kg $C_2H_4$-eq. | 1.50 | 1.48 | -1% |
| Ozone layer depletion | g CFC-11-eq. | 1.44 | 1.44 | 0% |
| Abiotic depletion, elements | g Sb-eq. | 9.59 | 9.59 | 0% |
| Abiotic depletion, fossil fuels | MJ | 160000 | 160000 | 0% |

### 3.4.4 Diesel

As discussed in section 3.3, diesel combustion contributes significantly to each environmental impact category and should therefore be reduced. Diesel is used for internal transportation on the facility grounds. Roughly one quarter of vehicles used for transport at SIE VIE LEB use diesel, the rest are electrically driven. Many of the diesel vehicles are forklifts, which could be replaced by electric models. Furthermore, the large rail vehicle transporters to move rail vehicles between halls are diesel powered, as well as a few large forklifts for heavy loads. To investigate the influence of replacing the smaller forklifts, a new scenario was defined which leads to a reduction of diesel demand at SIE VIE LEB of 75 %. The numeric results are shown in Table 14; the reduction lies between 2 and 7% in each category. This statement does not take into account the entire lifecycle of a forklift, nor the environmental impacts of producing batteries for electric vehicles. Only the simplified use-phase of a diesel and electric forklift are compared.

**Table 14: Comparison of environmental impact results from original scenario and a scenario with 75 % reduced diesel consumption.**

| Impact category | Unit | Initial scenario | Scenario with 75 % less diesel consumption | Reduction |
|---|---|---|---|---|
| Acidification | kg $SO_2$-eq. | 30.3 | 28.1 | -7% |
| Eutrophication | kg $PO_4^{3-}$-eq. | 8.08 | 7.70 | -5% |
| Global warming | kg $CO_2$-eq. | 11600 | 11300 | -2% |
| Photochemical oxidation | kg $C_2H_4$-eq. | 1.50 | 1.47 | -2% |
| Ozone layer depletion | g CFC-11-eq. | 1.44 | 1.40 | -3% |
| Abiotic depletion, elements | g Sb-eq. | 9.59 | 9.57 | 0% |
| Abiotic depletion, fossil fuels | MJ | 160000 | 156000 | -2% |

### 3.4.5 Acetylene

Acetylene is used at SIE VIE LEB mainly to manually preheat aluminum before it is welded. The preheating is necessary to achieve high quality welds. Other technology such as electrical heaters and infrared radiators could be considered. Alternatively, more efficient burners could be investigated, as well as indicators that inform the welder the necessary temperature has been reached, and no more heating is required. Workers will be notified of the environmental impacts related to acetylene consumption and that they should use the resource sparingly.

### 3.4.6 Argon

Argon is used at SIE VIE LEB as an inert shielding gas mostly while welding aluminum. Its consumption results in 1 to 9 % of environmental impacts in the investigated categories. Other inert gases available and used at SIE VIE LEB are helium and mixtures of helium and argon. As helium is more expensive, it is used in fewer situations. When discussing the shielding gas consumption with welders at the facility, some mentioned that shielding gas flow is sometimes increased to achieve a greater shielding effect, and therefore better welds. However, that is not often necessary and leads to an increase in wasted argon. Gas saving systems that automatically regulate the flow based on temperature, voltage, current and material properties could reduce the gas consumption. Companies advertise savings up to 60 % [61] using such gas savings systems.

## 3.4.7 Summary of resource use reduction

Some methods to reduce resource use have been discussed in sections 3.4.1 to 3.4.6. A new model has been defined, that includes various improved scenarios with the following adjustments:

- Green electricity mix chosen (see Table 8)
- Natural gas burner for surface treatment replaced by heat pump
- Total transport reduced to 150 km, assuming local sourcing and treatment
- 75 % less diesel consumption by replacing diesel forklifts with electric forklifts
- 10 % decrease of acetylene consumption by worker training or more efficient burners
- 30 % decrease of argon use by using gas saving systems

The environmental impacts using this optimised model have been calculated and can be seen in Table 15. The reduction of environmental impacts is significant. Global warming potential, fossil fuel depletion and ozone layer depletion are reduced by up to 80 %. Acidification, eutrophication and photochemical oxidation are reduced by 46 %, 38 % and 59 %, respectively. On this basis, further possibilities for improvement will be discussed in section 4.

**Table 15: Comparison of environmental impact results from original scenario and a scenario with 75 % reduced diesel consumption.**

| Impact category | Unit | Initial scenario | Optimised scenario | Reduction |
|---|---|---|---|---|
| Acidification | kg $SO_2$-eq. | 30.3 | 16.2 | -46% |
| Eutrophication | kg $PO_4^{3-}$-eq. | 8.08 | 5.03 | -38% |
| Global warming | kg $CO_2$-eq. | 11600 | 2660 | -77% |
| Photochemical oxidation | kg $C_2H_4$-eq. | 1.5 | 0.609 | -59% |
| Ozone layer depletion | g CFC-11-eq. | 1.44 | 0.306 | -79% |
| Abiotic depletion, elements | g Sb-eq. | 9.59 | 7.64 | -20% |
| Abiotic depletion, fossil fuels | MJ | 160000 | 31400 | -80% |

## 3.4.8 Limitations of the results

The results of any LCA are limited due to uncertainty of data and assumptions that may not fully represent reality. Such issues will be discussed further.

The LCI is built on data taken from generic sources and measurements. The generic sources such as the ecoinvent database may not reflect the production situation at SIE VIE LEB. Ecoinvent is used to roughly represent the flows of a broad list of processes, however is not adequate to accurately describe the exact inputs and outputs of a specific process chain. Measured data was acquired over a short period of time and when scaled over 12 months, may not represent the flows over a real fiscal year. As a result, the division of consumption into each manufacturing phase must be accepted with some inaccuracy.

The LCIA reveals that district heat consumed at SIE VIE LEB has an insignificant effect on any environmental impact category. This is attributable to district heating being sourced from waste incineration processes which have little to zero environmental impact in the ecoinvent database. Many of the district heating processes are “empty“, and therefore have no inputs nor outputs. A reason for this may be that energy from garbage incineration is seen as a waste product of the garbage and therefore already considered in the waste treatment processes. Further information regarding this topic should be discussed with the creators of the ecoinvent database to understand how the complex processes are linked.

The used closed loop recycling method also has a significant influence on the results of the study and shall be further discussed. The UNIFE standards define the recyclability of the materials used in the railway industry [46]. Most metals are assigned recoverability factors of close to 100 % and therefore nearly zero residue leaves the system boundary as waste. The material recovery factors and energy recovery factors of each material distribute the material and energy back within the system, which therefore results in few environmental impacts. As a result, the waste produced goes unnoticed in the LCIA profile. These results should be accepted with discretion and should be considered when making strategic decisions based on the LCA results.

It is partially due to the closed loop recycling method, that the difference in steel and aluminum vehicle production is nearly negligible. Since only 2 % of the actual metal consumed and expelled from the system boundary is taken into consideration, the impacts are small in comparison to the effects due to energy consumption. Additionally, since the welding processes only account for a small portion of the total energy consumption, the even smaller difference between the processes can be ignored. Therefore, the assumption which has been evaluated throughout the study is considered an acceptable solution when modelling the production of a generic vehicle in the LCI.

Regarding the completeness of the study, since all resource flows were considered, the total results of the LCA should represent a complete picture of actual consumption. The uncertainty in manual electrical energy measurements would have an effect on the allocation of energy to each manufacturing phase, however, would not affect the total energy consumption greatly since that was determined from the facility’s main energy meter. Since the LCA was conducted by one author using the same methods throughout the entire study, the methodology is deemed consistent. When comparing data in sensitivity analyses, the same base situation was used which allowed for consistent comparison to various other scenarios.

# 4 Possibilities for improvement

The analysis of resource use and the life cycle assessment have revealed fields at SIE VIE LEB than can be improved to reduce the environmental impacts of manufacturing. The discussion will focus on the following possibilities for improvement.

- Reduce electricity consumption by increasing transparency concerning energy flows and base load
- Reduce active standby power consumption
- Change electricity mix to renewable sources
- Investigate ways to generate electrical energy on-site
- Replace natural gas burners with other technology
- Implement systems to recover heat from manufacturing processes
- Cooperate will local partners to reduce transport of resources to and from the facility
- Demand more environmentally sustainable products from component suppliers
- Replace diesel forklifts with electric forklifts
- Reduce acetylene consumption through use of more efficient burner technology
- Reduce argon use by using a gas saving systems
- Replace non-efficient lighting with LED lighting
- Install better thermal insulation in buildings as well as in hot and cooling water distribution systems
- Install thermal component activation systems for even heating
- Investigate and optimise HVAC and compressed air generation and distribution systems presumably responsible for a high share of base load
- Expand lean manufacturing methods
- Track environmentally relevant key performance indicators
- Raise awareness for resource efficient production among all colleagues

As discussed in section 3.4, electricity consumption must be reduced since it accounts for nearly 50 % of all environmental impacts. In order to reduce consumption, transparency must be achieved at first to reliably identify the main energy consumers. This can be realised by expanding the energy monitoring structure and installing further energy meters. When the energy consumption of each hall or each process is constantly measured, then the power-time curve can be analysed in greater detail.

Energy profiling is a method to break the power consumption of a process or consumption area down into sub-processes or areas. By examining the load curve, one can identify increases in power demand at specific times of the year, week or day. Through further investigation where this demand arises from, one can identify individual consumers and achieve greater transparency. Once the consumption of each sub-processes has been identified, it can be analysed and reduced.

Figure 49 shows the power profile of an exemplary consumption area with a base load of 150 kW. This is consumed throughout the year, also over Christmas holidays when the plant operation is paused. During the rest of the year, there is an increase by 50 kW. During the week, the load is increased by around 100 kW and on workdays from 6 am to 6 pm by another 400 kW. Between 6 am and 9 am, 9:15 and 11:45 as well as 12:15 to 6 pm a further increase by 100 kW is observed. More detailed power consumption analysis would identify electricity consumers, which could be shut off during non-operation times. Examples of such systems that should be investigated are pumps, compressors, lighting and HVAC units.

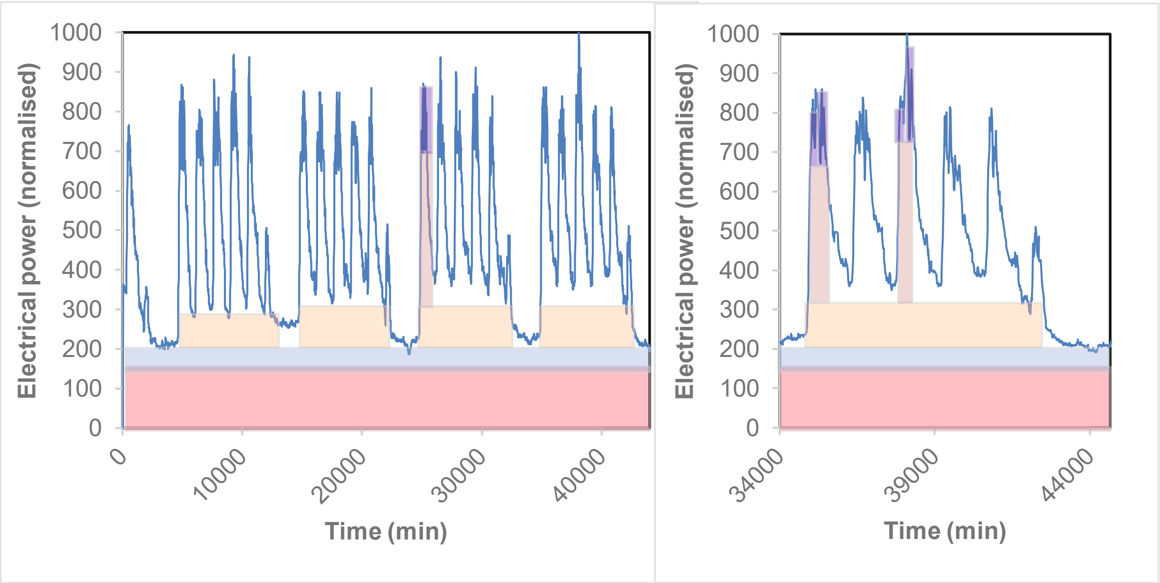


**Figure 49: Example load curve with an energy breakdown using energy profiling.**

Switching to a green electricity mix would drastically reduce the environmental impacts of the production. As seen in in the results in section 3.4.1 (Table 9), such a change could result in a 46 % lower global warming potential. Therefore, this is strongly recommended.

Generating electricity from renewable sources at SIE VIE LEB is also an option to reduce electrical energy consumption, cost and environmental impact. Photovoltaic systems could be installed on building roofs where static stability is available. Small wind turbines could generate power to heat boilers for hot water in showers. Geothermal heating could also be considered to reduce district heat use.

Natural gas consumption contributes a significant part to each environmental impact (ranging from 10 to 50 %) and should be reduced. The use of other technologies such as infrared heaters or heat pumps should be further investigated. The benefits of infrared heating technology are reduced drying times, good paint hardening and high-quality surface. Since the paint dries from the inside out, there is no limit to coating thickness. The benefits of heat pumps include electrical operation, increased efficiency, and the possibility to use recovered heat.

A possible system for heat recovery is shown in Figure 50. In this example there are two cycles; an air cycle and heat-pump cycle with a refrigerant. On the left, the drying cabin is heated with air blown over a heat exchanger which is heated from the heat pump cycle. The air leaves the cabin and flows over evaporator 1, giving off its thermal energy to the refrigerant in the heat pump cycle. It then gets filtered, dehumidified and mixed with other fresh air before repeating the process. The heat pump cycle implements a compressor which brings the refrigerant to a high temperature and pressure. This energy is given off to the air in the condenser. By flowing through the expansion valve, the pressure and temperature sink. Thermal energy is regained through a series of evaporators. Evaporator 2 can be used for heat recovery from the compressors that produce compressed air. This system may have lower environmental impacts than the current system and further investigation of this topic should follow in additional studies. If not implemented for drying processes, such a heat pump concept with heat recovery could be used to replace district heating or to warm water for showers.

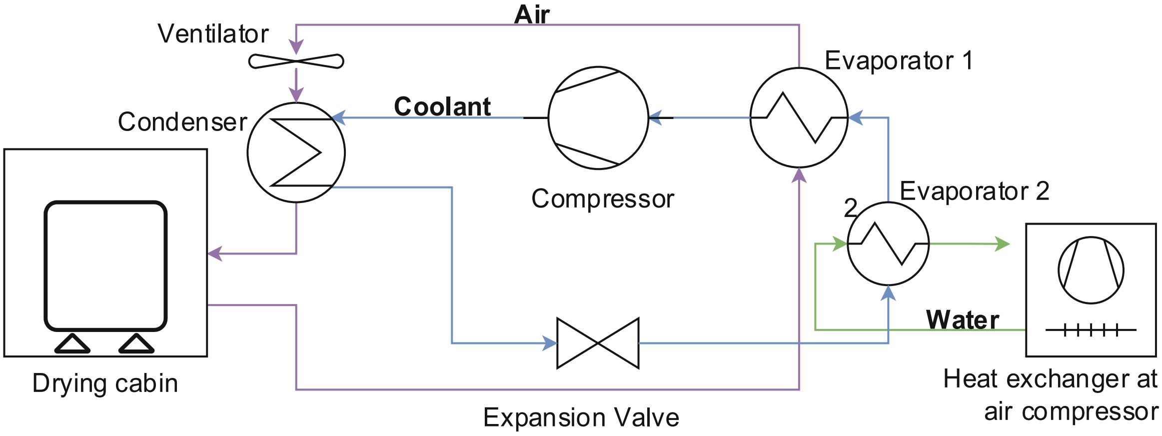


**Figure 50: Simplified concept of heat recovery using a heat pump.**

Since transportation of materials to and from SIE VIE LEB causes considerable environmental impacts (ranging from roughly 20 to 40 %), options should be discussed with logistic partners to reduce the distance. Reducing waste and material use would also reduce necessary transport. Furthermore, by demanding sustainable production through e.g. bonuses for $CO_2$ neutral production from component suppliers, sustainability across the entire value-chain can be reached. Components that are sustainably sourced and manufactured should be preferred.

By replacing current diesel forklifts with electric forklifts, diesel consumption would be greatly reduced. Solely the consumption of the flatbed rail vehicle transporters would remain. Before replacing the diesel models, however, a lifecycle assessment of the diesel and electric forklifts should be considered, to ensure that the net impacts are not higher than currently.

Acetylene consumption is necessary for welding aluminum; it could however be reduced by implementing more efficient burners and by notifying workers to not use more than necessary. Using thermometer systems that inform the worker to stop heating would allow for reduced acetylene use. Additionally, an alternative to acetylene could be investigated, i.e. to find a gas that results in lower environmental impacts.

Argon gas consumption can be reduced by implementing gas saving systems that automatically regulate gas flow. This option should be considered, since a large fraction of welds are still welded by hand and greatly influenced by worker’s judgement.

Since a large amount of energy is consumed due to lighting (estimated at 10 %), bulbs should be replaced by more efficient light emitting diodes. Daylight control systems that dim the lights when enough daylight is measured would also reduce energy consumption. Internal studies at SIE VIE LEB have shown that by switching from current lighting to LED with daylight control would result in 80 % less energy consumption for lighting.

Another improvement to the building infrastructure would be to increase thermal insulation in building and hot water distribution systems. Many halls are not adequately thermally insulated and therefore become too hot in summer and result in unnecessary heating in winter. Pipes that are not properly insulated also lose heat where not desired. Such a solution would result in both less district heating and less natural gas consumption.

An alternative heating and cooling technology gaining popularity is thermal component activation (TCA). For TCA, a network of water pipelines is laid into concrete, storing thermal energy and emitting heat to the building evenly. Installation of TCA systems is straightforward and cost effective. Another great advantage is that TCA systems can be powered by renewable energy using a heat pump. For example, photovoltaic (PV) panels could supply electricity to a heat pump, which delivers the thermal energy to the concrete building. Over night, when the PV panels are inactive, the building continues to emit heat until the next sunrise when the cycle starts over. Installation of a TCA system in new construction has potential to reduce heating costs and allow for decentralised conversion of renewable energy to heat.

By optimising HVAC and compressed air generation and distribution systems, significant energy savings could be achieved. Activity could be lowered when no ventilation is required in the halls i.e. on holidays or times of non-operation. Also, when not needed, air compression should be reduced. Furthermore, the air distribution lines should be continuously checked for leaks. A leak with a diameter of 5 mm can cause annual costs of roughly 4000 € [40]. Five holes of that size are not unrealistic and would have annual costs of 20000 €. Reduction of leaks by using smart metering systems or raising awareness to report leaks are viable solutions.

The implementation of lean manufacturing tools is a further method to reduce waste in various fields. Material and information flow mapping is an effective method to identify and eliminate non-value adding activities [62]. The Plan-Do-Check-Act (PDCA) cycle is a method to strive for continuous improvement [63] and could be used to aim for sustainable manufacturing. Other modern lean methods are discussed in [63,64].

Key performance indicators regarding environmental sustainability should also be defined to track and analyse the environmental impact of the production facility. As an example, all primary energy could be expressed in t $CO_2$-eq. or t $CO_2$-eq. per € turnover. Additional environmental KPI can be found in a report from the UK Department for Environment Food and Rural Affairs [64]. The LCA could be routinely updated, and the environmental impacts continuously tracked. Greater consciousness of environmental impacts may lead to their reduction.

Furthermore, raising awareness for resource efficient production among colleagues at SIE VIE LEB could lead to reduced consumption. Awareness campaigns to turn off lights, HVAC or IT equipment when leaving the facility are simple and have potential to generate resource savings.

# 5 Conclusion

The goal of the present study was to asses the environmental impacts related to rail vehicle manufacturing at the Siemens Mobility production facility SIE VIE LEB. The scope of the study was defined according to ISO 14040 and the relevant resource flows within and over the system boundary were analysed. Based on the results, a life cycle assessment (LCA) of vehicle manufacturing at the SIE VIE LEB was conducted. Under the given conditions, the LCA revealed that the production of one generic rail vehicle resulted in nearly 12 metric tonnes $CO_2$-eq. global warming potential, 8 kg $PO_4^{3-}$-eq. eutrophication potential and 30 kg $SO_2$-eq. acidification potential. Furthermore, photochemical oxidation, ozone layer depletion and abiotic depletion were investigated. In most environmental impact categories, the electrical energy consumption accounted for nearly 50 % of the total impacts. This is strongly influenced by the selected electricity mix. Natural gas combustion and transport of materials to and from the facility also have significant environmental impacts.

Using the obtained results, the developed SimaPro model of the core module will be implemented in the Siemens Generic LCA model and could be used in the future to create environmental product declarations. Since manufacturing processes are continuously changing due to new technologies and varying projects, the model should be updated on a regular basis.

When interpreting an LCA, it is necessary to consider uncertainties and simplifications of the study as well as their effects on the final results. Due to the complexity of large systems with non-transparent life cycles, caution is required when accepting the absolute values of the results. Focus should be rather laid on relative comparisons made during the study and should be used to identify possibilities to reduce environmental impacts.

In order to reduce the environmental impacts due to production, several possible approaches were conceived and presented. An important possibility for improvement is to reduce the electrical energy consumption by increasing transparency. When the energy meter structure has been expanded or further temporary measurements have been conducted, measures can be taken to individually identify and optimise unnecessary energy consumers. Furthermore, reuse of waste heat should be further investigated since it has potential to reduce primary energy consumption. Investigation into the use of heat pump technology and thermal component activation is also recommended in order to reduce gas and district heating demand.

As a result of this study, awareness of environmental aspects due to manufacturing has been raised. Additional discussions regarding sustainable production will continue at SIE VIE LEB and ideas presented in this work will be further developed. With the support of colleagues involved in environmental protection and business strategy development at Siemens Mobility Austria GmbH, an additional project in sustainable production has started in October 2019. The goal is to reduce energy consumption and eliminate $CO_2$ emissions by 2030. Methodology applied at the Siemens Mobility plant in Vienna could also be applied to other locations such as the plant in Graz, Krefeld, Sacramento, or Eastern Europe. Even if not all possibilities for improvement can be realised, all small improvements add up to a greater sum and will lower the environmental impacts of production at SIE VIE LEB. This ideology could be used for green marketing purposes to reflect the fact that Siemens delivers mobility solutions that were sustainably developed and manufactured.

# 6 References

[1] Brandmüller, T., Lupu, I., Önnerfors, Å., Corselli-Nordblad, L., Coyette, C., et al., 2016, Urban Europe - Statistics on cities, towns and Suburbs. Luxembourg: Eurostat. DOI:10.2785/91120.

[2] International Association of Public Transport, 2018, WORLD METRO FIGURES 2018, Brussels.

[3] UIC: International Union of Railways, 2018, Railway statistics 2017 synopsis, Paris.

[4] UIC: International Union of Railways, 2018, Rail Transportation in the World: 2004-2016, Paris.

[5] European Aluminium, 2018, Environmental Profile Report - Life-Cycle inventory data for aluminium production and transformation processes in Europe EXECUTIVE SUMMARY, Brussels.

[6] European Committee for Standardization, 2009, DIN EN ISO 14040 Environmental management – Life cycle assessment – Principles and framework, Brussels.

[7] Curran, M. A., 2012, Life Cycle Assessment Handbook. Cincinnati: Scrivener Publishing. DOI:10.1002/9781118528372.

[8] Stripple, H., Uppenberg, S., 2010, Life-cycle assessment of railways and rail transport - Application in environmental product declarations (EPDs) for the Bothnia Line, Stockholm.

[9] Del Pero, F., Delogu, M., Pierini, M., Bonaffini, D., 2015, Life Cycle Assessment of a heavy metro train, Journal of Cleaner Production, 87/1:787–799. DOI:10.1016/j.jclepro.2014.09.023.

[10] Yue, Y., Wang, T., Liang, S., Yang, J., Hou, P., et al., 2015, Life cycle assessment of High Speed Rail in China, Transportation Research Part D: Transport and Environment, 41:367–376. DOI:10.1016/j.trd.2015.10.005.

[11] Arntz, A.-K., Yasin, A., 2016, WORLDWIDE ROLLING STOCK MANUFACTURERS - Market Insights and Factsheets for Top 50 Manufacturers and Overview of 180 Companies and 330 Production Sites, Hamburg.

[12] Siemens AG, 2019, Siemens Annual Report 2018, Munich.

[13] Siemens Mobility GmbH, 2019, Siemens Mobility GmbH Werk Wien.

[14] Tomasek, P., 2016, Studie zum produktbezogenen Umweltschutz eines U-Bahn Wagens - Vorbereitung zu einer Ökobilanz und einer Konzeption einer Recycling-und Verwertungsrate, Fachhochschule Burgenland GmbH, Pinkafeld.

[15] Struckl, W., Dissertation: Green Line - Umweltgerechte Produktentwicklungsstrategien für Schienenfahrzeuge auf Basis der

Lebenszyklus- analyse des Metrofahrzeuges Oslo, Technischen Universität Wien.

[16] EPD International AB, 2018, Product Category Rules - Rolling Stock - Version 3.01, Stockholm.

[17] European Committee for Standardization, 2019, DIN EN ISO 14044 Environmental management – Life cycle assessment – Requirements and guidelines, Brussels.

[18] Lüdemann, L., Feig, K., 2014, Vergleich von Softwarelösungen für die Ökobilanzierung – eine softwareergonomische Analyse, Logistics Journal. DOI:10.2195/lj_NotRev_luedemann_de_201409_01.

[19] Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, E., 2013, Introduction to LCA with SimaPro, Amersfoort.

[20] Klöpffer, W., Grahl, B., 2014, Life Cycle Assessment (LCA) - A Guide to Best Practice. Wiley-VCH Verlag.

[21] Downer EDI Rail Pty Ltd, 2018, Environmental Product Declaration Sydney Growth Trains.

[22] European Committee for Standardization, 2011, DIN EN ISO 14025 Environmental labels and declarations – Type III environmental declarations – Principles and procedures, Brussels.

[23] EPD International AB, The International EPD® System. [Online]. Available: https://www.environdec.com/. [Accessed: 10-Jul-2019].

[24] ALSTOM, 2019, EPD: Sydney Metro Northwest Rolling stock.

[25] Bombardier, 2010, Environmental Product Declaration - TALENT 2.

[26] Bombardier, 2010, Environmental Product Declaration - SPACIUM.

[27] Bombardier, 2013, Environmental Product Declaration - INNOVIA APM 300.

[28] European Committee for Standardization, 2006, DIN EN 15380-2 Railway applications-Designation system for railway vehicles-Part 2: Product groups, Brussels.

[29] European Committee for Standardization, 2006, DIN EN 15380-1 Railway applications-Designation systematic for railway vehicles-Part 1: General English version of DIN EN 15380-1:2006-06, Brussels.

[30] Brandhorst, M., Schindler, C., 2014, Handbuch Schienenfahrzeuge: Entwicklung, Produktion, Instandhaltung. DVV Media Group GmbH | Eurailpress.

[31] Ihme, J., 2016, Schienenfahrzeugtechnik. Wiesbaden: Springer Fachmedien Wiesbaden. DOI:10.1007/978-3-658-13541-6.

[32] Kalpakjian, S., Schmid, S. R., Vijay, S., 2014, Manufacturing engineering and technology. Singapore: Pearson Education South Asia Pte Ltd.

[33] Pattnaik, S. K., Bhoi, N. K., Padhi, S., Sarangi, S. K., 2018, Dry machining of aluminum for proper selection of cutting tool: tool performance and tool wear, International Journal of Advanced Manufacturing Technology. DOI:10.1007/s00170-017-0307-0.

[34] European Committee for Standardization, 2005, DIN EN 14610 Schweißen und verwandte Prozesse – Begriffe für Metallschweißprozesse; Dreisprachige Fassung EN 14610:2004, Brussels.

[35] European Committee for Standardization, 2008, DIN 1910-100 Schweißen und verwandte Prozesse – Begriffe – Teil 100: Metallschweißprozesse mit Ergänzungen zu DIN EN 14610:2005, Brussels.

[36] Shrivastava, A., Krones, M., Pfefferkorn, F. E., 2015, Comparison of energy consumption and environmental impact of friction stir welding and gas metal arc welding for aluminum, CIRP Journal of Manufacturing Science and Technology, 9:159–168. DOI:10.1016/j.cirpj.2014.10.001.

[37] Gourd, L. M., 1986, Principles of welding technology. London: Arnold.

[38] Bertagnolli, F., 2018, Lean Management - Einführung und Vertiefung in die japanische Management-Philosophie. Wiesbaden. DOI:10.1007/978-3-658-13124-1.

[39] Von Hauff, M., Isenmann, R., Müller-Christ, G., 2012, Industrial Ecology Management - Nachhaltige Entwicklung durch Unternehmensverbünde. Heidelberg. DOI:10.1007/978-3-8349-6638-4.

[40] Fraunhofer ISI, 2003, Druckluft effizient, Deutschen Energie-Agentur.

[41] European Committee for Standardization, 201AD, DIN EN ISO 12944-1 Paints and varnishes – Corrosion protection of steel structures by protective paint systems – Part 1: General introduction (ISO 12944-1:2017); German version EN ISO 12944-1:2017, Brussels. DOI:10.1007/s00738-009-0685-2.

[42] European Committee for Standardization, 2018, DIN EN ISO 12944-2 Paints and varnishes – Corrosion protection of steel structures by protective paint systems – Part 2: Classification of environments (ISO 12944-2:2017); German version EN ISO 12944-2:2017, Brussels.

[43] European Committee for Standardization, 2018, DIN EN ISO 12944-3 Paints and varnishes – Corrosion protection of steel structures by protective paint systems – Part 3: Design considerations (ISO 12944-3:2017); German version EN ISO 12944-3:2017, Brussels.

[44] European Committee for Standardization, 2016, DIN EN ISO 12944-4 Paints and varnishes – Corrosion protection of steel structures by protective paint systems – Part 4: Types of surface and surface preparation (ISO/DIS 12944-4:2016); German and English version prEN ISO 12944-4:2016, Brussels.

[45] UNIFE - the European Rail Industry, 2019, Railway Industry Substance List v2019-04-09. Brussels.

[46] UNIFE Sustainable Transport Committee, 2013, Recyclability and Recoverability Calculation Method Railway Rolling Stock, Brussels.

[47] Bundesminister für Land- und Forstwirtschaft, U. und W., 2008, Abfallverzeichnisverordnung.

[48] MA 23 Stadt Wien, 2019, Monthly Data from the Weather Station Hohe Warte since January 1955 on Air Temperature, Air Pressure, Cloudiness, Wind Speed and Precipitation, Vienna.

[49] Smarter Together, 2019, Zu Gast im Siemens-Werk Simmering. [Online]. Available: https://www.smartertogether.at/zu-gast-bei-siemens-simmering/. [Accessed: 13-Jun-2019].

[50] Forum Ökologie & Papier (FÖP), 2012, Papier - Wald und Klima schützen, Hamburg.

[51] Chauvin Arnoux, 2015, Power Energy Logger PEL 100 Series - User Manual. AEMC Instruments, Dover.

[52] Hage Sondermaschinenbau GmbH, HAGEmatic Section machining. [Online]. Available: https://www.hage.at/en/sectionmachining/The-HAGEmatic-Concept.php. [Accessed: 13-Aug-2019].

[53] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., et al., 2016, The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment. DOI:10.1007/s11367-016-1087-8.

[54] Siemens Mobility GmbH, 2014, Internal study regarding energy management, Vienna.

[55] European Committee for Standardization, 2019, DIN EN 12464-1 Light and lighting – Lighting of work places – Part 1: Indoor work places, Brussels.

[56] Wien Energie, 2019, (personal e-mail communication). Vienna.

[57] Österreichisches Institut für Bautechnik, 2015, OIB-Richtlinie 6, Vienna.

[58] Brock, T., Groteklaes, M., Mischke, P., Strehmel, B., 2017, Lehrbuch der Lacktechnologie. Vincentz PP - Hannover.

[59] Simulation, B., 2011, EXERGY ANALYSIS OF RESIDENTIAL HEATING SYSTEMS : PERFORMANCE OF WHOLE SYSTEM VS PERFORMANCE OF MAJOR EQUIPMENT Stantec Consulting Ltd . Winnipeg Manitoba , CANADA Centre for Building Studies , Department of Building , Civil and Environmental Engineering , pp. 14–16.

[60] Rosen, M. A., Bulucea, C. A., 2009, Using Exergy to Understand and Improve the Efficiency of Electrical Power Technologies, pp. 820–835. DOI:10.3390/e11040820.

[61] Alexander Binzel Schweisstechnik, GmbH & Co. KG, Gas-Management-System EWR 2 / EWR 2 Net | ABICOR BINZEL. [Online]. Available: https://www.binzel-abicor.com/DE/deu/produkte/robotic-systems/sensorik/gas-management-system-ewr-2-ewr-2-net/. [Accessed: 28-Sep-2019].

[62] Rother, M., Shook, J., 2003, Learning to See Value Stream Mapping to Create Value and Eliminate Muda, Lean Enterprise Institute Brookline. DOI:10.1109/6.490058.

[63] Russell, R. S., III, B. W. T., 2010, Operations Management: Creating Value Along the Supply Chain, 7th Edition. Hoboken, NJ: Wiley.

[64] Sexauer, M., Bleicher, F., Lean Industrie 4.0-A novel approach to achieve sustainable production.

[65] Department for Environment Food and Rural Affairs, 2006, Environmental Key Performance Indicators - Reporting Guidelines for UK Business, London.

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# 9 List of abbreviations

| | |
|---|---|
| ADP | Abiotic depletion potential |
| AP | Acidification potential |
| As | Assembly |
| BUE | Built-up edge |
| CF | characterisation factors |
| CNC | Computer numerical control |
| Com | Commisioning |
| CT | Current transformers |
| EMS | Energy monitoring system |
| EP | Eutrophication potential |
| EPD | Environmental product declaration |
| FSW | Friction stir welding |
| GMAW | Gas metal arc welding |
| GWP | Global warming potential |
| HVAC | Heating, Ventilation and Air Conditioning |
| IT | Information technology |
| KPI | Key performance indicator |
| LCA | Life cycle assessment |
| LCI | Life cycle inventory |
| LCIA | Life Cycle impact assessment |
| LCIA | Life cycle impact assessment |
| LED | Light emitting diode |
| MIG | Metal shielding gas |
| MPG | Main product group |
| MQL | Minimum quantity lubrication |
| NDM | Near-dry machining |
| ODP | Ozone depletion potential |
| PCR RS | Product category rules for rolling stock |
| PDCA | Plan-Do-Check-Act |
| PEL | Power and Energy Logger |
| POCP | Photochemical ozone creation potential |
| rpm | Revolutions per minute |
| SESIS | Siemens Environmental and Technical Safety Information Systems |
| SGS | Siemens Building Services |
| SIE VIE LEB | Siemens Vienna Leberstraße |
| SPG | Sub product group |
| ST | Surface treatment |
| TCA | Thermal component activation |
| VBM | Vehicle body manufacturing |
| VOC | Volatile Organic Compound |

# 10 Annex

| | | | | | |
|---|---|---|---|---|---|
| **Life Cycle Inventory Analysis data collection sheet** | | | | | SIEMENS |
| **Process:** | | | **Reporting location: SIE VIE LEB** | | |
| **Contact person:** | | | | | |
| **Dates that data is valid for / was measured:** | | | **Date of completion:** | | |
| **Description of unit process:** (attach additional sheet if required) | | | | | |
| **Material flows (Inputs + Outputs)** | **Unit** | **Quantity** | **Flow direction** | **Description (incl. sampling procedures)** | **Origin of data*** |
| **Energy flows (Inputs + Outputs)** | **Unit** | **Quantity** | | **Description of sampling procedures** | **Origin of data*** |
| **Heat flows (Inputs + Outputs)** | **Unit** | **Quantity** | | **Description of sampling procedures** | **Origin of data*** |
| **Water flows (Inputs + Outputs)** | **Unit** | **Quantity** | | **Description of sampling procedures** | **Origin of data*** |
| * Directly measured, good educated guess, rough estimation | | | | | |