Life Cycle Assessment

U5-Metro Construction:

GHG Accounting and Reduction Strategy

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This report comprises 15 pages including a cover sheet and a 31-page long Appendix. Any publication of this material, including excerpts thereof, requires prior written approval.

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1 Objectives, strategy, and task definition

On behalf of the Free and Hanseatic City of Hamburg (FHH), Hamburger Hochbahn AG (HOCHBAHN) is managing and coordinating the planning and new construction of the U5-Metro as part of the mobility turnaround in the FHH. By the end of the 2030s, a completely new, approx. 25 km long subway line with a total of 23 stops will be built.

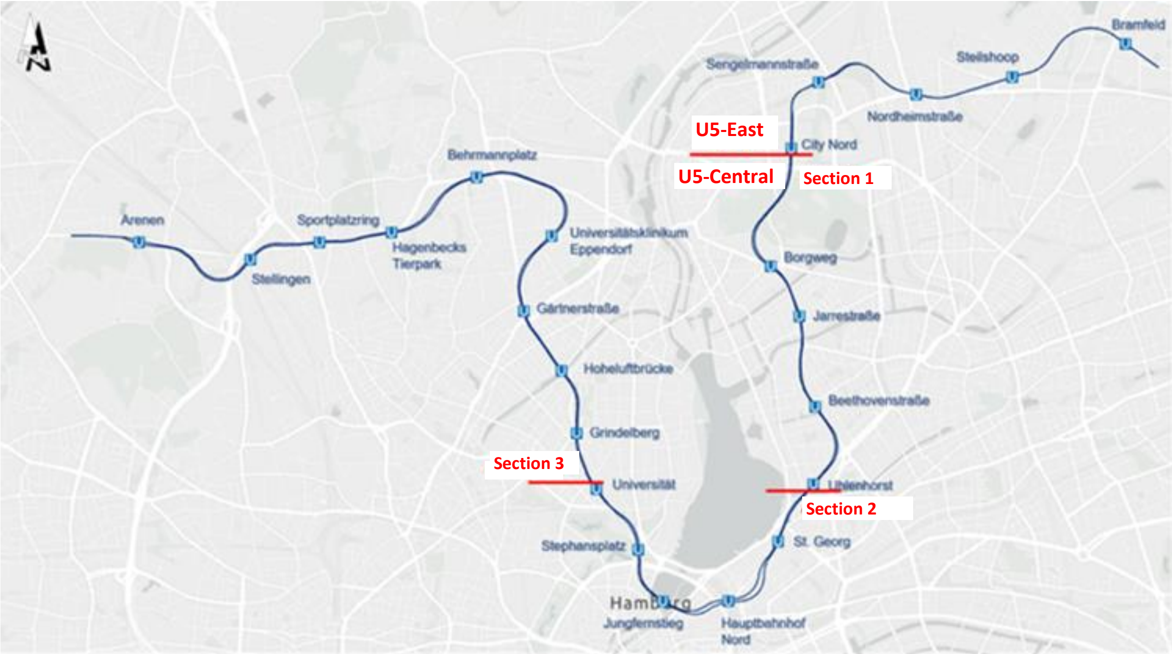

Figure 1: The U5 subway line within the Hamburg urban area showing the division of the construction and planning sections, source: HOCHBAHN

HOCHBAHN is aware that such a construction project has a considerable environmental impact and causes significant greenhouse gas (GHG) emissions. These are primarily due to the materials used and the necessary construction processes and procedures, including the energy consumption that is required.

LPI engineers (German: LPI Ingenieurgesellschaft mbH) advises and supports HOCHBAHN in the development and implementation of a transparent and traceable Global Warming Potential (GWP) reduction strategy for the U5 subway line construction. The GWP will be continuously evaluated during the planning, construction, and manufacturing phases and minimized with the help of a reduction strategy and coordinated packages of measures. The integration of GHG minimization as a planning and project objective is a novel approach in such a large-scale infrastructure project and is unique in terms of the level of detail and scope envisaged.

Part of the strategy is the Life Cycle Assessment (LCA) of expected GHG emissions, which is summarized in this Life Cycle Assessment (LCA) Report.

2 LCA framework and LCA procedure

2.1 Scope of the investigation

The selected LCA procedure follows ISO 14040 [N.1] in four steps and is based on the standards for the sustainability assessment of buildings, e.g. DIN EN 15978 [N.2], cf. Figure 2. In addition, essential parts and the basic systematics of the LCA standard for engineering structures E DIN EN 17472 [N.3], which is currently still in draft form, are also considered.

After defining the scope of the investigation and objectives, an LCA with all relevant quantities and process steps is drawn up for the respective construction methods and processes. Subsequently, the specific GHG emissions are assigned to the materials used. In the fourth step, these emissions are summarized, evaluated, and discussed according to the goal definition.

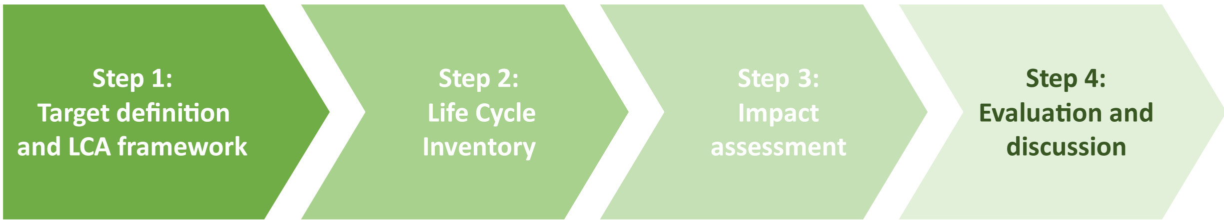

Figure 2: Overview of an LCA process following ISO 14040 [N.1]

The focus of the LCA is on the manufacturing phase up to the completion of the extended shell (life cycle phase modules A1–A5 according to DIN EN 15978 [N.2]). In addition, the carbonation of concrete in the phase of utilisation (life cycle phase module B1), as well as the phase of disposal and recycling of sectional steel (life cycle phases C1–C3, D), were included, cf. Figure 3. A corresponding justification for the selection made can be found in Appendix A.

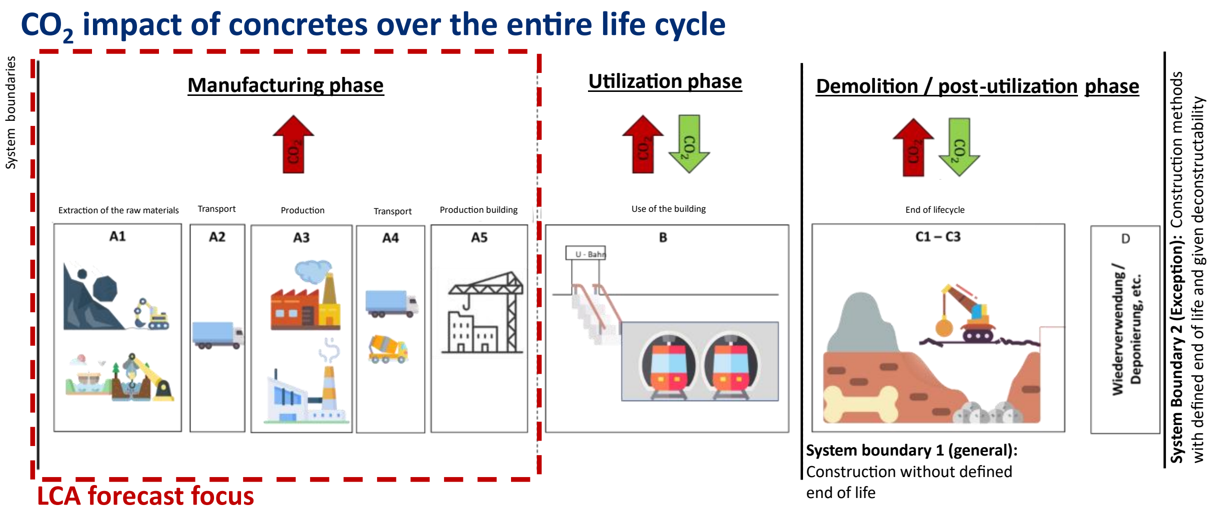

Figure 3: Illustration of the life cycle phases and system boundaries considered for the LCA forecast

The LCA of the extended shell construction was differentiated according to two scenarios:

- Baseline scenario ('do-nothing' scenario, conventional construction)
- Target scenario (climate-friendly construction, consideration of current and future GHG reduction potentials (including developments in the steel and cement industry))

The current and future reduction measures in the target scenario include reductions in material quantities and specific material emissions, as well as the improvement or optimization of construction processes. The basic function and performance of the structure will not be affected (maintenance of functional quality). In addition, future expected reductions as a result of technological developments in steel and cement production to reduce GHG emissions are considered. The assumptions are based on an exchange with companies and associations in the cement and steel industry, which was initiated by HOCHBAHN and LPI. The individual current and future reduction measures are presented in Chapter 3, differentiated according to areas (e.g. reinforced concrete construction, special foundation engineering, etc.).

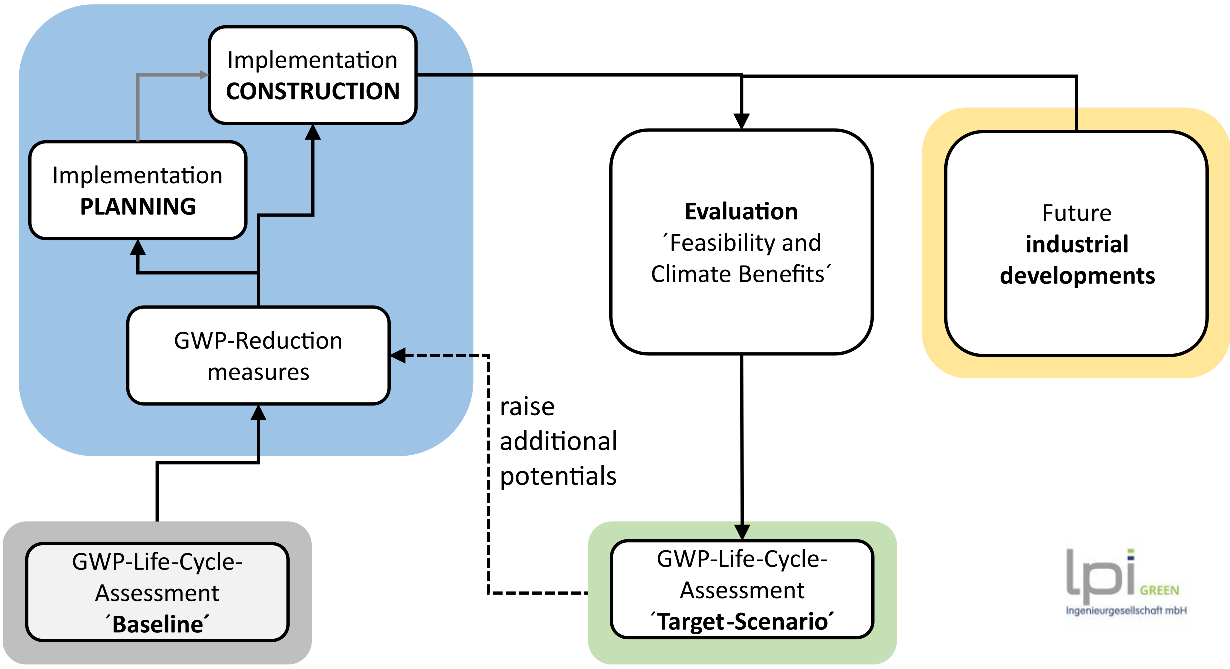

Figure 4: Overview of the strategy development from the baseline to the target scenario

3 Summarized description of the LCA

3.1 General information

Subsequently, the different LCA areas are described, the data basis from the Life Cycle Inventory is presented, and the resulting emissions from the baseline LCA ('do-nothing' scenario) as well as the climate-friendly target scenario are summarized. In the LCA, the following areas were examined in greater detail:
- Reinforced concrete construction
- Steel construction
- Soil management
- Special foundation engineering
- Mechanical tunnel boring using a tunnel boring machine (TBM) in closed construction
- Rail system
- Masonry work
- General site operations (water management and energy supply)
- Other services in extended shell construction
A complete overview of the LCA is provided in the Appendix of this document.

3.2 Reinforced concrete construction

Reinforced concrete construction constitutes the substantial core construction technique for the construction of the U5 subway line. Due to considerable GHG emissions inherent in the material, particularly from the production of the cement, a special focus was placed on possible GWP reduction potentials through optimized planning and material composition.

Baseline scenario
The total quantity of concrete for the U5 subway line construction amounts to approx. 3.43 million m³ of reinforced concrete and 343,000 t of reinforcing steel (quantity calculation by HOCHBAHN, ([3],[4],[5])). Depending on the required concrete quality, specific GHG emissions were assigned to the quantities of concrete and reinforcing steel, based on the recognized and freely accessible data records of ÖKOBAUDAT [1], an LCA database initiated by the German government (for the exact procedure, see Appendix A.0). In addition to production, this also includes transport and installation. The calculations result in an average GWP of:

- 233 kg CO_2-eq/m³ for unreinforced concrete
- 693 kg CO_2-eq/t for reinforcement

The baseline scenario thus yields a total GWP of approximately 1.02 million t CO_2-eq. for reinforced concrete.

Target scenario
In the context of planning and construction tendering, today's GWP reduction measures involve the:

- reduction of the required amount of reinforced concrete through planning adjustments. Result: 3.21 million m³ of reinforced concrete (approx. -218,000 m³) with approx. 303,000 t of reinforcing steel (approx. - 40,000 t of reinforcement).
- use of cement (clinker) reduced concretes by cement and concrete optimization Result: spec. mean GWP of the unreinforced eco-concrete: approx. 190 kg CO_2-eq/m³ (-18.5 %).

Technological developments to be expected in the future (based on industry exchanges):

- From 2025: Reduction of spec. GWP of reinforcing steel to 400 kg CO_2-eq/t through the use of green electricity in production and a high recycled scrap content
- From 2028: Reduction of spec. GWP of unreinforced concrete to approx. 96 kg CO_2-eq by partial CO_2 capture usage and storage (CCUS) during cement production, etc.
- From 2035: Reduction of spec. GWP of unreinforced concrete to 47 kg CO_2-eq through full CCUS during cement production, etc.

With the previously mentioned reduction measures and the currently expected industrial developments, a total GWP reduction of the reinforced concrete construction sector of approximately 440,000 t CO_2- eq (-57%) is projected in the target scenario. An overall summary of the LCA is provided in Section A.1 of the Appendix.

3.3 Steel construction

The projected steel construction is material-intensive and leads to significant GHG emissions due to the spec. GWP of steel products. As most of the steel construction is used for temporary excavation work, as well as for the construction of above-ground structures, the complete life cycle is included in the LCA.

Baseline scenario

For the production of the planned components and structures in the extended shell, rolled and sectional steels with a total mass of approx. 198,200 t are primarily used. For the LCA, a specific GWP according to ÖKOBAUDAT of 720 kg CO_2-eq/t for rolled and sectional steel is applied over the entire life cycle. This value also includes transportation to the construction site. The installation is accounted for via the general site emissions, cf. Section A.2 of the Appendix.

This results in a total GWP of approximately 142,700 t CO_2-eq in the baseline scenario.

Target scenario

For the target scenario, the following improvements were made:

- Increase in steel volumes to reduce other significantly more energy- and GHG-intensive construction methods.

Technological developments to be expected in the future (based on industry exchanges):

- From 2025: reduction of spec. GWP to 400 kg CO_2-eq through increased steel production using the electric arc furnace process (EAFP) and corresponding GWP certification by traders
- From 2035: Reduction of specific GWP to 100 kg CO_2-eq through climate-friendly production by means of CCUS, EAFP, and climate-neutral direct reduction plants (DR plants).

As a result of the previously mentioned changes and industrial developments anticipated in the future, a GWP reduction from steel construction in the target scenario of a total of approx. 66,200 t CO_2-eq. (approx. - 54 %) is projected. A complete overview of the LCA is provided in Section A.2 of the Appendix.

3.4 Soil management

The soil management includes extensive excavation and transport, and thus these processes as well as the recycling process must be assessed in the LCA.

Baseline scenario

Approx. 12 million t of excavated material are produced, which is removed by excavators and other excavation equipment and transferred by suitable means of transport (truck, rail, or ship) via a declaration area in the Port of Hamburg to a future recycling site. Consequently, a conventional transport chain with truck journeys is simulated for the LCA and a destination situated 75 km away (travel distance: 2 x 75 km, incl. empty truck journey) is assumed. The necessary spec. GWP values of the process steps were mapped via the available data sets for means of transport and excavation equipment in ÖKOBAUDAT.

This results in a total GWP of approximately 170,150 t CO_2-eq in the baseline scenario.

Target scenario

Various reduction strategies that are currently implementable were evaluated for their application to the U5 subway line construction:

- Selection of a recycling site in close proximity, with good transport connections
- Variation of the means of transport depending on the accessibility of the recycling site
- Avoidance of empty truck journeys by integrating the transport process into a transport chain

The following optimized scenario was developed in cooperation with a logistics partner:

- Distance to the recycling site: 70 km by truck
- Avoidance of empty truck journeys (return journey) through integration with a further logistics chain

As a result of the above-mentioned improvements, a reduction in GHG emissions of approx. 102,100 t CO_2-eq. (- 40 %) is predicted in the target scenario. A total overview of the LCA is provided in Section A.3 of the Appendix.

3.5 Special foundation engineering

As part of the specialised civil engineering work, special foundation and buoyancy-securing works are executed. This involves sealing elements as well as reinforcement and buoyancy-securing components in the form of jet grouted elements or ground anchors. Due to the intensive use of cementitious binders and the extensive material consumption, these works have a considerable influence on the total GWP and at the same time a high reduction potential through suitable measures.

Baseline scenario

Within the scope of the LCA, the production of the jet grouted components and the ground anchors are accounted for, excluding the structural supporting, which was already assessed in the chapter 3.3 on reinforcing steel. The part of the production life cycle that is considered comprises the production of the raw materials (cement, etc.), and the transport and production processes on site (drilling, jet grouting, grouting, etc.). Considering the component requirements, as well as the possible manufacturing influences and material parameters, the following material quantities and specific GWP were determined:

- Jet grouted soil element: volume = 485,325 m³, spec. GWP 1,710 kg CO_2-eq./m³
- Ground anchors: total length = 604,000 m; spec. GWP 250 kg CO_2-eq./m

This results in a total GWP of approximately 980,900 t CO_2-eq. in the baseline scenario.

Target scenario

The following reduction measures will be implemented:

- Reduction of required material quantities through planning optimization.
  Result: jet grouted soil element reduced to 287,135 m³ and ground anchors to 412,000 m.
- Use of clinker-reduced cement with low spec. GWP.
  Result: reduced spec. GWP of 810 kg CO_2-eq./m³ in jet grouted soil elements and 85 kg CO_2-eq./m for ground anchors.

In addition, the LCA includes the expected industrial development for the reduction of GWP in cement over the project period, as described in Chapter 3.2.

A reduction of the GWP of the special foundation engineering in the target scenario of a total of approx. 117,000 t CO_2-eq. (approx. - 88 %) is predicted as a result of the previously mentioned improvements. A total overview of the LCA is provided in Section A.5 of the Appendix.

3.6 Mechanical tunnel boring using a TBM

The tunnel sections are excavated using a TBM, whereby a considerable amount of electrical energy is required for its operation. The reinforced concrete tunnel tubes as well as other ancillary materials (annular gap mortar) are included in Chapter 3.2 (reinforced concrete construction).

Baseline scenario:

Based on the achievable tunnel dimensions and empirical values from comparable projects, a total electrical energy demand of 420,000 MWh is anticipated for the operation of the TBM, including all accompanying work (construction site equipment, separation plants, removal of overburden from the tube, etc.) [6]. For the LCA of electrical energy used during this project, the German electricity mix is applied with the following specific GWP according to ÖKOBAUDAT:

- From 2022: 0.5894 kg CO_2-eq./kWh
- From 2030: 0.5028 kg CO_2-eq./kWh

This results in a total GWP of 217,240 t CO_2-eq. in the baseline scenario.

Target scenario

The following reduction measures will be implemented:

- Use of green electricity for all construction processes facilitated by HOCHBAHN.
  Result: Reduction of the specific GWP to 0.01048 kg CO_2-eq./kWh (wind power approach).

As a result of the previously mentioned improvements, a reduction in GHG emissions for the TBM in the target scenario of approx. 4,405 t CO_2-eq. in total (-98 %) is predicted. A total overview of the LCA is provided in Section A.4 of the Appendix.

3.7 Other services accounted for in the extended shell work

In addition to the energy- and material-intensive areas of the extended shell and the resulting reduction measures, the following additional segments were also included in the LCA:

- Rail system
- Masonry work in the stations
- Construction site operations with general power consumption and water management

At present, however, only construction site operations are being investigated regarding possible reduction potentials, since the previously mentioned work on the overall GWP plays a subordinate role. A more detailed investigation is foreseen in further planning and construction processes, cf. Chapter 5.

3.7.1 Rail system

Depending on the requirements of the line, two different system structures are currently used for the construction of the rail system, and thus two standard cross-sections are evaluated in the LCA. At present, it is planned to install approx. 12.4 km of rail in the ballast bed in the U5-East section. In the U5-Centre section, 24.3 km of rail in a ballast bed and 24.3 km of solid rail track consisting of structural concrete (already included in the reinforced concrete) are to be installed. The LCA includes both the necessary production of the materials (rail, ballast, sleepers, conductor rail, etc.) and the transport and installation of the systems. Based on the standard cross-sections, the following specific GWP/m of rail are determined:

- Solid rail track (excluding concrete): 85 kg CO_2-eq./m
- Rail track in ballast bed: 218 kg CO_2-eq./m

This results in a total GWP of 10,070 t CO_2-eq. for both scenarios. An overall overview of the LCA is provided in Section A.6 of the Appendix.

3.7.2 Masonry work

The required masonry work includes the construction of sand-lime brick walls in various forms (e.g. wall thickness, plastered /unplastered, etc.). The scope of this work varies from station to station. Therefore, averaged values for the number of walls to be built and the associated specific GWP per wall were determined for the different stops:

- Average wall area per station: 756 m²
- Average specific GWP per wall area: 84 kg CO_2-eq./m²

Based on the number of stations and the previously mentioned parameters, the total GWP for the masonry work is 3,505 t CO_2-eq. in both scenarios. An overall summary of the LCA is provided in Section A.7 of the Appendix.

3.7.3 Construction site operations

General site operations include electrical energy for the site (equipment, lifting and working devices, etc.) and water management (dewatering and water treatment). For the LCA of the corresponding requirements, the required amount of electrical energy was calculated based on empirical values and previous design documents (e.g. required pumping and treatment capacity of water management). This results in the following required energy demand:

- General construction power supplies: 88,320 MWh
- Water management: 77,441 MWh

Considering the spec. GWP of the Germany-wide electricity mix (cf. Chapter 3.6), **the total GWP in the baseline scenario is calculated as amounting to 86,075 t CO_2-eq.**

Since HOCHBAHN uses green electricity for the construction of the U5 subway line, assuming a reduced GWP for green electricity (wind power), the total GWP can be reduced to 1,742 t CO_2-eq. in the target scenario. An overall summary of the LCA is provided in Section A.8 of the Appendix.

3.8 Further generalized services in the extended shell work

In addition to the previously described and individually assessed construction methods and processes, further work is incurred that is broadly assessed as part of the previous LCA. The work and processes estimated in this way include:

- general vehicle traffic,
- clearing work,
- temporary routing,
- other shoring works,
- waterproofing works,
- ancillary works for minor operations,
- site clearance,
- installation and assembly work not estimated in the LCA.

To estimate the works, 10% of the GWP emissions arising from the steel and reinforced concrete works are assumed in both scenarios. **Thus, a total GWP of 102,295 t CO_2-eq. is projected.**

4 Summary of the LCA results for the ‘baseline’ and ‘target’ scenarios

The previous sections summarize and compare the GWP for the construction of the U5 subway line in the baseline (‘do-nothing’, conventional construction) and climate-friendly target scenarios.

Figure 5 shows the results of the LCA from the different areas considered as stacked columns for the two scenarios.

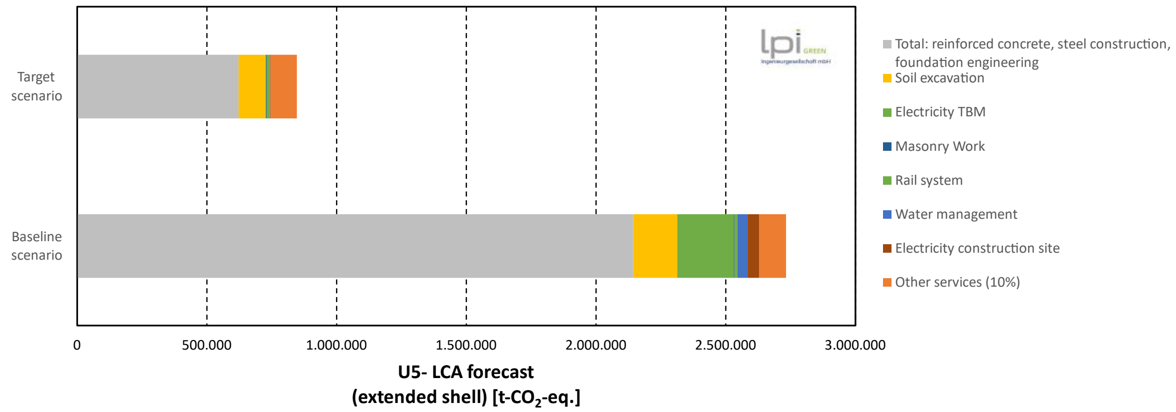

Figure 5: Overall LCA forecast in the baseline and target scenarios for the extended shell

According to the diagram, the total GWP of the subway construction can be significantly reduced in the target scenario compared to the baseline scenario. In the current progression, the target scenario results in a total GWP for the extended shell of approx. 850,000 t CO_2-eq. Projected over the entire lifetime of the structure, this would correspond to approx. 7,727 t CO_2-eq. per year for a life cycle of 110 years. In the baseline scenario, the total emissions for the extended shell are expected to amount to approx. 2.74 million t CO_2-eq.

In addition to the overall presentation, the temporal course of GHG emissions over the entire construction period is also relevant to illustrate both the temporal effects of the reduction measures and to obtain an estimate of the remaining annual GWP. This results in the annual emissions shown in Figure 6 and the cumulative GHG emissions shown in Figure 7.

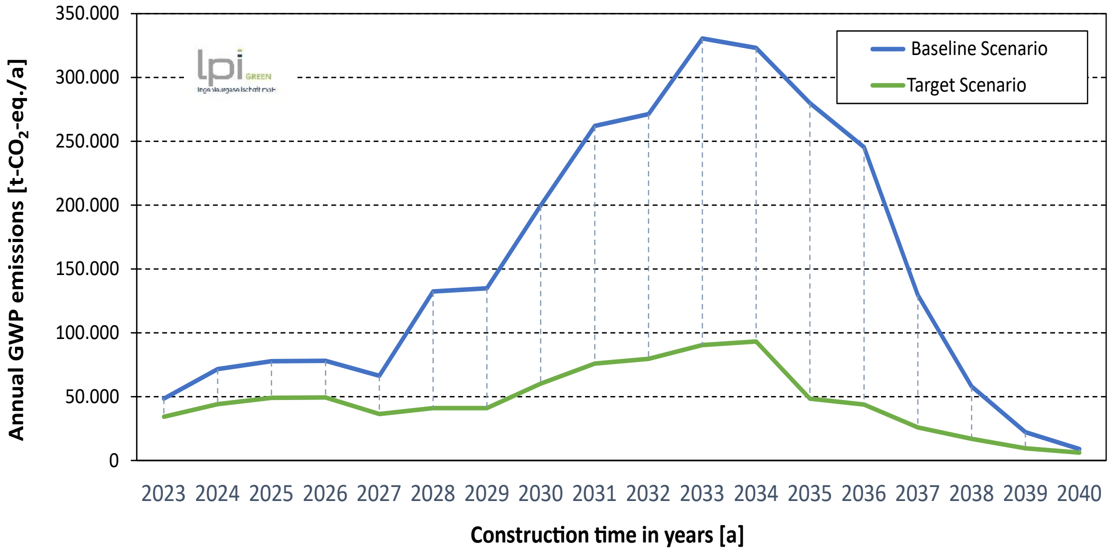

Figure 6: Projected annual GWP emissions in the baseline and target scenarios

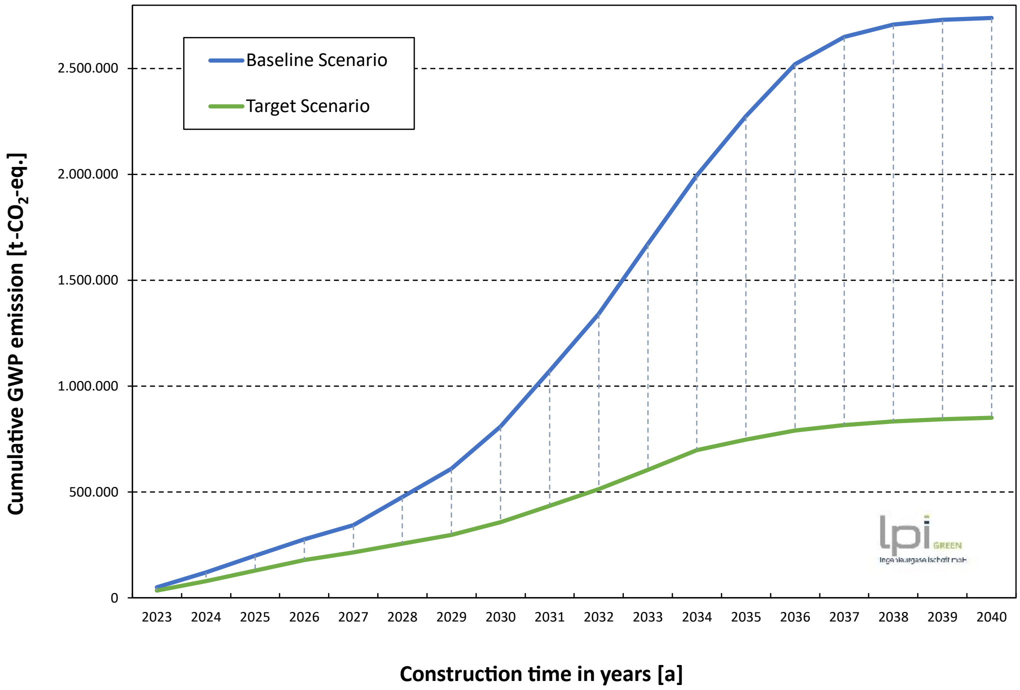

Figure 7: Projected cumulative GHG emissions in the baseline and target scenarios

The implementation of further project-specific measures is planned and will be continuously promoted (see Chapter 5). It is assumed that through the ongoing integration of LCA into the planning and construction process and the optimizations resulting from this, further reduction potentials in the range of at least 5–10% can be achieved.

5 Future development potential and further steps

The current LCA provides an assessment basis for the expected GHG emissions and an outlook concerning the reduction potentials that can be achieved by applying a reduction strategy with coordinated measures. In future, it is planned to continue the assessment and increase the level of detail as the project progresses. Work steps that were previously assessed on a generalized basis, such as building services or interior design, are to be included in the LCA as soon as a sufficient data basis is available.

Especially the first measures that were recently implemented impressively demonstrated that through efficient planning with the aim of avoiding the wasteful use of materials, significant improvements can be achieved without physical effort. For this reason, the entire planning process and, of course, the subsequent construction process, is intensively monitored and – where necessary – also validated and verified accordingly.

The goal of GWP-reduced construction has been embedded in the planning process. Therefore, in addition to providing an overall view of the LCA across the entire project, LCA will also be an essential tool for planning efforts. From the selection of materials and construction methods to the partial assessment of design variants for subsequent decision-making, GHG assessment and evaluation will take place so that these results are subsequently available in a reliable format for well-founded decision-making with the aid of all assessment criteria. The resulting successes and intermediate statuses are recorded for construction sections and can be transferred to subsequent work sections.

Another goal of the LCA is not only to obtain a forecast of the expected GHG emissions but also to evaluate the actual GWP generated as the work progresses. In this way, the work carried out will also be recorded in the future by means of GWP monitoring and the calculations and forecasts made to date will be validated with this data.

However, the LCA and the investigations of possible reduction potentials also give rise to the need to implement corresponding specifications for reducing the GWP. Here, as the awarding authority, HOCHBAHN is of particular importance, as it will define the requirements for the work to be performed and the products to be used. Only through these defined requirements will the other project participants be called upon to take appropriate planning and executive steps from the outset and to implement the GWP reduction paths. For this purpose, the tender documents increasingly include requirements regarding the environmental impact, especially concerning the GWP of the materials used and the requirements for the construction processes. In addition, the planning and construction process is accompanied in an advisory capacity by a sustainability consultancy. In civil engineering, this approach is still an exceptional case, especially in public tenders, hence the corresponding implementation can initially take place step by step, considering the anticipated technical and legal consequences of awarding contracts.

Figure 8 illustrates the interaction of the various LCA levels.

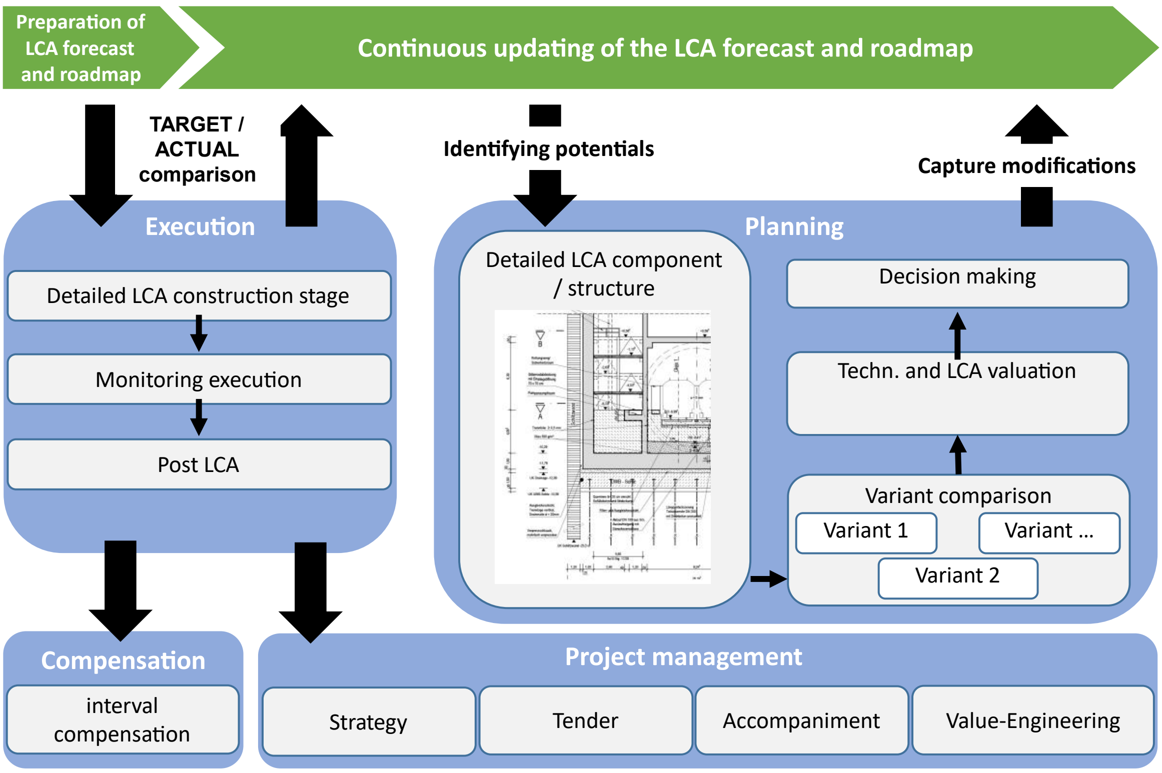

Figure 8: Incorporation of LCA monitoring and reporting into the project process and GWP reduction strategy

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A LCA Appendix

Overview:

A0 – Part 0: Detailed description of the LCA
A1 – Part 1: Reinforced concrete construction
A2 – Part 2: Steel construction
A3 – Part 3: Soil management
A4 – Part 4: Special foundation engineering
A5 – Part 5: Mechanized tunnelling with TBM
A6 – Part 6: Rail systems
A7 – Part 7: Masonry work
A8 – Part 8: Construction site operation
Part 8a: General construction electricity
Part 8b: Water management
A9 – Part 9: Other services
A10 – Part 10: Tabular summary of the results
A11 – Literature

A.0 Detailed description of the LCA

Building on the general statements on the LCA procedure presented in Chapter 3, the following pages will examine and describe the LCA in more detail.

Due to its type, size, scope, and associated duration, the U5 subway line construction project is considered a special construction project in terms of its related environmental impact assessment. While LCA has predominantly been used in building construction, this type of methodology has not yet been standardized in the field of infrastructure construction and structural engineering. For such construction projects, production-related peculiarities, such as special construction methods or energy-intensive construction processes (tunnelling, special foundation engineering, etc.) must also be considered.

A further distinctive feature of this project is the sectional planning and construction, which leads to a different level of detail in the existing data basis. For example, for the area of the U5-Central section, only rough quantity calculations and draft plans were available to date. For the U5-East section, in contrast, more detailed tender documents are already in existence. To enable a corresponding overall LCA, a joint quantity determination of the construction methods and construction processes was conducted.

For the LCA, further details (e.g. material properties) are required to select or define the specific GWP for the building materials. However, these specifications cannot be derived from the planning status of the U5-Central section as of today. To assess the required specifications for the impact assessment realistically, a 'representative station' in the East section of the U5 was chosen as a representative for the whole project. Based on the assumptions taken for the 'representative station' the lacking information was added to the general overview to derive the required data for the Life Cycle Inventory and impact analysis, as shown in Figure 9.

The GWPs needed for the LCA were ascertained using freely accessible data sets from the environmental database ÖKOBAUDAT. Although other databases offer a greater level of detail and more differentiated data sets, this assessment was initially limited to the freely accessible and comprehensible data sets of ÖKOBAUDAT in order to achieve unrestricted traceability.

For the development of the target scenario, project-specific GWP reduction measures are pursued, thereby eliminating the possibility of using the general GWP of materials and construction processes disclosed in the ÖKOBAUDAT. Instead, recalculations, e.g. for GWP-reduced concrete compositions, were performed. The recalculations include feasibility, technical constraints, and requirements as well as other aspects of planning and execution. The resulting adjusted GWPs are summarized and have been verified by the concrete industry (for GWP-reduced concrete). Compared to the baseline scenario, the target scenario also contains adjustments in the quantity of material used, which result from the first optimization stage of the preliminary planning for the U5-Central section.

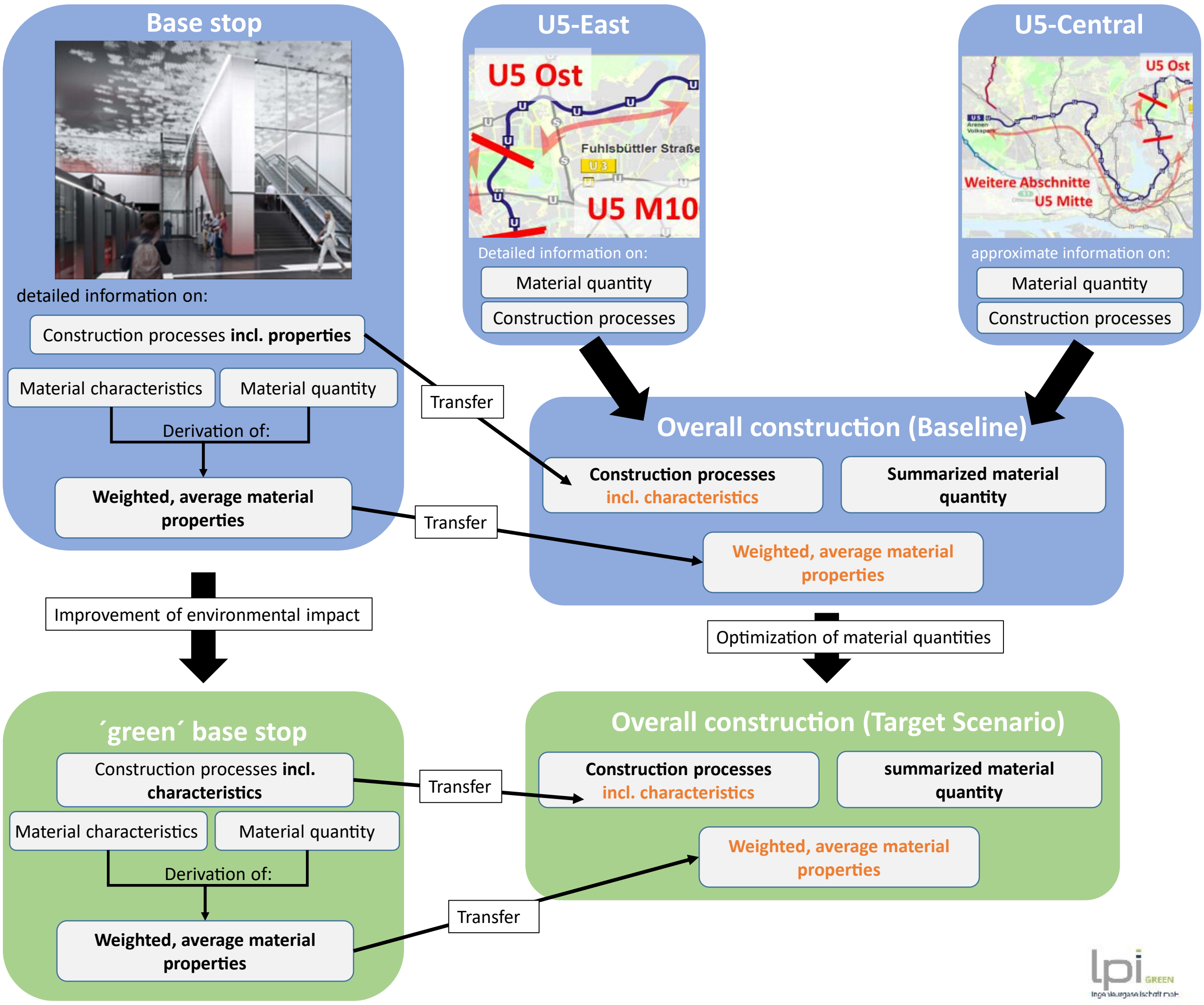

Figure 9: Description of the LCA procedure and handling of varying levels of detail between the different construction/project stages, own presentation

A.1 Part 1: Reinforced concrete structure

In addition to the descriptions in Chapter 3.2 and the detailed description of the LCA (see Section A.0), the LCA of the reinforced concrete construction is summarized below.

Life Cycle Inventory:

Based on the quantity surveys and tender documents provided by HOCHBAHN, the projected quantities were analysed and categorized (e.g. [2],[3],[4],[5]). For the manufactured reinforced concrete components, three categories were created: Temporary Structures/Shoring, Permanent Structures – Open Construction (mainly stations), and Permanent Structures – Tunnel Construction, see Table 1. In total, the baseline scenario assumes a total quantity of reinforced concrete of approx. 3.43 million m³. The total quantity indicated includes a reinforcing steel portion of approx. 343,000 t.

Table 1: Quantity calculation of the reinforced concrete quantities (rounded), BASELINE SCENARIO

Category	Unit	Construction stages		Total
		U5-East	U5-Central	
Temporary Structures/Shoring	m³	284,550	1,343,390	**1,627,940**
Permanent Structures – Open Construction	m³	230,000	1,163,600	**1,393,600**
Permanent Structures – Tunnel Construction	m³	77,500	329,860	**407,360**
Total reinforced concrete	**m³**	**592,050**	**2,836,850**	**3,428,900**
Included reinforcement[1]	**t**	**45,800**	**296,890**	**342,690**

In the first optimization step, the concrete quantities were systematically reduced by means of planning changes in the U5-Central section. Compared with the first quantity calculation, this resulted in a reduction of approx. 10% due to the shortening of the material-intensive stations and lengthening of the tunnel sections, as shown in Table 2. The reduced total quantities thus amount to 3.21 million m³ of concrete and approx. 303,000 t of reinforcing steel.

Table 2: Quantity calculation of the reinforced concrete quantities (rounded), TARGET SCENARIO

Category	Unit	Construction stages		Total
		U5-East	U5-Central	
Temporary Structures/Shoring	m³	284,550	1,209,050	**1,493,600**
Permanent Structures – Open Construction	m³	230,000	1,047,240	**1,277,240**
Permanent Structures – Tunnel Construction	m³	77,500	362,850	**440,350**
Total reinforced concrete	**m³**	**592,050**	**2,619,140**	**3,211,190**
Included reinforcement[2]	**t**	**45,800**	**256,650**	**302,450**

[1] The difference in the resulting reinforcement ratios (reinforcement/concrete) between the U5-Central and U5-East sections is due to the fact that the U5-Central section is still at an early stage of planning, so that corresponding uncertainties still have to be factored in. The reinforcement ratio is therefore currently still relatively high in the U5-Central section.

[2] See above

Impact assessment:

The LCA was performed based on the presented quantities and the calculation comprises four main steps as described below:

1. Calculation of the specific GHG emissions per m³ of unreinforced concrete for the above-mentioned construction categories
   a. Sorting of concrete quantities and requirements according to component categories (cf. Table 5)
   b. Compilation of the required GWP for the types of concrete used based on the recognized and freely accessible data sets of ÖKOBAUDAT (cf. Table 3)
   c. Allocation of the specific GHG emissions per m³ of unreinforced concrete to the concretes in one construction plant category (cf. Table 5)
   d. Calculation of the total GWP in one category (Table 5)
   e. Determination of the mean weighted GWP per m³ of unreinforced concrete in a component category (Table 5)
2. Calculation of the total GWP for the unreinforced concrete
   a. Transfer of the average weighted GWP from the 'base station' to the component category in the overall overview (cf. Table 6)
   b. Calculation of the resulting total GWP per construction category (cf. Table 6[3])
   c. Calculation of the resulting total GWP
   d. Reduction of the GWP by the amount of the reinforcement
3. Calculation of the GWP of the reinforcement
   a. Calculation of the GWP for the reinforcement based on the recognized and freely accessible data sets of the ÖKOBAUDAT (cf. Table 4)
   b. Allocation of specific GHG emissions per t of reinforcing steel (Table 6)
   c. Calculation of the GWP due to reinforcement (Table 6)
4. Calculation of the total GWP for the reinforced concrete structure (Table 6)

In the baseline scenario, a total GWP of 1.02 million t CO_2-eq. was assessed for reinforced concrete construction.

[3] Within the scope of this report, the aim was to provide a summary of the results. Further calculations for the additional component categories can be reviewed on request from HOCHBAHN at LPI Ingenieurgesellschaft mbH.

Table 3: Overview of the GWP for the EPD concretes listed in ÖKOBAUDAT [1]

Concrete strength class	LCA Modules [kg CO_2-eq./ m³]				Total GWP for unreinforced concrete (bulk density: 2,400 kg/m³)		Source/Year
	A1–A3	**A4**	**A5**	**B1**	kg CO_2-eq./ m³	kg CO_2 -eq./t	
C 20/25	178	3.9	1.08	-10	**173**	**72**	**ÖKOBAUDAT:** Beton der Druckfestigkeitsklasse C 20/25 **IZB 2018**
C 30/37	219	4.5	1.08	-10	**215**	**89**	**ÖKOBAUDAT:** Beton der Druckfestigkeitsklasse C 30/37 **IZB 2018**
C 35/45	244	9.1	1.08	-10	**244**	**102**	**ÖKOBAUDAT:** Beton der Druckfestigkeitsklasse C 35/45 **IZB 2018**

Note on Table 3: The data include emissions from the production of the materials (A1–A3) as well as from transport to (A4) and installation (A5) on the construction site. In addition, the concrete also absorbs CO_2 during its lifetime, which is included as a smaller, positive bonus. This is valid as a first approximation since it is assumed that the concrete surfaces are not sealed and are exposed to the corresponding atmosphere. CO_2 uptake by carbonation is a time-dependent process and the value given above represents an average value for a time horizon of 50 years according to the environmental product declaration. For the U5 subway line, a service life of ≥110 years is assumed. Further factors from the concrete composition and the environmental conditions also have an influence here. A more detailed analysis will be conducted when the study is updated.

Table 4: Overview of the GWP for reinforcement [1]

Reinforcing steel	LCA Modules [kg CO_2-eq./t]			Total GWP for reinforcement	Source/Year
	A1–A3	**A4**	**A5**	kg CO_2 -eq./t	
Reinforcement	683	10*	**	**693**	**ÖKOBAUDAT:** Bewehrungsstahl **IZB 2018**

** The following travel distance was assumed: Transport by truck-trailer (0.06444 kg CO_2-eq/tkm) and a transport distance of 150 km.*
*** The expenditure for the installation of the steel is covered by the overall GWP of the construction site.*

Table 5: Exemplary determination of the weighted average GWP for the concrete of a component category, here construction support and shoring ('Base-Station')

Component[1)]	**Strength class**	**Exposure classes**	**Quantity [m³]**	**GWP/m³ kg CO_2-eq./m³ (A1-A5, B1)**	**GWP t CO_2-eq.**
Diaphragm wall (summarized)	C30/37	XC4, XF1, XA1	30,600	215	6,579
Guide wall f. diaphragm wall	C20/25	–	765	173	132
Underwater concrete	C30/37	XF1, XA1	1,200	215	258
Shotcrete (summarized)	C20/25	X0	645	192	124
Drilled piles	C35/45	XC4, XF1, XA1	65	244	16
Strapping/Stiffeners	C35/45	XC4, XF1, XA1	640	244	156
Head beam	C35/45	XC4, XF1, XA1	605	244	148
Interception beam	C35/45	XC4, XF1, XA1	155	244	38
Total construction support/shoring			**34,675**	**-**	**7,451**
Weighted, mean GWP/m³ [kg CO_2-eq./m³]			**214**		

[1)] Some of the quantities and component points that are shown above consist of several component items with the same component properties, and hence they have been summarized here in terms of quantity for clarity.

Table 6: LCA overview of the reinforced concrete construction in the total U5 subway line construction project, baseline scenario

Category	Unit	Sections		Total	GWP	
		U5-East	U5-Central		spec. [kg-CO_2-eq. /Unit]	Total [t-CO_2-eq.]
Unreinforced concrete						
Temporary Structures/Shoring	m³	284,550	1,343,390	**1,627,940**	214	348,379
Permanent Structures – Open Construction	m³	230,000	1,163,600	**1,393,600**	234	326,102
Permanent Structures – Tunnel Construction	m³	77,500	329,860	**407,360**	294	119,764
Total	**m³**	**592,050**	**2,836,850**	**3,428,900**		**794,245**
Unreinforced concrete, reduced by reinforcement, ca. 1.283 Vol.-%				**3,359,754**		**784,055**
Reinforcement	t	45,800	296,890	342,690	693	**237,635**
Total GWP						**1,021,690**

Target scenario based on improved material properties:

The reduction measures presented in Chapter 3.2 were implemented for the derivation of the target scenario whereby the reduced material quantities from Table 2 provided the basis for the calculation. The further calculation was performed analogously to the procedure in the baseline scenario.

The following steps were adapted during the optimization process to consider the reduction measures resulting from material adjustments:

- Reduction of specific GWP per m³ of unreinforced concrete using eco-concretes[4] available today (Step 1.c)
- Recalculation of the weighted average GWP for the construction categories (Step 1)
- Transfer of the new weighted mean values This results in a reduced total GWP of 812,087 t CO2-eq. From the values in Table 7, a mean GWP per m³ of unreinforced concrete of approx. 190 kg CO2-eq./m³ can also be determined.

- Table 7 (Step 2.a)

[4] The basis for the optimization was a parameter study to calculate the GWP of cement clinker-reduced concretes (eco-concretes), which on the one hand ensure the required structural properties, are sufficiently manageable for the execution, and use cements with low clinker content. This work was based on experience with concrete compositions from previous similar construction projects and the know-how of LPI Ingenieurgesellschaft in the development and design of eco-concretes. The achievability of the determined GWP values were confirmed in an industry exchange with industry partners. Since the calculations of the determined data are very extensive and contain project-specific, confidential data, a presentation was omitted here.

- Analogous calculation and evaluation according to the above procedure

This results in a reduced total GWP of 812,087 t CO_2-eq. From the values in Table 7, a mean GWP per m³ of unreinforced concrete of approx. 190 kg CO_2-eq./m³ can also be determined.

Table 7: LCA overview of the target scenario of the steel and reinforced concrete construction in the U5 project

Category	Unit	Sections		Total	GWP	
		U5-East	U5-Central		Spec. [kg-CO_2-eq. /Unit]	Total [t-CO_2-eq.]
Unreinforced concrete						
Temporary Structures/ Shoring	m³	284,550	1,209,050	**1,493,600**	160	238,976
Permanent Structures – Open Construction	m³	230,000	1,047,240	**1,277,240**	188	240,121
Permanent Structures – Tunnel Construction	m³	77,500	362,850	**440,350**	297	130,784
Total	**m³**	**592,050**	**2,619,140**	**3,211,190**		**609,881**
Unreinforced concrete, reduced by reinforcement, ca. 1.212 Vol.-%				**3,175,230**		**602,489**
Reinforcement	t	45,800	256,650	302,450	693	**209,598**
Total GWP						**812,087**

Throughout the project, it is predicted that further reduction potentials will arise over the project period as a result of technical developments in the industry, both in cement production and in the production of reinforcing steel. These assumptions are based on an industry exchange with several industry and association representatives from the cement, concrete, and steel industries, in which the following points were highlighted:

- Further intensification of the use of clinker-reduced cements
- Use of hydrogen as an energy source
- Separation, storage, and (re)usage of process-related CO_2 (CCUS)

Based on the assumptions outlined above, the temporal course of the specific GWP for one cubic meter of unreinforced concrete and one ton of reinforcement steel was described with different development steps over the project duration, cf. Figure 10 and Figure 11.

To consider these values in the LCA, the expected concrete quantities were distributed over the project duration until the end of the 2030s. By taking the associated GWP from Figure 10 and Figure 11 into account for the annual concrete quantities, a total GWP of 440,080 t CO_2-eq. is obtained for the reinforced concrete construction in the target scenario.

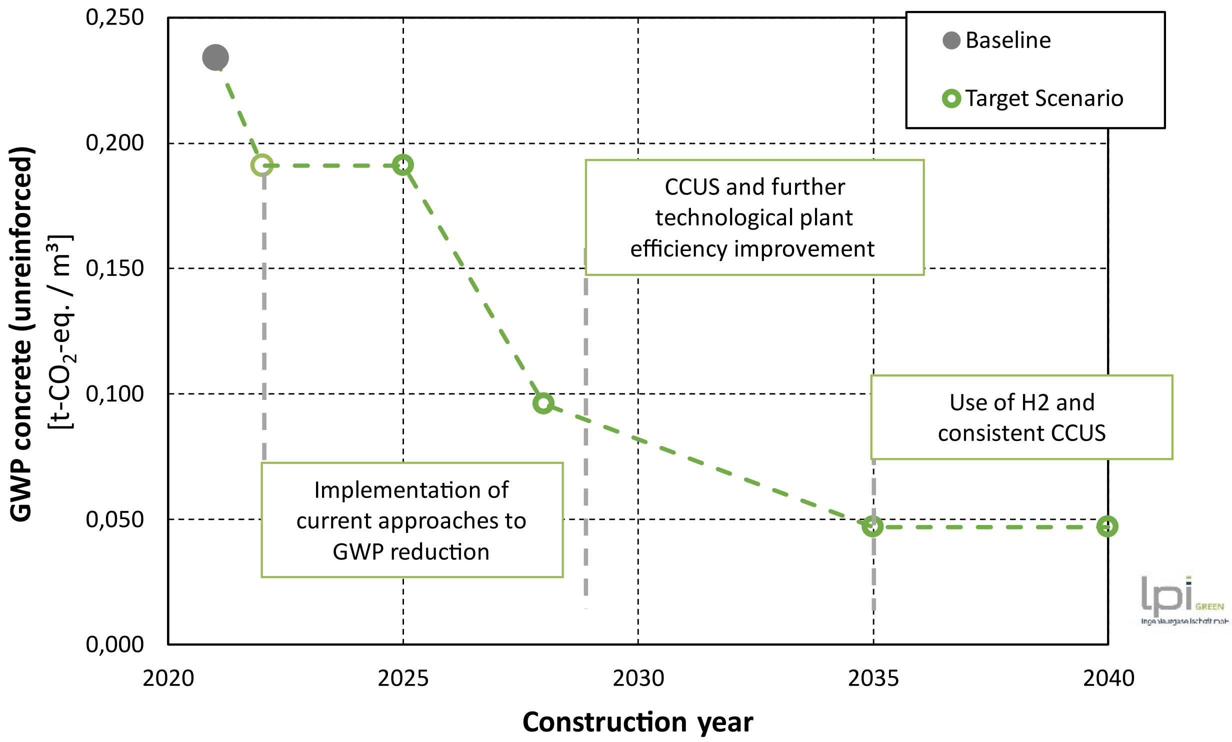

Figure 10: Predicted development of GWP for unreinforced concrete (mean value) based on industry discussions and expected technical developments (graph. representation)

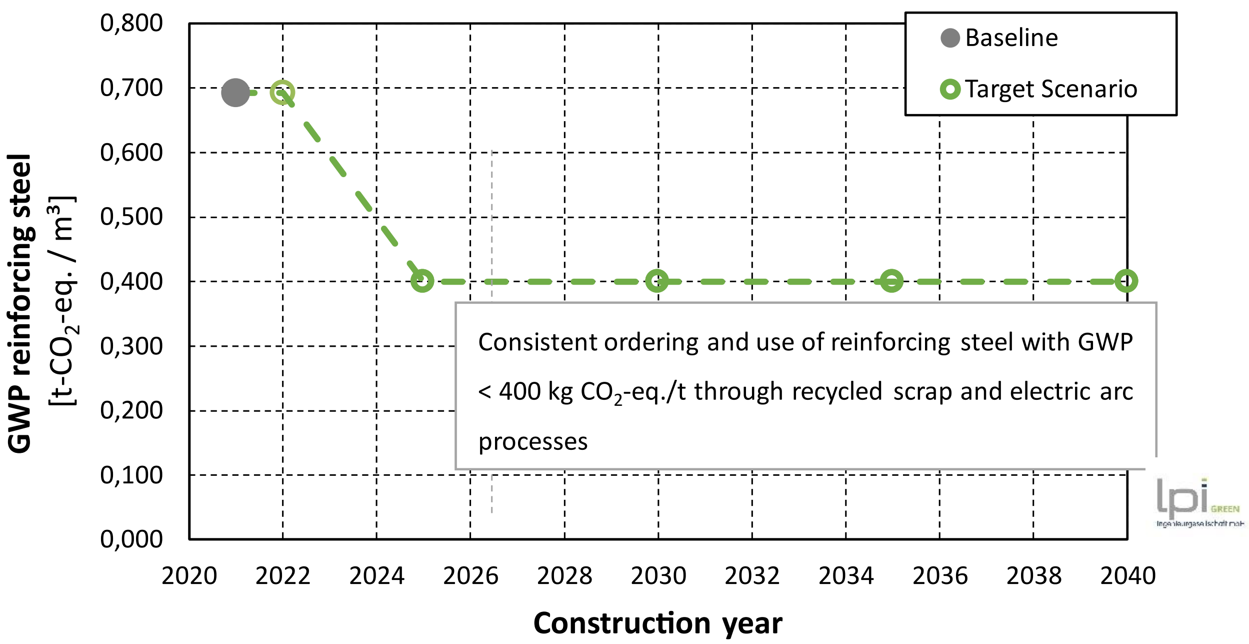

Figure 11: Predicted development of GWP for reinforcing steel (mean value) based on industry discussions and expected technical developments (graph. representation)

A.2 Part 2: Steel construction

In addition to the descriptions in Chapter 3.3 and the basic LCA procedure (see Section A.0), the LCA of the steel construction is summarized below.

Life Cycle Inventory:

Based on the quantity calculations and tender documents provided by HOCHBAHN, the quantities installed were analysed and categorized. Table 8 provides an overview of the expected steel quantities per construction phase. In the baseline scenario, a total steel quantity of approx. 198,185 t is assumed. The quantities indicated include rolled and sectional steels used for temporary excavation shoring and, to a lesser extent, for operating equipment and bridges. The striking difference in quantity between the U5-East and the U5-Central section is due to the fact that in the U5-East section, a large proportion of the shoring elements or entry and exit structures for the TBMs (e.g. sealing blocks) are made of (reinforced) concrete. In the area of the U5-Central, these will be made of steel.

Table 8: Quantity overview of the constructive steel quantities included in the baseline scenario

Scenario	Unit	Sections		Total
		U5-East	U5-Central	
Baseline	t	1,090	197,095	**198,185**

As part of an initial optimization of the required material quantities in the U5-Central area, the steel quantities were also adjusted [5]. Contrary to the other areas (e.g. reinforced concrete), the quantities of steel used in the target scenario have increased. The reason for this is that the work that previously planned to use a different construction method is now to be produced in steel construction in a material-reduced form. Accordingly, the proportion of steel increases, but at the same time, the amount of material and emission-intensive work (e.g. foundation engineering work) can be significantly reduced. Table 9 shows an overview of the steel quantities in the target scenario.

Table 9: Quantity overview of the constructive steel quantities included in the target scenario

Scenario	Unit	Construction stages		Total
		U5-East	U5-Central	
Target scenario	t	1,090	206,960	**208,050**

Impact assessment:

As part of the Life Cycle Inventory, the steels used were defined as rolled and sectional steels. According to ÖKOBAUDAT, this results in an applicable specific GWP profile according to Table 10.

Table 10: Overview of the GWP for the structural steels [1]

Steel	LCA Modules					Total GWP	Source/Year
	A1–A3	**A4**	**A5**	**C**	**D**	kg CO_2-eq./t	
Construction steels	1,125	6.4*	**	1.844	-413.4	**720**	**ÖKOBAUDAT:** Baustähle: Offene Walzprofile und Grobbleche **Bauforumstahl e.V., 2018**

** The following travel distance was assumed: Transport by truck-trailer (0.06444 kg CO_2-eq/tkm) and a transport distance of 150 km.*
*** The expenditure for the installation of the steel is covered by the overall GWP of the construction site.*

Baseline scenario based on commonly available data:

Based on the determined steel quantities and the spec. GWP of the construction steel, the total GWP in the baseline scenario is approx. 142,700 t-CO_2-eq.

LCA overview of the GWP for structural steelwork (rounded), baseline scenario

Category	**Unit**	**Sections**		**Total**	**GWP**	
		U5-East	**U5-Central**		**Spec. [kg CO_2-eq. /Unit]**	**Total [t-CO_2-eq.]**
Baseline scenario	t	1,090	197,095	**198,185**	**720**	**142,695**

Target scenario based on improved material properties:

In consideration of the adjusted material quantities, the target scenario results in an increase of the GWP in the steel construction to approx. 149,800 t-CO_2-eq.

LCA overview of the GWP for structural steelwork (rounded), target scenario

Category	**Unit**	**Sections**		**Total**	**GWP**	
		U5-East	**U5-Central**		**Spec. [kg-CO_2-Equiv. /Unit]**	**Total [t-CO_2-Equiv.]**
Target scenario	t	1,090	206,960	**208,050**	**720**	**149,800**

Similar to the industrial developments for the cement and steel industry, an industrial development towards GWP-reduced production is also expected for the steel industry. The assumptions on which this is based were presented in Chapter 3 of the assessment summary. The assumed development steps were derived from an industry exchange. The GWP reduction steps predicted in Figure 12 were confirmed as current industrial development targets in the industry discussions.

Based on these development steps and temporal distribution of the steel quantities over the project duration on the basis of the project schedule, the GWP of the steel construction is reduced to 66,200 t CO_2-eq.

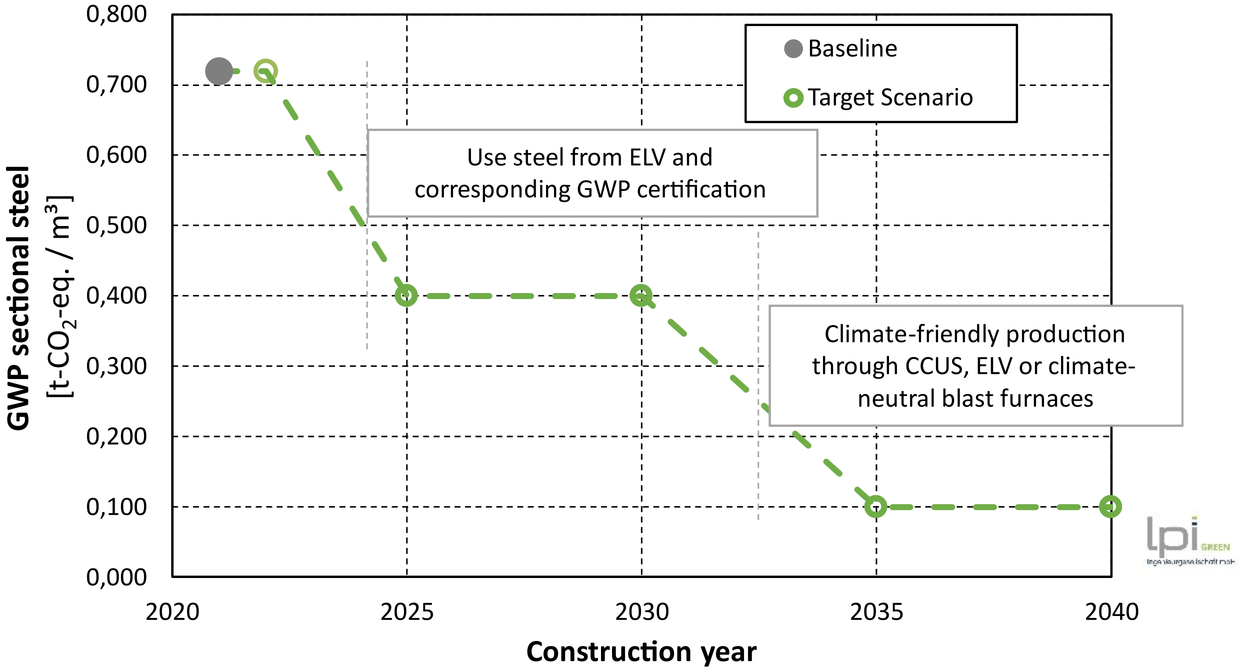

Figure 12: Predicted development of GWP for sectional steel (mean value) based on industry discussions and expected technical developments (graph. representation)

A.3 Part 3: Soil management

In addition to the descriptions in Chapter 3.4 and the basic LCA procedure (see Section A.0), the LCA of the soil management approach is summarized below.

Life Cycle Inventory:

Based on the quantity calculations and tender documents provided by HOCHBAHN, the quantities used were analysed and categorized. Table 11 shows an overview of the quantities of soil that must be removed and recycled. In total, approx. 12 million tons of material are generated.

Table 11: Input data for soil management (Source: Planungsdaten HOCHBAHN)

	Mass [t]		
	U5-East	**U5-Central**	**Total**
Total amount of soil for disposal/recycling location:	**3,000,000**	**9,000,000**	**12,000,000**

The GWP of soil management results from the required construction processes and the transport of soil material. Therefore, a construction process was designed, which is subsequently assessed. In principle, optimization of the process also offers an opportunity to reduce the resulting GWP. For the baseline scenario, a common processing and transport scenario was assumed. This is divided into:

- Removal/excavation by excavator,
- Transport by truck-trailer to a declaration area in the port of Hamburg,
- Handling,
- Further transport route (also truck-trailer to a recycling site, approx. 75 km distance), and
- Discharge/installation.

For the return trip from the recycling site to the construction site, an additional empty trip (75 km) was assumed. The baseline scenario is described in Table 12.

Table 12: Summary of the applied transport scenario in the baseline scenario

Scenario		**Excavation**	**Transport** (short): Declaration area		**Handling**	**Transport** (long): Recycling location		**Installation**
Location	Main means of transportation	[t]	Distance [km]	Means of transport	[t]	Distance [km]	Means of transport [-]	[t]
Baseline: Landfill approx. 75 km far from the port of Hamburg		12 Mio.	20	truck	12 Mio.	150	truck	12 Mio.

Significant reduction potential is expected for the soil management, which results from the optimization of the process chain. Therefore, an investigation of different disposal routes was conducted for which the following project boundary conditions were considered:

- Accumulating soil quantity and its distribution over time
- Different available recycling sites (with special consideration of capacity and transport accessibility)
- Different means of transport (truck, barge, train)
- Avoidance of empty runs through integration into transport cycles

For the target scenario, an optimized scenario resulted in which truck trips continue to primarily be used for transportation. The expected recycling location is approx. 70 km away from the declaration area. However, the transportation processes tie into a transportation cycle and within this cycle, the empty trips on the way back are omitted, as other transports are included. This reduces the transport distance on the long transport distance to approx. 70 km.

Table 13: Summary of the assumed transport scenario in the target scenario

Scenario		**Excavation**	**Transport** (short): Declaration area		**Handling**	**Transport** (long): Recycling location	
Ort	Main means of transportation	[t]	Distance [km]	Means of transport	[t]	Distance [km]	Means of transport [-]
Target scenario: Recycling location in northern Germany		12 Mio.	20	truck	12 Mio.	70	truck

Impact assessment:

To ensure that the previously mentioned construction processes are represented in the impact assessment, the spec. GWPs for the respective sub-processes (excavation, transport, etc.) were assigned to the process steps. The corresponding GWPs are summarized in Table 14.

Table 14: Input data (Source: ÖKOBAUDAT [1])

Process step	**Unit**	**GWP**	**Source/Year**
Excavation	kg CO_2-eq/m³	1.29	**ÖKOBAUDAT:** Bagger **IZB 2018**
	Transport		
Truck	kg CO_2-eq/tkm	0.06444	**ÖKOBAUDAT:** LKW-Zug **IZB 2018**
Loading 1)	kg CO_2-eq/m³	1.29	**ÖKOBAUDAT:** Bagger 100 kW Aushub **IZB 2018**

1) For loading and handling, appropriate process energies from wheel loaders, conveyor belts, or excavators must be evaluated. The corresponding processes can only be described in detail after they have been defined by the contractor. Since no exact process scenario can be described at present, emissions from handling by excavator were assumed for simplicity. This is to be verified in the further course of the project.

Baseline scenario based on commonly available data:

Considering the process data shown in Table 12 and the spec. GWP for the process steps provided in Table 14, GWPs are derived for the process steps shown in Table 15.

Table 15: Approximate GWP of the soil management by truck transport (distance of recycling point 2 x 75 km) – baseline scenario

Main type of transport	**Construc-tion sec-tion**	**Process stages**					**Total**
		Excavation	**Transport (short)**	**Handling – Declaration**	**Transport (long)**	**Recycling location**	
		[t CO_2-eq.]	[t CO_2-eq.]	[t CO_2-eq.]	[t CO_2-eq.]	[t CO_2-eq.]	**[t CO_2-eq.]**
Truck	U5-East	1,935	3,865	1,935	29,000	1,935	38,670
	U5-Cen-tral	5,805	11,600	5,805	86,995	5,805	116,010
	Total	7,740	15,465	7,740	115,995	7,740	**154,680**

To reflect the corresponding uncertainties in the described process, an imponderability surcharge of 10% is considered. This results in a total GWP of approx. 170,150 t CO_2-eq.

Target scenario based on optimized transport chain:

Table 16: Approximate GWP of the soil management by truck transport (distance of recycling point 1 x 70 km) – target scenario

Main type of transport	**Construc-tion sec-tion**	**Process stages**					**Total**
		Excavation	**Transport (short)**	**Handling – Declaration**	**Transport (long)**	**Recycling location**	
		[t CO_2-eq.]	[t CO_2-eq.]	[t CO_2-eq.]	[t CO_2-eq.]	[t CO_2-eq.]	**[t CO_2-eq.]**
Truck	U5-East	1,935	3,870	1,935	13,535	1,935	23,210
	U5-Central	5,805	11,600	5,805	40,595	5,805	69,610
	Total	**7,740**	**15,470**	**7,740**	**54,130**	**7,740**	**92,820**

Considering the decreased transportation process effort, the target scenario results in a reduced GWP potential of approx. 92,820 t CO_2-eq. Including the consideration of uncertainties, the target scenario results in a total GWP of 102,100 t CO_2-eq.

A.4 Part 4: Mechanical tunnel driving by means of TBM

In addition to the descriptions in Chapter 3.6 and the basic LCA procedure (see Section A.0), the LCA of mechanized tunnel driving is summarized below. Corresponding material costs, e.g. for segment production, and annular gap mortar or transportation of excavated soil, are included in the previous sections. In this section, therefore, the GWP emissions arising from the TBM operation, including all ancillary processes (separation plants, TBM equipment, conveyor, and transport belts), are assessed.

Life Cycle Inventory:

The corresponding energy quantities for the operation of the TBM originate from the required electrical energy. Therefore, as already mentioned in Chapter 3.6, the tunnel construction process using the TBM was analysed based on empirical values and mapped in terms of processes by HOCHBAHN [6]. This yielded the predicted electricity consumption for the operation of the TBM shown in Table 17.

Table 17: Predicted electricity consumption per construction section by TBM [6]

Section	Electricity consumption TBM
	[MWh]
U5-East	70,000
U5-Central	350,000
Total	**420,000**

Impact assessment:

To determine the resulting emissions, the use of the Germany-wide electricity mix was assumed in the baseline scenario. According to ÖKOBAUDAT, two different GWPs are available for this mix over the project period until the end of the 2030s, cf. Table 18.

Table 18: Specific GWP for electricity consumption, according to ÖKOBAUDAT datasets [1]

Process step	Unit	GWP	Data set acc. to ÖKOBAUDAT
German electricity mix Scenario 2020	kg CO_2-eq/kWh	0.5894	**ÖKOBAUDAT:** Strom-Mix-Szenario 2020; <1kV **IZB 2018**
German electricity mix Scenario 2030	kg CO_2-eq/kWh	0.5028	**ÖKOBAUDAT:** Strom-Mix-Szenario 2030; <1kV **IZB 2018**
Electricity from wind power	kg CO_2-eq/kWh	0.01048	**ÖKOBAUDAT:** Strom aus Windkraft **IZB 2018**

Baseline scenario based on commonly available data:

The specific GWPs are assigned to the determined electricity consumption in the U5-East and U5-Central sections according to Table 18, cf. Table 19. As shown, the assignment considers that the area of the U5-Central will be built starting around 2030, and hence the adjusted GWPs are assumed based on the forecast values for 2030.

This results in a total GWP for mechanized tunnel boring of approx. 217,240 t CO_2-eq.

Table 19: Calculation of the GWP for the electricity consumption of the TBM (rounded), baseline

Section	Electricity consumption TBM	GWP/kWh	GWP
	[MWh]	[kg CO_2-eq / kWh]	t- CO_2-eq.
U5-East	70,000	0.5894	41,260
U5-Central	350,000	0.5028	175,980
Total	**420,000**	**Variable**	**217,240**

Target scenario based on the use of green electricity:

Contrary to the previous assumption of the Germany-wide electricity mix in the baseline scenario, HOCHBAHN intends to provide green electricity, e.g. from wind power, to supply the construction sites. Therefore, the specific GWP for 1 kWh of electricity is reduced to the value provided in Table 18 for electricity from wind power. The recalculation of the GWP for mechanized tunnel boring using green electricity is shown in Table 20 and results in a reduced total GWP of approx. 4,405 t-CO_2-eq.

Table 20: Calculation of GWP for the electricity consumption of the TBM – green electricity (rounded), target scenario

Section	Electricity consumption TBM	GWP/kWh	GWP
	[MWh]	[kg CO_2-eq / kWh]	t- CO_2-eq.
U5-East	70,000	0.01048	735
U5-Central	350,000	0.01048	3,670
Total	**420,000**	**0.01048**	**4,405**

A.5 Part 5: Special foundation engineering

In addition to the descriptions in Chapter 3.5 and the basic LCA procedure (see Section A.0), the assessment of special foundation engineering is summarized below. Special foundation engineering is mainly required to construct the excavation pits and to secure the uplift of structural elements. They are divided into the construction of diaphragm walls, which, however, have already been included in the LCA for reinforced concrete construction. Furthermore, various ground anchors are required for tie-back and uplift protection of components. In addition, ground anchors for sealing and bracing excavation pits are produced using the jet grouting method. To produce the ground anchors, anchor holes are drilled and fitted with a steel support structure. The remaining gap between the support structure and the ground is then grouted. The grout mainly consists of a cement paste. The injection bodies are used, among other things, to create a horizontal seal or horizontal bracing, e.g. of diaphragm walls in the subsoil. For this purpose, cement paste is also injected over a defined height into deeper soil layers (jet grouted elements). The work required and the associated material and energy input for production depend on various boundary conditions (e.g. subsoil conditions, required properties, and process parameters).

Life Cycle Inventory:

For the construction of the U5 subway line, approx. 604,000 m of grouted and micropiles must be produced according to the quantity calculation in the baseline scenario, cf. Table 21. In addition, approx. 485,320 m³ of jet grouted elements must be produced for various sealing bodies, horizontal bracing, and sealing in the baseline scenario, cf. Table 22.

Table 21: Quantity overview of the micropile lengths (Baseline scenario)

Scenario	Unit	Sections		Total
		U5-East	**U5-Central**	
Baseline	M	107,000	497,000	**604,000**

Table 22: Quantity overview of the jet grouted elements (Baseline scenario)

Scenario	Unit	Sections		Total
		U5-East	**U5-Central**	
Baseline	m³	8,550	476,775	**485,325**

Within the scope of an initial material and quantity optimization analogous to the reinforced concrete, an adjustment of the required material quantities, e.g. by rescheduling stiffening work, was conducted. As a result, the required grouted and micropiles for the target scenario can be reduced to approx. 412,000 m according to the current status, cf. Table 23. The quantity of DSV bodies is reduced to approx. 287,130 m³, cf. Table 24.

Table 23: Quantity overview of the micropile lengths (Target scenario)

Scenario	Unit	Construction stages		Total
		U5-East	**U5-Central**	
Target scenario	m	107,000	305,000	**412,000**

Table 24: Quantity overview of the jet grouted elements (Target scenario)

Scenario	Unit	Sections		Total
		U5-East	U5-Central	
Target scenario	m³	8,550	278,585	**287,135**

Impact assessment:

In contrast to the previous procedure, no general specific GWP based on freely accessible databases can be assessed for the production of the micro grouted piles and the jet grouted soil elements. The required material quantities and material properties of the grouted material and the required process efforts, from which the resulting specific GWP are derived, depend on various boundary conditions from the construction project (e.g. ground conditions) and process parameters. Accordingly, the spec. GWP can vary from case to case. Therefore, a parameter study for the expected material and process properties was conducted based on project-specific parameters. This procedure requires corresponding empirical knowledge and process-related special knowledge. As a result of the analysis, it was possible to estimate specific GWP for the foundation engineering works considered in this study, cf. Table 25. In general, the selection of cements used for the execution of the foundation engineering works is not limited, so that cements rich in clinker (high GWP) can also be used. This results in a significant GWP to produce the micropiles and the jet grouted soil elements. By using clinker-reduced cements (e.g. CEM III/A), the specific GWP can be significantly reduced. Accordingly, these specific values are used for the target scenario. Further reduction potentials, for instance in the manufacturing process (e.g. reuse of pre-run suspensions), have not yet been considered but will be investigated in the subsequent optimization steps.

Table 25: GWP for the construction methods considered for special foundation engineering

Construction method	**Unit**	**GWP per Unit**	
		CEM I	**CEM III**
	[-]	[kg CO_2-eq/Unit]	[kg CO_2-eq/Unit]
Micropile*	m	250	85
Jet grouted elements**	m³	1,710	810

** Without a support structure*

***In addition to the pure material requirements for the manufacture of the shell, the values provided also include corresponding additional quantities for the manufacture of the pile. The material compositions used have been estimated based on empirical values and corresponding process knowledge. For uncertainties, an allowance of 10% is included in the unit values.*

Baseline scenario

Considering the quantities mentioned in the baseline scenario, cf. Table 21, and the calculated specific GWP for the production of the jet grouted elements and micropiles, the total GWP amounts to approx. 151,000 t-CO_2-eq, cf. Table 26.

Table 26: Estimated GWP for the production of micropiles (rounded), baseline scenario

Section	Length	Spec. GWP	Total GWP
	[m]	[kg CO_2-eq/m]	t- CO_2-eq.
U5-East	107,000	250	26,750
U5-Central	497,000	250	124,250
Total	**604,000**	**250**	**151,000**

Table 27: Estimated GWP for the production of the jet grouted elements (rounded), baseline scenario

Section	Volume	Spec. GWP	Total GWP
	[m³]	[kg CO_2-eq/m³]	[t- CO_2-eq.]
U5-East	8,550	1,710	14,620
U5-Central	476,775	1,710	815,285
Total	**485,325**	**1,710**	**829,905**

Table 27 shows the equivalent calculation of the GWP of the jet grouted soil elements, resulting in a total GWP of approx. 829,900 t CO_2-eq.

In total, the baseline scenario for the foundation engineering works results in a GWP of 980,900 t CO_2- eq.

Target scenario based on improved material properties:

In consideration of the reduced material quantities according to Table 23 and the reduced, specific GWP according to Table 25, due to the required use of clinker-reduced cement, the total GWP of the micropile production in the target scenario is reduced to approx. 35,020 t CO_2-eq.

Table 28: Estimated GWP for the production of micro grouted piles (rounded), target scenario

Section	Length	Spec. GWP	Total GWP
	[m]	[kg CO_2-eq./m]	t- CO_2-eq.
U5-East	107,000	85	9,095
U5-Central	305,000	85	25,925
Total	**412,000**	**85**	**35,020**

Similarly, the total GWP of the jet grouted soil elements can be reduced to approx. 232,580 t-CO_2-eq. by applying the reduced quantities, cf. Table 24, and a reduced specific GWP (Table 25), cf. Table 29.

Table 29: Estimated GWP for the production of the jet grouted soil elements (rounded), target scenario

Section	Volume	Spec. GWP	Total GWP
	[m³]	[kg CO_2-Equiv./m³]	[t- CO_2-Equiv.]
U5-East	8,545	810	6,921
U5-Central	278,585	810	225,654
Total	**287,135**	**810**	**232,575**

Without considering further reductions due to industrial development, this results in a total GWP of approx. 267,600 t-CO_2-eq.

Consideration of future industrial developments in the target scenario:

Similar to reinforced concrete construction, it is expected that cement with reduced GWP will be available in the future as a result of further industrial development in cement production. The industrial development for cement production described in Figure 10 is also translated into a stepwise reduction of the spec. GWP for the production of the micropiles and the jet grouted soil elements. Considering the time distribution of the production, the total GWP of the special foundation engineering works is reduced to approx. 117,000 t-CO_2-eq. This also illustrates the significant dependency of the work on the binder cement.

A.6 Part 6: Rail system

According to the current planning status, two different standard superstructures will be used to produce the rail system, depending on the requirements of the track:

- Rail in ballast bed
- Rail on a solid concrete track

Life Cycle Inventory:

Based on the current planning, the route lengths shown in Table 30 are determined for the two systems.

Table 30: Overview of the length of the track per roadway structure

Section	System design	Length
	[-]	[km]
U5-East	gravelled	12.4
U5-Central	slab track	24.3
	gravelled	24.3
Total		**61**

Impact assessment:

For the calculation of the specific GWP of the two rail systems, the standard cross-section was described separately based on the materials used and the construction processes contained therein. The standard structure for the ballasted track consists of the ballast bed, the steel-concrete sleeper, the two rails, and the conductor rail incl. support. For this standard structure, a specific GWP of approx. 218 kg CO_2-eq./m was determined. The standard structure of the slab track comprises the two rail tracks and the conductor rail. The required concrete structure has already been included in the LCA for the reinforced concrete work. Accordingly, the additional specific GWP for the slab track is calculated as 85 kg CO_2-eq./m.

Considering the corresponding route lengths for the ballasted and slab track, the total GWP is approximately 10,070 t CO_2-eq, cf. Table 31.

Table 31: Overview of the calculated GWP of the installed rail system (rounded)

Section	Structure	Length	Spec. GWP/m	Total GWP
		[km]	[kg CO_2-eq./m]	[t CO_2-eq.]
U5-East	gravelled	12.4	218	**2,705**
U5-Central	gravelled	24.3	218	**5,300**
	slab track	24.3	85	**2,065**
Total	**-**	**61**	**variable**	**10,070**

A.7 Part 7: Masonry work

The masonry work includes the construction of various wall components at the stations. Sand-lime brick walls are planned in different thicknesses and as plastered or unplastered variants. While details of the quantities and properties to be produced are already available for the U5-East section, no more precise information is yet available for the U5-Central section, hence, analogous to the previous sections, average values for the wall quantities per stop and the proportionate design variants were determined on the basis of the previous planning for the U5-East.

Life Cycle Inventory:

In the U5-East section, an average wall area of approx. 315 m² per station could be determined. Transferring this average value to the U5-Central section results in a total area of approx. 7,245 m², cf. Table 32.

Table 32: Quantity overview for the masonry walls (plastered and unplastered)

Section	Averaged wall area per station*	Number of stations	Total requirement
	[m²]	[-]	[m²]
U5-East	756	5	3,780
U5-Central	756	18	13,608
Total	-		**17,388**

** The average wall area per stop was calculated based on the previous tender documents for the U5-East area [2], [3]. The individual values vary between 75 and 1,000 m² per unit. The system structures vary between unrendered walls and rendered walls. A total of four different wall constructions are distinguished in the area of the U5-East. In the area of the U5-Central, it is assumed that a similar average wall area with a similar ratio of the superstructure types can be assumed per stop.*

Impact assessment:

To determine the total GWP, specific GWP values for one square meter of wall surface were calculated for the different wall systems in the stops of the U5-East. Based on the quantity distribution of the different wall systems, a weighted average GWP could be determined. As a basis, different GWP values of the materials were used according to the datasets of ÖKOBAUDAT, cf. Table 33.

Table 33: Existing material parameters for the GWP to describe material-immanent emissions for masonry work

Material	Unit	Spec. GWP A1–A3
	[-]	[kg CO_2-eq./Unit]
Sand lime brick: density = 1,800 kg/m³	t	136
Masonry mortar - standard masonry mortar (density = 1,500 kg/m³)	t	72.8
Plaster mortar standard plaster/precious plaster (density = 1,800 kg/m³)	t	208

Further surcharges were provided for the transportation of materials to the construction site.

The weighted average GWP of the wall area was determined to be 84 kg CO_2-eq./m². Based on the quantity determination and the weighted average GWP, the total GWP for the masonry work was determined according to Table 34. As shown in the table, it was assumed that the masonry walls would have to be replaced once during the envisaged service life of the subway. In addition, an uncertainty allowance of 20% was considered. This results in a total GWP of approx. 3,505 t-CO_2-eq.

Table 34: Overview of the total GWP for the U5 determined from the masonry work

Section	**Mean wall area per station**	**Mean GWP per m²**	**Estimated renewal per service life of structure**	**Surcharge**	**Mean GWP per station**	**Number of stops**	**Total GWP**
	[m²]	[kg CO_2-eq./m²]	[-]	[M-%]	[t CO_2-eq./stop]	[-]	[t- CO_2-eq.]
U5-East	756	84	2	20	152.4	5	760
U5-Central						18	2,745
Total					**152.4**	**23**	**3,505**

A.8 Part 8: Site operation

Site operations are subdivided into the areas of construction, site electricity consumption, and water management.

Part 8a: General electricity consumption of the construction site

The general electricity consumption includes all electricity consumption of the construction sites that cannot be allocated to a specific manufacturing process. This includes work processes such as crane work, welding work, or the operation and maintenance of construction site equipment (offices, etc.).

Life Cycle Inventory:

The required electricity for a large construction site was estimated at approx. 480,000 kWh/a based on empirical values. It is assumed that the scope of a major construction site is to be assumed for each stop and the associated route sections, each of which is operated for approx. 8 years.

Accordingly, this assumption results in a total electricity demand of approx. 88,320 MWh, cf. Table 35.

Table 35: Rough calculation of the general electricity consumption of the construction sites

Section	Number of stops	Construction time/stop	Electricity demand per stop and year	Total demand
	[-]	[a]	[kWh/a]	[MWh]
U5-East	5	8	480,000	19,200
U5-Central	18			69,120
Total	**23**			**88,320**

Impact assessment:

Baseline scenario based on commonly available data:

The specific GWP for electricity can be described in the baseline scenario by the specific GWP of the Germany-wide electricity mix (approach analogous to mechanized tunnelling). Under consideration of a corresponding development in the future, this value is slightly reduced, cf. Table 36. Based on the determined amount of electricity, the baseline scenario results in a GWP of approx. 46,075 t-CO_2-eq, cf. Table 36.

Table 36: Rough calculation of GHG emissions from general electricity consumption at construction sites (rounded), baseline scenario

Section	Number of stops	Construction time /stop	Electricity demand per stop and year	Total demand	GWP/kWh	GWP
	[-]	[a]	[kWh/a]	[MWh]	[kg CO_2-eq/kWh]	t- CO_2-eq.
U5-East	5	8	480,000	19,200	0.5894[1)]	11,320
U5-Central	18			69,120	0.5028[2)]	34,755
Total	**23**			**88,320**	**Variable**	**46,075**

[1)] GWP of Germany-wide electricity mix, see ÖKOBAUDAT, 2020. [2)] GWP of Germany-wide electricity mix 2030, see ÖKOBAUDAT

Target scenario based on the use of green electricity:

HOCHBAHN intends to provide green electricity, e.g. from wind power so that in the target scenario the GWP according to Table 37 is reduced to approx. 930 t-CO_2-eq.

Table 37: Rough calculation of GHG emissions from general electricity consumption at construction sites (rounded), target scenario

Section	Number of stops	Construction time /stop	Electricity demand per stop and year	Total demand	GWP/kWh	GWP
	[-]	[a]	[kWh/a]	[MWh]	[kg CO_2-eq/kWh]	t- CO_2-eq.
Total	**23**	**8**	**480,000**	**88,320**	**0.01048**[3)]	**930**

[3)] GWP Wind electricity, see ÖKOBAUDAT

Part 8b: Water management

Water management is subdivided into dewatering for the excavation pits and water treatment for various construction processes. The GWP for water management results from the electricity required to operate the facilities.

Life Cycle Inventory:

A basis for the expected quantities and the further boundary conditions (e.g. pumping height, operating time, etc.) of the groundwater and construction water to be pumped and treated can be taken from the planning approval document for the U5-East. Based on this document, the required pumping and plant capacities for dewatering and water treatment can be estimated by considering typical empirical values. For the U5-Central section, no planning data are available yet. Analogous to the previous sections, the determined, required capacities and quantities from the U5-East are therefore transferred to the U5-Central area. For this purpose, averaged system outputs from the systems in the U5-East are determined. The expected number of systems results in a total energy requirement as shown in Table 38 and Table 39.

Table 38: Overview of the electricity required to operate the dewatering system (rounded)

Section	Average pump capacity per system[1)]	Retention period per system	Electricity consumption per System	Number Systems	Total demand
	[kW]	[a]	[kWh]	[-]	[MWh]
U5-East	20.8	2	364,420	13	4,740
U5-Central	26.6		466,030	59	27,496
Total	**-**				**32,236**

[1)] The estimated pump capacity for the area of the U5-East was determined from 13 systems for installation, for which the relevant input data (max. pumping capacity per hour; total volume to be pumped, duration of operation, delivery head) are available based on the planning approval documents. The performance values determined for the systems were also given a 50% markup for imponderables. In the area of the U5-Central, the highest individual value of the 13 systems considered from the U5-East was used to determine the pump capacities.

Table 39: Overview of the electricity required for the operation of the water treatment (rounded)

Section	Average power per plant[1)]	Retention period per system	Electricity demand per plant	Number of plants	Total demand
	[kW]	[a]	[kWh]	[-]	[MWh]
U5-East	55.5	3.1	1,507,160	5	7,536
U5-Central	approx. 5 times the electricity compared to U5-East[2]				37,680
Total	-				**45,216**

[1)] The system capacity was determined for the area of the U5-East from five systems to be installed, for which the relevant input data (max. quantity to be treated per hour; the total quantity to be conveyed, duration of operation, etc.) are available based on the planning approval documents. In addition, a markup of 30% was added to the calculated performance values of the systems to account for uncertainties.

[2)] Since the five turbines in the U5-East area serve a total of 13 systems, it is assumed that 4.5 times the number of power/turbines are required for the U5-Central area.

Impact assessment:

Baseline scenario based on commonly available data:

The resulting GWP is derived from the amount of energy and the specific GWP required for its generation. Analogous to the areas of general construction electricity and mechanized tunnel driving, the Germany-wide electricity mix is used for the electricity demand in the baseline scenario. According to Table 40, this results in a total GWP of approx. 40,000 t-CO_2-eq.

Table 40: Comparison of the calculated GWP for water management (Baseline scenario)

Section	Water drainage	Water treatment	Total water management	GWP/kWh	GWP
	[MWh]	[MWh]	[MWh]	[kg CO_2-eq/kWh][1)]	t- CO_2-eq.
U5-East	4,740	7,536	12,276	0.5894[2)]	7,235
U5-Central	27,491	37,675	65,166	0.5028[3)]	32,765
Total	**32,231**	**45,211**	**77,442**	**Variable**	**40,000**

[2)] GWP of Germany-wide electricity mix, see ÖKOBAUDAT, 2020. [3] GWP of Germany-wide electricity mix 2030 see ÖKOBAUDAT
[4)] GWP Wind electricity, see ÖKOBAUDAT

Target scenario based on the use of green electricity:

The envisaged provision and use of green electricity in the target scenario reduces the expected total GWP to 43approx. 812 t-CO_2-eq, cf. Table 41.

Table 41: Comparison of the calculated GWP for water management (Target scenario)

Section	Water drain-age	Water treat-ment	Total water management	GWP/kWh	GWP
	[MWh]	[MWh]	[MWh]	[kg CO_2-eq/kWh][1)]	t- CO_2-eq.
Total	**32,231**	**45,210**	**77,441**	**0.01048[4)]**	**812**

[2)] GWP of Germany-wide electricity mix, see ÖKOBAUDAT, 2020. [3] GWP of Germany-wide electricity mix 2030, see ÖKOBAUDAT
[4)] GWP Wind electricity, see ÖKOBAUDAT

A.9 Part 9: other services

Life Cycle Inventory:

Within the scope of the construction project, further work will be conducted that has not yet been recorded in detail and which will be recorded in this LCA in a simplified manner using a flat-rate approach. The work and processes estimated in this way include:

- General traffic,
- Clearance work,
- Temporary routing,
- Other shoring work,
- Waterproofing work,
- Secondary work for minor operations,
- Site clearance, and
- Installation and assembly work are not estimated in the LCA.

Impact assessment

As a rough estimate for the services to be performed here, a flat-rate value of 10% of the GWP from the steel and reinforced concrete work in the baseline scenario is applied. This corresponds to approx. 102,295 t CO_2-eq.

A.10 Part 10: summary of the results

The following table shows a total overview of the expected GWP in the baseline and target scenarios.

Table 42: Total overview of the expected GWP for the baseline scenario and the target scenario.

<table>
<tr><th colspan="2" rowspan="3"></th><th>Baseline scenario</th><th>Target scenario</th></tr>
<tr><th>GWP</th><th>GWP</th></tr>
<tr><th>Total
[t-CO_2-eq.]</th><th>Total
[t-CO_2-eq.]</th></tr>
<tr><td colspan="2">Reinforced concrete construction</td><td>1,020,000</td><td>440,000</td></tr>
<tr><td colspan="2">Steel construction</td><td>142,700</td><td>66,200</td></tr>
<tr><td colspan="2">Soil management</td><td>170,150</td><td>102,100</td></tr>
<tr><td colspan="2">Mechanical tunnelling</td><td>217,240</td><td>4,405</td></tr>
<tr><td colspan="2">Special foundation engineering</td><td>980,900</td><td>117,000</td></tr>
<tr><td colspan="2">Rail systems</td><td>10,070</td><td>10,070</td></tr>
<tr><td colspan="2">Masonry work</td><td>3,505</td><td>3,505</td></tr>
<tr><td rowspan="2">Site operation</td><td>General power consumption</td><td>46,075</td><td>930</td></tr>
<tr><td>Water management</td><td>40,000</td><td>812</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="2">Other services</td><td>102,295</td><td>102,295</td></tr>
<tr><td colspan="2">TOTAL</td><td>2,732,935</td><td>847,317</td></tr>
</table>

A.11 Literature

[1] ÖKOBAUDAT Database of the Federal Ministry for Housing, Urban Development and Construction (Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen (BMWSB)), Weblink: https://www.oekobaudat.de/

[2] Tender ready service specifications for the U5-East – Part 1, Hamburger Hochbahn AG, Status: 02/2022

[3] Draft Service Specifications for the U5-East – Part 2, Hamburger Hochbahn AG, handed over on 03/2022

[4] Approximate quantity determination for the U5-Central based on Preliminary planning (VP1), Hamburger Hochbahn AG, Status: 2021

[5] Draft of the approximate quantity determination for the U5-Central based on preliminary planning (VP2), Hamburger Hochbahn AG, Status: 05/2022

[6] Overview of the determination of energy consumption of a tunnelling boring machine and processes for mechanical tunnelling, Hamburger Hochbahn AG, Status: 09/2021

[N.1] DIN EN ISO 14040: Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006 + Amd 1:2017 + Amd 2:2020); German version EN ISO 14044:2006 + A1:2018 + A2:2020, Status 02/2021

[N.2] DIN EN 15978: Sustainability of construction works – Methodology for the assessment of the performance of buildings – Part 1: Environmental Performance; German and English version prEN 15978–1:2021, Status 10/2012

[N.3] E DIN EN 17472: Sustainability of construction works – Sustainability assessment civil engineering works – Calculation methods; German and English version prEN 17472:2020, draft of standard, Status 03/2020