Comparative Climate Assessment of Alternative Tunnel Construction Scenarios

A case study of a service tunnel in the Otterhällan subproject, part of Västlänken

Master's thesis in Infrastructure and Environmental Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2026
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Abstract

The construction and civil engineering sector accounts for approximately 20 percent of Sweden's total share of greenhouse gas emissions. These may involve road and rail infrastructure which contribute both through emissions from traffic and production of materials and construction activities. Trafikverket has therefore set national goals to achieve a climate neutral infrastructure by year 2040, with interim reduction targets along the way, such as a reduction of 60% by 2030. The aim of this study is to analyze how the choice of materials can influence the climate impact in a tunnel production process, by focusing on a case study within the Västlänken project, service tunnel 202 in the sub-project Otterhällan. The study was carried out through a scenario-based comparative analysis using Trafikverket's climate tool, Klimatkalkyl, Environmental Product Declarations and project specific data. The optimized scenario resulted in the lowest climate impact, with a reduction of 30 percent compared to the reference scenario, which was insufficient to meet Trafikverket's climate target for 2030. The results also show that shotcrete and rock bolts account for the biggest emissions in the tunnel, where cement- and steel-based materials dominate the climate impact. Furthermore, the results highlight that using 4D-reinforced shotcrete instead of 3D result in a reduction of emissions by 4,3-tons CO_2 with no additional cost, while using PC-bolts instead of rebar bolts result in a reduction of 9,3-tons CO_2 and a 92 percent increase in material cost, despite the rebar bolt being made of recycled steel. Simultaneously, PC-bolts contribute to a safer working environment and a reduction of 41 percent in labor, machinery and CO_2-related costs. The results therefore highlight that climate optimization should be balanced out with cost and feasibility aspects. Additionally, material optimization alone is unlikely to achieve future climate targets, highlighting the need to integrate technologies targeting the production process of cement and steel, such as CCS and HYBRIT, in order to decrease carbon emissions more effectively.

Keywords: Rock Tunnel, Shotcrete, Rock Bolt, Klimatkalkyl, Greenhouse gas emissions, Climate Optimization, Life Cycle Assessment (LCA), Environmental Product Declaration (EPD), HYBRIT, CCS

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Mari & Amanda, Gothenburg, June 2026

Definition of Terms

Klimatkalkyl: Trafikverket's tool for calculating climate impact and energy use from infrastructure projects throughout their life cycle.

EPD: stands for Environmental Product Declaration, which is a standardized document and presents the environmental impact of a product over its entire life span.

GWP: stands for Global Warming Potential and measures how much a greenhouse gas contributes to global warming compared to CO_2.

Hydraulic fracturing: is a method where fluid under high-pressure is injected into rock to create fractures and improve permeability.

Clinker: a product in cement production which is formed by heating limestone and other raw materials in a furnace.

LCA: stands for Life Cycle Assessment and is a method used to evaluate the environmental impact of a product or project throughout its life cycle.

3D fiber: three-dimensional fiber reinforcement structure.

4D fiber: a smart fiber structure designed to adapt to changes in its environment.

CCS: stands for Carbon Capture and Storage, which is a technology used to capture and store carbon dioxide emissions to reduce their release into the atmosphere.

ASEK: Trafikverket's framework for cost-benefit analysis and socioeconomic assessment.

Service tunnel: a tunnel used for maintenance, access and technical operations.

Shotcrete: a concrete mix sprayed onto a surface at high velocity and used for reinforcement.

Rock Bolt: a steel anchor installed in rock to improve stability and reinforce rock masses.

EvoZero: a near-zero carbon cement which is produced by using carbon capture and storage technology.

HYBRIT: a fossil-free steelmaking initiative that uses hydrogen instead of coal in the steel production process.

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1 Introduction

This chapter presents the background, aim, objectives and delimitations of the thesis, followed by an overview of the structure of the report.

1.1 Background

The construction and civil engineering sector have a significant impact on greenhouse gas emissions and accounts for 20 percent of Sweden's total greenhouse gas emissions (Fossilfritt Sverige, 2024). Projects which involve road and railway infrastructure have a large environmental impact over their lifetime, not only through emissions from traffic, but also through emissions related to the production of materials, construction activities and energy use (G. Andrea Penaloza, 2024).

Tunnel projects require large amounts of materials and energy compared to different types of infrastructure (G. Andrea Penaloza, 2024). They play an important role in the city's transport infrastructure, as road and railway networks are expanding and require improvement due to higher populated cities (A. Sjölander V. B., 2023). Tunnels allow different types of transport to pass through mountains, beneath water or densely built urban areas where on ground constructions would be highly disruptive or be technically challenging. Several studies have shown that the production and construction phases are the biggest contributors to emissions in tunnel projects (G. Andrea Penaloza, 2024). It is especially the use of conventional cement and concrete which stands for the largest sources.

The importance of reducing emissions from tunnel constructions is emphasized by Trafikverket (the state administrative authority of Sweden) and their climate targets. They are responsible for providing specialist expertise in the bridge and tunnel section, which involves developing methods for management, technical requirements and lead research or development efforts (Trafikverket, 2023). Trafikverket has implemented tools in infrastructure projects to achieve climate reduction from construction, materials and maintenance (Trafikverket, 2026). The goal is to reach a climate-neutral infrastructure by 2040, with some reduction targets along the way. A calculation tool "Klimatkalkyl" is used to evaluate the effect of different reduction measures. There is a large and comprehensive European legislative package, called "Fit for 55" and is aimed to reduce the net emissions in EU with 55 percent to 2030 compared to 1990 and reach a climate neutrality 2050 (Europeiska rådet, 2025). For tunnel projects, fit for 55 will have an effect with driving the development of legislation, energy systems, materials markets and technical solutions, while Trafikverket's climate targets are the ones that govern how the climate impact of the project is calculated and reduced in practice. These climate targets are especially relevant for large infrastructure projects which involve extensive tunnel construction.

An example of this is Västlänken, which is an underground railway project in central Gothenburg and is designed for commuter and regional train traffic (Trafikverket, 2023). It is a part of the national plan for the Swedish transport system and the West Swedish Agreement (Trafikverket, 2021). The project expects to promote regional growth and an expansion of the labor market. Improved rail connections will reduce travel times for commuters, which makes it easier for people in Gothenburg and western Sweden to access jobs both within the city and in surrounding areas (Eriksson, n.d.). Approximately eight kilometers will consist of railways, of which more than six kilometers are constructed in tunnels under the city (Trafikverket, 2023). There will be three new underground stations at Korsvägen, Haga and Gothenburg central station. Full-scale Västlänken is expected to operate by 2030, except Gothenburg central station which will open in the end of 2026 as an endpoint station (Trafikverket, 2023).

Against this background, the master's thesis is conducted in collaboration with Trafikverket as part of their work to reduce the climate impact of infrastructure projects. A service tunnel with a work name of "ST202" in the sub-project Otterhällan, a part of Västlänken, is the case study of this master thesis. This tunnel is constructed in rock, meaning that the rock mass forms the main load-bearing system (Trafikverket, 2025). The study focuses on the tunnel's design phase, which includes dimensioning, material selection and blasting methods. There will be three types of scenarios, a reference tunnel which is based on default values from 2015 that are obtained from Klimatkalkyl, a conventional configuration and an implemented configuration, both of which are based on Environmental Product Declaration (EPD) values from the service tunnel. Climate impact from the three tunnel scenarios will be computed and compared to each other to see how well the different building components in the tunnels perform from a climate perspective in greenhouse gas emissions.

1.2 Aim and Objectives

The aim of this study is to compare the climate impact of three tunnel construction scenarios which are based on material quantities of the service tunnel in the sub-project Otterhällan and to evaluate the potential climate savings of optimized technical solutions.

The following objectives should be answered:

- Identify the most critical steps and material selection in the production process of a standard rock tunnel with regard to the climate impact.

- Define and evaluate relevant climate optimization measures.
- Quantify and compare the climate impact across three scenarios: a reference tunnel, a conventional configuration and an implemented configuration, using the Klimatkalkyl tool.
- Assess the potential of contributing to the transport sector’s climate goals with the optimization measures.
- Discuss the applicability of the results from the selected optimization methods to future tunnel projects.

1.4 Delimitations

To keep the scope of the thesis manageable and allow for sufficient depth of analysis, a number of delimitations have been developed. These will ensure that the focus remains on the aspects of the Västlänken project that are most relevant to the research objective.

The study is limited to evaluating the climate impact, quantified by the Global Warming Potential (GWP, expressed in CO_2e), as well as cost assessment of selected climate optimization measures within the rock-tunnel building project. The cost assessment will only be applied in scenario 2 and 3, thus the first scenario’s components are just standards, resulting in no specific material costs to provide. It will be limited to the planning phase, as the main source of impact is expected to come from the selection of materials, design choices and selected construction process methods. Therefore, the operational and maintenance phase will not be included in this analysis. The focus will be on the materials and construction processes that will be identified as the main contributors to the overall climate impact. The drill and blast method will be discussed, but no in-depth analysis of mass-handling will be included. The study will further be limited to rock tunnels, not considering the stations, installations and railway systems as they involve different technical systems and fall outside the scope of this thesis.

The thesis will be based on project documentation, literature and information from stakeholders and companies related to the field, along with necessary assumptions. Some parameters may be simplified or estimated due to the study being conducted at an early planning level, these will be clearly identified and discussed in the report and the effects they have on the results will be considered. Furthermore, the work will be conducted within a Swedish regulatory and project framework and does not consider tunnelling practices or requirements in other countries.

2 Climate Assessment and Optimization in Rock Tunnel Construction

This chapter presents the theoretical foundation for the study, which includes information about rock tunnel construction, climate assessment methods, data sources, Trafikverket's climate requirements and optimization measures for tunnel construction. Cost management will also be addressed.

2.1 Rock Tunnel Construction

The process of building rock tunnel constructions is complex and aimed at supporting and creating underground spaces like railways and roads (Skanska, 2023). In the design phase of building rock tunnels, the planning is guided by measures that are adapted to the actual quality of the rock (U. Lindfors, 2024). First step of this phase is to understand the characteristics of the mountain which creates the foundation for continued work through geophysical measurements, hammer and core drilling. The rock is analyzed by looking at fracture systems, rock types and water flow to ensure that the assumed design assumptions are correct. There is a central strategy called the "observational method" where the behavior of the rock is observed and, if necessary, the technical solution is adjusted if the conditions are different from what was expected (U. Lindfors, 2024).

There are different types of tunneling techniques and the two most common ones are the drill and blast method and a Tunnel Boring Machine (TBM) (ITA, 2000). A TBM drills a completely circular tunnel and depending on the type of function the tunnel is intended for, there may be unused spaces (Trafikverket, 2023). The consequence is an unnecessarily large amount of rock extraction, which leads to more transport and higher environmental impact. There is also an economic limit to the machine, as the method is not considered to be price competitive for shorter tunnels. A rough estimate is that the tunnel length needs to be longer than 4 km for TBM to be an economically viable alternative. See Figure 1 for an example of what a TBM might look like.

Figure 1 Tunnel Boring Machine, AI generated picture

Drill and blast, on the other hand, is the most common one in Sweden and has more flexibility in execution (Trafikverket, 2023). The work can be continuously adapted to local conditions, such as changing rock quality or too little rock cover. A major challenge with blasting, however, is the vibrations that can affect nearby buildings. This requires extensive risk analysis and control programs. Alternative techniques such as wire sawing or hydraulic fracturing may be needed in very sensitive areas instead of blasting (Trafikverket, 2023).

2.1.1 Drill and blast method

The drill and blast method is defined as a natural work steps cycle (Skanska, 2023). Before the blast begins, sealing is performed to prevent water from leaking into the tunnel, which could lower the groundwater level in the surrounding area. Holes are drilled into the rock and then cement mortar is pumped in under high pressure to fill cracks in the rock. Hundreds of holes are then drilled according to a predetermined pattern and are filled with explosive material (Skanska, 2023).

The most common explosives are based on ammonium nitrate and are sensitized when pumped into the borehole, which increases safety during handling (Trafikverket, 2016). These explosives are connected to an ignition system which takes place in a carefully planned sequence where millisecond delays are the most common ones, especially with electronic igniters, to control the blasting process, reduce vibrations and get a more controlled result (M.B. Lovitt).

The blasting begins with a technique, often called as a “burn cut” and the purpose is to create a free face with a void where the blasted rock can expand (M.B. Lovitt). This is necessary for the rest of the blast round to work effectively and the remaining holes in the round could be detonated toward this free space. Step by step, the rock will break towards the free face, which creates a more controlled excavation. The tunnel is ventilated after the blast has detonated to remove blast fumes and other harmful gases (M.B. Lovitt). The remaining blasted rock is then transported away from the tunnel, and the loose rock (scrap) is cleared from the tunnel (Skanska, 2023). See Figure 2 as an example of how the method could look like.

Figure 2 Drill and Blast Method, AI edited picture

When it comes to different types of support elements in tunnels and underground mines, rock bolts are the most common ones (Li, 2017). Their main purpose is to tie the rock together to help stabilize the fractured parts so the rock mass can support itself, which is often done together with mesh and shotcrete. Within the Swedish infrastructure, the so-called SN-bolts are the most frequently used ones, today referred to as fully grouted rebar bolts (Gustavsson & Spijkerman, 2024). This represents a method that has developed over several decades and requires manual installation of the bolts, where the borehole is filled with cementitious grout prior to installation, after which the bolt is pushed into the borehole, leading to spillage of the excess grout. See Figure 3 as an example of what a rebar bolt could look like.

Figure 3 Rebar Bolt, AI edited picture

It is stress conditions which determine the design of the tunnel (Li, 2017). In shallow tunnels with stress, bolts mainly carry the loose block's weight. In the opposite with high stresses in deep tunnels, the rock can both deform or break, therefore, the bolts need to be able to absorb energy and resist deformation. The length and spacing of bolts are an important factor and should extend further than the fractured zone and be secured in unbroken rock mass, which is usually at least about one meter. (Li, 2017).

When using the drill and blast method, shotcrete together with rock bolts will form the main support system (Sjölander, 2020). Shotcrete is sprayed concrete onto the rock surface under high pressure, where it gains strength quickly and acts as a protective layer. Figure 4 shows a shotcrete machine from the service tunnel.

Figure 4 Shotcrete Machine, own image from the service tunnel

Shotcrete also improves the contact and seals the rock surface and stabilizes smaller rock blocks between the rock bolts. Together with the bolts, they transfer loads through adhesion and their own bending and shear strength. The thickness of shotcrete in tunnels is often around 50 to 150 millimeters which depends on the rock quality. For example, thicker layers are required in weaker rock. When it comes to tunnel applications, shotcrete is reinforced with steel fibers, which helps improve the strength of the material, along with its load-bearing capacity and ability to absorb energy, making it especially suitable for rock support systems (Betongindustri, n.d.). See Figure 5 of an example of how steel fibers look like.

Figure 5 Steel fibers, AI generated image

The third part of the support elements is mesh and acts like a complementary element to shotcrete and rock bolt to form a combined stabilizing system (ITA , 2009). It will help prevent bigger rocks from falling and improve safety for workers.

2.2 Climate impact of tunnel project components

A large share of construction-related emissions come from the production of energy-intensive materials, such as steel and concrete. In Figure 6 the climate impact of a standard service tunnel is illustrated. The distribution is based on data from Trafikverket's Klimatkalkyl and is representative of a typical Swedish service rock tunnel.

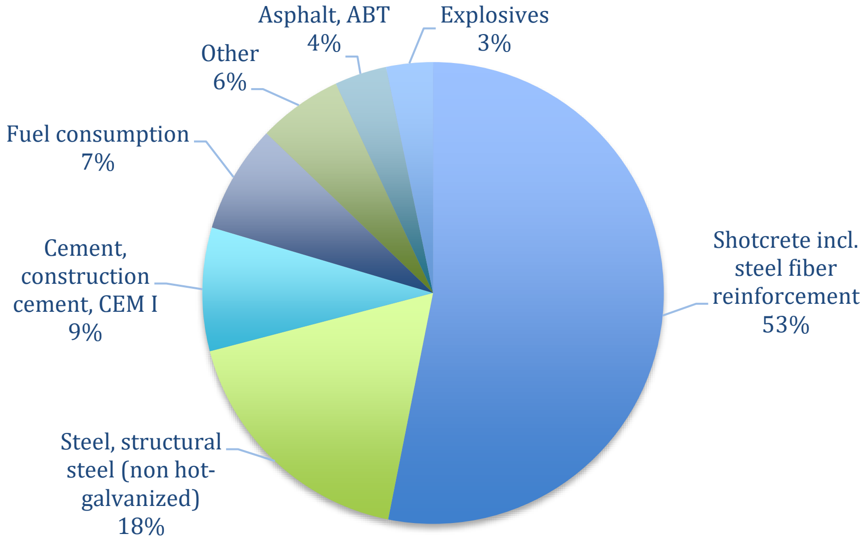

Figure 6 Climate Impact of a Standard Service Tunnel

The results show that shotcrete is the main contributor, accounting for approximately 53%. The high climate impact can be explained by its high cement content, which is mainly due to both the chemical decomposition of limestone and energy-intensive heating processes (Andrew, 2019). Cement contains a wide variation of clinker, and it is the production of clinker that is the main contributor leading to the process of CO_2 emissions (Intergovernmental Panel on Climate Change (IPCC), 2000).

The second highest contributors of emissions come from steel, accounting for approximately 18% of emissions. Steel production is highly energy-intensive and relies on fossil fuels, whereas surface treatments contribute also to a lesser extent (Jernkontoret, 2018). In this case, the steel used is not hot dip galvanized, meaning that additional emissions from surface treatment are limited, with a default emission factor of 2,27 kg CO_2/kg, compared to hot dip galvanized steel with an emission factor of 2,6 kg CO_2/kg (Trafikverket, n.d.). Construction cement used for injection grouting and fuel consumption also contributes significantly to the climate impact, with around 9% and 7% in total, respectively. The fuel category represents the fuel consumed during construction activities and machinery operation, which is a combination of HVO100 and fossil diesel.

The climate impact distributed by the components of a tunnel project are represented in Figure 7 below, in order to further understand the origin of the material-related emissions.

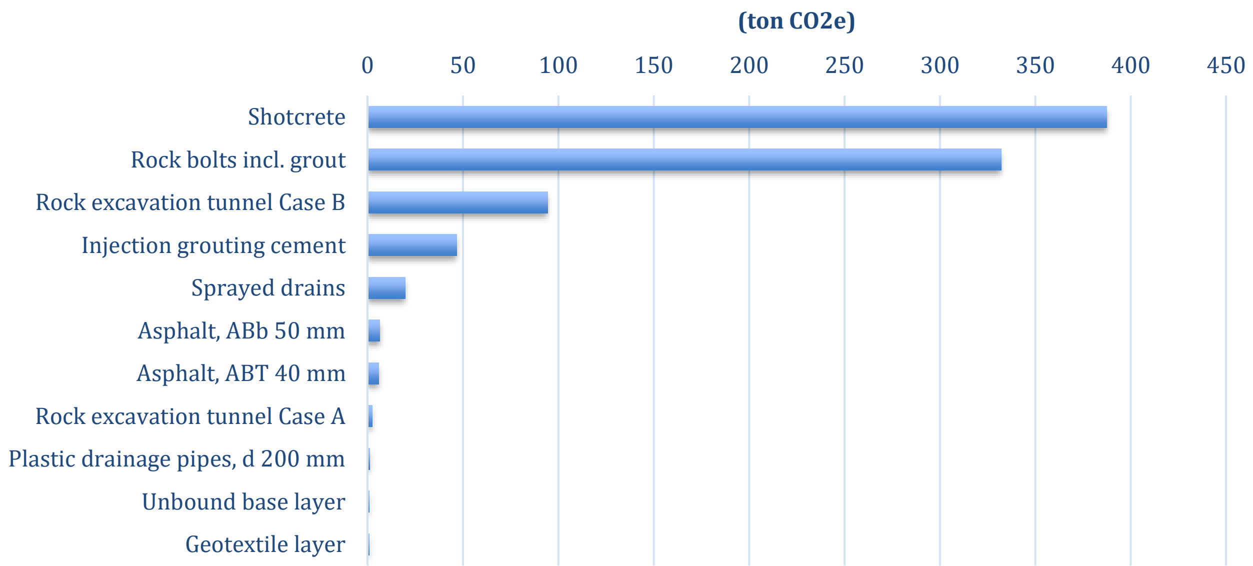

Figure 7 Climate Impact of a Standard Service Tunnel

The results show that shotcrete and rock bolts including grout are the largest contributors, followed by rock excavation activities and the cement used for injection, that also represent a significant share. The high contribution from rock excavation is particularly due to the use of explosives and diesel-powered equipment. The most commonly used explosives in tunnel construction are based on ammonium nitrate, which is associated with environmental impacts such as greenhouse gas emissions and nitrogen-related pollution (Trafikverket, 2016). High emissions of nitrogen compounds that occur during the production and use of these explosives also cause the formation of photochemical oxidants, soil acidification and human toxicity (Huang., 2014). Another source is the handling and transport of excavated rock masses. Different scenarios are defined as Case A and Case B. According to definitions provided in Klimatkalkyl version 8.0, Case A represents projects where the excavated rock can be deposited close to the construction site, resulting in relatively low transport distances. In contrast, Case B represents projects located in more constrained environments, where the rock masses need to be transported longer distances.

On the other hand, components such as drainage systems, geotextiles and asphalt have a relatively minor impact. This can be explained by their relatively low material quantities and, in some cases, less energy-intensive production processes compared to major contributors such as steel and cement-based materials.

2.3 Life Cycle Assessment Framework

This section presents the theoretical framework related to life cycle assessment, environmental product declaration and data sources used to conduct this study.

2.3.1 Life Cycle Assessment (LCA)

In order to analyze this impact and identify suitable measures for optimization, Life Cycle Assessment (LCA) methodology is applied, which relies on Environmental Product Declarations (EPDs) for construction products. These are developed using the EN 15804 standard, which ensures that all the environmental data is transparent and comparable, by dividing the life cycle into specific modules and enable systematic analysis (Circular Ecology, n.d.), see Figure 8.

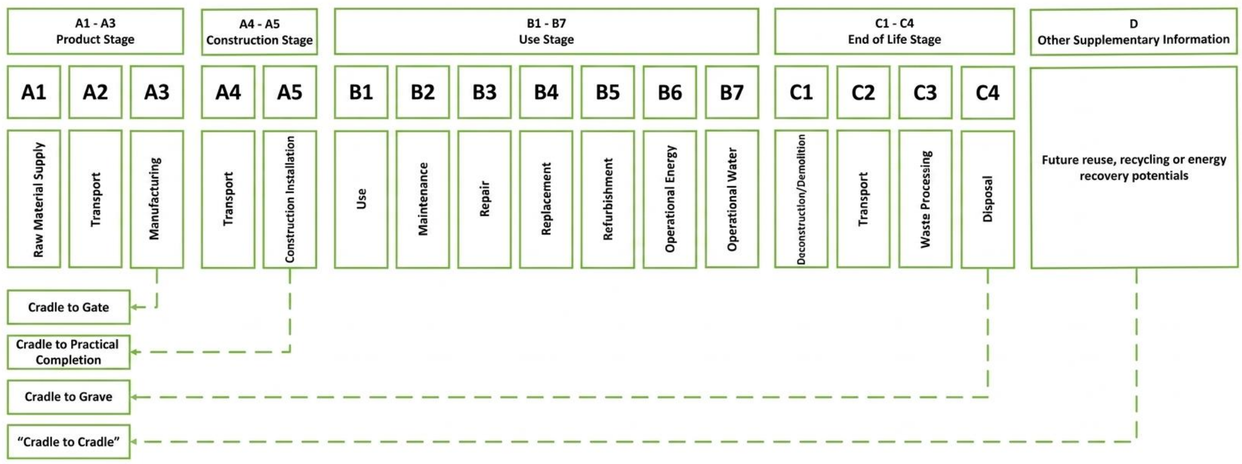

Figure 8 Life cycle stages and system boundaries for construction productions according to EN 18054 framework. Source: Circular Ecology

Within the LCA framework, the emissions from the product stage are divided into modules A1-A3, which typically are the largest contributors to emissions in tunnel projects, the reason being that high energy and material intensity is present due to the used materials.

2.3.2 Environmental Product Declarations (EPDs)

An EPD is a standardized document that provides information on the environmental impact of a specific product throughout its lifecycle and is therefore an important source of information to conduct an LCA (Boverket, 2024). These are usually developed in accordance with certain standards and typically include environmental indicators that quantify emissions, one of which is the Global Warming Potential (GWP), which is used to quantify greenhouse gas emissions. It should however be noted that updates have been made to the newer versions of EPDs, where climate indicators such as GWP-fossil (emissions from fossil carbon sources), GWP-biogenic (emissions related to biogenic carbon) and GWP-luluc (emissions from land use and land use change) have been added. Although aggregated indicators such as GWP-total enable comparison, this difference makes direct comparisons between EPDs developed under different versions require careful interpretation. (Trafikverket, n.d.).

To ensure reliability, Trafikverket has several requirements that EPDs must meet. They should for instance comply with product-specific rules for environmental declarations according to the EN 15804 standard, be third-party verified in accordance with ISO 14025 and be valid at the time of product use (Trafikverket, 2022). In addition, the EPD must be technically and geographically representative of the specific product and supplier, rather than industry averages, to ensure results that are accurate and relevant for the project.

In case of differences between product-specific climate performance and default emission factors from Klimatkalkyl, Trafikverket allows the use of verified EPDs to improve the accuracy of climate assessments (Trafikverket, 2021). The review and approval of these can be done within the Klimatkalkyl tool itself and thereafter be linked to adjusted emission factors, allowing projects to account for product-specific data and showcase verified emission reductions.

2.4 Klimatkalkyl Methodology

This chapter is about the methodology of Trafikverket's tool Klimatkalkyl that is used in climate impact analysis, as well as the emission factors that are applied to quantify the impact.

2.4.1 Klimatkalkyl

Klimatkalkyl is the official tool of Trafikverket for the calculation of energy use and climate impact of transport infrastructure from a life-cycle perspective (Toller, Norberg, & Westerberg, 2024). The tool is mainly used as support for decision making, enabling systematic climate improvements and comparing alternative technical solutions throughout various stages of infrastructure projects, such as planning and implementation (Trafikverket, 2022). It can also be used in both full investment projects and individual components. It is based on LCA methodology and applies emission factors together with resource templates and project-specific input data to estimate the total greenhouse gas emissions, expressed as CO_2-equivalents.

The climate impact is calculated primarily based on predefined building components, mainly representing raw material extraction, transport and manufacturing processes (A1-A3). However, the tool itself also includes construction and maintenance activities, including both operations that are ongoing and replacement of components (Trafikverket, 2022). Transport processes are included both within the material production chain and those generated within the construction process. In recent versions of the tool, transport from production sites to construction sites is explicitly included. It should also be noted that certain limitations exist, such as the exclusion of various types of emissions from the use phase, for example traffic-related emissions, along with full end-of-life processes as the complete decommissioning of infrastructure is considered uncommon (Trafikverket, 2022).

2.4.2 Emission factors

Emissions factors are the main component of the Klimatkalkyl model (Toller, Norberg, & Westerberg, 2024). The tool applies predefined emissions factors, formally decided by Trafikverket in order to quantify the climate impact and energy use associated with materials, fuels and construction processes. The primal formula used for this process is based on multiplying quantified resource use by the corresponding emissions factor:

$$\text{Climate impact } (CO_2e) = \text{Resource quantity} \times \text{Emissions factor}$$

The emission factors used in Klimatkalkyl include upstream and direct impacts, meaning that they cover emissions from raw material extraction, processing and transport, as well as the manufacturing process (Trafikverket, 2024). In version 8.0, which is the latest version, the emissions factors have been revised and complemented, primarily based on more transparent data sources such as EPDs. The reference values currently represent the year 2015, as they are aligned with Trafikverket's climate requirement targets, while corresponding values for 2020 are available for reporting and aggregated assessments. This standardized approach ensures methodological consistency across projects and planning stages.

2.5 Trafikverket’s climate requirements

Trafikverket is working to achieve a climate-neutral infrastructure by 2040, regarding being in line with both Sweden’s national climate targets and international ones (Trafikverket, n.d). The work is based on a life cycle perspective, where climate impact is included from raw material extraction, processing and delivery to construction, as well as operation and maintenance. To enable the achievement of the goals, there are clear interim targets along the way for reduced climate impact compared to 2015 levels (Trafikverket, n.d). In 2025 with a reduction of 30 percent, in 2030 with 60 percent and in 2035 with 80 percent. To verify and follow up on the requirements, Trafikverket’s Klimatkalkyl is primarily used, where verification is carried out through EPDs, climate declarations and digital reporting. These goals are translated into concrete requirements in procurements by contractors, consultants and material suppliers and are divided into three main categories (Trafikverket, n.d):

1. Requirements for percentage emission reduction and climate declaration where the supplier must reduce emissions compared to a set baseline (Trafikverket, n.d). This is introduced for projects with a total cost ≥ SEK 150 million and a climate declaration is mandatory for all investment projects ≥ SEK 50 million.

2. Requirements for specific products and materials that have demonstrated a large climate impact, such as concrete, steel, reinforcement and asphalt (Trafikverket, n.d). All projects have accounting requirements that are presented as an EPD, together with performance requirements that show maximum permitted emission levels.

3. Requirements for 100 percent renewable fuels for work machines and vehicles apply from 2030 regardless of the size of the projects (Trafikverket, n.d). Several step targets are set as requirements and gradually increase over time (T. Olsson from Trafikverket, personal communication, 2026). During the period 2024 to 2025, at least 50 percent of the total fuel must be renewable. For 2026 to 2027, the requirement is raised to at least 70 percent, and during 2028 to 2029, it must be at least 90 percent renewable.

2.6 Optimization measures

This chapter presents various climate-optimized solutions for tunnel constructions that include both material and blasting optimization.

2.6.1 Optimization of shotcrete design and material composition

To be able to improve the shotcrete in terms of climate considerations, the choice of material is one of the most important factors (W. Aldrian, 2022). As already explained in section 2.2, the reason behind is cement and clinker's share of emissions, which accounts for two-thirds of the total CO2e caused by the construction of a new tunnel. Since cement is the largest source of emissions in concrete mixes, reducing clinker content is the key strategy to lower the emissions. Portland cement clinker has a very high GWP-value, but with additive material which replaces parts of the clinker, the emissions could be reduced dramatically (W. Aldrian, 2022). Some highlighted materials are AHWZ (hydraulically active additives and contains blast furnace slag and fly ash), limestone powder and calcined clay. It should be noted that higher strength concrete is often more clinker efficient, because it requires less clinkers per MPa of compressive strength and unit volume (W. Aldrian, 2022).

When it comes to grouting with specific recipe, standard cement can be replaced with special mixtures such as CEM II/A-V 42.5N which contains 15% fly ash leading to a reduction of emissions from the grouting process by approximately 19% (G. Andrea Penaloza, 2024). Concrete manufacturers today are actively working to optimize recipes that are based on current standards, which have gradually been opened to allow higher proportions of alternative binders (Svensk betong, 2025). The aim of optimizing is to use exactly the amount of binder which is required to achieve the given strength class and durability. Figure 9 shows the difference in appearance between cement and fly ash.

Figure 9 Cement vs fly ash, AI generated picture

However, further optimization through a higher number of alternative binders in cement is challenging in shotcrete applications, due to concretes with alternative binders generally gain slower early strength development than conventional mixes (Representative from Thomas Betong AB, personal communication, 2026). This becomes especially critical for shotcrete, where its fast and early strength is a key functional requirement. A possible explanation is that slag is not usually used together with construction cement FA (fly ash) in concrete, even though this combination could be a solution to further reduce climate impact (Representative from Thomas Betong AB, personal communication, 2026).

Different types of reinforcement play a big role in impacting both material quantity and for the climate (J. Golser, 2022). By using steel fiber reinforcement instead of traditional reinforcing mesh and lattice arches, the total concrete thickness can often be reduced, the work cycle shortens and thus improve the carbon dioxide balance. Although, the use of fiber-reinforced shotcrete in tunnel constructions is still associated with a significant climate impact, which makes the choice of material and fiber dosage crucial to reduce the carbon dioxide emissions (A. Sjölander A. A., 2023).

The climate footprint of fibers is usually calculated per kilogram material, which makes the total climate impact dependent on the amount of fibers added per cubic meter shotcrete (A. Sjölander A. A., 2023). A lower dose of fibers could therefore contribute to lowering the emissions, if the technical requirements are achieved. This is possible through more reliable design and testing methods, for example panel test according to ASTM C1550, which measures the flexural toughness and energy absorption of fiber-reinforced concrete (A. Sjölander A. A., 2023). The aim is to evaluate the ability of concrete to carry loads and absorb energy after the first crack has occurred, which is a critical stage for rock supports in tunnels where the material must be able to deform without failing. With better data to assess the actual performance of shotcrete, the amount of fiber could be adjusted more precisely, without compromising structural safety. This means that overdesign could be avoided and with a more resource-efficient material use (A. Sjölander A. A., 2023).

One thing of great importance is the choice of fiber type (A. Sjölander A. A., 2023). Within tunnel construction, 3D fibers have long been the conventional reinforcement material for shotcrete (Representative from Thomas Betong AB, personal communication, 2026), but have gradually been replaced by more advanced steel fibers, such as Dramix 4D, which has shown higher efficiency compared to 3D fibers and especially at larger deformations where the residual strength is crucial (A. Sjölander A. A., 2023). The steel fibers have hooked ends that provide direct resistance, allowing the concrete to still carry load even after cracking. 4D fibers have an extra hooked end compared to 3D, resulting in better anchorage and stronger steel (Bekaert, 2022). 4D fibers have a higher performance per fiber, which allows them to have the same requirements on energy absorption and to achieve the residual strength with a lower fiber dose (A. Sjölander A. A., 2023). This means that the amount of steel could be reduced, which in turn reduces total CO_2 emissions. Figure 10 shows the difference between 3D and 4D fibers.

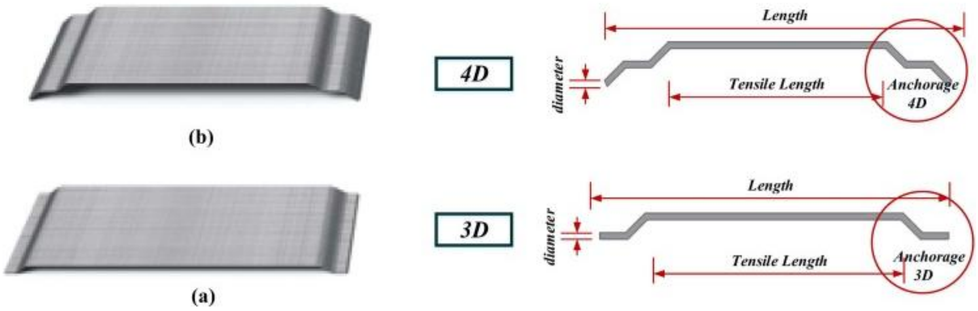

Figure 10 3D vs 4D fibers. Source: Sheikh, Katkhuda and Shatarat (2025)

There are also solutions where the focus is not on the choice of cement material itself, but on the production of the cement material. As mentioned earlier in chapter 2.2, the production of cement is what drives the climate impact the most in tunnel constructions and there is now a solution to the problem, called EvoZero cement. It is a revolutionary technology from Heidelberg Materials that aims to achieve net emissions from the production of cement by using CCS (Carbon Capture and Storage) (Heidelberg Materials, 2025). Through this technology, Heidelberg Materials also wants to contribute to stronger demand with a significantly lower climate footprint for building materials to strengthen the development towards a more sustainable sector (Heidelberg Materials, 2025).

The factory captures around half of the carbon dioxide which is released during cement production, and these are emissions that cannot be removed by simply changing the fuels, because a large part of the emissions come from the chemical process itself when limestone is burned (Heidelberg Materials, 2025). This reduction will then be distributed between different cement products, enabling various options with varying climate impacts. Everything from traditional cement without reduction to products with a significantly lower climate footprint and with close to net zero emissions. Customers can then choose products based on a project's specific requirements and sustainability goals (Heidelberg Materials, 2025).

To produce EvoZero cement, carbon dioxide is first captured during cement manufacturing by using an absorber that separates the gas from the factory's flue gases (Heidelberg Materials, 2025). The solution which contains the captured carbon dioxide is then transferred to a regeneration unit, where heat gained from the cement production process is used to separate the carbon dioxide from the liquid solution. The solvent is recirculated back into the system to be reused for further carbon dioxide capturing (Heidelberg Materials, 2025). Next step for the captured carbon dioxide is to be compressed and cooled into a liquid form for a more simplified transportation and storage. The transport is by ship to a temporary storage terminal, before being transferred through pipelines to a permanent storage site. Finally, the carbon dioxide is pumped deep underground beneath the seabed. In these formations, the carbon dioxide can be permanently stored and prevent it from being released into the atmosphere. Thereby, reducing the overall climate impact of cement production will be achieved. See Figure 11 for an overview of this process (Heidelberg Materials, 2025).

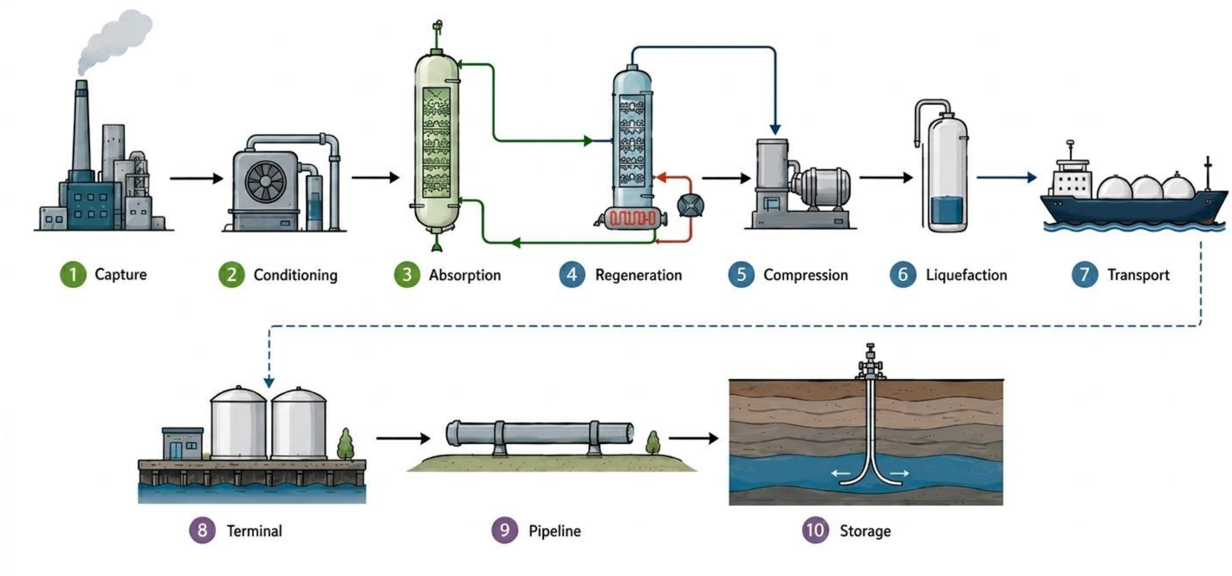

Figure 11 CCS process. Source: Heidelberg Materials. Modified by authors using AI

To ensure that the climate benefit reaches the customer, a certification system, called Carbon Bank, is used where all stored carbon dioxide is recorded digitally (Heidelberg Materials, 2025). This will further be verified by an independent third party to ensure full traceability and avoid calculation errors. The technology is still very new, therefore, prospective EPDs are used to report climate performance before twelve months of full operational data are available (Heidelberg Materials, 2025).

Currently, there is a full-scale plant in Brevik, Norway, which was put into operation in 2025, which is also the world's first full-scale demonstration project for carbon dioxide capture in the cement industry (Heidelberg Materials, 2025). Next in line is, among other things, a corresponding full-scale CCS facility in Slite on Gotland, which is expected to capture over 1.8 million tons of carbon dioxide annually (Heidelberg Materials, n.d). This corresponds to 4 percent of Sweden's total emissions and is to be commissioned in 2030.

The technical properties and function of the cement are not affected as no changes in design solutions, exposure classes or work steps such as drying times are required (Heidelberg Materials, 2025). However, extensive and costly infrastructure is required for the actual transport and storage of carbon dioxide, which means a certain increase in the usual project costs, but CCS is described as very cost-effective in relation to the climate benefit, especially compared to other measures such as electrification of work machines. In addition, current standards and regulations do not always keep pace with technological developments, which requires active cooperation with authorities and organizations to ensure that CCS is fully included in all frameworks (Heidelberg Materials, 2025).

2.6.2 Optimization of rock bolt solutions and material choices

When it comes to rock-bolts, both the steel content and the cement used for grouting are considered among the biggest contributors to the overall climate impact, as described in section 2.2. The traditional method of steelmaking relies on blast furnace technology that uses coal and coke to remove oxygen from iron ore (Lager, Nuur, & Feldmann, 2025). Steel production requires high energy demand and its production process results in large greenhouse gas emissions, alongside emissions from indirect sources, such as the extraction of raw materials, generation of electricity and transportation (Jernkontoret, 2018). The direct emissions generated within the Swedish steel industry, including process and fuel combustion emissions, account for approximately 11% of the total greenhouse gas emissions in Sweden, where the use of coal in the reduction of iron ore accounts for the largest share of emissions.

Fully grouted rebar-bolts are typically made of recycled steel and have undergone extensive studies to increase the use of recycled material, meet the requirements and get them certified (Representative from Pretec, personal communication, 2026). They typically weigh around 4 kilograms per meter per bolt and can be up to 9 meters long with a standard diameter of 25 millimeters (Gustavsson & Spijkerman, 2024). During the installation process, the bolt is pressed into a grout-filled borehole and full reinforcement is only provided when the surrounding grout has hardened, adding an extra step in the process and may therefore require temporary support in the form of extra bolts before achieving the final load-bearing capacity (Design manager of the Otterhällan tunnel, personal communication, 2026). Besides the material inefficiencies of the installation process, it is also physically demanding and may cause material spill on the installation personnel (Gustavsson & Spijkerman, 2024)

To improve the performance and efficiency of conventional systems, alternative solutions have been developed. One such solution is replacing the rebar bolts with PC bolts, which are relatively new and not as established out on the market yet (Design manager of the Otterhällan tunnel, personal communication, 2026). The bolt differs in both design and installation method, compared to traditional systems, less material is required for the production of PC-bolts. They typically weigh around 2,5 kilograms per meter, resulting in a significant reduction in the total amount of steel used for rock bolts in a project, as well as contributing to the improved working conditions during installation (Design manager of the Otterhällan tunnel, personal communication, 2026). The PC-bolt is first placed into the borehole and is equipped with an anchoring body, enabling installation horizontally, as well as vertically in upward-oriented holes (Pretec, 2023). This allows the bolt to carry a certain amount of load temporarily immediately after installation. The grout is thereafter injected within 24 hours through the bolt's tube, spreading from the bottom of the borehole towards the opening, a method that minimizes grout loss and makes it an integrated part of the load-bearing system, rather than being partially displaced and wasted. After being fully grouted, the bolt turns into a permanent support element and a bearing plate is placed in order to ensure structural interaction and load transfer (Pretec, 2023). See Figure 12 for a simplified illustration of a PC-bolt's installation process.

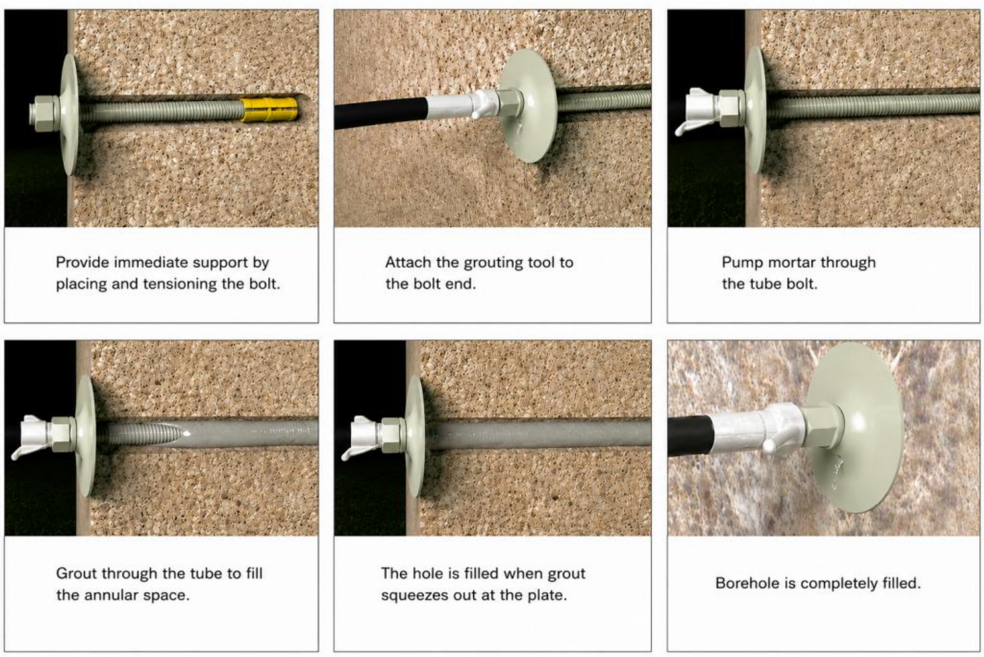

Figure 12 PC-Bolt installation process, adapted from (Pretec, 2023) and modified using AI

PC-bolts are generally produced from conventional steel and a potential area of development to reduce the climate impact of PC-bolts would be an increase in the use of recycled steel, which would, however, require finding steel producers that meet the requirements and get them certified (Representative from Pretec, personal communication, 2026). The consumption and production of steel have increased significantly in recent decades, and both are globally distributed, the share of global trade amounting to 30% of global distribution (Jernkontoret, 2018). This reflects a highly interconnected market, with China being the dominating manufacturer and accounting for the greatest growth, see Figure 13.

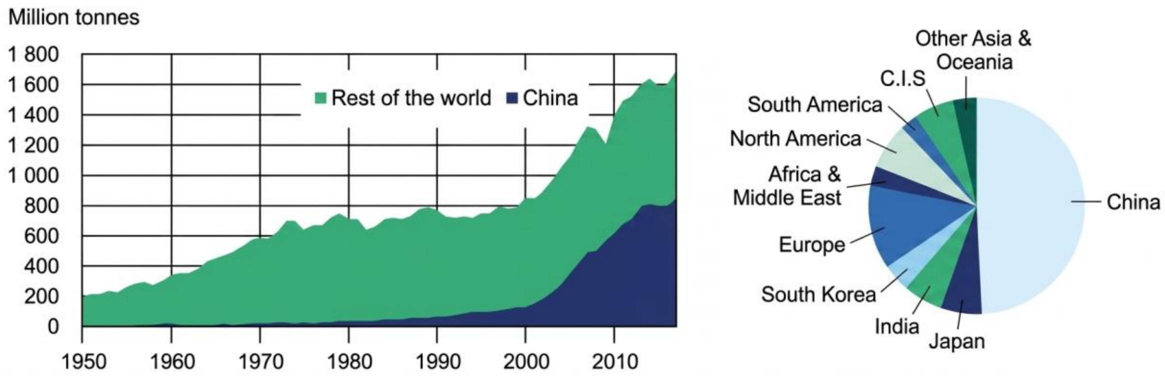

Figure 13 Global crude steel production trend from 1950 to 2018 (left) and regional share of production (right). Highlighting China's growth. Source: Jernkontoret, 2018

The country's share of steel consumption amounts to approximately 45%, while imports to the country are insignificant, suggesting strong domestic production (Jernkontoret, 2018). Alongside the large consumption of their own steel production, significant quantities get exported, which indicates that the steel market is global and subject to significant competition. From an industry perspective, this is reflected in where current steel production for PC-bolts is located, which, according to a representative from Pretec, is in China due to greater control over certification, production processes, quality and capacity (Representative from Pretec, personal communication, 2026). Pretec further suggests that there may be a possibility of moving some of the manufacturing processes to Europe in order to lower the transportation distances, but parts of the raw material are still from global sources, limiting the potential benefits of relocating production. Furthermore, when it comes to bolts, certain dimensions are not of standard steel sizes, which adds further constraints to the material availability.

Considering these limitations, the reduction of climate impact in steel-based products cannot solely rely on changes in supply chains but may require adapting new technologies that aim to reduce the climate impact from the production process itself. One such technology that is already under development is HYBRIT (Hydrogen Breakthrough Ironmaking Technology), which uses hydrogen in the ore-to-steel reduction process, and instead of carbon dioxide this process produces water instead (Jernkontoret, 2018), see Figure 14 below for a simplified process flow for this technology. In the event of successful results, blast furnaces can be phased out and emissions from carbon dioxide in the production process can be ruled out (Jernkontoret, 2018)

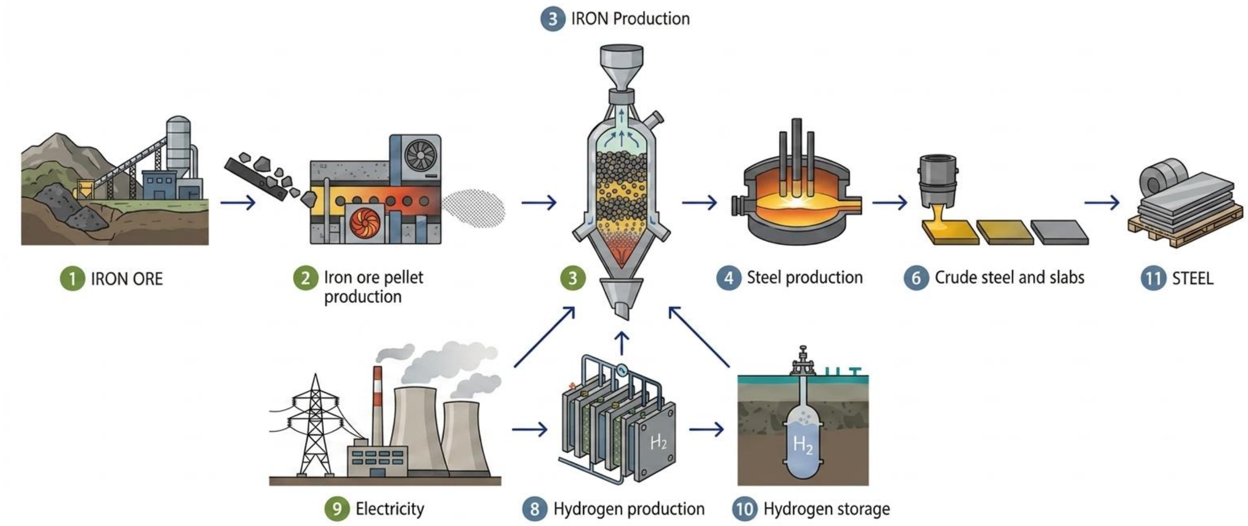

Figure 14 A simplified process flow for HYBRIT technology. Source: HYBRIT Development.

It is a newly developed Swedish initiative and a joint venture between the steel company SSAB, mining company LKAB and energy producer Vattenfall, that has the potential to reduce the country's total carbon dioxide emissions by at least 10% (HYBRIT Development AB, 2024). However, several challenges are involved in the transitioning process into this new technology, both on a technical and societal scale (International Renewable Energy Agency, 2021). These challenges include moving the technology from laboratory and pilot stages to full industrial implementation, providing sufficient renewable electricity production and large-scale hydrogen storage. It should also be noted that implementing this technology would lead to an increased energy demand of about 15 TWh at the current production level (Jernkontoret, 2018). The collaboration between the three ventures covers the entire value chain, from extracting the iron ore to producing finished steel. However, in order to achieve a fossil-free process, the production of hydrogen should also occur without fossil emissions, consequently, Vattenfall's main focus is to supply the process with energy through fossil-free electricity through electrolysis, converted to hydrogen.

Other measures have also been identified for the reduction of climate impact of steel production, these include switching to bio-based fuels and gases in cases where the process is difficult to electrify, as well as the development of biochar as a substitute for fossil coal in certain melting processes (Jernkontoret, 2018). Furthermore, steel is a type of material with strong circular potential, as no significant property losses of the material occur when it gets remelted several times.

2.6.3 Optimization of drill and blast process

To fully climate-optimize a tunnel, it requires a holistic perspective which focuses not only on the building materials, but also on the processes that drive the construction itself. The three sources of environmental impact during the excavation phase are explosives, diesel and electricity when looking at life cycle assessments (Huang., 2014). By improving these resources, the project's GWP could be significantly reduced.

It is very much about having good control when drilling during excavation. An improved drilling accuracy reduces over-excavation, because very extra centimeters that are blasted outside the theoretical profile must be filled with concrete, which increases the climate footprint unnecessarily (J. Golser, 2022). There is a difference between how the drilling is planned and the actual drilling in the rock, giving an average 3D error of 0.11 meters per meter drilled (J. Navarro, 2019). These deviations are strongly linked to the appearance of the rock structure and are related to sudden changes in the direction of the boreholes. The rig is carefully positioned prior to drilling using a navigation system, while the boom is kept stationary throughout the entire sequence of events. However, the actual path of the drill pipe is not measured, since neither the drill pipe nor the drill bit has sensors. This could result in the borehole still being able to deviate from the planned direction due to, for example, rock structure or bending in the drill pipe, even though the rig is correctly set (J. Navarro, 2019). During the study visit to the service tunnel in the Otterhällan sub-project, it became clear that the drilling machines currently used in the project have very high precision, with deviations of only a few millimeters (Construction manager of the Otterhällan tunnel, personal communication, 2026). The larger deviations that occur are mainly due to variations in the rock, which is very difficult, in practice almost impossible, to control. See Figure 15 which shows a bore rig from the service tunnel.

Figure 15 Bore Rig from the Service Tunnel, own image

When it comes to explosives, a more environmentally friendly alternative is something called Hypex Bio, which is an explosives technology and describes as the world's first explosive that is based on stable hydrogen peroxide emulsions instead of nitrate salts (Hypex Bio, 2026). Production often happens in modular facilities where the explosives activate purely chemically first when the bore holes are loading. The emulsions are possible to adjust based on the customer's needs regarding energy and detonation velocity and can perform the same or even better than conventional techniques (Hypex Bio, 2026).

The biggest advantage of Hypex Bio is its significantly lower environmental impact compared to explosives with nitrate salts, where the usage could reduce the greenhouse gas emissions from blasting with over 90 percent (Hypex Bio, 2026). Without any nitrates in the explosives, neither this nor ammonia will leach into the groundwater, which minimizes the need for costly water treatment (Trafikverket, 2025). Technology also eliminates the formation of gases that are hazardous to health which often occur when ammonium nitrate is used, leading to shorter ventilation times after blasting. Still, in Sweden is Hypex Bio quite new and is a bit uncommon in the industry, which affects the availability of the technology (Trafikverket, 2025).

Today, Hypex Bio is used by the contractor Implenia and has been used in the Haga (Vasastan) section of Västlänken (Trafikverket, 2025). The reason behind this is mainly due to nearby housing and sensitive water environments, which makes it important to minimize hazardous emissions and impact on the environment, and this is something that Hypex Bio can contribute to (Trafikverket, 2025). Trafikverket no longer uses Hypex Bio as there are still several problems and technical solutions to be solved before it can be fully implemented (T. Olsson from Trafikverket, personal communication, 2026). At present, the nitrogen-based explosive is therefore still used as the development of Hypex Bio did not achieve the desired results. At the same time, Hypex Bio is still considered to have potential as an interesting alternative, provided that the technology can be further developed into a practically functional and economically viable solution (T. Olsson from Trafikverket, personal communication, 2026).

2.7 Cost management

A cost calculation tool was used to evaluate the economic impact of different climate improvement measures in the project which is based on principles and calculation values from ASEK 8.1, developed by Trafikverket. ASEK (working group for socio-economic calculation and analysis methods) contains recommended methods for analyzing and standardizing calculation values for socio-economic analyses in the Swedish transport sector (Trafikverket, 2026).

In this study, the ASEK value of 2.93 SEK/kg CO_2-eq was used, which is based on the 2019 price level for the calculation year 2030 and can be found in table 14.1 on Trafikverket's website, called "ASEK 8.1 kalkylbilaga" (Trafikverket, 2026).

The cost management calculation is created in Excel and works as a tool for decision-support where emission reductions can be compared with any additional costs linked to proposed measures (T. Olsson from Trafikverket, personal communication, 2026). The purpose of the model is to be able to assess whether different climate measures are cost-justified or not. Measures with a low cost per reduced amount of CO_2 can be considered more effective from an economic perspective, while those with a high reduction cost may be more difficult to justify if the corresponding climate benefit can be achieved in another way. This enables a comparison between several alternatives and can thus make it easier to prioritize the measures that provide the greatest climate benefit per SEK invested in (T. Olsson from Trafikverket, personal communication, 2026).

3 Case study – Otterhällan

This chapter presents the service tunnel 202, which represents the case study of this thesis. First, the chapter introduces information about the Otterhällan sub-project, following the background and main characteristics of the service tunnel project. More detailed information with particular focus on the tunnel design and selected construction solutions will also be mentioned. Furthermore, this chapter is based on project-specific information and documents provided by the project stakeholders and governing documents.

3.1 Project Otterhällan

Otterhällan sub-project is a part of Västlänken that takes place in the central part of Gothenburg, between sub-project Rosenlund and Stora Hamn-kanalen and covers approximately 500 meters (Veidekke, 2024). Veidekke is the company to which Trafikverket has awarded this project and is carried out as a design-bid-build contract. The project is situated near existing infrastructure like Götatunneln and other underground constructions and involves a double track railway tunnel and two rock service tunnels ST B2/201 and ST 202 (Trafikverket, 2024). In this study, the ST 202 tunnel will be chosen to analyze, see Figure 16 below.

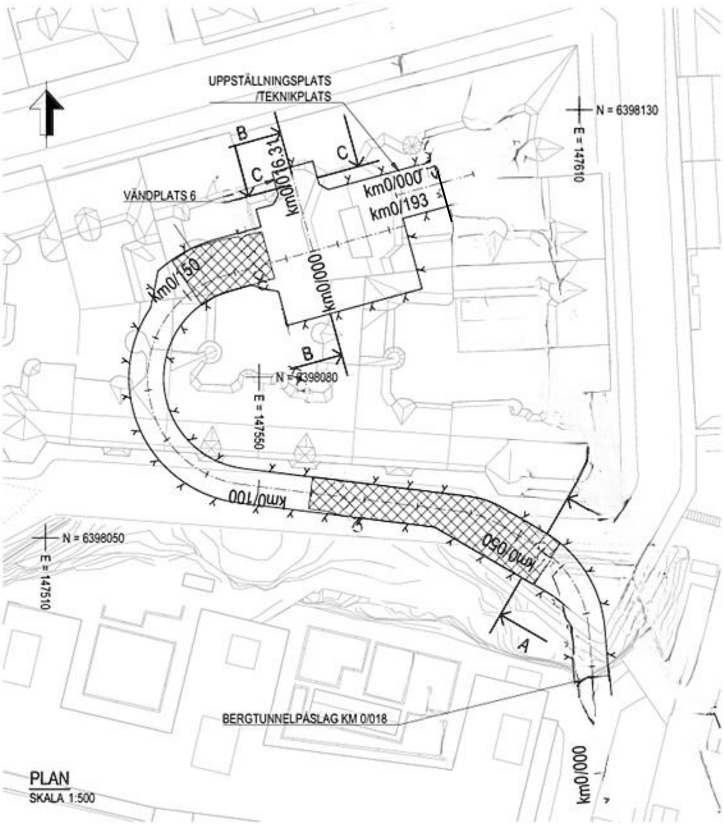

Figure 16 Plan drawing of ST202 based on internal project documentation, Modified by authors

As shown in Figure 17 below, ST202 is approximately a 190-meter service rock tunnel operated from Rosenlundsplatsen (Trafikverket, 2025). A service tunnel is aimed at making the building easier for the main tunnel such as transporting material, personnel, machinery and removing rock masses during the construction stage. The service tunnel will act as support in maintenance work, inspections and emergency exits once the main tunnel is finished. They also give access to ventilation, power and other technical systems (Trafikverket, 2025). The availability of project specific data and implemented reinforcement solutions in this rock tunnel is what made it relevant as a case study for climate impact analysis.

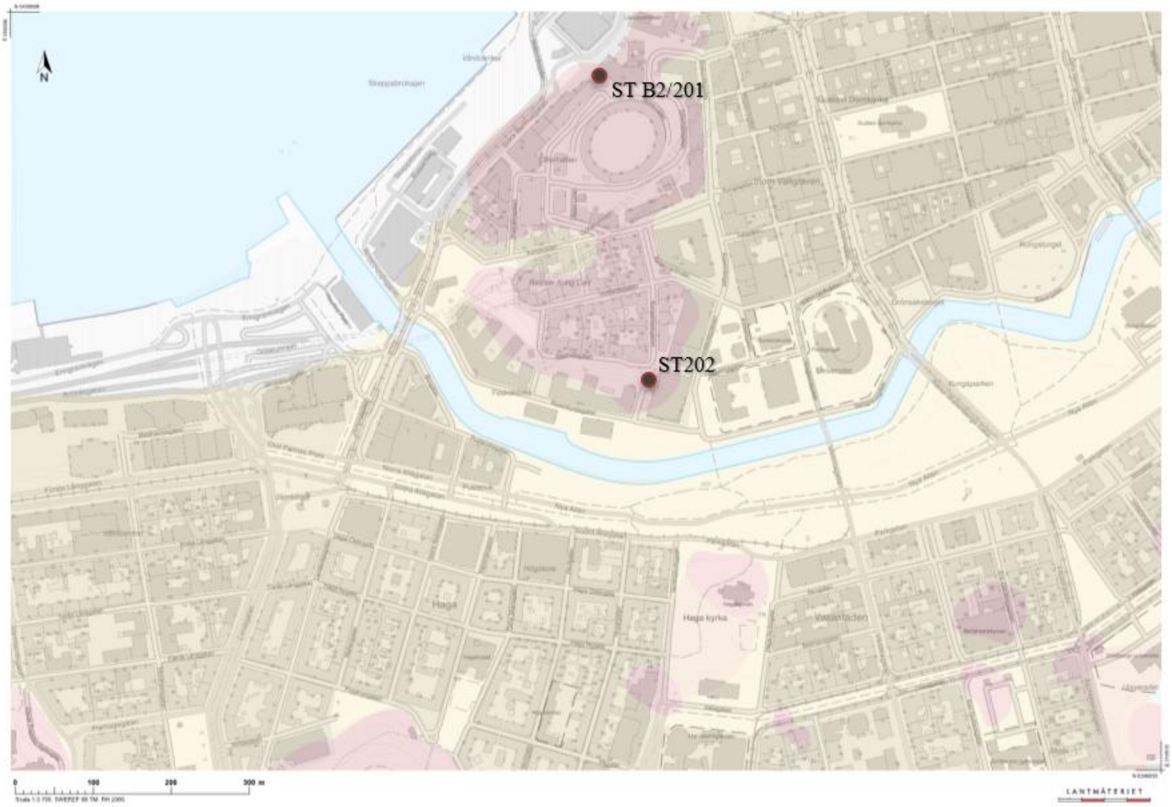

Figure 17 Location of the Otterhällan study area in Gothenburg. Base map: Lantmäteriet. Modified by authors

3.2 Governing documents

When constructing a rock tunnel in Sweden, it is governed by a structured hierarchy of legal, regulatory and technical documents (Trafikverket, 2025). The hierarchy helps to solve potential conflicts between these documents by clarifying which requirement to apply first. In order of a possible conflict, the following order of precedence will be applied:

1. Ordinances, legislation and authority regulations
2. Requirements of tunnel construction (TRVK tunnel)
3. Project specific documents

Together with this general hierarchy of documents, there are also some specified rules for how technical standards should be applied and are called Eurocodes (Trafikverket, 2025). This series must comply with the Swedish authority regulations. There is an internal order for applying Eurocodes and especially if they are governed by national directives and make sure of a compliance between European standards and Swedish safety requirements. The requirements for materials, workmanship and quality control follow AMA Anläggning. It is the standard technical guide within this area, but parts of tunnel-specific rules can be changed or replaced when needed (Trafikverket, 2025).

TRVK tunnel is the main governing document for technical tunnel requirements for planning, designing and building tunnels and is used in the design of both new tunnels and the improvement of existing ones (Trafikverket, 2011). The aim is to ensure that tunnel facilities meet requirements for function, safety and long-term sustainability. Both road and railway tunnels are covered in the document and for rock tunnels, the requirements will be applied regardless of the length of the tunnel (Trafikverket, 2011).

For concrete or steel tunnels, the requirements apply when the tunnel length exceeds 100 meters (Trafikverket, 2011). A central part of the document is the requirements regarding the load-bearing capacity, stability and durability of the structure. This means that the tunnel must be able to carry the loads to which it is exposed, be stable both during the construction phase and operation time and have a sufficient service life without unacceptable degradation (Trafikverket, 2011). The safety class must be defined in the design phase, which ensures the function of the structure throughout its technical life. Loads such as rock pressure, soil pressure, frost, exceptional events, traffic and water load, must also be considered in the design. TRVK Tunnel also contains information about the safety and function of the tunnel during operation, for example, fire protection and ventilation. The tunnel's construction and installations must be able to withstand fire for a specific time for evacuation and rescue missions and ensure good air quality in normal operation (Trafikverket, 2011).

Technical description of Otterhällan

Technical Description Rock, ST202 describes technical aspects regarding rock works in Västlänken, subarea E10 Otterhällan and refers to service tunnel 202 Kungshöjd (Trafikverket, 2024). The document works as a project-specific control document and describes how rock-related work will be performed, controlled and documented. It is linked to AMA Anläggning 23 and contains, for example, requirements for investigations, rock excavation, reinforcement, sealing, shotcrete and inspection (Trafikverket, 2024).

When it comes to the geological conditions in the service tunnel, the rock is described as hard and crystalline (Trafikverket, 2024). The bedrock is primarily composed of gneissic rock formations with minor variations in rock composition. Fracturing and weathered zones are factors which impact the need for reinforcement, which is why fracture groups and local zones of weakness are important, which the rock mass is significantly affected by (Trafikverket, 2024).

For structural geology, the rock has three main fracture groups and two zones of weakness, where one is fractured and the other one is weathered, both approximately 4 meters thick (Trafikverket, 2024). The rock may be very fractured, weathered and clayey in these zones, with poorer quality and greater need for reinforcement and restrictions in driving. Therefore, the Q system is used to classify the rock quality, which is directly linked to the choice of reinforcement class. The rock mass is divided into four rock quality classes, all of which have specific properties and are based on a basic value, Q_{base} (Trafikverket, 2024).

$Class$ I ($Q_{base} > 10$): very good rock with few rough and wavy cracks.

$Class$ II ($4 < Q_{base} < 10$): good rock with rough to smooth cracks

$Class$ III ($1 < Q_{base} < 4$): half-good rock with smooth and undulating to planar cracks.

$Class$ IV ($0{,}1 < Q_{base} < 1$): poor rock with frequent weak zones and smooth cracks.

$Class$ V ($Q_{base} < 0{,}1$): consists of zones of weakness with a rock excavation that is considered to have a particularly adverse impact on stability.

For ST202, a correction has been made from Q_{base} to a Q-value to consider the impact of rock extraction, resulting in five different rock classes (Trafikverket, 2024). The first four correspond to the same interval as above and the fifth consists of: Q < 0,1. This fifth class consists of weakness zones where rock extraction has a particularly adverse impact. The new Q-value with its interval is linked to a reinforcement class which determines bolt spacing and the quality of the shotcrete. With lower intervals of Q, the rock quality also becomes worse, and the blast length is limited (Trafikverket, 2024). See Table 1 for the different rock classes for each tunnel section.

Table 1 Rock classes for each tunnel section

Rock class	Tunnel section *(meters)*
Class **I**	None
Class **II**	18 to 42, 132 to 147, 172 to 189
Class **III**	86 to 137
Class **IV**	42 to 86, 147 to 172
Class **V**	189 to 198

For the first 10 meters of the service tunnel, the rock excavation is carried out by sawing and splitting, continued with the conventional drilling and blasting method (Trafikverket, 2024). For the reinforcement building parts such as rock bolts, shotcrete and injection, there are project specific guidelines mentioned in the document (Trafikverket, 2024). For the rock bolts, these guidelines are described under the code CDC.14. The bolts should have a dimension of Ø25 mm and be cast in with a cement mortar which cannot contain sand. Those installed plate washers should be provided with a rolled metric thread of type M24, with a thread length of at least 150 mm. The grouted part of the bolt must be protected with a combination of hot-dip galvanizing, epoxy coating and cement grouting. When it comes to the length of selective bolts, they should be produced according to the client's instructions. Bolting must be proceeded according to reinforcement drawings and adjusts after the current rock class (Trafikverket, 2024).

For the injection, the guidelines are according to CDD.1, sealing work should primarily be carried out through pre-injection (Trafikverket, 2024). The grout itself must be of cement class 1 and meet the requirements of SS-EN 197-1. For the shotcrete, the material and product requirements are durability class: C32/40, chloride content class: Cl 0.20 and life span class: L100. Its exposure class is mentioned under the code EBF.3142, which should be XS3/XF4 for shotcrete on a surface that is to be cast against by a cast-in-place or prefabricated concrete structure. For other surfaces, the exposure class should be XS2/XF4 (Trafikverket, 2024).

3.3 Project-specific data

For the three different scenarios, the tunnel quantities are the same when it comes to the total volume and area of shotcrete and total quantity and length of bolts. Reinforcement drawings have been obtained from the design manager of the Otterhällan tunnel at Trafikverket which are based on the real quantities in the service tunnel, as a foundation for the quantity calculations (Design manager of the Otterhällan tunnel, personal communication, 2026). These drawings show the tunnel geometry and reinforcement requirements for different tunnel sections. The information concerns bolts and shotcrete and shows bolt length, bolt diameter, bolt spacing, presence of selective bolts and the thickness of the shotcrete in the roof and walls for each section. This information, together with the tunnel geometry, has been used to calculate the exact quantities of bolts and shotcrete in the tunnel. Only the chosen construction parts to be analyzed in this study are reported below.

When it comes to shotcrete with 4D fibers, its density is based on a value given by a contact person from Thomas Betong, who are the suppliers of the shotcrete used in this project (Representative from Thomas Betong AB, personal communication, 2026). The density of shotcrete with 3D fibers is an estimated value based on the density of shotcrete with 4D fibers by adding an extra 10 kg/m^3. This is a value given by the contact person from Thomas Betong and accounts for the extra density of fibers with 3D. Apart from the fiber content, the shotcrete recipe is the same for 3D shotcrete as for 4D (Representative from Thomas Betong AB, personal communication, 2026).

Masses for both shotcrete with 3D and 4D fibers have been calculated by multiplying project-specific volume with the material densities from Thomas Betong, see Table 2. As for the rock bolts, the property with mass per meter is given by the design manager of the Otterhällan tunnel and the specific mass of the different bolts have been calculated by multiplying the total length with the value for mass per meter, see Table 3.

Shotcrete:

Table 2 Properties of shotcrete

Property	3D Fibers	4D fibers	Source
Volume	933 m^3	933 m^3	*Own calculation based on reinforcement drawings given by the design manager of Otterhällan tunnel*
Area	8594 m^2	8594 m^2	*Own calculation based on reinforcement drawings given by the design manager of Otterhällan tunnel*
Density	2244 kg/m^3	2234 kg/m^3	*(Representative from Thomas Betong AB, personal communication, 2026)*
Weight	2 092 728 kg	2 083 402 kg	*Own calculation*

Rock bolts:

Table 3 Properties of rock bolts

Property	Rebar bolt	PC bolt	Source
Quantity	5481 pcs	5481 pcs	*Own calculation based on reinforcement drawings given by the design manager of Otterhällan tunnel*
Total length	28588 m	28588 m	*Own calculation based on reinforcement drawings given by the design manager of Otterhällan tunnel*
Mass per meter	3,9 kg/m	2,5 kg/m	*(Design manager of Otterhällan tunnel, personal communication, 2026)*
Weight	111 495 kg	71 471 kg	*Own calculation*

The choice of fuel type used at the construction site in the project is shown in Table 4 for each scenario. Scenario 3 is the real and project-specific scenario that exists in the service tunnel today, which means that the information about the third case's fuel is based on its project contract (T. Olsson from Trafikverket, personal communication, 2026). For scenarios 1 and 2, however, the fuel information is based on an assumption from Trafikverket's climate requirements for renewable fuel in chapter 2.5 and has been set at 60 percent HVO100 and 40 percent regular diesel.

Table 4 Total amount of renewable fuels for each scenario

Fuel type	Scenario 1	Scenario 2	Scenario 3
HVO100	60%	60%	100%
Fossil diesel	40%	40%	0%

Emission factors for the LCA-stages A1-A3 are shown in Table 5. The first scenario’s emission factors are, as mentioned before, based on standard values from Klimatkalkyl, while for the other ones, they are based on EPDs provided by Veidekke for the rock bolts and Thomas Betong. For shotcrete in the second scenario, it is based on the same emission factor as the value for 4D fibers, but accounts for the additional climate emissions for the fibers specifically, as mentioned before, 3D fiber has 10 kg more steel per cubic meter (Representative from Thomas Betong AB, personal communication, 2026). Cement class 1 is used for grouting across all three scenarios.

Table 5 Emission factors for support system used in different scenarios

Support system	Scenario	Emission factor (kg CO2 eq/kg)	Source
Shotcrete (standard)	1	0,172	*Klimatkalkyl version 8.1*
Shotcrete (3D fibers)	2	0,159	(Thomas Betong, 2025) + *own calculation*
Shotcrete (4D fibers)	3	0,158	(Thomas Betong, 2025)
Rebar bolts	1	2,27	*Klimatkalkyl version 8.1*
Recycled rebar bolts	2	0,667	(The Norwegian EPD Foundation , 2021)
PC-bolt	3	0,919	(Pretec Norge AS, 2024)
Grout for bolts	All	0,87	*Klimatkalkyl version 8.1*

The estimated cost for each scenario and support system is shown in Table 6. Scenarios 2 and 3 are project specific and provided by Veidekke, while Scenario 1 is not included, as it does not contain specific products and only provides default emission factors.

Cost:

Table 6 Cost for each support system and scenario

Support system	Scenario 2	Scenario 3	Source
Shotcrete (SEK/m^3)	2995	2995	*(Representative from Veidekke, personal communication, 2026)*
Rock bolt (SEK/bolt)	277	533	*(Representative from Veidekke, personal communication, 2026)*

There is no available project-specific cost difference for shotcrete between scenario 2 and 3, which is why a more detailed cost breakdown was developed only for the rock bolt alternatives. As highlighted in section 2.6.2, PC-bolts contribute to improved working conditions, so in order to study the purchase cost further, additional cost data related to installation rate (see Table 7), labor, machinery and CO_2 taxation was therefore provided by the design manager of the Otterhällan tunnel.

The cost calculations were based on general assumptions, including labor costs of 790 SEK/h, machinery costs of 3700 SEK/day and a CO_2 taxation of 1200 SEK/ton CO_2, a value based on the taxation rate in 2021, when Otterhällan tunnel had first started construction. It was also assumed that a work shift consists of 10 h, with two installation personnel on site.

Table 7 No. of bolts installed per work shift and no. of shifts required, for each bolt type

	No. of bolts per work shift	No. of shifts	Source
Rebar bolt	80	69	*(Design manager of Otterhällan tunnel, personal communication, 2026) + own calculation*
PC-bolt	150	37	*(Design manager of Otterhällan tunnel, personal communication, 2026) + own calculation*

3.4 Project-specific perspectives

There is some project-specific information on different optimization solutions for the service tunnel given by the design manager from Trafikverket of this project (Design manager of the Otterhällan tunnel, personal communication, 2026). Changing from rebar bolts to PC bolts was one of the main measures which is very relevant from different perspectives, one of them being the climate and the reason is that the choice of bolt system has a major impact on several parts of the life cycle and not just the amount of steel in the bolt. The installation of rebar bolt means that the bolt's equivalent volume in grout is squeezed out, resulting in waste material that must be disposed of in the production water, which creates more alkaline water. Carbon dioxide must in turn be pressed into the production water in a treatment plant to lower its pH before the water can be discharged to the wastewater network. The process thus ends with the liquid carbon dioxide finally being released into the atmosphere (Design manager of the Otterhällan tunnel, personal communication, 2026).

It is not only from a climate perspective that the material waste from rebar bolt becomes a problem, but also for the working environment (Design manager of the Otterhällan tunnel, personal communication, 2026). The grout can spill onto the worker during installation, which is a common occurrence. Additionally, when installing these types of bolts, especially in overhead applications, there is a risk that the bolt may fall before the grout has fully hardened or even be forgotten to fill in the drill hole, which in worst case scenario can lead to fatal injuries (Design manager of the Otterhällan tunnel, personal communication, 2026). By using the PC bolt instead, these risks can be reduced in the short term, as the bolt is equipped with a spring that creates an initial preload position before the final tightening takes place. This way, the bolt can take up load immediately after installation. By changing to PC bolt, it could provide an improvement in the climate impact in steel production, product design, installation method and work environment safety (Design manager of the Otterhällan tunnel, personal communication, 2026).

A change from 3D steel fiber to 4D steel fiber was also described as one of the most relevant measures to study, due to that shotcrete with 4D fibers can achieve the same residual strength as with 3D fibers, but with a lower fiber dose (Design manager of the Otterhällan tunnel, personal communication, 2026). With a lower amount of fiber, material consumption and thus also climate impact will be reduced.

The choice of fiber type could also have practical significance for both purchasing and production, as too open requirements risk that suppliers will choose a less climate-efficient solution, for example a solution that requires a higher fiber content (Design manager of the Otterhällan tunnel, personal communication, 2026). In addition, it often means that the shotcrete becomes more difficult to pump with a higher fiber content, which can cause production disruptions, greater wear and tear and in some cases more transport or more material handling (Design manager of the Otterhällan tunnel, personal communication, 2026).

It is also worth mentioning that after contacting both Veidekke and Implenia, both of whom are and have been involved in the constructions in Västlänken, as well as concrete suppliers such as Thomas Betong, no valid EPD for shotcrete with 3D steel fibers could be obtained. This is because 3D fibers are now used to a very limited extent and current projects with steel fiber-reinforced shotcrete are instead based on 4D fibers.

The amount of shotcrete used and the potential for optimizing this are less relevant in this case, as the amount of shotcrete is primarily governed by design and safety requirements, rather than environmental ambitions (Design manager of the Otterhällan tunnel, personal communication, 2026). In practice, this means that the amount of shotcrete is often determined by technical requirements, which makes it difficult to reduce it only for climate savings reasons. The use of unreinforced shotcrete in certain parts could be potentially relevant, but only as a cover spray in parts where fire protection is not required (Design manager of the Otterhällan tunnel, personal communication, 2026). The usability is therefore strongly dependent on the function and tunnel section.

Another very relevant measure to consider is the choice of materials with lower carbon dioxide levels, focusing on cement, concrete and steel (Design manager of the Otterhällan tunnel, personal communication, 2026). Depending on the choice of supplier, the climate footprint could differ significantly. However, the possibility of being able to use such alternatives depends on market access and how the requirements are formulated in projects. The environmental potential therefore exists, but it is strongly linked to what can be procured and delivered (Design manager of the Otterhällan tunnel, personal communication, 2026).

When it comes to blasting and driving, a nitrogen-free explosive such as Hypex Bio would have the potential to improve the climate and is interesting in theory but difficult in practice (Design manager of the Otterhällan tunnel, personal communication, 2026). This type of explosive has performed too poorly in actual production to be assessed as a realistic solution at present. It could also lead to re-shooting and certain work environment problems. The measure therefore has theoretical climate relevance but limited practical feasibility at present (Design manager of the Otterhällan tunnel, personal communication, 2026).

Larger bursts could also be an alternative but were described primarily as a dimensioning and design issue rather than a direct environmental measure (Design manager of the Otterhällan tunnel, personal communication, 2026). This would be a valuable topic for further research and discussion, since burst length and blasting layout can affect production efficiency, transport and shaft logistics. The same applies to generally optimizing the mining process itself, for example, excavating slightly more rock in certain places to create storage space and thereby streamline the transport of masses to the landfill.

Resource and mass management could be a very relevant alternative, such as reusing own rock masses and recirculating water (Design manager of the Otterhällan tunnel, personal communication, 2026). This is something that is done to a relatively large extent in the field, but it is limited by requirements and environmental conditions, for example due to ammonium levels or other quality-related restrictions. The measure therefore has great potential but is not entirely under the project's own control (Design manager of the Otterhällan tunnel, personal communication, 2026).

A general optimization of the facility through reduced material consumption is a measure that would be less suitable to focus on within the framework of the study (Design manager of the Otterhällan tunnel, personal communication, 2026). Such types of optimizations are very facility-specific and strongly governed by regulations, external actors, safety requirements and technical functional requirements. Even if the basic principle of reducing material consumption is justified, it is considered difficult to draw general conclusions about such measures in this particular case (Design manager of the Otterhällan tunnel, personal communication, 2026).

4 Method

This chapter presents the method used in the study. The chapter begins with information about the overall research design and the scenario-based comparative approach. The methods used for climate assessment and optimization are then presented, followed by an overview of the case study and the different scenarios that are analyzed. Finally, the methods used for climate calculations and cost estimations are explained.

4.1 Research Design – Scenario-Based Comparative Study

This master's thesis is structured as a case study where the focus is on the Otterhällan service tunnel 202. Since the thesis is project-specific, realistic conditions such as actual quantities, technical solutions and special requirements are obtained. The work is carried out as a scenario-based comparative study where three different scenarios have been developed and analyzed. All scenarios are based on the same quantities and tunnel geometry, which means that the basic assumptions are the same. The scenarios differ in the choice of materials and different climate-improved measures. This opens for a clear comparison of different choices and measures.

To achieve the objectives of the study, different methods were used, which will be presented and explained in following chapters and by combining these methods, a structured comparison and analysis between the different scenarios is enabled from both economic and climate-related perspectives. This provides a basis for assessing whether different climate-improving measures are justified from both a climate and cost perspective.

4.2 Climate Assessment and Optimization in Rock Tunnel Construction

This chapter presents the methods that are used to assess and compare both climate impact and costs for the different scenarios in the service tunnel 202. Both qualitative and quantitative methods were used, which include literature studies, personal communications, climate calculations and cost assessments based on project-specific data and EPDs.

4.2.1 Qualitative method

The qualitative method is based on two different approaches where information and knowledge have been collected through. A study of literature is the first, which has been a central part of the work where collected scientific articles, reports and technical documents have been analyzed, aiming for a theoretical basis for identifying climate optimizations and knowledge about the entire area. To obtain this type of information, searches have been conducted using Chalmers Library databases and online sources with different search terms that have suited the area itself from which the information was taken.

In addition to a literature study, information has also been collected through contacts with suppliers, industry companies and Trafikverket itself. This has been done through both direct conversations on study visits and at various meetings, but also through contact by email. Such information has been classified as personal communication and is intended to support the literature study with information that can almost only be obtained through this type of contact, which also provides industry perspective.

To guarantee that the information provided is of high quality and reliable, various selection criteria have been applied. Scientific sources have primarily been selected if they are peer-reviewed, while technical reports and other product information have been obtained from Trafikverket or well-known suppliers or companies. The information that has been collected is the basis for identifying possible climate-improved measures and for developing basic knowledge about materials, production methods and their environmental impact, which forms the basis for the scenarios that will later be analyzed in the study. The people who have been chosen as personal communications all have a role or foothold in the industry or are involved in the tunnel project, which makes them reliable sources.

4.2.2 Quantitative method

The quantitative method focuses on evaluating and comparing the climate impact and cost of the different scenarios for the service tunnel in the Otterhällan sub-project. The analysis is based on project-specific quantities together with environmental data from EPDs and cost data provided by Veidekke.

Climate calculation method

The quantitative comparative analysis between the three scenarios was mainly done using the latest version of Klimatkalkyl - version 8.0, and the reference values currently represent the year 2015, as they are aligned with Trafikverket's climate requirement targets, like previously stated in 2.4.3. The calculations were based on the predefined tunnel category "Construction tunnel/Service Tunnel, rock (6.3)" in Klimatkalkyl and performed according to the methodology described in Section 2.4. The construction components included were, among others, shotcrete, rock reinforcement bolts, injection cement, asphalt, explosives and drainage systems. Results from the Klimatkalkyl was then exported to Excel for further processing and comparison.

Based on the hotspot analysis done in chapter 2.2, shotcrete and rock bolts resulted in the largest contribution in climate impact, which is why the primary focus was placed on these two components in the analysis. Project specific quantities for the shotcrete and rock bolts were retrieved from internal reinforcement drawings and technical documentation provided by Trafikverket, where the tunnel was divided into sections based on varying reinforcement requirements, Q-values and tunnel geometry, after which details like the shotcrete thickness, sprayed area, bolt type, length and pattern were identified. The total amount of the shotcrete was then calculated by combining the sprayed area of each section, while the total amount of rock bolts was calculated based on specified center distances and reinforcement patters in each section, where the total number and length of bolts was calculated. These quantities were then used as basis for climate calculations in all three scenarios.

As noted earlier in section 3.3, verified and project specific EPDs were used for the identified hotspot-components, shotcrete and rock bolts. However, due to the absence of a valid EPD for the shotcrete with 3D steel fibers reinforcement, the emission factor was calculated separately based on available data and guidance from a contact person at Thomas Betong. The calculations were primarily focused on modules A1-A3 as they represent the emissions from the product stage, aligning with the scope of this study.

It should be noted that the selected EPDs were developed under different versions of the EN 15804 standard, which, as described in 2.4.3, include different GWP indicators. To ensure comparability between the EPDs, the GWP-total indicator was used where available as it corresponds most closely to the aggregated GWP values from the older versions.

Cost estimation method

The cost estimation method is based on project-specific costs and prices for the service tunnel provided by Veidekke, where the ASEK calculations have been carried out in a ready-made excel file from Trafikverket. The cost estimation was only applied in scenarios 2 and 3, because these are the project specific scenarios with actual material prices. The proposed climate optimized measures for shotcrete and rock bolts were first filled in to the excel file, together with the corresponding estimated emission reduction and any additional cost. The model automatically calculates the reduction cost in SEK/kg CO_2 for each optimized measure, which is based on the value of 2,93 SEK per kg CO_2-eq which Trafikverket is willing to pay for each kg of reduced carbon dioxide equivalent achieved. The tool also summarizes the total achieved and remaining reduction, as well as the proportion of the climate requirement that has been met. This makes it possible to monitor how far the project has come in relation to the climate goals set.

4.3 Presentation of the different scenarios

As previously mentioned in 4.1, the three scenarios are based on the same quantities and tunnel geometry to ensure consistency and comparability. The difference lies in material configurations and levels of optimization used in each scenario, which are defined below. In addition, different scenarios assume different fuel configurations for the construction activities in accordance with current requirements from Trafikverket. Scenarios 1 and 2 assume the use of 60% HVO100 and 40% fossil diesel, while scenario 3 assumes 100% HVO100. This assumption is only applied to activities that are included in Trafikverket's fuel requirements and does not include external transportation processes.

Scenario 1 – Standard Tunnel

The first scenario represents default values obtained from Trafikverket's Klimatkalkyl. These are based on standardized emission factors that are usually used in service tunnel construction, with no application of project specific data or EPDs. The quantities of the construction components that were included in this scenario were based on standardized tunnel geometry, so in order to ensure comparability and consistency between the scenarios, the quantities were scaled to correspond to the length and size of the Otterhällan tunnel.

Scenario 2 – ST202 with Conventional Configuration

Conventional material choices have been used for this scenario, where reinforcement has been done using fully grouted rebar bolts and shotcrete reinforced with 3D steel fibers, which represent standardized modelling in many tunneling projects. Furthermore, the concrete used in shotcrete and the cementitious grout are replaced with low-CO_2 concrete. The scenario thereby presents a conventional execution of tunneling processes, with no further implementations of climate impact reduction methods.

Scenario 3 – ST202 with Implemented Solutions

In this scenario, alternative material choices are used based on the implemented solutions in the service tunnel. Instead of using fully grouted rebar bolts, the reinforcement system consists of PC-bolts, and instead of 3D steel fibers reinforced shotcrete, it is instead reinforced with 4D fibers. Similarly to scenario 2, concrete with low-CO_2 was implemented in this scenario as well.

5 Results and Analysis

This chapter presents the results and analysis of the studied scenarios, which includes the total climate impact for each scenario, a breakdown of major climate hotspots, and the corresponding cost results.

5.1 Total Climate Impact per Scenario

Table 8 shows that in comparison to scenario1, scenario 2 results in a reduction in emissions of approximately 23,9 percent, while scenario 3 results in a reduction of approximately 29,5 percent. Nonetheless, the difference between scenario 2 and scenario 3 is only about 7,4 percent.

Table 8 Results of the total climate impact for each scenario

Scenario	**Total ton CO_2e**
1	904,82
2	688,83
3	637,85

Scenario 3 results in the lowest total climate impact among the compared alternatives, corresponding to a reduction of 266,97-ton CO_2e compared to scenario 1. The results are illustrated in Figure 18 below.

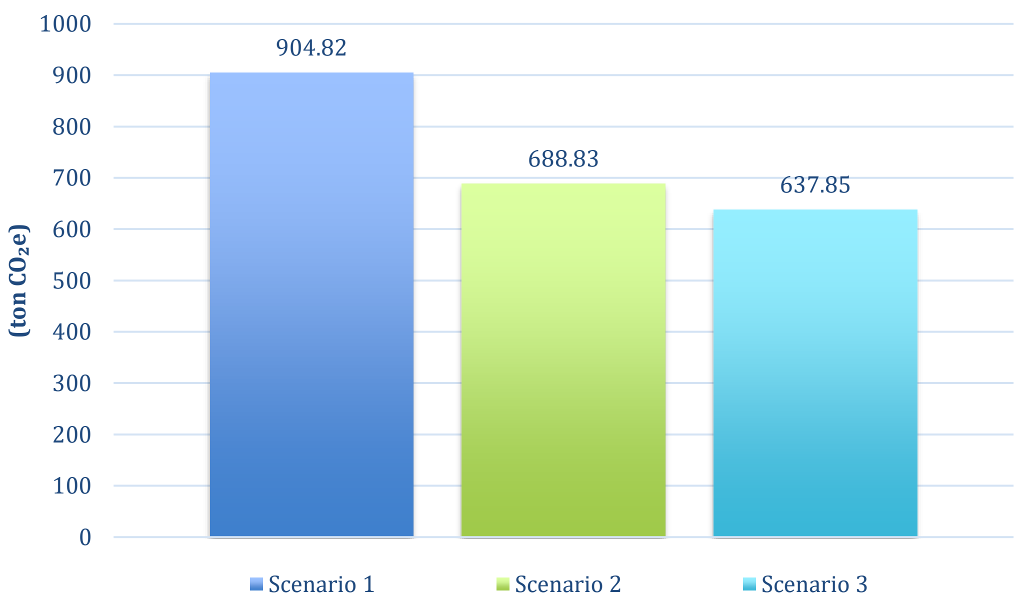

Figure 18 Total Climate Impact per Scenario

Figure 19 shows the climate impact distribution of each component and scenario, where it is apparent that shotcrete with steel fiber reinforcement stands for the biggest amount of the total climate impact in all three scenarios, followed by rock bolts, which is the second highest component in scenario 1 but is noticeably reduced in scenario 2 and 3.

In general, scenario 1 exhibits the highest total climate impact, while scenarios 2 and 3 show lower impact in both shotcrete and rock bolts, which is connected to the choice of bolt and steel fiber reinforcement systems. The remaining categories, such as asphalt and injection material, present unchanged values because no changes were applied to these categories across all three scenarios in the analysis. Moreover, these categories contribute to a relatively small amount of the total climate impact compared to shotcrete and steel-related components.

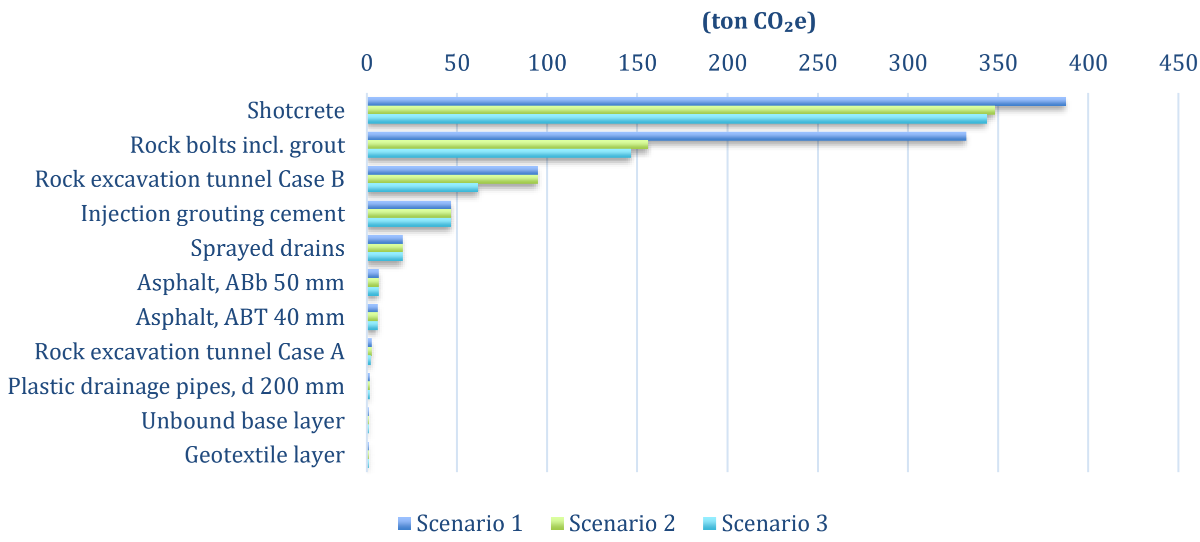

Figure 19 Climate impact by material and scenario

5.2 Hotspots Breakdown

Since shotcrete and rock bolts were identified previously in section 5.1 as the largest contributors to the total climate impact, they will be looked into more closely in this section. Table 9 shows the results obtained in Klimatkalkyl of the total climate impact of each component.

Table 9 Results of the total climate impact of shotcrete and rock bolts in each scenario

Scenario	Rock bolts incl. grout (ton CO_2e)	Shotcrete (ton CO_2e)
1	332,24	387,54
2	155,80	347,99
3	146,54	343,66

Compared to scenario 1, the climate impact of rock bolts including grout, has decreased by 53 percent in scenario 2 and 56 percent in scenario 3. When it comes to shotcrete, the corresponding reductions were approximately 10 percent and 11 percent, respectively. The difference between scenario 2 and

3 is relatively small, with scenario 3 showing a reduction of 6 percent for rock bolts and 1 percent for shotcrete.

Figure 20 below shows the climate impact of rock bolts including grout and shotcrete for each scenario. The results show that rock bolts display a clear reduction in emissions in scenarios 2 and 3, in comparison to scenario 1. Although to a lesser extent, shotcrete also shows some reduction between the scenarios.

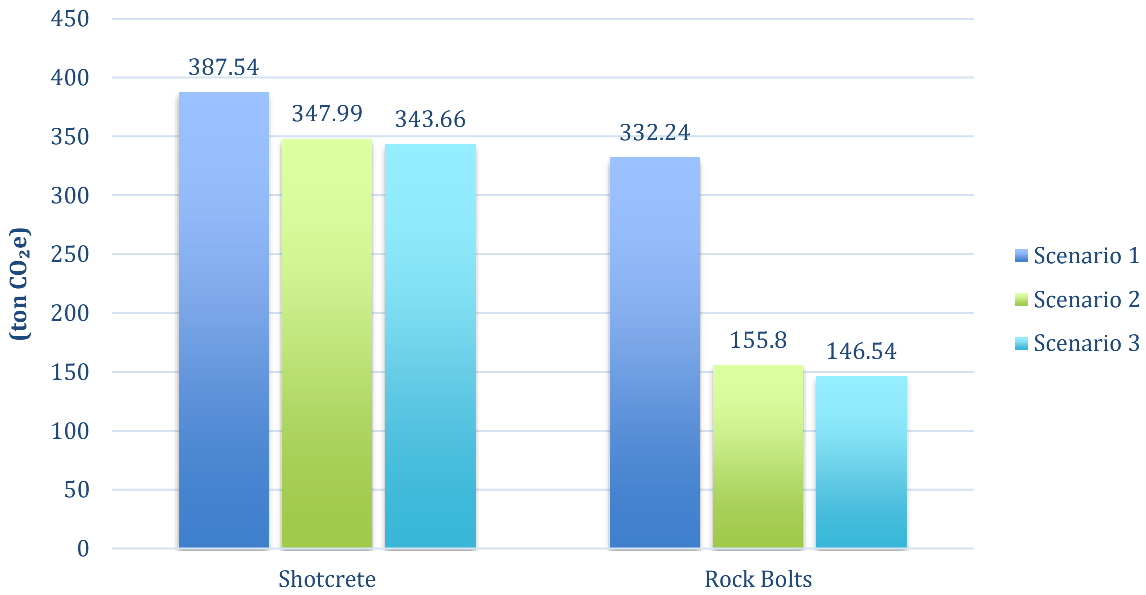

Figure 20 Climate Impact of Rock Bolts and Shotcrete for each Scenario

5.3 Cost Results

To further assess the optimization measures related to rock bolts and shotcrete, a cost analysis was conducted. Figure 21 below is based on the cost data obtained from Table 5, and it shows that when it comes to rock bolts, PC-bolts acquire a relatively higher purchase cost than fully grouted rebar bolts, with around 48 percent higher. As for shotcrete, the same value was applied in both scenario 2 and scenario 3.

Figure 21 Material Cost Comparison

However, the additional costs associated with the optimization measure indicate that PC-bolts lead to lower labor and machinery costs, as almost twice as many PC-bolts can be installed in the same amount of time as rebar bolts. This leads to shorter working hours as well as lower machinery costs, as shown in Figure 22 below, and considering CO_2 taxation costs leads to an additional saving of around 11,000 SEK.

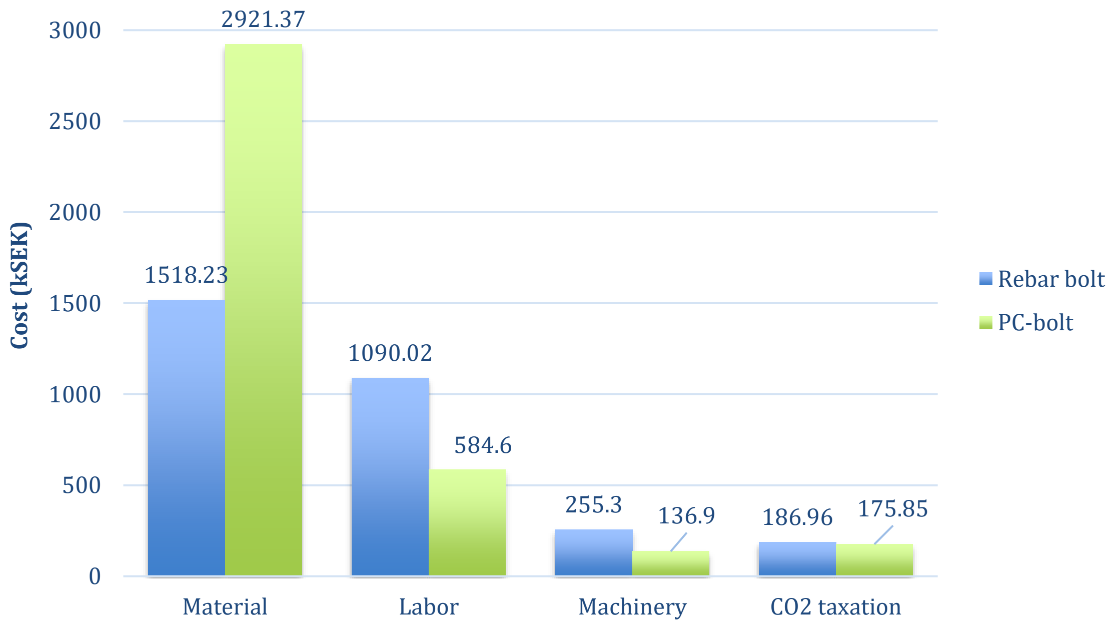

Figure 22 Cost Comparison of Rock Bolts

Given this, the change from rebar bolt to PC-bolt means a total cost increase of about 769,000 SEK. The evaluation of the cost-effectiveness of the optimization measure resulted in a reduction cost of 82,94 SEK/kg CO_2e which is about 80 SEK higher in comparison to Trafikverket's reference value 2,93 SEK/kg CO_2e, see Table 10.

Table 10 Socio-economic assessment of the selected optimization measures

Measure	**Emission reduction (ton CO_2e)**	**Additional cost (kSEK)**	**Reduction cost (SEK/kg CO_2e)**	**Trafikverket reference value (SEK/kg CO_2e)**
Rebar bolts to PC-bolts	9,26	769	82,94	2,93
3D to 4D reinforcement in shotcrete	4,33	-	-	2,93

When it comes to shotcrete, the cost for both 3D and 4D reinforced shotcrete is set to be the same, resulting in no additional reduction costs.

6 Discussion

This chapter presents a discussion about the findings in the literature study and the results and is structured to discuss the scenarios, achievement of climate targets, hotspots, economic implications of climate optimization, requirements, sources of error and data reliability.

6.1 Scenario comparison and achievement of climate targets

Based on Figure 18, it is shown that scenario 1 had the highest climate impact with 905 tons of CO2-eq, while scenarios 2 and 3 had significantly lower emissions. This result was quite expected, as scenario 1 is based on default values that are partly more conservative and based on 2015 values, while scenarios 2 and 3 are based on project-specific materials and EPDs that have already undergone some type of climate improvement. The amount of HVO used as biofuel in the different cases also has a major impact on the differences between the scenarios, which can be seen in Figure 19. The reason why scenario 3 is clearly the best of all the cases is not only due to better material optimization in the shotcrete and bolts, but also because 100 percent HVO is used on the construction site.

However, the difference is relatively small in reduction between scenario 2 and 3, even though the third is supposed to be the optimized and real case. Figure 18 shows that scenario 2 resulted in climate emissions of approximately 689 tons of CO2-eq and scenario 3 accounted for approximately 638 tons of CO2-eq. Despite several material changes in scenario 3, the reduction was limited, only 7,4 percent. This result strongly indicates that the greatest climate improvements were already achieved in scenario 2 with recycled rebar bolt and low CO_2 cement with 3D fibers. The continued optimization with PC bolts and 4D fibers in the shotcrete instead of 3D fibers provides a smaller marginal benefit. This also shows the great impact the material choices themselves have on the tunnel's climate impact, since the quantities have been kept constant, the differences can be directly linked to the materials.

The final reduction between scenarios 1 and 3 was approximately 30 percent, which according to the climate requirements in chapter 2.5 is set at a 60 percent reduction for all projects that are estimated to be completed by 2030 compared to 2015 values. A 30 percent reduction is only half of the climate savings that must be achieved, which indicates that considerable research and development are still needed.

6.2 Evaluation of hotspots

The results from the study shown in Figure 20 indicate that shotcrete constituted the largest source of emissions in all scenarios. This is mainly due to the high cement content in the large quantities of shotcrete and, as previously mentioned in chapter 2.2, high levels of carbon dioxide that are emitted in connection with cement production. Figure 19 shows the difference in emissions between the building parts in the tunnel across all scenarios, which also emphasizes that shotcrete, steel used in rock bolts, and grouting cement constitute the largest emission sources. Choosing to optimize other building parts with lower emissions gives a limited total effect.

The type of cement used in service tunnel 202 is mentioned in the literature review as a relatively climate-optimized solution compared to more traditional cement alternatives. At the same time, it is clear from chapter 2.6.1 that research and development in the concrete area is in full swing to develop further improved solutions, which have to do with alternative binders and lower clinker contents. Despite this, the possibility of further reducing the climate impact of shotcrete through a lower CO_2 footprint in the material currently appears to be limited by technical requirements, which according to the contact person from Thomas Betong are primarily linked to strength and function.

The optimization solution between scenario 2 and scenario 3 was to change from 3D fibers to 4D fibers in the shotcrete. The difference between them lies primarily in the lower steel fiber dose with 4D, which contributes to less material use and thus a lower climate impact. Based on the results shown in Figure 20, the difference in emissions for shotcrete is not particularly large between cases 2 and 3 despite further optimization of the shotcrete, only about 4,3 tons CO2-eq. The result thus indicates that 4D shotcrete has a lower climate impact than the one with 3D fibers, which is also consistent with the literature study. This means that optimizing fiber solutions can still contribute to reduced climate impact, but that the large reduction should be linked to the cement content or its production.

When it comes to rock bolts, these resulted in significantly lower climate impact in both scenarios 2 and 3 compared to scenario 1. This is mainly because the rebar bolt steel in scenario 2 is made of recycled steel and the production took place in Norway, which results in a quite short transport distance to the project. For the PC Bolt, this difference lies in a significantly lower steel mass per meter than both the default value for the bolt in scenario 1 and the rebar bolt steel in scenario 2. The reduced amount of steel results in a lower total amount of material and thus also a lower climate impact, which is also described in the literature review. The result therefore shows that optimizing steel use can be an effective measure to reduce the climate impact from rock reinforcement, as steel production contributes to high carbon dioxide emissions.

Despite a significantly lower steel mass per meter for the PC bolt compared to the rebar bolt, the result in Figure 20 does not show a huge difference in emissions, only about 10 tons more CO2-eq for the rebar steel. The main reason is that the PC bolt is not made of recycled steel, which results in a higher emission factor in the production stage compared to what the rebar bolt steel has. The possibility of further reducing the climate impact of PC bolts is therefore closely linked to the development of more climate-improved steel production and the access to certified producers who meet the technical requirements set in tunnel construction. According to the literature study in chapter 2.6.2, the production of PC bolts currently takes place in China, which contributes to increased transport-related emissions and limits parts of the potential climate savings.

In addition to the lower climate impact, practical advantages were also identified with the PC bolt, including those related to the installation and assembly of the bolts. It has both a simpler and safer installation process which contributes to an improved working environment and more efficient production compared to rebar bolt, according to chapter 2.6.2. This shows that optimized climate solutions can also provide practical advantages.

6.3 Economic Implications of Climate Optimization

The reduction of climate impact from 3D to 4D reinforced shotcrete results in about 4,33-ton CO_2 with no additional cost, making it a cost-effective optimization measure. As for the rock bolts, the change from fully grouted rebar bolts to PC-bolts does result in a reduction of 9,26-ton CO_2, a change that leads to an increase in the cost of the project of approximately 768 thousand SEK and requiring a reduction cost of 83 SEK/kg CO_2, according to socio-economic evaluation. However, benefits related to the installation process, as mentioned in chapter 2.6.2, such as improved working conditions and more effective installation processes should be considered. Additionally, other practical benefits such as the reduction in installation complexity and safer execution were not quantified.

PC-bolt is still very new and not as established out on the market yet compared to rebar bolt, which could be a big reason for the very high material cost. With the basic supply and demand logic, generating more projects with more suppliers who would choose PC-bolt over rebar bolt could create higher volumes of the bolt and more competition from suppliers out on the market, resulting in pressuring down the price.

6.4 Practical Implications for Climate Optimization

The results of the study not only show the great potential for several climate optimization solutions in tunnel construction, but also that the possibility of implementing these is affected by several external factors. Requirements, standards, market access and certifications have great importance for which climate measures can be implemented in projects. Several of the analyzed solutions show a technology that is already available to reduce climate impact, such as the CCS technology in chapter 2.6.1 from Heidelberg Materials. The company emphasizes the problem that current regulations and standards do not always develop at the same pace as technology, which complicates the implementation of climate-improved materials and production methods, even though it is technically possible to use them.

In infrastructure projects, the requirements also have a great influence on which solutions are chosen in practice. In chapter 2.5 it is clear that Trafikverket has a central role, since requirements set in the design and procurement stages determine which materials and methods are later to be used in the projects. How climate requirements are emphasized and designed could therefore set requirements for both suppliers' material choices and the market's development towards more optimized climate solutions. According to the design manager of Otterhällan in chapter 3.4, for example, overly open requirements risk leading to less optimized climate alternatives. With clearer requirements, suppliers could have more reason to develop and offer wider improved climate solutions.

At the same time, climate optimization needs to be balanced against other vital requirements that are linked to safety, technical performance and function. Every project with rock tunnel construction is unique, as according to chapter 2.1 on the drill and blast method, all technology depends on the geology and structure of the rock itself. Products used in such projects are often subject to high technical requirements and certification processes, as can be seen for this service tunnel 202 in its project description in chapter 3.2. This can limit the possibility of quickly implementing new materials or alternative production methods. Something that shows proof of this is, for example, the possibility of using recycled or fossil-free steel in the PC bolt, according to chapter 2.6.2, both technical requirements and certification affect the potential of real implementation. The same applies to the opportunity of higher use of fly ash in shotcrete according to chapter 2.6.1, as the technology exists to produce it, but the technical aspects are what currently prevent the solution.

The results also show that the use of project-specific EPDs resulted in a significantly lower climate impact compared to the scenario that was based on default values. This indicates that more detailed and product-specific climate data can provide a more representative decision-making basis for climate assessments.

6.5 Sources of Error and Data Reliability

The results linked to the study contain certain uncertainties, as the content is based on project-specific quantities, EPDs and climate data from several different sources. Despite a strong ambition to use as representative and reliable data as possible, there are some factors which can affect how accurate and comparable the results are.

One of these uncertainties is strongly linked to the EPDs that have been used for the climate calculations in scenarios 2 and 3. Its emission factors have the potential to vary depending on, for example, production methods, system boundaries, energy mix and geographical conditions. The rock bolts and the shotcrete were the two reinforcement systems identified as the biggest hotspots in the study, which accounted for large shares of the total emissions from the tunnel compared to other construction parts. Even minor changes in the emission factors for these two reinforcement systems could mean that the total climate impact can be affected relatively much. If the emission factors were to decrease or increase by 5 percent, this would result in primarily affecting the materials for which account for the largest share of the emissions. Despite this, the comparison between the different scenarios and hotspots is still considered relevant and reliable, since the same methodology and calculation principles have been used consistently in all scenarios.

Additional uncertainties are linked to the data quality where some values have had to be calculated independently within the study. This applies, among other things, to a big part of the project-specific data presented in chapter 3.3, such as: area, volume, quantity, mass and length of either bolts or shotcrete. This basic data is based on drawings for the service tunnel provided by Trafikverket, where information for each section and calculations were then made to determine the final quantities. The human factor can be an uncertainty such as miscalculation or incorrect conclusions or assumptions. Accuracy was therefore strived for when converting between volume, mass and emission factors to ensure comparable values between the scenarios.

Properties such as mass, volume and emission factors of the shotcrete with 3D fibers are a further uncertainty in the work where it was not possible to obtain a project-specific EPD for this material. Consequently, the values had to be calculated based on available EPDs and technical documentation given by the contact person from Thomas Betong to ensure as representative values as possible. The uncertainty in this therefore lies in the fact that the data are not project-specific, unlike other building components that have project-specific EPDs registered.

Despite these uncertainties, the results are considered to provide a reasonable and relevant picture of how different optimized climate measures and material choices affect the climate impact in rock tunnel construction and the study should therefore primarily be interpreted as a comparative analysis between scenarios rather than an exact forecast of future emission levels.

6.6 Further research

Since the climate requirements of 60 percent reduction compared to 2015 values are not met, there is a great need for future research in the area to find alternative ways to meet these requirements. A better alternative that has greater potential in terms of climate is CCS-based cement production, as a promising future solution. The advantage of CCS cement is that the climate impact can be reduced significantly without the properties of the concrete needing to change at all, since it is the cement production that is being treated. At the same time, the technology is new and demands more research into large-scale production, energy requirements, costs and long-term function. An important challenge is that CCS needs a lot of energy and has higher production costs, which can shift parts of the climate burden to the energy system.

As for rock bolts, there is great future potential in using fossil-free and recycled steel instead of conventional steel, since the biggest climate impact in the production of PC-bolts comes from the production of the material itself alongside long-distance transportation, as it takes place far from the area of use. Moving parts of the production to Europe and Scandinavia is currently not considered advantageous as many of the raw materials are global and transportation will still be required. At the same time, extensive work would be required to find steel that meets the requirements and get it certified. An alternative with greater climate mitigation potential could be the newly developed HYBRIT-technology, its advantage being a significant reduction in the climate impact in the production process itself, as the focus lies on eliminating carbon dioxide emissions. However, the technology is still in the early stages of development and requires further research to better understand large-scale production potential, economic aspects and long-term performance. It is also highlighted that HYBRIT is energy intensive and will rely on fossil-free electricity production, which may increase demands on electricity supply instead. Additional future mitigation opportunities are offered in steel production, such as using alternative fuels, bio-based reduction pathways and increased utilization of steel’s circular potential that should be explored further.

7 Conclusion

In this study, the climate impact of different tunnel scenarios has been investigated regarding material selection and technical solutions in rock tunnel construction, using service tunnel 202 in the Otterhällan subproject within Västlänken as a case study. The results clearly showed that shotcrete and rock bolts were the largest contributors to the climate impact among the construction components used in the tunnel construction, mainly due to the high emissions linked to cement clinker and steel production, but also the high material quantities.

Several climate-optimizing measures have been identified and evaluated in the study. The most relevant measures were changing from 3D to 4D shotcrete with lower CO_2 cement, changing to PC-bolt instead of rebar bolt and increasing the use of recycled steel in rock reinforcement. The results indicate that material optimization has the potential to significantly reduce the climate impact without compromising the technical function of the tunnel.

The scenario analysis showed that scenario 1 had the highest climate impact, where the reduction between cases 1 and 3 resulted in approximately 30 percent lower climate impact. Although this shows a large improvement, the reduction is not sufficient to achieve the infrastructure sector's climate target of 60 percent reduced emissions by 2030 compared to 2015 levels. The difference between Scenario 2 and 3 resulted in relatively small, even though additional optimization measures have been implemented in scenario 3, which at the same time resulted in much higher economic costs for the PC bolt than the rebar bolt.

From a socio-economic perspective, scenario 3 does not appear to be the greatest climate benefit relative to its cost, since the emission reduction between cases 2 and 3 is relatively small in relation to the higher cost. However, the choice of the PC bolt can still be justified based on aspects other than the climate impact itself, for example through simpler and faster installation, increased safety and an improved working environment compared to the rebar bolt. This means that the value of the PC-bolt lies primarily in its practical and technical advantages, rather than simply in its climate-related societal effectiveness in cost. To be able to reduce the material cost of the PC-bolt, the bolt must be the standard choice in projects with more suppliers who produce it out on the market.

The results therefore indicate that focusing only on material optimization will probably not be sufficient to achieve future climate goals, but that additional measures linked to production methods, transport, energy systems and construction processes will also be required. For future projects that will use either cement or steel as a building material, there is great potential for better technologies that can meet climate requirements, which are the analyzed technologies CCS-based cement production and HYBRIT. These two have the capacity to capture a majority of the carbon dioxide in the production of cement and steel. Both technologies are currently still in an early stage of development and are at the same time associated with challenges linked to energy needs, large-scale implementation, certification requirements and market access.

To conclude this study, the possibility to achieve climate-neutral infrastructure by 2040, a balance between climate, economy and feasibility is required, as well as early decisions already in the planning and design phase. There is a need for collaboration between clients, contractors, material suppliers and decision-makers, since climate optimization is not only about reduced CO_2 emissions, but also cost, work environment and production time.

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