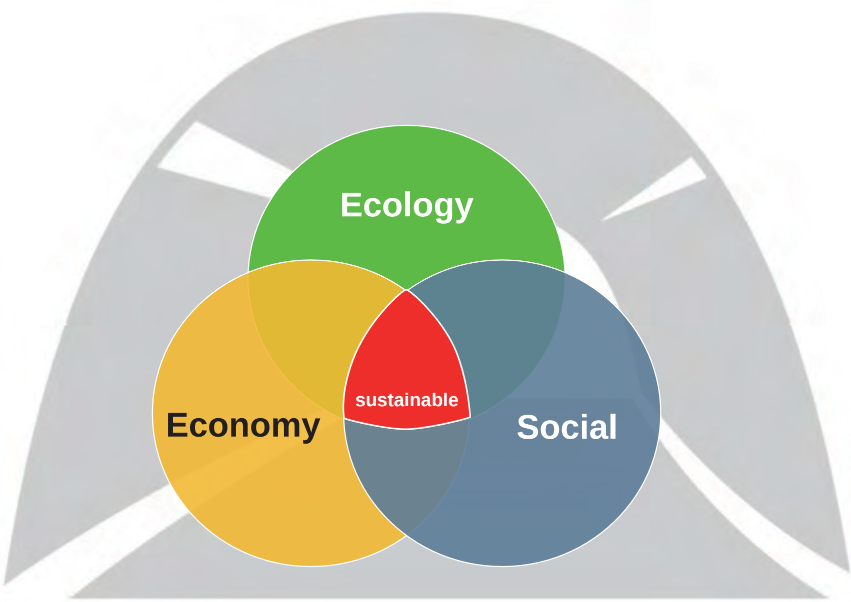


Recommendations for

Sustainability in Underground Construction

Part 1: Framework Conditions, Challenges, Solutions, and Project Assessment

Deutscher Ausschuss für unterirdisches Bauen e. V.
German Tunnelling Committee (ITA-AITES)

Recommendations for Sustainability in Underground Construction – Part 1: Framework Conditions, Challenges, Solutions, and Project Assessment

Publisher
Deutscher Ausschuss für unterirdisches Bauen e. V. (DAUB)
German Tunnelling Committee (ITA-AITES)
Mathias-Brueggen-Str. 41, 50827 Cologne, Germany
Tel. +49 - 221 - 5 97 95-0
Fax +49 - 221 - 5 97 95-50
E-Mail: info@daub-ita.de
www.daub-ita.de

Please send any comments regarding these recommendations to the above-mentioned e-mail address.

Developed by the DAUB Subcommittee "Sustainability in Underground Construction"

Members of the Working Group:

Dr.-Ing. Frank Abel	HOCHTIEF Infrastructure GmbH, Essen
Delia Albrecht-Vogelsang, M.Sc.	Ed. Züblin AG, Stuttgart
Dipl.-Ing. Lars Babendererde	BabEng GmbH, Lübeck
Lotta Bänsch, M.Sc.	BabEng GmbH, Lübeck
Dipl.-Bauing. ETH Heinz Ehrbar (Head)	im Auftrag der DB InfraGO AG
Prof. Dr.-Ing. Stephan Engelhardt	Hochschule München
Dr.-Ing. Stefan Franz	DEGES Deutsche Einheit Fernstraßenplanungs- und -bau GmbH, Berlin
Dr.-Ing. Claudia Klotz	Ed. Züblin AG, Stuttgart
Prof. Dr.-Ing. Roland Leucker	Studiengesellschaft für Tunnel und Verkehrsanlagen – STUVA e. V., Köln
Helena Loga, M.Sc.	DB InfraGO AG, München
Dr.-Ing. Peter-Michael Mayer	Ed. Züblin AG, Stuttgart
Dipl.-Ing. Karl-Heinz Reikat	Stadt Bochum
Dipl.-Ing. Rainer Rengshausen	PORR GmbH & Co. KGaA , Düsseldorf
Dr. techn. Klaus Rieker	Wayss & Freytag Ingenieurbau AG, Frankfurt am Main
Dr.-Ing. Christian Thienert	Studiengesellschaft für Tunnel und Verkehrsanlagen – STUVA e. V., Köln
Dr.-Ing. Götz Vollmann	Ruhr-Universität Bochum
Prof. Dr.-Ing. Gerhard Wehrmeyer	Herrenknecht AG, Schwanau
Dr.-Ing. Thorsten Weiner	Wayss & Freytag Ingenieurbau AG , Düsseldorf

Typesetting, layout and editorial work:

Gabriele Konopka	Studiengesellschaft für Tunnel und Verkehrsanlagen – STUVA e. V.
Prof. Dr.-Ing. Roland Leucker	Studiengesellschaft für Tunnel und Verkehrsanlagen – STUVA e. V.

November 2025

Cover picture: Own illustration

Table of Contents

For reasons of readability, the simultaneous use of female, male, or neutral language forms is dispensed with in the following, and the generic masculine form is used. All references to persons apply equally to all genders.

Index

Abbreviations

Abbreviation	German Term	English Term
AbfRRL	EU-Abfallrahmenrichtlinie	EU Waste Framework Directive
AP	Acidification Potential (Versauerungs-potenzial)	Acidification Potential
ASFINAG	Autobahnen- und Schnellstraßen-Finanzierungs-Aktiengesellschaft	Austrian motorway and expressway financing company
ASV	Automated Service Vehicle	Automated Service Vehicle
BBodSchV	Bundes-Bodenschutz- und Altlastenverordnung	Federal Soil Protection and Contaminated Sites Ordinance
BIM	Building Information Modelling	Building Information Modelling
BMDV	Bundesministerium für Digitales und Verkehr	Federal Ministry of Digital and Transport
BREEAM	Building Research Establishment Environmental Assessment Method	Building Research Establishment Environmental Assessment Method
BVWP	Bundesverkehrswegeplan	Federal Transport Infrastructure Plan
CBD	Convention on Biological Diversity	Convention on Biological Diversity
CCS	Carbon Capture and Storage	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation	Carbon Capture and Utilisation
CEN	European Committee for Standardization	European Committee for Standardization
CSA	Calcium-Sulfo-Aluminat	Calcium Sulfoaluminate
CO_2	Kohlenstoffdioxid	Carbon Dioxide
CO_2-eq.	CO_2-Äquivalente	CO_2 Equivalents (CO_2e)
CO_2-eq/cap	CO_2-Äquivalente pro Kopf	CO_2 Equivalents per capita
DAUB	Deutscher Ausschuss für unterirdisches Bauen	German Tunnelling Committee
DepV	Deponieverordnung	Landfill Ordinance
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen	German Sustainable Building Council
DIN	Deutsches Institut für Normung e. V.	German Institute for Standardization
EBV	Ersatzbaustoffverordnung	Substitute Building Materials Ordinance
EPD	Environmental Product Declaration (Umweltproduktdeklaration)	Environmental Product Declaration
GWP	Global Warming Potential (Treibhausgaspotenzial)	Global Warming Potential
HOAI	Verordnung über die Honorare für Architekten- und Ingenieurleistungen	Fee Structure for Architects and Engineers
IBU	Institut Bauen und Umwelt e. V.	Institute for Construction and Environment
ITC	Integrated Tunnel Carrier	Integrated Tunnel Carrier
KrWG	Kreislaufwirtschaftsgesetz	Circular Economy Act

Abbreviation	German Term	English Term
KSG	Klimaschutzgesetz	Climate Change Act
LAGA	Länderarbeitsgemeinschaft Abfall	Federal State Working Group on Waste
LCA	Life Cycle Assessment (Ökobilanz)	Life Cycle Assessment
LCC	Life Cycle Costs (Lebenszykluskosten)	Life Cycle Costs
LCI	Life Cycle Inventory Analysis (Sachbilanz)	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment (Wirkungsabschätzung)	Life Cycle Impact Assessment
MADM	Multi attribute decision making (Multiattributive Entscheidungsfindung)	Multi-Attribute Decision Making
MCDM	Multi criterial decision making (Multikriterielle Entscheidungsfindung)	Multi-Criteria Decision Making
MODM	Multi objective decision making (Mehrstufige Entscheidungsfindung)	Multi-Objective Decision Making
MSV	Multi Service Vehicle	Multi-Service Vehicle
NISTRA	Nachhaltigkeits-Indikatoren für Straßeninfrastrukturprojekte	Sustainability Indicators for Road Infrastructure Projects
NKA	Nutzen-Kosten-Analyse	Cost-Benefit Analysis (CBA)
NKI	Nutzen-Kosten-Indikator	Benefit-Cost Indicator (BCI)
NWA	Nutzwertanalyse	Utility Analysis (UA)
ODP	Ozone Depletion Potential (Ozonschichtabbaupotenzial)	Ozone Depletion Potential
PCR	Product Category Rules (Produktkategorie-Regeln)	Product Category Rules
PENRT	Primary energy non-renewable, total use (nicht erneuerbarer Primärenergiebedarf)	Primary Energy Non-Renewable, Total Use
PERT	Primary energy renewable, total use (erneuerbarer Primärenergiebedarf)	Primary Energy Renewable, Total Use
PP	Polypropylen	Polypropylene
SDG	Sustainable Development Goal (Nachhaltigkeitsziel)	Sustainable Development Goal
SNBS	Standard Nachhaltiges Bauen Schweiz	Swiss Sustainable Building Standard
TAS	Tunnelaufweitungssystem	Tunnel Widening System
THG	Treibhausgas	Greenhouse Gas (GHG)
TiT	Tunnel-in-Tunnel Methode	Tunnel-in-Tunnel Method

Glossary

Term	Definition
Agenda 21	The action programme of the United Nations, adopted in 1992 by 178 states at the UN Conference on Environment and Development (UNCED) in Rio de Janeiro. "Agenda 21" sets guidelines for sustainable development in the 21st century.
Agenda 2030	The "2030 Agenda for Sustainable Development" is the first international agreement that links the principle of sustainability with poverty reduction and economic, ecological, and social development. It was adopted on September 25, 2015, at the UN General Assembly in New York. It contains 17 Sustainable Development Goals (SDGs).
CCS	Carbon Capture and Storage, the separation and permanent (underground) storage of carbon dioxide (CO_2) from power plant flue gases and industrial processes.
CCU	Carbon Capture and Utilisation, the capture of carbon dioxide (CO_2), especially from combustion flue gases, and its subsequent use in chemical processes.
CO_2-eq.	CO_2 equivalents (CO_2-eq., English CO_2e) are a unit of measurement used to standardise the climate impact of different greenhouse gases (e.g., methane has a 28-fold greater climate impact than CO_2, while nitrous oxide exceeds that of CO_2 by almost 300 times).
EU Green Deal	The European Green Deal is a concept presented by the European Commission on December 11, 2019, with the goal of reducing net greenhouse gas emissions in the European Union to zero by 2050, thus becoming the first "climate-neutral continent".
EU Green Deal Industrial Plan	The EU Industrial Plan is part of the EU Green Deal and aims to strengthen the competitiveness of Europe's carbon-neutral industry and support the rapid transition to climate neutrality. The Industrial Plan is intended to create a more favourable environment for expanding the EU's production capacity for carbon-neutral technologies and products needed to achieve Europe's climate goals.
EU Taxonomy Regulation	The European Taxonomy Regulation (TR, Regulation (EU) 2020/852) establishes a unified system of criteria to determine whether an economic activity can be classified as environmentally sustainable.
Federal Climate Change Act (KSG)	A German federal law intended to ensure the fulfilment of national climate protection targets and compliance with European targets. The Climate Change Act legally enshrined the climate protection and sector targets set out in the Climate Action Plan 2050 for the first time. Accordingly, greenhouse gas emissions are to be reduced by at least 65% by 2030 compared to 1990 levels, and by at least 88% by 2040. Net greenhouse gas neutrality is to be achieved by 2045. This is based on the commitment under the 2015 Paris Agreement to limit the increase in the global average temperature to well below 2°C and, if possible, to 1.5°C above pre-industrial levels in order to minimise the effects of global climate change.
German Sustainability Strategy	In Germany, a first national sustainability strategy was developed in 2002. Since 2004, it has been updated every four years. Based on the "2030 Agenda" adopted by 193 UN member states in September 2015, a fundamental revision was carried out in 2016, and the name was changed to "German Sustainability Strategy". The German Sustainability Strategy incorporates the goals of the UN "2030 Agenda" (SDGs) into a national strategy. With the 2021 update, the goals of the EU Green Deal were also included.

Term	Definition
Greenhouse Gas Balancing	Greenhouse gas balancing covers the amount of greenhouse gas emissions generated by a company, product, or service
Greenhouse Gases (GHG)	Greenhouse gases are those gases in the Earth's atmosphere that cause the so-called greenhouse effect. Greenhouse gases can be of natural or anthropogenic (man-made) origin. Greenhouse gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorinated greenhouse gases (F-gases), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF_6), and nitrogen trifluoride (NF_3).
GWP	The Global Warming Potential is a measure of the relative contribution to the greenhouse effect, i.e., the average warming effect on the Earth's atmosphere over a specific period (usually 100 years: GWP100). It indicates how much a certain mass of a greenhouse gas contributes to global warming compared to the same mass of CO_2. The GWP is a dimensionless value with the symbol CO_2e or CO_2-eq.
Pocket Parks	A pocket park is a small, landscaped open space in an urban context that was previously unnoticed or lay fallow as a "dead" corner (Wikipedia).
Sponge City	Sponge City is a new urban planning concept to absorb and store as much rainwater and surface water as possible locally. Valuable water should no longer be quickly drained away and disappear into the sewer system. This is intended, for example, to prevent or reduce flooding during heavy rainfall events, improve the urban climate, and promote the health of urban trees and the resilience of entire urban ecosystems, which is becoming increasingly important in the context of global warming and the biodiversity crisis. In addition, urban plants contribute to improving "green infrastructure", urban hygiene, and the microclimate.
Tiny Forest	A tiny forest (also micro-forest/nano-forest) is a forest planted on a relatively small area with a high density of trees. The aim of such new plantings is to create diverse, fast-growing, and self-sustaining habitats on small areas in urban spaces, thereby improving the environmental situation (Wikipedia).

Preamble

The preservation of the natural foundations of life for current and future generations has long been a concern for society and politics. At the same time, there is a continuing demand for housing, work, education, mobility, supply/disposal, and the exchange of services and goods. These needs are to be met in the future while considering sustainability goals . To this end, the infrastructure in Germany must be significantly upgraded and, where necessary, expanded. Underground construction makes a significant contribution to this.

These recommendations show facts and figures on the topic of sustainability in underground construction in order to clearly identify the need for action in this area, so that the goals set by the political framework can be achieved. This is intended to create the basis for objective discussions and specifically defined measures. Catalogues of measures illustrate how the formulated goals can be implemented.

Underground structures often compete with alternative solutions above ground. The best option, considering the requirements of sustainability, can only be found if the assessment systems used depict all aspects of sustainability correctly and comprehensibly. These recommendations also present approaches to solutions for this.

The already noticeable consequences of climate change require consideration in the planning and execution of structures that are to be used and operated safely. Resource conservation and achieving climate neutrality are closely linked. Both goals require the awareness and cooperation of all parties involved from industry, politics, execution, and planning.

The DAUB recommendations “Sustainability in Underground Construction” consist of the following two parts:

- Part 1: Framework Conditions, Challenges, and Solutions
- Part 2: Greenhouse Gas Balancing for the Manufacturing and Construction Phase

It is assumed that these recommendations will be successively adapted to evolving requirements in the coming years and supplemented with further sections.

This document, as Part 1 of the recommendations “Sustainability in Underground Construction”, deals with the general political framework conditions and outlines the status quo and current challenges. Furthermore, it explains the contributions that underground structures can make to sustainability. Ecological, social, and economic aspects are addressed. Solutions are shown on how underground construction can become even more sustainable, in particular by addressing the topics of sustainable planning, circular economy, new materials and improved construction methods, biodiversity, and the conversion of underground structures. The theoretical approaches to project assessment are explained, and possible assessment methods for use in underground infrastructure projects are presented and evaluated

Part 2 of the recommendations “Sustainability in Underground Construction” [1] provides information and guidance on conducting greenhouse gas balancing in underground construction. This is intended to enable clients and planners to perform uniform calculations. Two concrete examples for the greenhouse gas balancing of underground structures are presented. These examples are intended to illustrate how to proceed with greenhouse gas balancing for underground structures.

On the topic of sustainability in underground construction, reference is also made to the existing DAUB recommendations “Life Cycle Costs” **[2]** and “Recycling of Tunnel Excavation Material”**[3]**.

1 Political Framework Conditions

1.1 UN Sustainability Goals

With the UN Conference on Environment and Development in Rio de Janeiro in 1992, the first cornerstones were laid for an internationally coordinated approach to dealing with the demands for the sustainable development of Planet Earth and humanity in the form of Agenda 21. The equal importance of ecology, economy, and social issues was established as a fundamental prerequisite for sustainable development (**Figure 1-1**). Two legally binding framework agreements on climate change and on biological diversity were also adopted.

In the meantime, the agreements have been further developed and provided with concrete targets. The 2015 Paris Climate Agreement, for example, stipulated that greenhouse gas emissions should be reduced to such an extent that global warming is limited to 1.5 °C compared to the pre-industrial era.

With the Agenda 2030, unanimously adopted by the UN General Assembly (also from 2015), 17 specific Sustainable Development Goals (SDGs) were formulated (**Figure 1-2**). These are aimed at governments worldwide, but also at civil society, the private sector, and science.

The construction industry, and thus also underground construction, can have an impact on the 17 SDGs. In relation to underground construction, the leverage for achieving the goals is probably greatest for the following sustainability goals:

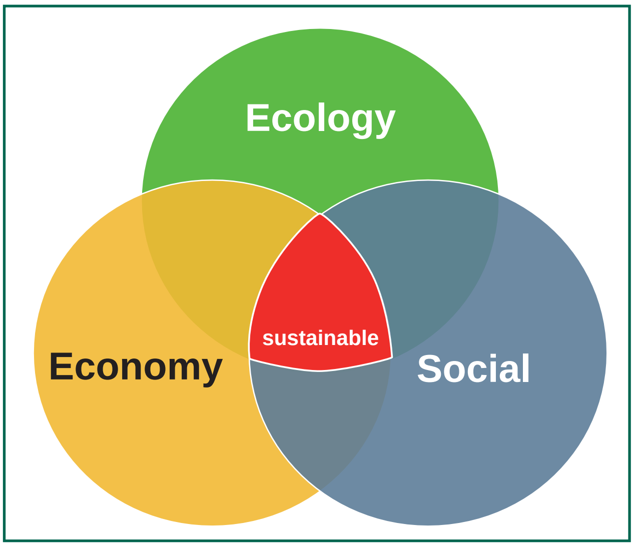


Figure 1-1 *Equal importance of ecology, economy, and social issues, based on Agenda 21*

6 Clean Water and Sanitation
7 Affordable and Clean Energy
8 Decent Work and Economic Growth
9 Industry, Innovation and Infrastructure
11 Sustainable Cities and Communities
12 Responsible Consumption and Production
13 Climate Action
14 Life Below Water
15 Life on Land

Figure 1-2 *The 17 UN Sustainable Development Goals [8]*

1.2 EU Regulations

Based on the overarching international framework, the EU has set itself the goal of becoming the first climate-neutral continent. According to the goals of the EU Green Deal published in 2019, no net greenhouse gas emissions should be released from 2050 onwards, and economic growth should be decoupled from resource use.

The EU intends to promote the necessary transformation in the economy and society with the Industrial Plan published in 2023 and to facilitate it through appropriate legal and improved framework conditions.

The EU Taxonomy is a measure laid down in the EU Action Plan "Sustainable Finance," which was codified in the Taxonomy Regulation in 2020. The aim of the action plan is to channel capital flows into environmentally sustainable activities. According to the Taxonomy Regulation, economic activities are considered sustainable if the following six environmental objectives are met:

1) Climate change mitigation
2) Climate change adaptation
3) The sustainable use of water and/or marine resources
4) The transition to a circular economy
5) Pollution prevention or control
6) The protection and restoration of biodiversity and ecosystems

Since the end of 2021, larger companies have been required to publish an annual sustainability report on their business activities, showing the degree of implementation of the environmental goals.

1.3 Implementation in Germany

Germany supports the UN and EU targets and even aims to achieve climate neutrality by 2045. Since 2016, the German Sustainability Strategy has been aligned with the SDGs. This was updated again in 2021 [11]. It defines the following six transformation areas for Germany:

- Human well-being and capabilities, social justice
- Energy transition and climate protection
- Circular economy
- Sustainable building and transport transition
- Sustainable agricultural and food systems
- Pollutant-free environment

These are implemented through corresponding legal requirements. For example, the Federal Climate Change Act (KSG) standardises climate policy targets and includes, among other things, the requirement that public authorities must ensure that their planning and decisions are in line with the purpose of the KSG and comply with European targets.

> Embedded in the political framework conditions, underground construction must and will also make its corresponding contribution to meeting the sustainability goals.
>
> These DAUB recommendations highlight ways in which this contribution can be achieved in Germany.

2 Status Quo and Current Challenges

2.1 General Situation

Regardless of the demands for a socially and economically sustainable development of our society, there are still needs for housing, work, mobility, supply, disposal, exchange of services and goods, etc. In future, these needs are to be met also taking into account the ecological sustainability goals.

Underground construction, particularly in the field of infrastructure, makes a significant contribution to social well-being and sustainable development. In the future, it will be necessary to implement the ecological sustainability goals in infrastructure construction as well, especially with regard to climate protection, the protection of natural resources (circular economy), and the preservation and promotion of biodiversity, in a socially just and economically viable manner.

Before the following sections outline possibilities for more sustainable underground construction, a description of the current initial state is given prior to the actual recommendation for underground structures.

2.2 Atmosphere and Climate Protection

In 2022, 53,800 million tons of CO_2-equivalent greenhouse gases were emitted worldwide (**Figure 2-1**). Germany's share of global greenhouse gas emissions in 2021 was 760 million tons of CO_2-equivalent, which corresponds to 1.4 %.

Around 46 % of greenhouse gas emissions remain in the atmosphere. The rest is absorbed by ecosystems on land or by the oceans. [4] Regarding the atmospheric share, scientific findings indicate that the

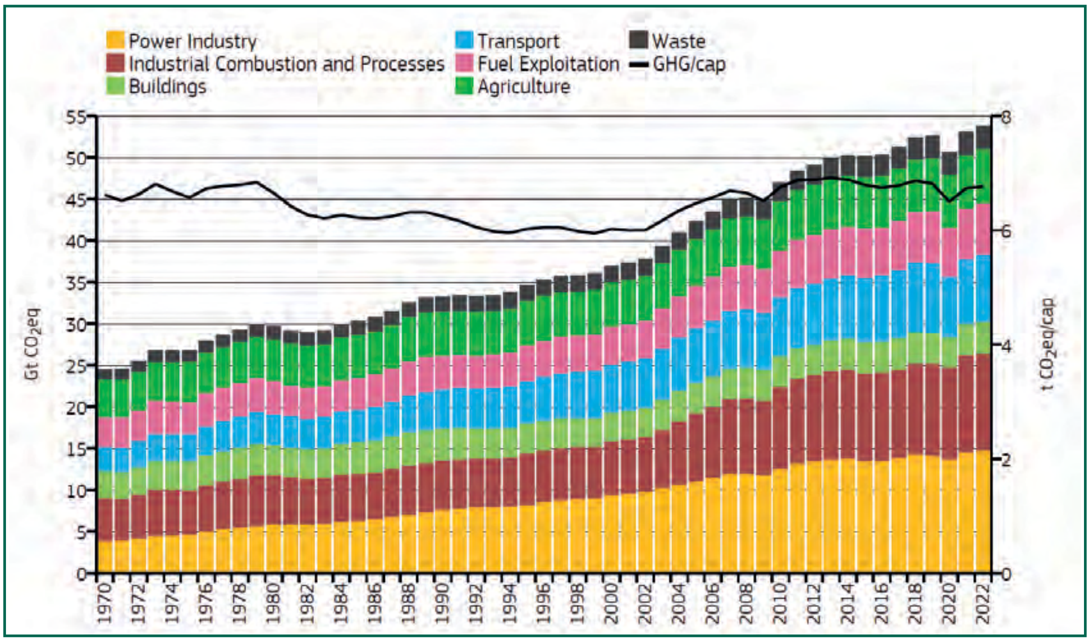


Figure 2-1
Development of global CO_2 emissions [12]

steadily increasing proportion of greenhouse gases in the atmosphere correlates directly with the measurable temperature increase [14].

To stop this development, the EU has decided to become climate neutral by 2050, i.e., to only emit as many greenhouse gases as can be offset by changes in land use and other (technical) measures (see **Chapter 1.2**).

Embedded in the EU objectives, Germany has decided with its Climate Change Act to become climate neutral by 2045 (**Figure 2-2**).

To date, only a few or no reliable figures have been published on the relevance of underground construction works to total greenhouse gas emissions. The following is an attempt to classify the relevance of underground structures transparently and neutrally based on available figures.

Emissions relevant to the construction of buildings are not assigned to the "buildings" sector in accordance with the KSG, but to the industry" sector. The latter includes the combustion of fuels in the manufacturing and construction industries, industrial processes and product use, as well as CO_2 transport and storage. The "buildings" sector, on the other hand, only includes emissions from the combustion of fuels to generate heat for the operation of buildings [16].

In 2014, according to a publication by the Federal Institute for Research on Building, Urban Affairs and Spatial Development, direct emissions from the construction industry (from construction processes)

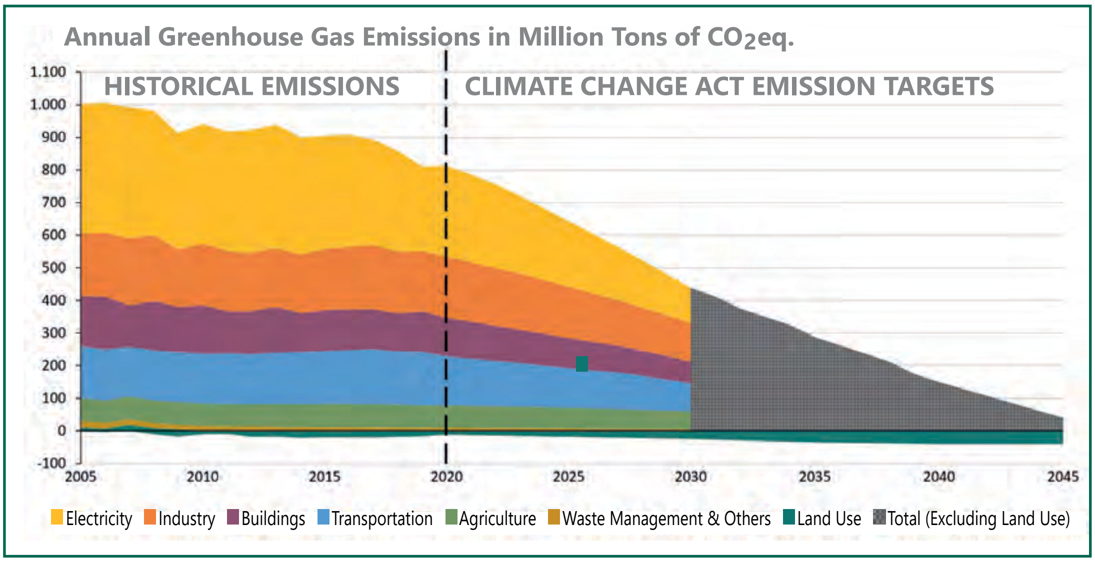


Figure 2-2
Emission targets for greenhouse gas reduction according to the German Climate Change Act [15]

and direct and upstream emissions of its suppliers (building materials industry and others) in Germany amounted to approx. 65 million tons of CO_2-equivalent. Material supplies from abroad accounted for a further 35 million tons of CO_2-equivalent [17].

Based on the 2014 emission [18] values of approx. 891 million tons of CO_2-equivalent, the share attributable to the construction or modernisation of buildings in the reference year was approx. 11 %. Assuming unchanged conditions, the total German emissions of 760 million tons of CO_2-equivalent in 2021, the year under review, result in emissions of 84 million tons of CO_2-equivalent for the German construction industry (see **Figure 2-3**).

A further breakdown by individual disciplines is not yet available. The following section therefore attempts to estimate the relevance to total GHG emissions based on the turnover figures for underground construction.

According to the Federal Statistical Office, the total turnover in the main construction trade in 2021 was approx. €147.6 billion [19] [20]. The bridge and tunnel construction sector generated a turnover of around €2.2 billion, which corresponds to a share of 1.5 % [20]. Assuming that the two sectors have roughly the same turnover volume, underground construction accounts for approx. 0.75 % of the total turnover in the main construction industry.

Due to the more complex construction method compared to structures above ground, a share of 1.0 % of underground structures in the GHG emissions of the construction industry is assumed here.

Based on this parameter and assuming uniform CO_2 emissions across all sectors, underground construction would contribute approx. 0.8 million CO_2-equivalents, or approx. 0.1 % to total emissions (**Figure 2-3**).

The following comparative analysis serves to verify the derivation of the share of total emissions attributable to underground construction:

Various greenhouse gas assessments of German tunnel structures show average greenhouse gas emissions of around 10,000 t to 30,000 t per kilometre of tunnel constructed, depending on the size and type of tunnel (**Figure 2-4**).

According to STUVA tunnel construction statistics [21], an average of around 23 km of tunnel tubes per year have been built over the last 20 years (2003 to 2023). Based on a conservative estimate of emissions of 30,000 t CO_2-eq./km of tunnel tube, this analysis results in annual GHG emissions for the construction of German tunnels of 690,000 t CO_2-eq., which is relatively consistent in magnitude with the previously derived figure of 800,000 t CO_2-eq. per year.

Based on the previous determination of the parameters, it is clear that the influence of underground construction on the total GHG balance is very limited (**Figure 2-3**).

Regardless of this, underground construction must and will take up the challenge of reduction and eliminate its share of greenhouse gases as far as possible in accordance with the national climate targets.

It should be noted that the main driver of GHG emissions in underground construction is the cement contained in concrete (see Part 2, Chapter 5). In addition, there are emissions from other materials (e.g. steel, explosives). Another portion of CO_2 emissions results from the excavation of the tunnel profile, depending in particular on the tunnelling method and the energy sources used for this purpose, as well as the necessary transport distances and means of transport for the use or disposal of the excavated material.

Currently, both the building materials and construction equipment industries are making considerable efforts to meet the climate targets. For example, the German cement industry has developed a scenario for becoming climate neutral by 2050.

Since, for chemical reasons, CO_2 emissions cannot be completely reduced to zero, particularly in the pro-

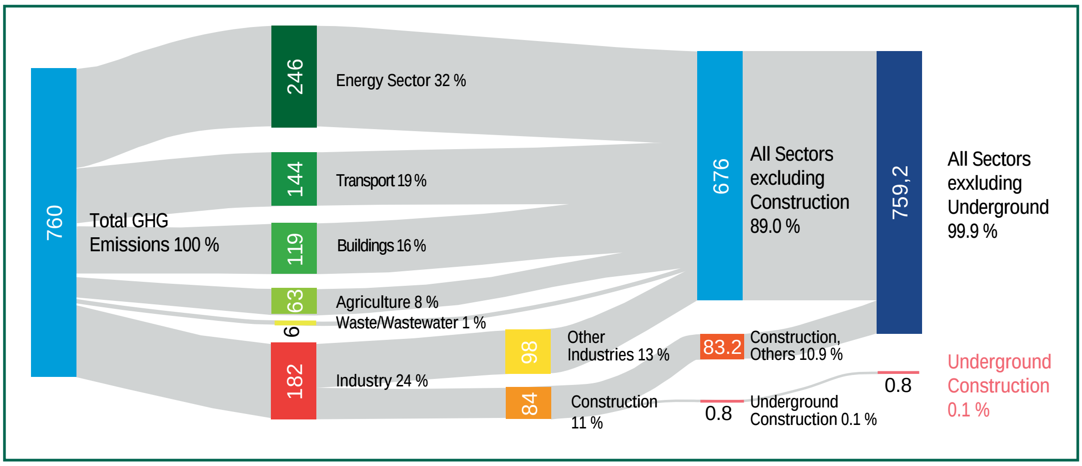


Figure 2-3
Share of GHG emissions from underground construction in total emissions in Germany for 2021 in million t CO_2-eq. and %

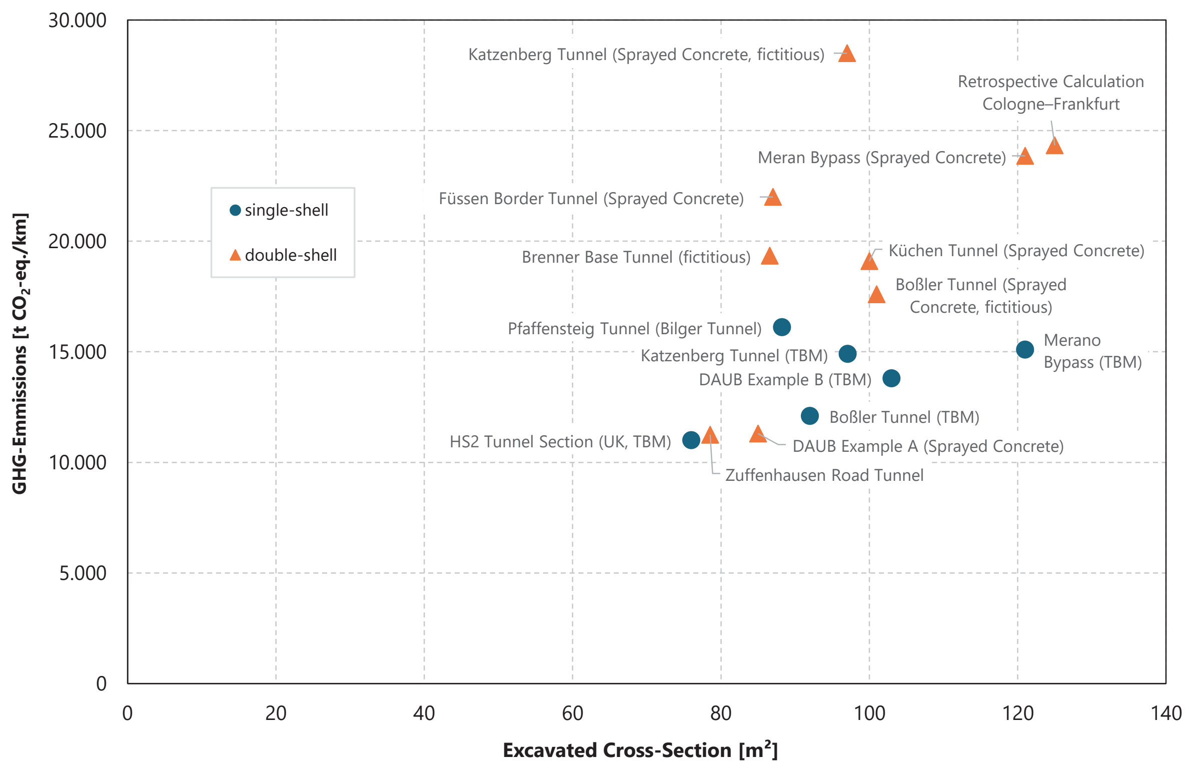


Figure 2-4 *CO_2 emissions during the construction of various tunnels; Note: The data points for the individual projects have not been determined using a uniform method.*

duction of cement, the remaining emissions must be offset by suitable technical measures. The following technologies are available for reuse (carbon capture and utilisation CCU) and for storing CO_2 (carbon capture and storage, CCS). The long-standing political resistance to the use of these technologies, especially CCS, now seems to have been overcome [23]. This creates the conditions for achieving climate neutrality in the construction of underground structures.

It should be noted that during the operational phase, underground structures can make a positive contribution to reducing greenhouse gas emissions in the transport and power generation sectors.

Many underground structures require hardly any energy to operate. Only underground railway stations, road tunnels and underground production facilities require energy for lighting and ventilation. These facilities are electrically powered, so the greenhouse gas balance depends on the type of electricity production.

Despite accounting for only 0.1 % (as of 2021) of Germany's greenhouse gas emissions, underground construction is also required to achieve climate neutrality in accordance with the provisions of the KSG.

This requires innovative developments in the production of building materials and in construction processes, as well as a strategy for the use and storage of residual greenhouse gas emissions that are unavoidable for chemical reasons.

In order to achieve the climate protection goals in the construction process of the underground structure, climate protection must be taken into account at the latest when the contract is awarded. The monetary valuation of climate impact costs using a CO_2 shadow price is an essential, politically motivated control instrument available for this purpose.

The total CO_2 emissions of the service offered are assessed using a CO_2 price that is uniformly defined and made transparent by the client. The climate- impact costs determined in this way form a so-called "CO_2 shadow price". For the assessment, the bid price and the shadow price of the climate impact are added together to form the evaluation total. It should be emphasised that the CO_2 shadow price is only fictitiously added to the bid price for the purposes of evaluating the bid. The bidder with the lowest evaluation total is awarded the contract.

Competition arises from the fact that bidders are given the opportunity to reduce the greenhouse potential calculated in the life cycle assessment, for example by using CO_2-optimised materials, construction methods, logistics processes or construction machinery. To this end, bidders are given the opportunity to state in their bids the greenhouse potential of their services that they can influence, deviating from the values in the client's life cycle assessment in CO_2. This enables them to reduce the CO_2 emissions of their services, lower the CO_2 shadow price and gain a competitive advantage through their contribution to climate protection. Taking the shadow price of CO_2 into account in the tender evaluation is permissible under German procurement law. As a general rule, the contract must be awarded to the most economically advantageous bid.

However, there is no „correct" CO_2 price; the range of models currently used is between €30 [33] and €809 [34] per ton. If the chosen price is high enough, additional costs for better achievement of climate targets can also be compensated for in the evaluation total. These additional costs are then actually incurred when the contract is awarded, but from the public sector's point of view they represent a sustainable investment.

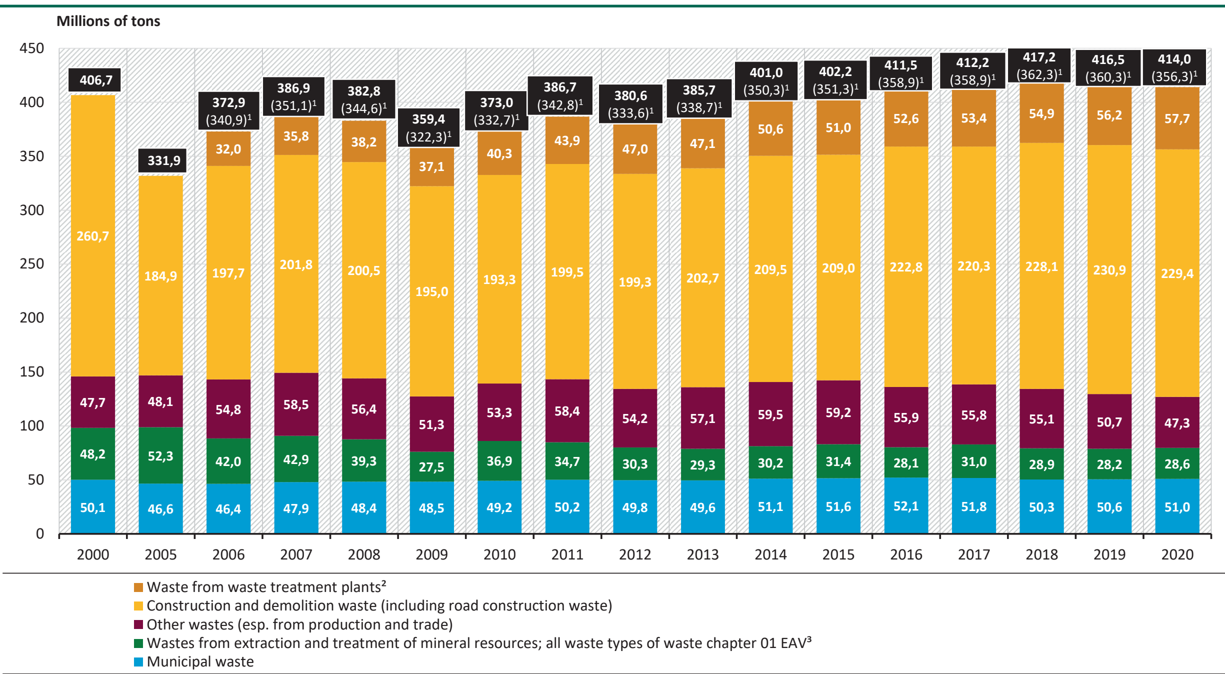
The consideration of a CO_2 shadow price for the tender evaluation is an internationally established control instrument. The shadow price model is standard in Norway and the Netherlands. In Austria, ASFINAG evaluates the life cycle assessment of asphalt and steel. The challenge lies in the expert examination of the CO_2 shadow prices stated in the bid.

2.3 Natural Resources

While the share of underground construction in Germany's overall carbon footprint is small, the issue of protecting natural resources and introducing the circular economy raises other, greater considerations.

Since all excavated material leaving the construction site must currently be declared as waste due to legal requirements, the construction industry plays a key role in waste management and, according to evaluations by the Federal Statistical Office , contributed 54 % (= 216 million t) to the total tonnage of gross waste (= 399 million t) in Germany in 2022 (**Figure 2-5**).

Thus, in 2020, the share of the category „soil, stones and dredged material", which is produced in large quantities in underground construction, was about 122 million t. Underground construction accounts for approximately 3 % of this amount. In the category „soil, stones and dredged material", up to 85 % of the material is already being processed or re-



[1] Net waste generation, excluding waste from waste treatment plants; surveyed as part of waste generation for the first time in 2006.

[2] Excluding wastes from wastewater treatment plants (SAB 1908), wastes from the preparation of water for human consumption or industrial process water (SAB 1909), wastes from soil and groundwater remediation (SAB 1913) and secondary wastes leaving the disposal process as raw materials/products.

[3] Wastes from extraction of mineral resources.

Source: Federal Statistical Office, Waste Balance Sheet, Wiesbaden, various years

***Figure 2-5** Waste generation in Germany 2000 – 2020 [24]* used today. Nevertheless, from a legal point of view, the total amount is considered waste.

Despite the already relatively high recycling rate for excavated material today, waste prevention and the reintroduction of construction waste into the circular economy are important imperatives for the entire construction industry and underground construction in particular. DAUB therefore published recommendations for the recycling of tunnel excavation material in 2024 [3]. Appropriate measures are to be taken to increase recycling for the production of building materials in order to conserve, for example, naturally occurring gravel, sand and clay deposits and the associated ecosystems.

According to current legal requirements, tunnel excavation material – unless it is recycled on the construction site – is considered waste.

With its recommendations on the recycling of tunnel excavation material (2024), the DAUB presents solutions for increasing the recycling rate of tunnel excavation material and thus promoting the circular economy.

2.4 Biodiversity

The United Nations defines the diversity of all living organisms, habitats and ecosystems on land, in fresh water, in the oceans and in the air as biodiversity (UN1992 - CBD) [25]. The term biodiversity encompasses:

- the diversity of different species, including within a species (taxonomic diversity)
- the genetic diversity within individual species and the diversity of all organisms in a habitat (genetic diversity)
- the diversity of biotopes and ecosystems as well as ecosystem functions such as pollination and seed dispersal (ecological and functional diversity)
- the diversity of animal behaviour (cultural diversity)

In recent years, public awareness has grown that all animals and plants play an important role in the Earth's ecosystem. Without them, humanity could ultimately not exist on Earth. Biodiversity provides food, active ingredients for medicines, serves as a source of recreation and plays an important role in climate regulation. Species-rich forests and meadows can absorb more carbon and thus remove the greenhouse gas carbon dioxide from the atmosphere. Different species also occupy different niches in the ecosystem. If species are missing, ecological cycles are disrupted. For example, when insect species become extinct, this affects both birds that feed on these insects and the pollination of plants and thus human harvests. The decline in biodiversity is therefore ultimately also a threat to our species.

Currently, biodiversity within and between ecosystems is declining faster than at any other time in human history. This dramatic decline is currently not yet considered an important short-term problem in many places, but the importance of the problem is recognised for its medium-term consequences [26].

The decline in biodiversity also affects Germany. An indicator of this is that around one third of all animal and plant species in Germany are considered endangered (**Figure 2-6**).

The global threats to animal and plant species are diverse and mostly man-made. Loss of habitat due to ever-expanding agriculture, mining/open-cast mining, cities, transport routes or over-exploitation of natural resources such as overfishing and poaching, but also global warming, environmental pollution and introduced invasive species threaten the original biodiversity. The individual mechanisms also reinforce each other.

In Germany, wild animal and plant species are threatened primarily by the following causes (cf. [28]):

- Destruction, fragmentation and loss of natural habitats
- Over-exploitation
- Climate change
- Pollution
- Displacement of native species by invasive species

According to the report „Wirtschaften im Einklang mit der Natur – Handlungswege zur Sicherung der Biodiversität“ (Economis in harmony with nature – courses of action to safeguard biodiversity) [29], infrastructure construction is responsible for approx. 7 % of the impact on biodiversity (**Figure 2-7**), the main causes being „destruction, fragmentation and loss of land“.

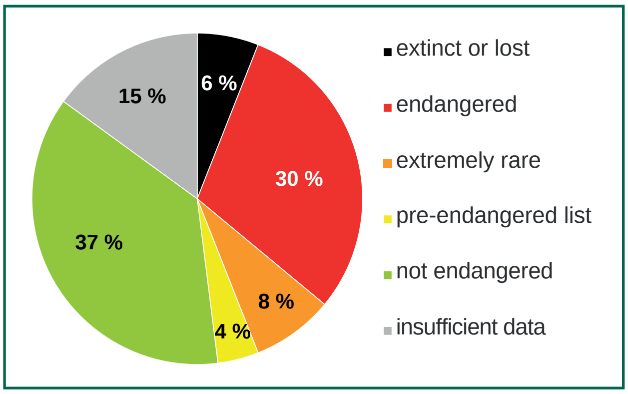


Figure 2-6 *Endangerment situation of animals, plants and fungi in Germany, which were assessed in the Red Lists from 2009 onwards [27]*

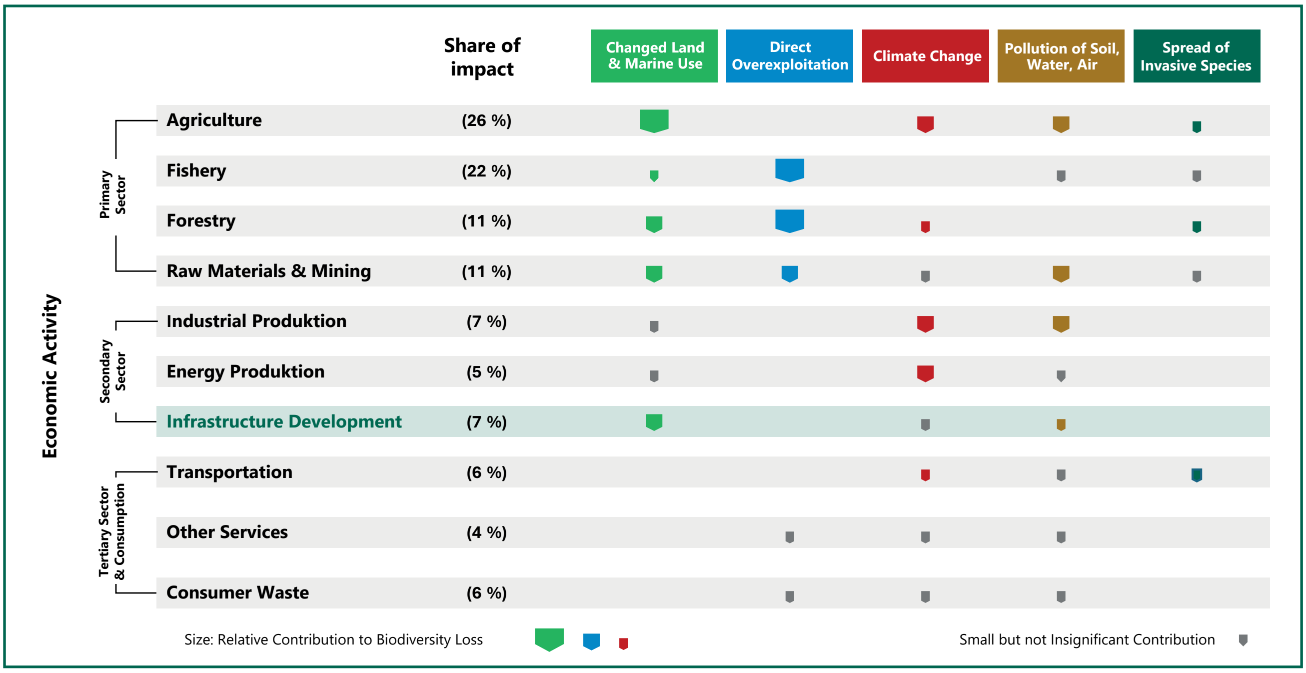


Figure 2-7 *Economic activities and their contribution to the pressures on biodiversity (based on [29])*

Although land loss is declining in Germany, it still amounted to 55 hectares per day in 2021, which corresponds to the consumption of approx. 78 football pitches per day (**Figure 2-8**). The loss of this land is accompanied by the displacement of the flora and fauna in these areas, i.e. negatively affecting biodiversity. Transport infrastructure currently accounts for the smallest share of land loss.

The German sustainability strategy aims to reduce daily land loss to 30 hectares per day by 2030 in order to achieve the transition to a circular land economy (net zero target) by 2050, in line with the European Union's resource strategy and the German government's climate protection plan [30]. Further measures to promote biodiversity are discussed in **Chapter 4.5.3**.

The underground construction method has the advantage that it requires very little space and that it

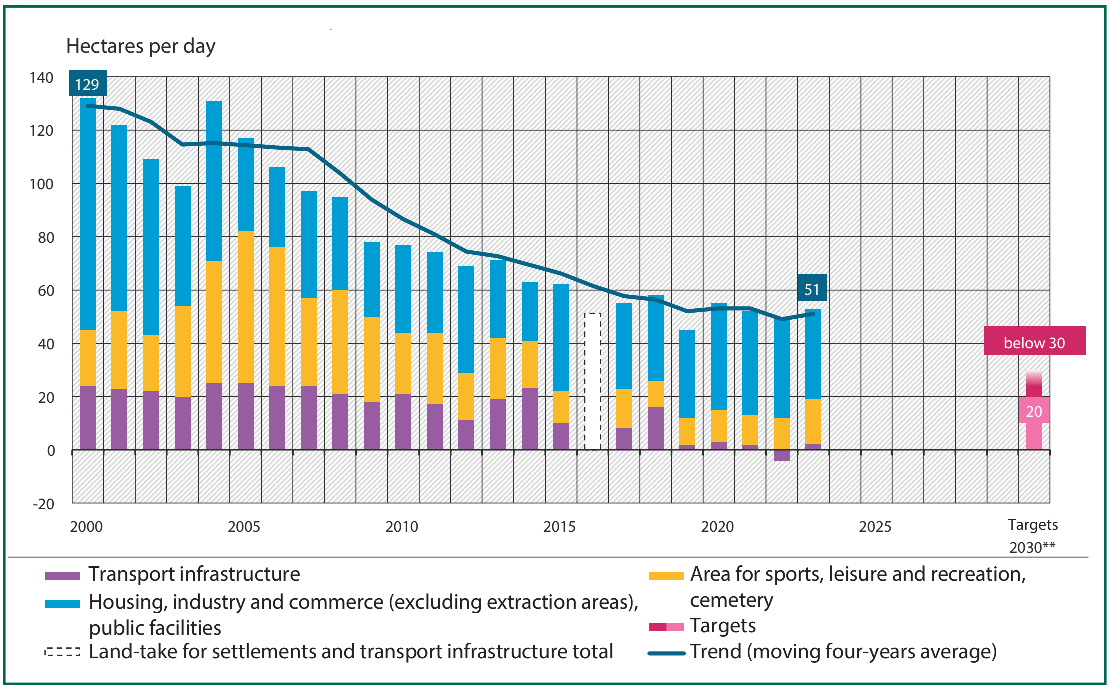


Figure 2-8
Land consumption in Germany [31]

runs beneath ecosystems rather than dissecting them (**Figure 2-9**). If, in addition, above-ground traffic areas are relocated underground, there is an opportunity to recultivate destroyed areas and eliminate fragmentation effects, which has a positive effect not only on biodiversity, but also on social sustainability.

In addition, the excavated material is often used for the renaturation of mining areas and for landscaping, which leads to less intensively used areas that make a positive contribution to the preserving and improving biodiversity.

Underground structures inherently fulfil many of the sustainability goals listed above, as, for example, relocating infrastructure underground creates space for other uses and avoid adverse effects on people and nature.

Appropriate compensation and replacement measures on landfill sites for excavated material, demonstrable contributions can be made to the preservation and promotion of biodiversity.

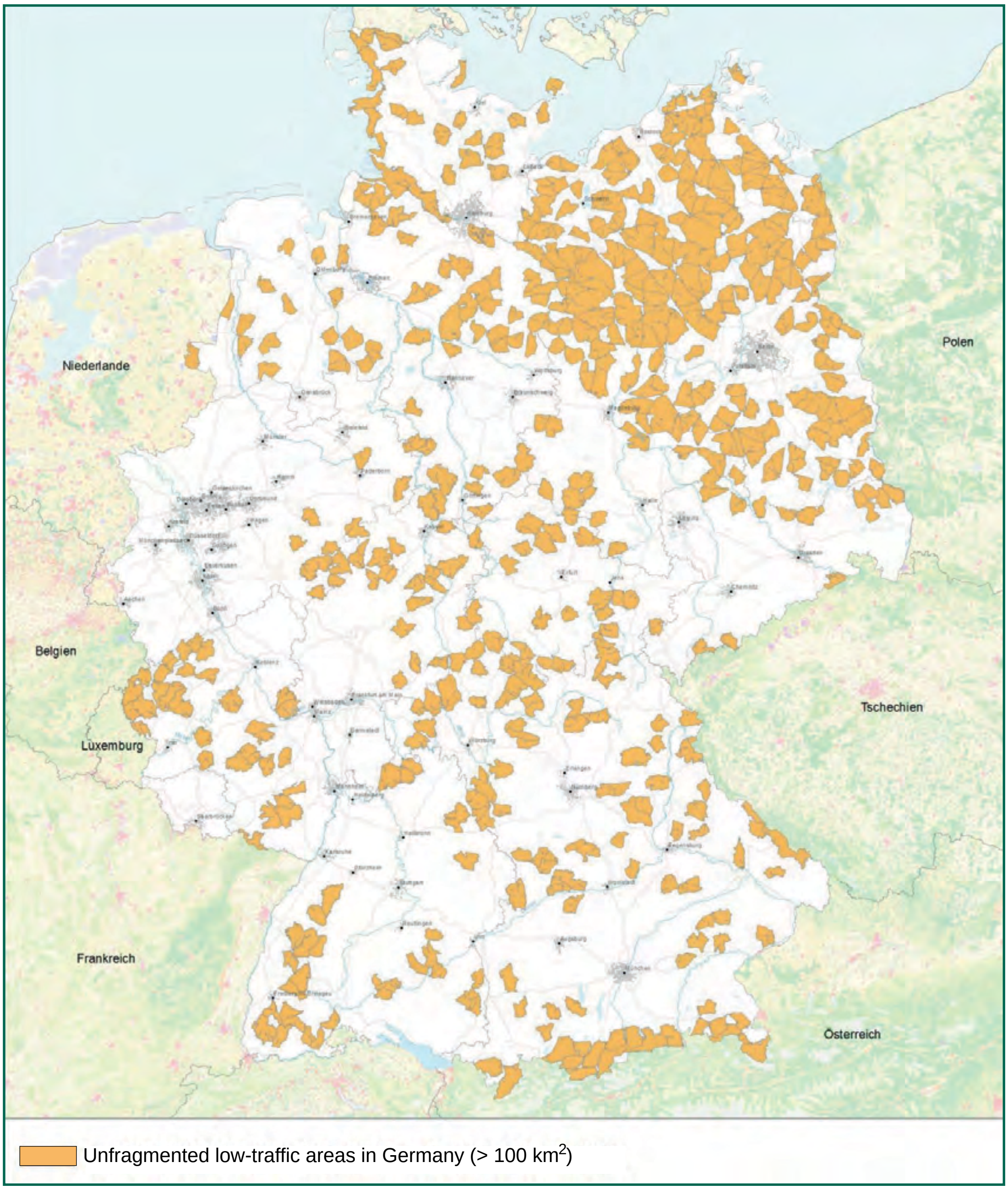


Figure 2-9
Unfragmented, low-traffic areas in Germany [32]

3 Contributions of Underground Structures to Sustainability

3.1 Ecology

3.1.1 Ecological Aspects – Urban

Against the background of an equal consideration of all three pillars (ecology, economy, social aspects) and with a view to reducing the potentially harmful impacts of transport infrastructure, the contribution of underground structures to increasing sustainability in city centres is considerable. If we broaden our view and look at more than just the GHG balance sheet for each project, other substantial effects come to light that must be taken into account in any serious assessment of a measure's sustainability.

By relocating traffic routes below the surface, previously sealed areas can be used for renaturation and infiltration, for example. A more orderly flow of traffic reduces congestion and thus travel times, which, apart from GHG, also reduces other emissions such as fine dust, noise, or nitrogen oxides. Through many sustainable measures, such as the construction of rainwater infiltration ditches in the middle of the roads, the installation of additional tree infiltration ditches or the planting of mini-parks or tiny forests in parts of the area, urban regions can be developed into so-called "sponge cities".

However, space in narrow inner-city streets is limited or determined and shaped by existing buildings and infrastructure. If more infrastructure is to be installed on the road (e.g., cycle paths and sponge cities), something else must be removed or relocated to an elevated or underground location (e.g., as an underground light rail system). The elimination of private transport is not entirely possible, as at least one lane must remain open for emergency services, passenger and freight transport, waste disposal, etc., in order to maintain public services. In general, however, moving traffic underground has many advantages for the municipalities concerned and contributes to an increase in quality of life and sustainability.

Selected Criteria and Indicators in Detail

Reduction of Air Pollutants

Motorised private transport is responsible for a large proportion of air pollutants beyond pure Carbon footprints. The combustion of fossil fuels also releases nitrogen oxides, which in turn form ground-level ozone. In addition to these gaseous air pollutants, fine dust particles are also present. These originate not only from vehicle exhaust gases, but from brake and tyre abrasion. For this reason, although traffic-related particulate matter emissions will be reduced in the future as more vehicles are powered by electricity or green fuels, they will continue to occur. This is particularly true in the case of congestion on inner-city roads, for example during rush hour, which already leads to considerable additional travel times due to traffic jams in many conurbations. Ozone, NO_x, CO_x, and particulate matter concentrations, which are typically registered at several measuring stations in large cities, can be used as indicators for air quality.

Traffic tunnels can make a major contribution to ensuring that traffic flows much more smoothly both in urban and rural areas. They not only help to avoid congestion but also significantly reduce acceleration and braking, which are particularly high in emissions. This can be achieved, for example, by relocating roads underground or by shifting the mode of transport in favour of underground public transport systems.

For example, the implementation of the "Boston Big Dig" project reduced carbon monoxide pollution in downtown Boston by 12 % after completion of the tunnel and rerouting of traffic [36]. Immediately after its opening in 2003, the newly created traffic situation also resulted in a reduction in the average daily time spent on the road by approx. 60 %, despite an increase in average daily traffic of more than 23 % [37].

Increase in the Proportion of Open Space

A significant portion of urban areas is largely taken up or influenced by transport routes. Many surfaces are sealed by roads or railway lines, or areas are fragmented by these transport routes, which significantly limits the available open space.

Either the percentage of open space within area under consideration or the absolute size of a contiguous open space can be used as an indicator for assessing the proportion of open space. Both can be derived from land use plans.

Cleverly planned traffic tunnels create new open spaces on the surface. These should not be sealed off again by other transport areas but should be provided with green and blue infrastructure (i.e., contiguous green or water areas) wherever possible. In this way, they contribute to people's well-being, promote urban biodiversity, improve the urban climate and serve as retention areas during heavy rainfall. Exemplary projects in Düsseldorf, Hamburg, etc., are creating new open spaces that are being used for ecological purposes.

One of the most prominent examples of the creation of open spaces is the relocation of traffic on the M-30 in Madrid. By moving traffic into a tunnel, a 6-kilometre-long park was created along the Manzanares River, offering various leisure and recreational opportunities. The project was realised between 2006 and 2012, was one of the most ambitious greening projects in Europe and today covers a total area of around 120 hectares. The park includes green spaces, playgrounds, sports facilities, paths for pedestrians and cyclists, as well as cultural facilities (**Figure 3-1**).

Similar effects were also achieved in the Boston Big Dig project. Here, the creation of new green spaces has improved biodiversity. The approx. 11 hectares of inner-city space that has been freed up extends over 2.4 km across several districts and will remain permanently undeveloped Rose Fitzgerald Kennedy Greenway). 5,000 trees and over 30,000 bushes were planted on the site, which also features gardens, lawns, and tree-lined avenues, as well as cultural and social offerings and various leisure activities. The area is managed by the non-profit Greenway Conservancy and is a prime example for urban revitalisation and sustainable urban development, water management and microclimate [38].

Water Management

Durch die Verlagerung von oberirdischem Verkehr iThe relocating of surface traffic to tunnels makes it possible to install rainwater infiltration ditches in the middle of the road to retain water from heavy rainfall and torrential rain in these ditches and release it with a time delay into a receiving watercourse, e.g., a renaturalised stream. The rainwater stands in the vegetated infiltration channels, where it partially seeps away and evaporates, thereby improving the microclimate and reducing the heating of city centres in summer. At the same time, the green rainwater infiltration channels also provide a habitat for microorganisms, insects, amphibians and birds, thereby contributing to biodiversity in the built-up city centre. Ultimately, this green-blue infrastructure makes the city centre more liveable and healthier for residents and visitors. An example of this sustainable solution on main roads in the city centre can be found in Bochum (**Figure 3-2**).

3.1.2 Ecological Aspects – Non-Urban

Similar to the positive effects in inner-city areas, clear advantages of underground infrastructure can also be identified in non-urban environments. Underground construction methods are increasingly being used, particularly in the implementation of national and international transport corridors and in the course of the energy transition – for example in the construction of power lines or energy plants.

An efficient rail connection between metropolitan areas and conurbations is a key component of a sustainable and future-proof infrastructure for long-distance trade, freight and passenger transport. As part of the energy transition, new power lines and plants for pumped storage and hydroelectric power plants are also being built. In all these areas of application, underground construction methods enable routes to be laid out in a way that preserves the landscape, especially when crossing under natural obstacles such as mountain ranges and hilly landscapes.

Examples of this are the Gotthard and Lötschberg Base Tunnels in Switzerland, which are already in operation, the Brenner Base Tunnel currently under construction between Austria and Italy, and the planned Ore Mountains Base Tunnel between Germany and the Czech Republic.

One critical aspect of underground transport routes is the concentration of emissions at tunnel portals, which can have a local impact on the sur-

Figure 3-1 *Cityscape of Madrid before and after the lowering of the M-30 motorway in the area of the Segovia Bridge (Photos: AETOS)*

rounding area. For this reason, particular attention must be paid to the location of the portals and the development of suitable ventilation concepts during the planning process.

The targeted relocation of these infrastructure structures underground not only reduces interference in the landscape, but also emissions from the operation of above-ground facilities. In this way, contiguous ecosystems and protected areas can be preserved or newly created. High-speed rail lines that pass through sensitive areas underground also contribute to reducing domestic air traffic in Germany – a contribution to the ecological transformation of the mobility sector. At the same time, this strengthens social acceptance for the construction of such forward-looking infrastructure projects.

Selected Criteria and Indicators in Detaill

Land Management and Urban Emission Protection
Bypasses with tunnels are an example of a particularly sustainable road infrastructure measure with a positive effect in terms of emission protection for citizens. The roads needed to cross towns can be relocated as bypasses outside the towns. This will give residents back the centres of their villages and towns, which will be almost traffic-free, thereby significantly reducing noise pollution in addition to reducing particulate matter and nitrogen oxides in urban areas. Regardless of the topographical conditions, it may be advisable to construct the bypass as a tunnel in order to avoid cutting up open spaces [39].

The same applies if additional economic areas are to be connected to the existing road network. If this involves crossing bodies of water, this can be done in a way that preserves the landscape and does not interfere with shipping by means of tunnels. Examples can be found on the Elbe and Weser rivers in northern Germany, among other places.

Shaping and Realising the Energy Transition
A central challenge of the energy transition is the development of a suitable infrastructure for the storage and distribution of renewable energies. This requires underground caverns, tunnel systems for pumped-storage plants, and underground distribution networks.

Underground facilities are indispensable, particularly for the use of hydropower – both for energy generation and for storage. They are deliberately built underground to preserve the landscape. Even during the construction phase, access is usually via tunnels, which largely minimises interference with the surface.

Transporting electricity over long distances – for example from large-scale wind and solar power plants to consumption centres – also places high demands on environmental compatibility and public acceptance. Utility tunnels offer a sustainable solution here: they enable power lines to be laid in a way that preserves the landscape and are already being implemented on a large scale, particularly in the vicinity of offshore wind farms, by grid operators, In addition, these tunnel systems are also suitable for the integration of gas, hydrogen, and CO_2 pipelines – a further step towards a cross-sector energy infrastructure.

Tunnels and other underground facilities contribute to improving the ecology in both urban and supra-regional areas. They help to reduce emissions, protect habitats from harmful influences, improve the microclimate, create open spaces in urban areas, and are indispensable as essential infrastructure structures in the course of the energy transition.

Figure 3-2 *Green rainwater infiltration channel in Hattinger Strasse in Bochum after lowering the tram line (left before and right after implementation; Photo: City of Bochum, Press Office)*

3.2 Social Aspects

3.2.1 Social Aspects – Urban

On the surface, underground structures have many clearly noticeable effects on social and economic life in the city: traffic flows shift, sustainable pedestrian and bicycle traffic develops anew and improves, and traffic areas that are freed up can be returned to the population in the form of green spaces, for example, Pedestrian zones have a positive impact on retail, restaurants, entertainment, etc. Where areas of conflict with trams, private transport, pedestrians, and cyclists are eliminated by tunnel traffic, traffic accidents are reduced. Fire engines and ambulances can also reach their destinations more quickly and with less conflict.

This principle has been known in urban areas for over 100 years: for 160 years now, underground railways and underground light rail systems have been part of metropolitan transport infrastructure and urban life. The London Underground has been in operation since 1863 and the Berlin U-Bahn since 1902. In Germany, there are a total of 20 major cities with underground railways and underground light rail systems. In 2024, 663 underground stations and over 1,000 km of underground tunnels were in operation. They are the main arteries of public transport and, in most cases, of all inner-city transport. The transport advantages of underground railways and light rail systems are evident: the performance and capacity of an underground system are higher than those of a tram or bus line. The travel speeds of 80 km/h for an underground railway and 70 km/h for a tram in underground sections are significantly higher than those of a tram or bus with a permissible speed in the city of 50 km/h and an actual average speed of 25 km/h in traffic flow. This significantly reduces travel times.

The impact of this fast and independent underground mode of transport extend to all areas of urban life, especially social aspects. Increased mobility and shorter journeys have a positive impact on all functions and areas of life: living, working, learning, shopping, retail, culture, entertainment, recreation, health, and social activities. Everyone can enjoy and experience the benefits on their way to work, school, university, shops, the library, cinema, theatre, hospital, daycare centres, retirement homes, etc. every day.

Selected Criteria and Indicators in Detail

Reducing travel times, improving accessibility

Mobility is an essential prerequisite for modern society and a prosperous economy. This is linked to a growing interest in society in reducing travel times and thus an increasing demand for well-functioning infrastructure.

The size of the target area that can be reached within a certain period of time (e.g., 10 minutes) can be used as an indicator for assessing accessibility. Such accessibility maps can be determined on the basis of public transport timetable data.

Traffic tunnels can make a significant contribution to improving the accessibility to urban areas and reducing travel times. Additional transport routes are being created underground, which are largely independent of disruptive influences (especially from other modes of transport and the weather) and thus have a particularly high transport capacity, as can be clearly seen in **Table 1**. The underground infrastructure significantly reduces commuting times, which improves the quality of life for commuters and leads to the development of new residential and commercial areas, as can currently be seen in the example of Crossrail in London.

Demand for inner-city mobility continues to rise: according to a 2018 forecast, global demand for inner-city mobility is expected to rise to 48.4 trillion

Table 1 *Average real passenger numbers for various public transport modes in Germany (according to VDV surveys [41])*

Transport Mode		Average real passenger numbers [passengers/day] 1)
Rail line service	S-Bahn (Suburban train)	20,000 – 120,000
	U-Bahn (Underground railway)	100,000 – 200,000
	Stadtbahn (Light rail)	20,000 – 100,000
	Straßenbahn (Tram)	10,000 – 30,000
	Regionalbahn (Regional train)	2,000 – 5,000
Bus line service	City bus in dense areas	2,000 – 15,000
	Regional bus in rural areas	1,000 – 3,000
On-demand transport	On-demand bus (corridor)	500 – 1,000
	Dial-a-ride taxi (area) 2)	40 – 100
	Community bus (area) 2)	20 – 50

1) These are not performance figures, but actual daily values in both directions for the service areas and lines; in individual cases, the figures may therefore be exceeded or not reached

2) Usually only used at certain times of the day

passenger kilometres by 2050; in 2010, the figure was 25.8 trillion passenger kilometres [40].

Larger metropolitan areas such as London, Paris or Berlin require efficient underground transport infrastructure. Worldwide, 251 cities have a well-functioning subway or light rail system (as of 2025).

Increase in road safety

In recent years, vehicle safety has continuously improved, resulting in a steady decline in the number of vehicle occupants killed or injured. However, tragic accidents in which pedestrians or cyclists are injured by vehicles still occur relatively frequently. One reason for this is inadequate separation of vulnerable road users from motorised traffic.

The number of fatalities and injuries within a certain period of time along the route under consideration, as recorded in police accident statistics, can be used as an indicator for assessing road safety.

Traffic tunnels inherently avoid conflicts and create additional free space on the surface when tracks or multi-lane roads are relocated underground. These open spaces can be used, for example, to create separate cycle paths and improve visibility in the traffic area, thus making a further contribution to increasing road safety. In addition, it can be statistically proven that the frequency of accidents on open stretches of road is significantly higher than in tunnels [72] [73].

Improving quality of life in the area surrounding the measures

By clearing areas used for traffic, quiet zones and traffic-free areas can be created in city centres, which substantially improve the quality of life for residents and neighbours. In addition to the aforementioned ecological effects (e.g., reduction of emissions), such constructions measures also have an impact on the social fabric of the city centres. The examples already listed in **Chapter 3.1.1** under "Increasing the proportion of open space" also lead directly to an improvement in the quality of life in the area surrounding the measures.

3.2.2 Social Aspects – Non-Urban

By relocating infrastructure projects underground, interference with the landscape is avoided and nature reserves and ecosystems are preserved or newly created. These areas can be easily reached for local recreation by public transport and thus contribute significantly to improving the quality of life of the residents of the adjacent cities and to promoting biodiversity.

Traffic tunnels enable traffic flows to be moved underground, thereby substantially improving the quality of life in urban areas: new open spaces are created, accessibility and mobility are generally improved, and travel times for residents are reduced. This increases personal well-being and acceptance of specific urban development measures.

3.3 Economy

3.3.1 General

While it makes sense to distinguish between urban and rural areas when identifying social and environmental aspects, economic aspects have an impact on either the national economy or business management. Therefore, no distinction is made below between urban and non-urban, categories; instead, a differentiated assessment is made based on economic benefits, service life and durability, maintenance and repair, and availability. No quantified statement is made at this point, but rather a general reference to effects to be taken into account is formulated. These must be considered and examined on a project-specific basis in the course of an evaluation.

3.3.2 Economic Benefit

Underground infrastructure structures can generate economic benefits in many different ways, contributing to sustainable development. By shortening travel and transport routes, for example by passing under rivers or mountain ranges, delivery times are reduced in a resource-efficient manner. This helps to promote business locations and connect entire regions to larger economic areas. The Pirmasens region is a prime example, which experienced a renaissance with the opening of the Cologne-Frankfurt high-speed railway line. The direct and fast connection to Frankfurt allows many employees from the region to participate in the labour market of the Main metropolis and generates substantially increased local revenue from income and trade taxes. In city centres, the shift from private transport to underground public transport, in addition to the ecological and social effects already mentioned, reduces traffic congestion and thus the amount of time spent in traffic. This results in savings in fuel consumption and less time spent in traffic for road users. As a rule, underground railways can continue to operate during snowfall, storms or heavy rain, even when traffic on the surface has already come to a standstill due to weather conditions. As a result, these transport systems make a valuable contribution to the security of supply in local transport thanks to their high availability.

3.3.3 Service Life and Durability

The existing underground structures have laid the foundations for a thriving and resilient national economy: they ensure the supply of water and energy, they relieve city centres of traffic thanks to underground and suburban railway systems and underground roads, they ensure safe transport connections over long distances and across the region, and they enable underground disposal systems such as sewage systems.

Underground infrastructure in Germany is currently designed for a long technical service life, generally 100 years. In some cases, existing structures for all modes of transport are already showing significantly higher life expectancies than initially assumed or projected (**Figure 3-3**).

Comparable figures can also be found for other modes of transport– e.g., in the underground railway networks of large cities. For example, shortly after the beginning of the 20th century, around 80 % of the Berlin U-Bahn in use today was already in operation. This means that the structures have substantially exceeded their intended service life in accordance with the applicable regulations.

Renewal and upgrading campaigns ensure that, even after their intended service life, they continue to meet the current traffic, normative and regulatory requirements and can continue to perform their service efficiently for decades to come.

Impressive examples of the long service life of underground transport structures are the first long railway tunnels through the Alps (Mont Cenis Tunnel, 1871; Gotthard Railway Tunnel, 1882; Simplon, 1906), which have carried significant traffic loads for well over a hundred years and continue to do so today.

There are even older tunnel structures that are still in operation today, such as the Urner Loch opened in 1708 (road tunnel, Switzerland), the Hauenstein Summit Tunnel (1858, railway tunnel, Switzerland) or the Tunnel ferroviaire du Lioran (1868, France).

3.3.4 Maintenance and Repair Costs

In Germany, tunnels are classified as civil engineering structures within the meaning of DIN 1076 and are planned, built and maintained in accordance with the rules of the respective modes of transport.

Like all other types of structures, underground structures are subject to degradation effects throughout their service life: influences from the structure's environment have damaging effects on tunnel and bridge components, for example in the form of chlorides from de-icing salts. These penetrate the concrete structure and sometimes cause considerable damage to the reinforcement. Compared to bridges, however, tunnels show significant differences in operation, which have a direct impact on the life cycle costs of the structures:

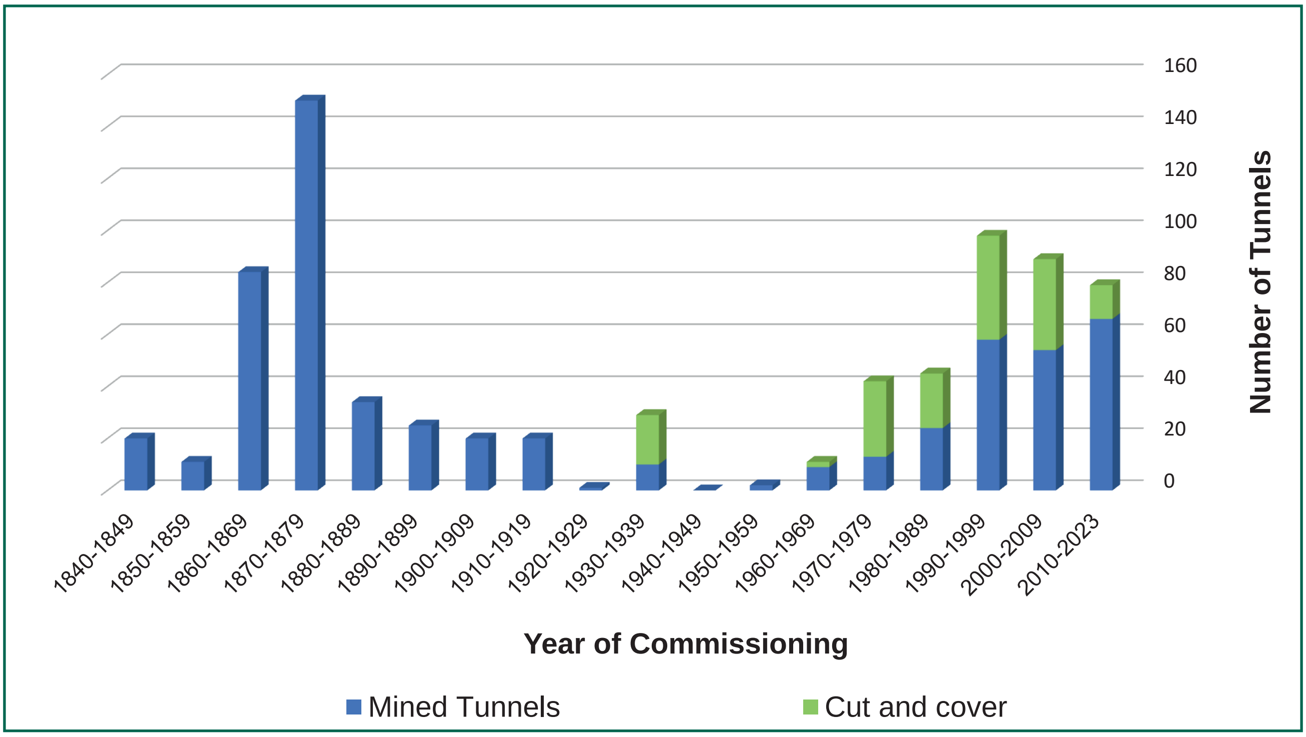


Figure 3-3 *Age structure of DB's railway tunnels, as of Dec. 2022 [42]*

- Bridges are affected by changing traffic flows, particularly the increase in heavy goods traffic. The electrification of private transport is also expected to contribute to a further increase in the risk profile in future due to the increasing weight of vehicles. Tunnels, on the other hand, are completely unaffected by this, as traffic does not have a direct impact on their supporting structure. For this reason, ICE trains, for example, can still travel through the tunnel structures of the old Rhine route today, some of which are over 100 years old. Structural loss – as can currently be observed at the Rahmedetal Bridge on the A 45 near Lüdenscheid – is therefore not a relevant scenario for tunnels.
- Tunnels, on the other hand, must be equipped with operational facilities to protect users, which, in the event of an incident, ensure that users can rescue themselves and support external rescue operations. These facilities must also be maintained and, if necessary, replaced when the components of the system reach the end of their service life.

The maintenance costs for tunnel facilities are therefore largely independent of the intensity of traffic use and, in terms of the effort involved and the resulting costs, are largely calculable. This distinguishes tunnels significantly from bridge, structures, which generally show progressive damage due to ageing and increasing traffic loads.

> Not only in Germany, but also worldwide, there are underground structures with service lives of more than 100 years and examples of how these can be extended through upgrading campaigns. Underground structures have positive economic effects and at the same time, low maintenance costs. In terms of long-term use, underground structures.

4 Ways to Sustainable Underground Construction

4.1 Prerequisites and Framework Conditions

Achieving sustainability goals is not something that happens automatically. Decisions made in the past were often based on the conviction that they had been weighed up with a view to securing the future. On closer inspection, however, it often becomes clear that only a small part of the sustainability goals recognised today was taken into account. A rethink is therefore required above all else. This implies that there must be a willingness to change behaviour, or at least this willingness must be awakened.

This goes hand in hand with an expansion of consciousness, a way of looking “beyond the horizon”, so to speak, nowadays often referred to as ‘abandoning silo thinking’. It is no longer just a matter of one’s own immediate concerns, but of recognising and evaluating all associated effects, so that a balanced weighing process based on the three pillars of sustainability can be set in motion. This requires holistic evaluation systems, which are discussed in more detail in **Chapter 5**.

Advancing digitalisation provides valuable tools and methods for comprehensively mapping all these aspects. Digital planning methods such as BIM provide reliable quantity structures for various planning variants based on parameterised planning, even in the early planning phases. This allows decisions to be made that are forward-looking and oriented towards sustainability goals, largely without the need for subjective assessments. Such a methodology also makes it much easier to reach a consensus, because of the possibility of comprehensively considering all relevant aspects, as the process already incorporates the willingness to compromise.

If we break this approach down further, we see that it also affects approval procedures, release processes and licensing procedures for innovative materials etc. A rethink is required across the board, because a wide range of criteria must always be incorporated into the decision-making processes. However, this also presents an opportunity to classify ultimate individual bans and restrictions in favour of overarching objectives. In doing so, it should be expressly permitted to weight objectives depending on the issue and the facts of the case.

It is also necessary to review the regulations surrounding us with regard to political guidelines for achieving sustainability goals. For example, the Federal Transport Infrastructure Plan [43] pursues objectives that clearly conflict with other sustainability goals. These include efficient transport infrastructure for greater personal mobility, ensuring the supply of goods and increasing road safety. The other objectives such as reducing emissions (by reducing traffic congestion), limiting land consumption and improving quality of life are also mentioned. The approach is to expand and increase the capacity of existing transport routes, and in some cases to build new ones.

Such a conflict is normal at first. However, there is room for improvement in terms of creating greater transparency of the evaluation system used to select and prioritise measures. So far, instead, the explanation has been that the objectives are “deliberately not quantified”.

Another example of a set of rules that tends to hinder he achievement of objectives can be found in the

"Guidelines for planning decisions cut or tunnel" [44]. The evaluation here is based exclusively on a pure economic analysis. The document, which dates from 1998, is currently being revised, and an expansion of the evaluation criteria is necessary.

4.2 Genesis of a Project

4.2.1 Requirements, Project Objectives

The need for infrastructure measures is regularly demonstrated by indicators such as delays in rail transport, traffic jams in road traffic, accident frequency, technical disruptions or failures, the need for a secure supply of energy and water, but also by citizens' complaints, citizens' initiatives and petitions that become apparent through political processes. This is therefore a reactive mechanism, which results in a corresponding time lag until a project is realised. Another indicator is regular updates of traffic forecasts for the respective modes of transport - rail, road and water - in conjunction with key figures for the performance of the existing infrastructure.

Initial project objectives can be defined based on requirements. These are naturally based initially on the aforementioned indicators. So far, the effects are then assessed, and compensation is sought through supplementary measures in order to achieve approval. In future, a much stronger focus on the overarching sustainability goals will be necessary in order to develop a more comprehensive set of tasks whose solutions can also meet the expanded requirements.

4.2.2 Tasks and Responsibilities of the Client

In consultation with the building authority, the client bears a special responsibility, especially at the beginning of a project, to ensure that the development of the project focuses on sustainability goals. The necessary space, time and financial resources must be made available for sustainability in project planning and implementation. In order to ensure decision-making processes with regard to approvability, planning must be transparently and evenly aligned with these objectives from the outset.

An effective approach lies in establishing a suitable project organisation. Clear responsibilities and accountabilities, as well as the equipping project participants with the appropriate skills and decision-making powers, are fundamental to successful project management.

The project organisation should be broadly based and have sufficient expertise to assess the impact of planning decisions. The decision-making processes must be documented. The project organisation must be capable of formulating tasks for those involved in the project and identifying risks and conflicts that arise when pursuing often conflicting goals. Transparent methods for evaluating projects as objectively as possible are the key to ensuring broad acceptance of the chosen solutions. It is the client's responsibility to involve affected citizens and stakeholders at an early stage and to organise transparent communication of the weighing processes. It may be advisable to seek professional support for this as well as to involve specialist consultants and experts at an early stage. Open communication helps to reduce resistance, which is often due to a general mistrust based on incomplete information.

However, planners, contractors and the entire construction industry are also called upon to continue searching for innovative solutions to improve the sustainability of underground structures and to incorporate these into their projects.

4.3 Project Structuring

Once the need for an infrastructure measure has been identified, it is generally in the (economic) interest to immediately begin project development, taking into account the classification or prioritisation of the measure, and to proceed swiftly. This conserves resources for all parties involved.

This includes binding project structuring at the earliest possible stage, right through to planned contract award units. First of all, the project objectives must be defined, which in future will also include the overarching sustainability objectives. All individual objectives must be consistent and build on each other in order to achieve the sustainability goals. Project tasks must be developed from this and differentiated from one another.

Task packages must be described and assigned so that their processing can begin promptly. There are often other existing or future requirements in the project environment that could also be taken into account. Combining these increases sustainability and thus the benefit to the general public. Regular exchange with other infrastructure providers is therefore recommended.

In the course of project structuring, catalogues of measures should also be developed that promise the best possible achievement of objectives. To this end, quantification and comprehensible evaluation of the sustainability achieved are of central importance. Against this backdrop some key issues relating to underground construction and subsequent use are examined in more detail in the following sections.

Here, too, the DAUB expressly recommends innovative procurement concepts based on partnership-based contract models. The early involvement of the expertise of potential future partners in the construction process offers potential for a goal-oriented project execution that has hardly been exploited in

Germany to date. Cooperation should be organised in such a way that participatory cooperation is initiated and promoted on an equal footing and the interests of all parties involved are aligned.

One option is to assign tasks - wherever possible - in conjunction with incentive systems. The criteria for this can be directly based on the degree to which sustainability goals are achieved. This can be taken into account for planning tasks, in the context of procurement procedures, as well as in the construction phase.

4.4 Planning and Project Execution

4.4.1 Integral Planning Process

From the outset, the underground structure is considered throughout its entire life cycle, as the construction phase is short compared to the operating period. This life cycle includes material extraction and production, construction, operation and dismantling or conversion of the structure, as well as recycling and waste disposal. Even within individual project phases, specialist planners are working more closely together, as they need to coordinate the mutual interactions of their different plans (and interests) in order to achieve the best overall result. Sustainable planning and construction preparation thus become an integral planning process. The following features are part of the integral planning:

- Early consolidation and integration of the various planning disciplines
- Overall concept for all structural and technical works
- Overall concept for the underground structure, taking into account the entire life cycle: construction, operation, conversion, refurbishment, demolition
- Overall concept with equal consideration given to economic aspects (investments, running costs, etc.), social aspects (user comfort, etc.) and ecological aspects (resource conservation, cradle to cradle, etc.)
- Open and goal-oriented communication as well as interdisciplinary thinking of those involved in planning
- Enabling feedback processes (iteration) in planning

The central approach of integral planning consists of the early integration of all specialist disciplines and clearly structured, continuous communication between those involved in the project. This promotes more efficient and sustainable project development. Early action in the interests of sustainability is particularly crucial here: especially in the early planning phases (variant studies as part of preliminary planning), significant steps towards sustainable solutions can be taken with comparatively little effort.

Sustainable infrastructure planning should include variant studies on construction methods, use and life cycle based on common basic values and resulting in comprehensible and reliable findings. Sensitivity analyses should be carried out in order to assess the influence of the basic values.. For the variant studies, different execution options can be evaluated and their environmental impact in terms of sustainability described. This can be useful both when choosing an overall construction method and when weighing up materials in detailed decisions. The total greenhouse gas balance is less meaningful in this context than the respective internal project comparisons. The balance is particularly useful for assessing which materials or processes have the greatest impact on the overall balance and what potential this offers for reducing total emissions.

4.4.2 Integrated Project Management

Integrated project management means that the planning process is brought forward. Decisions are made earlier than in the traditional planning process, possible risks are identified and remedied at an early stage, and communication between those involved is improved. Earlier decisions on materials, cross-sections and construction methods also allow earlier influence on the environmental impact of the structure. Since the performance phases are thus shifted, it may also be necessary to adjust the remuneration limits.

4.4.3 Cross-Section Optimisation

A reduction in greenhouse gas emissions can also be achieved indirectly by optimising the use of the tunnel cross-section at an early planning stage. In this context, a distinction must be made between conventional and mechanised tunnelling. In general, the cross-section should be selected and designed based on the recognisable long-term usage requirements. This means, for example, adapting the cross-section of a railway tunnel so that there is no excessive energy loss during passage. Another example would be the dimensioning of a collection channel designed for future, potentially more frequent, heavy rainfall events in order to make the infrastructure more resilient.

If, for example, additional cable ducts for laying supply lines can be accommodated in a road tunnel, there is no need to build two separate tunnels. The circular cross-section of tunnels in mechanised tunnelling, leaves a space below the road level after construction, which can be put to ideal us. For example, the lower area can be used as an escape route or as a catch basin for heavy rainfall events in large cross-sections. An example project with such an implementation can be found in **Appendix B**.

There is more flexibility in designing the cross-section of a conventional tunnel than in mechanised tunnelling. The cross-section can be tailored more individually to the effects in order to achieve an optimisation of the stress. For example, a more rounded invert may require a thinner shotcrete layer and inner lining than a flat invert [68]. This is offset by a larger excavation volume. When planning a cross-section, different invert designs can be compared and evaluated in terms of their sustainability.

4.4.4 Use of Recycled Materials

When using recycled materials, additional requirements must be met during the planning process. For example, it must be proven that the building material used is as suitable as a primary building material. Compliance with construction and environmental regulations is verified by independent certification bodies. This must be taken into account in the planning process. Likewise, the properties of primary and secondary building materials must be compared and the effects taken into account in the planning.

4.4.5 Durability

When deciding on the materials to be used, the focus should be not only on the environmental impact but also on the performance and durability of the material. If, for example, the material has a significantly longer service life it will need to be replaced or maintained later and will therefore have a lower environmental impact over time. A more efficient material may be able to be used with a smaller cross-section or thickness, thereby contributing to a lower environmental impact.

Haist [48] therefore defines the sustainability of material selection as the ratio of performance, service life and environmental impact (**Figure 4-1**). This approach should be taken into account in particular when selecting building materials and defining components.

This approach to assessing the sustainability of components was developed for concrete but can also be applied to other building materials. The environmental impacts are converted to the component in each case.

4.4.6 Waste Heat, Energy Generation

The planning of energy generation in parallel with the actual use of the tunnel must also be determined at an early stage. In cable tunnels in particular, energy generation can be useful due to the waste heat. Here, room should also be left for future technical developments so that new and innovative solutions can be realised. In mechanised tunnels, geothermal activation of the tunnel segments (see **Figure 4-2**) can be used to generate energy and supply a nearby residential area, for example. Conventional tunnels can also be geothermally activated.

4.4.7 Contractual Provisions

During the planning stage, it is possible to work with the client to establish contractual sustainability targets for the contractor. These could include, for example, requirements for recycled materials or maximum transport distances for regular or larger transports. At the very least, sustainability issues should be integrated into the tender and award process. For example, a less sustainable design can be monetised in the evaluation.

The more specifically the relevant objectives and precise implementation options are regulated in the draft planning, explained in the tender and incorpo-

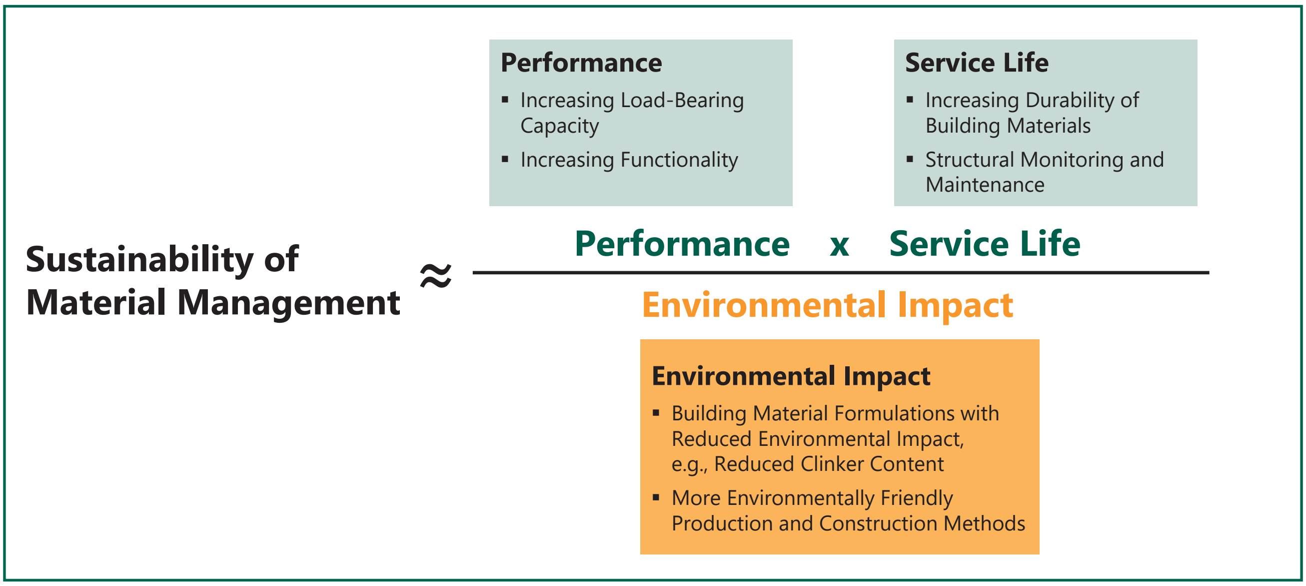


Figure 4-1 *Approach to quantifying the sustainability of concrete at the building material level according to [48]*

rated in the appropriate bill of quantities items, the more sustainably the implementation of the construction project can be designed.

The realisation of sustainable underground infrastructure requires planning and project management that is geared towards pursuing sustainability goals from the outset and throughout all phases.

4.5 Measures

4.5.1 Climate Protection Measures

4.5.1.1 Preliminary Remarks

In the infrastructure sector, complex soil-structure interactions and high demands on the durability of structures mean that large quantities of materials are consumed, the production of which is associated with significant CO_2 emissions and resource consumption. This applies in particular to tunnel construction. Tunnel structures differ both in their type (road, rail, underwater tunnels, etc.), the resulting durability requirements and the ground in which they are built. This results, on the one hand, in widely varying requirements for the tunnel support system and the concrete used, and on the other hand, it also means that the properties of the tunnel excavation material to be recycled vary greatly. In addition, there are geological variations which, when reusing the materials for concrete production, can currently only be controlled in practice by limiting quantities and increasing the cement content.

4.5.1.2 Innovative Materials

Various approaches are currently being pursued in the development of CO_2- and resource -optimised concretes, all of which aim to increase the proportion of raw materials with low specific emissions without compromising the required concrete properties [47]. Accordingly, new cements with greatly reduced clinker content have been introduced in recent years [48], [49], but these have not yet found their way into tunnel construction, or only to a limited extent. This is due, on the one hand, to their insufficient workability and robustness, and on the other hand, to the slower setting speed of such concretes. However, this behaviour can be controlled by adding chemical additives such as superplasticisers and accelerators (including those based on renewable raw materials). In particular, the controlled liquefaction of chemically very heterogeneous binder mixtures (such as composite cements consisting of a large number of components) still poses a challenge and is currently being addressed in various research projects. The strength development of the concretes is of great economic importance here, as it has a significant influence on the production cycle, e.g. in segment production. Fast-setting, low-CO_2 cements based on calcium sulfoaluminate clinker (CSA) could provide a remedy here.

Until low-clinker cements, which currently still require building authority approval, are ready for the market, CO_2 emissions can already be reduced by using selected binders with reduced clinker content and specially tailored additive systems. Portland cements of class CEM I with a rapid strength development of strength class 52.5 R are usually used in the production of shotcrete. These cements contain a clinker content of 95 to 100 %. By substituting the Portland

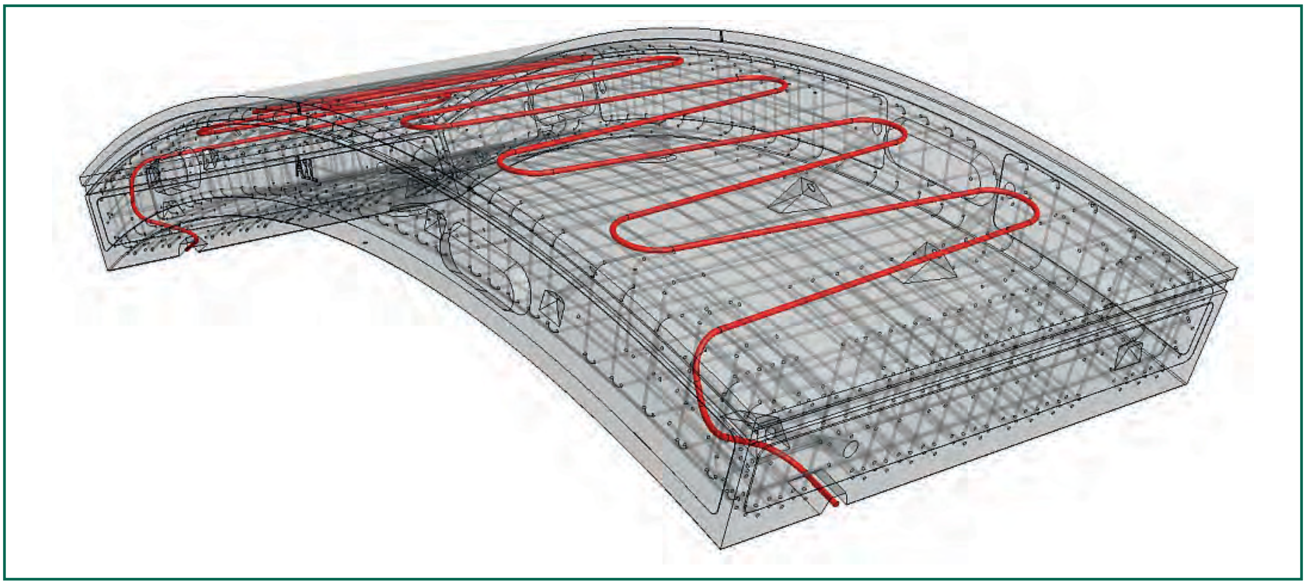


Figure 4-2 *System sketch of an energy segment*

cement clinker with suitable additives (e.g. limestone powder, ground granulated blast furnace slag, fly ash, etc.), cement-related CO_2 emissions can be avoided. Practical experience has already been gained with the use of CEM III/A cements as a substitute for classic CEM I cement in shotcrete. By using a CEM III/A cement, the clinker content can be reduced by up to 50 % and the cement-related CO_2 emissions can be reduced by over 45 % compared to a CEM I cement [50].

Due to the cycle construction method and the aim of early formwork removal, fast-setting cements of class CEM II/A are often used for the production of tunnel inner linings. However, when planning the recipes, the favourable influence of hydration heat development and the associated faster strength development in the component compared to concretes tested under laboratory conditions is not taken into account to be on the safe side. As a result of extended initial tests with heat-treated test specimens, inner lining recipes using CEM III/A cements can also be developed during project preparation that meet the requirements of cycle construction (production of one inner lining block per day). The clinker content in CEM III/A cement is 35 to 64 %, which is significantly lower than the clinker content in CEM II/A cement (80 to 94 %), meaning that there is also potential here to reduce cement-related CO_2 emissions using raw materials already available on the market.

The use of CEM III/A cements for the production of tunnel inner linings has a favourable effect on the development of hydration heat in the component. Particularly in the case of thin inner linings, fresh concrete temperatures >25 °C are therefore acceptable from a technical point of view, which means that energy-intensive measures for cooling the fresh concrete can be reduced.

Cement-free building materials based on geopolymers

Geopolymers are inorganic binders that do not contain cement and whose structure can be traced back to aluminosilicates. Geopolymer-based concretes and mortars consist of ground granulated blast furnace slag, fly ash, aggregates, various activators and superplasticisers. Compared to traditional concretes, these systems require alkaline activators to achieve the material properties of concrete. Compared to conventional cement-based systems, geopolymer concretes and mortars have a comparatively lower Carbon footprint due to the use of by-products from cement production. Experience has shown that cement-free concrete is characterised by a high early strength, similar compressive strength values and increased flexural strength [51]. Furthermore, reduced shrinkage potential and lower susceptibility to cracking were observed. In addition, geopolymer concretes exhibit increased acid and sulphate resistance, as well as increased resistance to particularly high temperatures in the event of a fire [52].

One disadvantage is that geopolymer concrete can be more alkaline than conventional concrete, which can affect the corrosion protection of the reinforcement. It is important to take appropriate protective measures for the reinforcement. The adhesion between geopolymer concrete and the reinforcement can vary, which could affect the structural integrity. This must be taken into account. Geopolymer concrete behaves differently to conventional concrete during processing. Polymer concrete can be thixotropic, which means that it becomes more liquid when stirred or shaken, which can make it difficult to remove components from the formwork.

Cement-free annular gap grout

In mechanised tunnelling, a gap is created between the surrounding rock and the segmental lining as a result of the process. To transfer forces and reduce surface settlement, this annular gap must be completely filled with annular gap filling material. These are generally referred to as annular gap mortars, whereby a basic distinction is made between so-called 1K and 2K annular gap mortars. 1K annular gap mortars are composed according to concrete technology and contain cement, additives, aggregates and water. Concrete additives control the special processing properties. 2K annular gap filling materials consist of cement, bentonite and water. Here, stabilisers ensure the processing properties.

In Germany, an annular gap mortar in which the cement was replaced by an alternative geopolymer-based binder was used for the first time in the construction of the new Emscher sewer. Such a system was used again in the major Stuttgart 21 project, which, among other things, mastered the great challenge of mechanised tunnelling in anhydrite-containing, swellable rock. For use in anhydrite-containing soils, the transfer of excess water from the annular gap mortar to the surrounding rock had to be prevented, which was made possible by the properties of the geopolymer which completely absorbs the added water into the structure of the building material.

The binding agent in this type of annular gap grout consists of granulated blast furnace slag and fly ash. Aggregates are used as supporting grains. At the segment joint through which the annular gap grout is introduced into the annular gap, an activator is added to trigger the reaction of the binding agents. The phosphates contained in the compound counteract the swelling process.

Cement-free shotcrete

As part of the project work of the KOINOR research project, a sprayable fire protection coating for existing tunnel structures was developed based on an alkali-activated binder (geopolymer). The coating developed can be used both as a sprayed mortar and as a shotcrete system for repair as well as for structural improvement and can be applied using wet or dry spraying methods. The key advantages of cement-free systems are

a) the thermal properties that meet the current requirements of the guidelines for fire protection in tunnel structures and prevent spalling in the event of a fire without the addition of PP fibres (mono-/ multifilament microfibres),
b) the very high sulphate resistance and the high chloride penetration resistance of the hardened concrete, as well as
c) the reduction of the carbon footprint as part of the upgrading of the entire tunnel structure.

The investigations carried out showed that the injectable geopolymer systems developed work very well in terms of process engineering and perform well in terms of the expected benefits. This opens up the possibility for the first time of coating existing tunnel systems using a cement-free coating without extensive interference with the required clearance profile [53].

The follow-up project KOINOR-Pro is scheduled to begin in Q3/2024 and will involve further adjustments to the developed system with a view to creating far-reaching operational capability in the long term. To this end, the research project will also focus on the approval status of the cement-free shotcrete as a repair system. As part of an expert assessment, the basic layout of a step-by-step plan for obtaining approval in individual cases (ZiE) is to be developed, thereby accelerating its subsequent practical application. Technically, further research is being carried out on the composition of materials, among other things. In the latest exploratory tests, modifying the recipes with regard to the activator used has already increased the melting point of the material, and adding new types of additives has reduced its permeability. The additives used are recycled products that have been proven to have a better carbon footprint. This opens up the prospect of further improving the already favourable carbon footprint of the developed product – measured against comparable cement-based products – by reducing its permeability.

Cement-free structural concrete

Cement-free systems can also be used as in-situ concrete or for precast concrete elements. Such systems have already been approved by the German Institute for Building Technology (DIBt) in Germany and are therefore permitted for use in everyday construction work. Due to its high acid and sulphate resistance, cement-free concrete is ideally suited for the construction of precast pipes and shafts as well as for the construction of agricultural and municipal water management structures with requirements for acid and sulphate resistance.

4.5.1.3 Improved construction methods

Sensor data-based and AI-supported methods for automated concrete production

Today, the production of concrete as a material or of components made of concrete is still based exclusively on empirical methods. Despite enormous repetition rates (in Germany alone, well over 10,000 batches of concrete are produced every day), Industry 4.0 methods have not yet found their way into this area. However, these are a key prerequisite for achieving CO_2 reduction targets in the construction industry. A major reason for this is that there are currently no suitable sensor methods or evaluation algorithms available to record and control production processes inline. Initial groundbreaking approaches in this field have been made in various development projects. For example, digital image analysis makes it possible to record the grain size distribution and other properties of aggregate for concrete production online and to use this real-time data as a control variable for concrete control [54]. These techniques are currently being applied to tunnel excavation material in development projects and are expected to be implemented in initial construction projects in the medium term. These current developments are laying the groundwork for the scalable use of excavated material for concrete production in tunnel construction.

Based on AI approaches, STUVA has developed a measuring system for determining the binder content in mineral building materials [55]. The combination of these techniques makes it possible to record the entire process of raw material provision and concrete production in real time using sensors, thereby enabling the development of control algorithms for concretes with minimised resource consumption and their application on a project scale.

Reinforcement and robotic production

In international tunnel construction projects, conventional steel bar reinforcement has been replaced for years by alternative fibre reinforcement made of steel or, in some cases, in combination with plastic. Under appropriate boundary conditions, the targeted use of fibres allows a reduction in the amount of steel required in structural concrete. So far, this has not been possible in Germany due to the applicable regulations. For the first time, as part of the new DAUB recommendation for the design, production and installation of segment rings [56] for the design of segments with fibre-reinforced concrete, the regulations have been specifically expanded and adapted to the special boundary conditions of tunnel construction. The combination of fibre-reinforced segments with innovative concrete enables significant CO_2 savings.

Regardless of this, initial projects have succeeded in partially automating the production of conventionally reinforced segments, thereby optimising the production process [57]. Automated process steps using industrial robots allow steel to be minimised. This requires high precision in the positioning of the reinforcement cage. Targeted savings in steel are also made possible through standardised welding processes. The combination of automated processes and innovative design creates the conditions for significant CO_2 savings.

In addition, digitalisation in tunnel construction opens up numerous opportunities for optimisation and the use of innovative AI methods for production control (drilling rigs, automated segmental lining, etc.).

4.5.1.4 Efficient construction processes and logistics

Due to their scope and complexity, tunnel construction projects often extend over periods of several years. This also offers opportunities for establishing sustainable and resource-saving construction processes through the appropriate installations at the construction site.

This begins, for example, with the general construction site setup by installing photovoltaic elements on the container systems, controlling the construction site lighting using motion detectors, or using energy-saving LED spotlights. The clever installation of tyre washing systems, spraying systems for dust reduction or conveyor belts for material transport not only meets the increased requirements for the reduction of emissions, but also reduces the costs for street cleaning and the number of truck journeys.

Particularly in the field of mechanised tunnelling, special emphasis is placed on the energy-efficient design and conception of TBMs, separation and conveyor systems as well as logistics, primarily for economic reasons. This can be reinforced, for example, by using intelligent agitator controls for bentonite preparation/storage or sensor-controlled spraying systems.

Another option is to reuse the water generated by tunnelling and construction sites. In one project, for example, the water treatment plant was designed and set up in such a way that the purified construction water was fed back into a storage tank for reuse instead of being discharged into the receiving watercourse. This reduced the consumption of fresh water by over 30 % over the duration of this tunnel construction project.

4.5.2 Resource Management

4.5.2.1 Preliminary Remark

In recent years, the topic of resource efficiency has also gained increasing importance in the construction industry. Tunnel projects play a special role in this context, as large quantities of excavated material are concentrated in terms of time and location, and any excavated material that leaves the construction site must currently be declared as waste due to legal requirements. Making sensible use of this material, i.e., integrating it into a resource-efficient circular economy in line with global sustainability goal 12 "Responsible consumption and production", is one of the major challenges currently facing the tunnel construction industry (**Figure 4-3**).

Given the particular relevance of this topic, the DAUB published a "Recommendation on the recycling of tunnel excavation material" [3] in 2024. For this reason, only a few key points are presented in these recommendations.

4.5.2.2 Legal basis

An essential legal basis in Germany is the Circular Economy Act (KrWG), which transposes the EU Waste Framework Directive (2008/98/EC, AbfRRL) into German law. According to § 1, the promotion of the circular economy is intended to conserve natural resources and ensure the environmentally sound waste management. In this context, pursuant to § 7 and § 8, a hierarchy of measures must be observed that

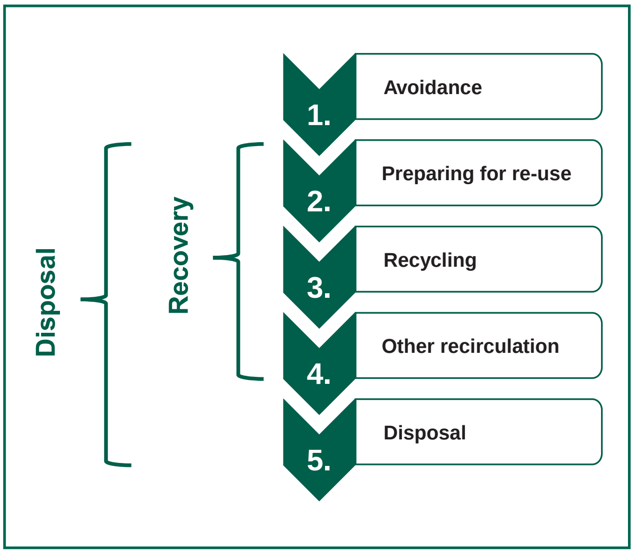


Figure 4-3 *Waste hierarchy according to [69]*

best ensures the protection of people and the environment in the generation and management of waste, taking into account the principles of precaution and sustainability. The technical feasibility, economic reasonableness and social consequences of the measure must be taken into account.

The so-called "Mantelverordnung" (Ordinance on the Introduction of a Substitute Building Materials Ordinance, the Revision of the Federal Soil Protection and Contaminated Sites Ordinance and the Amendment of the Landfill Ordinance and the Commercial Waste Ordinance) has been in force since August 1, 2023. The core of the Mantelverordnung is the introduction of a Substitute Building Materials Ordinance (EBV) and the revision of the Federal Soil Protection and Contaminated Sites Ordinance (BBodSchV).

These ordinances specify legally binding requirements for the recycling of mineral waste and substitute building materials that apply uniformly throughout Germany. Mineral substitute building materials within the scope of the ordinance include, among others, recycled building materials from construction and demolition work or soil material, including tunnel excavation material. They replace the previous technical rules and decrees, some of which differed at state level. The "LAGA classification values", frequently used in practice to assess the recyclability of mineral construction waste, are largely losing their significance. The Landfill Ordinance (DepV) supplements the requirements of the Substitute Building Materials Ordinance if the material cannot be recycled due to excessive pollutant contamination and must be disposed of (e.g., in a landfill).

The EBV regulates in particular the conditions under which mineral substitute building materials may be used in technical structures. On the one hand, this ordinance specifies how substitute building materials are to be produced and classified. On the other hand, it contains so-called installation tables, which show in which installation methods of a technical structure (e.g., dam or embankment) the respective classified mineral substitute building material may be installed. For the classification of the tunnel excavation material within the meaning of the KrWG and the Mantelverordnung, it must be sampled in a pure and representative manner.

4.5.2.3 Planning

In the current standard planning phases for underground structures up to the planning approval stage, the recycling of excavated material is usually given only a secondary level of attention. In order to find the preferred solution, a basic choice is made between "cut or tunnel", but the criteria only partially cover the actual consequences. Often, it is only during the tender planning phase that in-depth considerations regarding material management are made. However, it is easiest to aim for optimal mass balance during the planning phase by selecting the elevation profile of the route, taking into account the topography, so that the excavation volumes are kept as low as possible and can be reused within the construction lot as far as possible.

Even if the tunnelling and process technology have usually not yet been determined at the time of the preparing the geotechnical report and project-specific knowledge regarding the construction site set-up or material storage is lacking, possible changes in properties must be described. It should also be borne in mind that, in order to assess suitability for use by industrial sectors (e.g., clayey material for brick production), additional investigations may sometimes be necessary, such as determination of the mineral phases by means of X-ray diffraction (XRD analysis). Furthermore, depending on the expected soil or excavation material properties, the effects resulting from geogenic, anthropogenic and tunnelling-related contamination (e.g., enrichment with chemical or clay components for conditioning the support and lubricating fluids, especially bentonite, in mechanised tunnelling with a fluid-supported working face) must be described exhaustively and specified at the latest in the tender documentation.

4.5.2.4 Execution

Not only in planning, but also and above all in execution, new challenges will arise in the future for both the contractor and the client. At least the following points are to be considered decisive:

- Space requirements
- Transport routes
- Delivery Reliability
- Variable material properties

Space requirements

Particularly if external recycling is to take place outside the tunnel construction project, it is usually necessary to create extensive temporary storage facilities. After all, tunnel construction projects are characterised by the fact that large quantities of excavated material are concentrated in terms of time and space. Even if an industrial company has been identified that can use a large proportion of the excavated material for the manufacture of its products, the material flow from the tunnel construction site must be buffered on the one hand and the properties of the material must be quality assured, on the other. This requires additional temporary storage, sampling, handling and material processing areas.

Transport routes

The extent to which tunnel excavation material can actually be recycled is largely determined by the location of the tunnel construction site and the potential recycling sites in the vicinity. After all, the economic viability of using raw materials with a low specific value [EUR/t] - which undoubtedly applies to tunnel excavation material - is significantly influenced by the transport costs. Thus, transport connections (road, rail, water) also play a role that should not be underestimated in terms of the prices that can be achieved on the market. According to evaluations by Resch [45], different transport distances can be assumed for different recycling options, within which recycling is usually economically feasible. In the planning phase, it therefore makes sense to carry out a project-specific review of recycling options within a radius of 100 km. In the case of transport by ship or rail, longer transport distances may also be economically viable under certain circumstances.

Security of supply

Particularly when it comes to the external recycling of excavated material, it is not only the price that plays an important role; the issue of " supply chain security" is also becoming increasingly relevant. It is not only important that producers (supply) and recyclers (demand) agree on the total quantity to be delivered, but especially in the case of high-quality ecological recycling (i.e., raw material substitution), a certain quantity must usually be actually available at a certain point in time.

Variable material properties

The original, undisturbed soil or rock is subjected to varying degrees of change during tunnelling work, whether mechanical (e.g., transformation to paste or crushing or chemical (e.g., contamination with bentonite or explosives and shotcrete rebound). The construction contract should stipulate that the maximum level of change and contamination typical for the process is not exceeded; to this end, geotechnical properties and chemical parameters to be complied with must be defined. However, it should also be noted that no excessive demands should be made that would only be achievable at disproportionately high effort and would therefore no longer be economically viable.

4.5.2.5 Classification of usability

All parties involved in construction should agree that adequate recycling of the materials produced is essential for an optimal material cycle. For example, "high-quality" concrete demolition material should be used as aggregate, while tunnel excavation material can certainly be used for frost protection.

In tunnel construction, it must also be ensured that suitable excavated material, such as, for example, gravel or hard rock, which can certainly be used as aggregate in concrete, is actually used as a raw material substitute. Even if the KrWG generally aims to conserve natural resources, technical possibilities and economic feasibility must be taken into account, so there is no need for "recycling at any price".

Those excavated materials that can be recycled within the project or are assessed as "potentially recyclable for the circular economy" (external recycling) are subject to a more in-depth consideration, taking into account the local market situation. Based on the proposal in [46] and the waste hierarchy according to KrWG, it is appropriate to divide these materials into different groups:

- **Group 1:** Substitution of raw materials
  Group 1 covers the recycling of excavated material within and outside the project or in industrial sectors that would otherwise use other raw material sources. As shown in [45], there are many different recycling options for tunnel excavation material from solid and loose rock:
  - Aggregate for concrete,
  - Aggregate for base courses,
  - Aggregate for asphalt mix,
  - Railway ballast,
  - Brick clay, loam,
  - Limestone as an industrial raw material.
- **Group 2:** Use as soil in earthworks and traffic route construction
  Group 2 covers the use for earthworks and traffic route construction purposes within and outside the project. This includes, for example, aggregates for embankments, for base courses without binders and noise barriers. For classification in this usability group, it is irrelevant whether use is possible without further modification of the material or whether processing measures for are necessary.
- **Group 3:** Optional use as soil in earthworks
  If a project involves large quantities of excavated material that cannot be recycled in accordance with Group 1 or 2, this material is often incorporated into earthworks or landscaping projects or used to fill old gravel pits or quarries, so the excess material does not have to be disposed of.

4.5.2.6 Current developments

Soil exchanges are positive examples of active resource conservation. The idea behind such soil exchanges is to market excavated material from tunnel construction as well as soil excavated from above ground infrastructure construction, such as gravel, sand, clay and natural stone in an economically viable manner. The aim is not only to conserve natural resources in line with the circular economy, but also to significantly reduce construction costs in some cases. After all, up to 15 % (sometimes up to 25 %) of construction costs are often attributable to the disposal of the excavated material. Soil exchanges offer available material on digital platforms, specifying the characteristics that are relevant for recycling, and provide support for various process steps, from marketing checks to assess the material's potential, to assisting with official approvals, to logistics planning for transport by rail, water or road to the customer.

4.5.3 Promoting Biodiversity

Flora and fauna ecosystems are highly susceptible to external influences such as land sealing, environmental pollution or climate change and are therefore at serious risk. During both the construction and operational phases, it is therefore important to avoid the impact of our infrastructure on plants and animals and their habitats as much as possible or to limit it to the necessary minimum. The unavoidable impact of our structures on biodiversity must be offset as far as possible by compensatory measures, so that both humans and flora and fauna benefit from the project.

Especially in urban areas, the creation of additional green spaces has a significant impact on biodiversity. The well-being of humans and nature is significantly influenced by plants and their ecosystem services, e.g., by providing shade, humidifying the air or providing an attractive environment for leisure and recreation. For this reason, generously dimensioned traffic areas should be reduced and at least partially unsealed [59]. Thus, it is also part of the EU Biodiversity Strategy for 2030 to curb land consumption and restore soil ecosystems [60]. The reclamation of green spaces, as has been done in Stuttgart, for example, with the lowering of the long-distance and local transport network, has a positive effect on urban biodiversity.

Linear transport infrastructures (roads or railways) in particular have numerous negative effects on biodiversity through the fragmentation of habitats and habitat networks [62]. When planning new linear infrastructure or expanding existing infrastructures, it is necessary to preserve existing connections in such a way that populations can colonise and recolonise habitats in sufficient numbers and sufficiently often. Tunnel structures offer the possibility of passing under such habitats worthy of protection, thereby minimising any impact on habitats. This prevents the fragmentation of landscapes and disturbances to the environment, allowing habitats to remain undisturbed. In particular, tunnel structures with a length of 1,000 m or more represent an interruption to fragmentation [63].

It is not always possible to avoid impacting flora and fauna. In such cases, compensatory measures offer the opportunity to compensate for or replace unavoidable interventions in terms of biodiversity. A flexible solution is the establishment of so-called eco-accounts, which, based on the precautionary principle, create compensation and replacement measures. In this way, advance measures can be used to compensate for future impacts in a temporally and spatially decoupled manner. The compensatory measures are subject to specific requirements with regard to the areas of impact, without which recognition is not possible [64]:

- Improvement of biotope quality,
- Creation of higher-quality biotope types,
- Promotion of specific species,
- Restoration of natural retention areas,
- Restoration and improvement of soil functions,
- Improvement of groundwater quality.

The current challenges lie in the forward-looking willingness to finance such measures with regard to construction projects that have generally not yet been approved, even though their eligibility for approval often depends on proof of appropriate compensation and replacement measures.

A holistic view and assessment of all measures in terms of their sustainable impact, requires all sustainability criteria to be comparable. Biodiversity must not be left out of this equation. However, biodiversity defies simple description and quantification. Compared to other sustainability criteria, such as life cycle costs or a carbon footprint, its value is difficult to measure. Consistent systems that enable equal evaluation do not yet exist but should be a mandatory objective for future evaluation systems.

4.5.4 Extending Service Life and Conversion

4.5.4.1 Preliminary Remark

Underground structures in Germany are designed for a long technical service life, currently around 100 years. Existing structures for all modes of transport are already showing significantly higher life expectancies than initially assumed or predicted (**Figure 3-3**). Refurbishing and upgrading campaigns ensure that they subsequently meet current traffic, normative and regulatory requirements and can continue to serve efficiently for decades to come.

While the underground structures themselves have a very long service life, the built-in components do not. In underground tunnels and stations, mechanical equipment such as escalators must be replaced every

20 to 30 years. This equipment also includes ventilation systems, lighting, track superstructure materials, switches or other electrical installations, depending on the use of the structure. However, the replacement of these built-in components always has a significant impact on the operation and capacity of the structures in question. Robust built-in components with a long service life are therefore preferable so that the entire system can be used without restrictions.

4.5.4.2 Extending Service Life

Underground structures are inspected regularly. During these inspections, defects in the structure are recorded and the extent to which measures are necessary is defined. These measures can generally be divided into maintenance measures or renewal.

Repair work involves restoring the structure to its functional target condition through technical measures. If this is no longer possible, partial or complete renewal is necessary. In the case of complete refurbishment, the entire structure is restored in accordance with all valid regulations. In the transport sector, requirements relating to cross-sectional design and the rescue concepts are particularly important, since, for example, the "old" railway tunnels usually require electrification and do not comply with current safety regulations.

Here, decisions must always be made on a project-specific basis as to what form of renewal is possible. The basis is always the type of traffic that is to be carried out after the renewal. Whether motorised private transport, rail transport or footpaths and cycle paths, different requirements always apply here to the cross-section and the necessary installations.

In railway tunnels, it must also be considered whether the line is used exclusively for freight trains or for mixed traffic with both passenger and freight trains. In project-specific planning, the task often arises of adapting the profiles of the existing tunnels to today's requirements (**Figure 4-4**). In this pro-

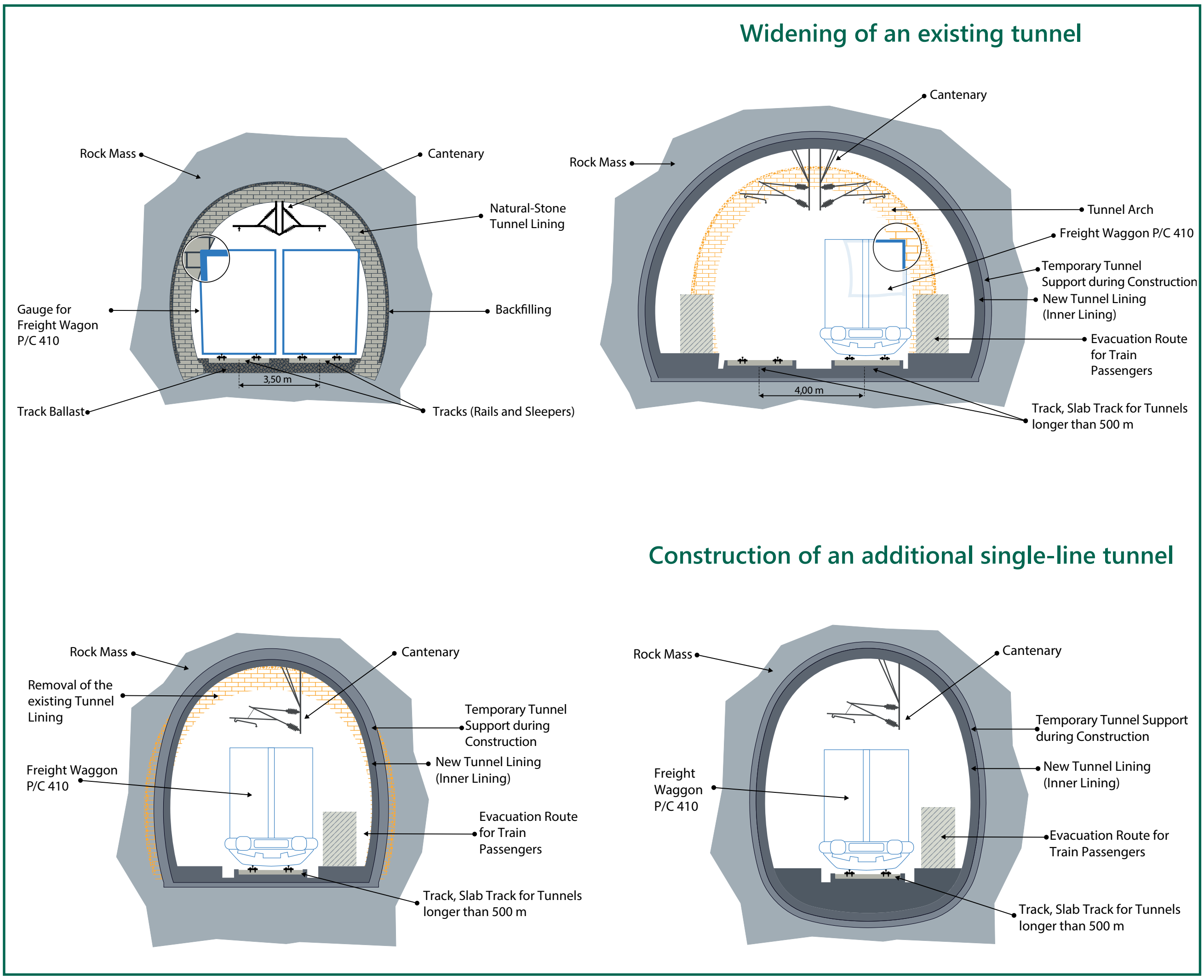


Figure 4-4 *Variants of tunnel widening [67]*

cess, existing profiles can be widened using the tunnel-in-tunnel method (TiT) [66] or the existing tunnels can be widened for single-track operation that meets current requirements and supplemented with a second new tunnel.

The basic idea behind the TiT concept is that railway operations are maintained on a single track in the centre of the tunnel (**Figure 4-5**, right) while refurbishment work can be carried out at the same time with the aid of a so-called tunnel enlargement system (TAS, **Figure 4-5**, left). The TAS is continuously transported along with the tunnelling work. Examples of this are the refurbishment of the Petersberg Tunnel (reopened in 2019) or the Fachinger and Cramberger Tunnels, which were first put into operation in 1862. Construction of these two tunnels began in January 2023, and commissioning is planned for 2027.

4.5.4.3 Repurposing

However, there are also tunnel structures for which the original use has ceased. For many years, these tunnels have been filled in. In recent years, the focus has shifted to considering repurposing options. The challenge here may lie in the fact that the change of use results in different operators and thus different ownership structures. These contractual arrangements and transitions often become the focus of discussion in this country and make it difficult to achieve the objective. Examples of the change of use of existing tunnels can be found in **Appendix B**.

5 Project Assessment

5.1 General Remarks

At the time of writing this recommendation, several sustainability rating models are already available nationally and internationally or are currently being developed or refined. In some cases existing approaches are being refined – for example, based on the so-called Standardised Assessment [74] – or existing methods from high-rise or infrastructure construction are being adapted for tunnel construction – for example, in the form of the approaches of the German Sustainable Building Council (DGNB) [75] or the BREEAM-Infra assessment model [76], which is frequently used internationally, especially in the Scandinavian region.

Figure 4-5 *Refurbishment of the Fachinger Tunnel: Interior view of the existing tunnel with tunnel enlargement system (left) and view of the portal (right); (Source: Porr)*

Furthermore, there are currently plans on the part of German clients to develop their own methods and procedures for sustainability assessment, with a view to prioritising aspects that are important for Germany and to have control over the methods used.

All these assessment models have advantages and disadvantages and/or – such as Standardised Assessment (see **Chapter 5.4.4**, for example – were primarily developed and implemented for specific modes of transport. However, none of these methods is currently designed specifically for use in underground structures, which has a negative impact in that the long service live of these structures and the resulting benefits for the structural, network-relevant and socio-cultural environment are not sufficiently taken into account. These and other points are underrepresented in all currently available assessment models, which must inevitably lead to misjudgements when applied to underground infrastructure.

Against this background and with a view to future developments, DAUB has decided to make recommendations here on the selection of an assessment methodology, but not to favour one methodology over another and thus effectively exclude others or even develop its own methodology. Given that Standardised Assessment (see **Chapter 5.4.4**) was designed for the public transport sector and, by definition, must be applied here, at least with regard to the economic aspects of a construction measure, it is hardly possible to make any further recommendations at this point. The following explanations should therefore be understood as guidance to help users to make the best choice of assessment method for their project and the associated challenges, taking into account the current status quo. Under certain circumstances, this may currently also mean that, for example, economic criteria of a project must be examined using a method such as Standardised Assessment, while other aspects are considered with the aid of more advanced assessment procedures. The explanations in this chapter also provide the basis for the analysis presented in the following **Chapter 6** of the gaps in knowledge that still need to be filled in order to be able to consider underground structures appropriately and holistically.

5.2 Theoretical Approaches to Project Assessment

5.2.1 General Information on Sustainability Assessment of Underground Infrastructure Projects

As already explained in the previous chapters, there is international scientific consensus that sustainability in general should be represented by the three pillars of ecology, social issues and economics. In the field of ecology, the main aspects that come into play are those described in **Chapters 3 and 4** of this recommendation. With regard to the economic criteria, all costs incurred during the life cycle are taken into account. The focus is therefore on the life cycle costs of the structure, its economic efficiency and value stability. As also shown in the DAUB recommendations on determining life cycle costs for underground structures [2], the follow-up costs of underground structures can exceed their construction costs many times over, which is a significant distinguishing feature compared to other buildings and infrastructure. Given lifespans of 150 years and more, as can be observed particularly in the rail network, this creates enormous leverage in sustainability assessment, and this by no means exclusively related to economic aspects.

Social aspects of sustainability can largely be identified as soft factors and have only been quantified to a limited extent to date. In addition to the functionality of the structure, questions of aesthetics and design as well as aspects of health protection and comfort come to the fore.

On the one hand, underground infrastructure projects generate value in terms of the quality of life for users in the vicinity of the structures, for example by relocating noisy and polluting traffic routes underground (e.g. lowering of the Rheinuferstraße in Düsseldorf, **Figure 5-1**). On the other hand, entire regions can be structurally promoted and living conditions improved by connecting them to the supra-regional transport network (e.g. DB high-speed rail lines Cologne–Frankfurt, Wendlingen–Ulm, Berlin–Munich, **Figure 5-2**). A holistic sustainability assessment must integrate these effects on the benefits side, although it is difficult to offset these aspects against GHG emissions.

In order to carry out the sustainability assessment of a specific object in a structured and reproducible manner, different assessment methods are currently used both nationally and internationally. The basic structure of such approaches is always the same:

- Based on a defined evaluation object, criteria are developed which characterise this object and at the same time represent the protection goals in terms of sustainability.
- Various indicators can then be assigned to each criterion to define and describe the respective criterion in terms of its characteristics. For example, indicators such as “investment costs” or “operating costs” can be assigned to the criterion “life cycle costs”.

Figure 5-1 *Düsseldorf Rheinuferstraße in the past and today (Photos: Landeshauptstadt Düsseldorf/Stadtarchiv (left) and alamy (right))*

- Taking into account the weighting of the criteria in the overall assessment, these individual assessments can then be aggregated into criterion-related assessments and subsequently into an overall assessment.

A sufficient level of expert knowledge is required to identify the relevant criteria and assign the relevant indicators to them. In addition, a global evaluation standard is needed to be able to classify the respective characteristics of individual criteria. This applies in particular to the final overall assessment of the sustainability of the respective object. Such a standard is commonly referred to as a "target system". A key requirement for such a target system is that it should be complete, i.e. it must cover all relevant criteria and indicators. At the same time, impacts must not be recorded twice, which leads to the selectivity of the target system as a further requirement.

There are numerous certified assessment methods for sustainability issues worldwide, but all of them were developed with a focus on building construction or infrastructure construction. An uncritical application of such proprietary systems to underground construction is bound to cause problems, misinterpretations, and inadequate assessment criteria given the constraints involved. In particular, the enormous lifespans of underground structures mentioned above represent a key distinguishing feature in this regard. In addition, such assessment methods are sometimes very strongly oriented toward economic aspects, as this has been the main focus of development in the past.

Figure 5-2 *Project VDE 8, ICE replaces air traffic on the Berlin–Munich route (Photo: Deutsche Bahn/Frank Barteld)*

For this reason, assessments that were carried out using methods developed for building construction or infrastructure construction should be viewed critically, at the very least. Consequently, there are currently various initiatives for the development of a tunnel-specific assessment system, but at the time of writing these recommendations, many of these initiatives have not yet been fully developed.

5.2.2 Assessment Matrix for Underground Structures

As already indicated in the previous section, the difficulty, especially in the case of underground structures, lies in the fact that the assessment of sustainability aspects represents a heterogeneous and multi-criteria assessment situation. Clearly defined indicators – i.e. those that can be clearly quantified (e.g. investment costs of a measure) –must be weighed against vague indicators that can only be assessed qualitatively (e.g. improvement in the quality of life of users or the environment), especially since the latter often describe the key advantages of underground construction. Here, care must be taken to ensure that the relevant criteria are assessed in their entirety. These premises give rise to structural requirements for the development of a specific assessment system for underground structures:

- Ideally, the assessment of sustainability aspects should be flexible enough to allow both quantifiable and purely qualitative indicators to be classified equally.
- Non-monetisable indicators should not be directly linked to monetisable ones, but rather aggregated independently for a particular decision. This enables transparency and traceability of the decision-making process even at a later stage of consideration, for example in the context of a subsequent audit of the sustainability classification.
- The presentation of the assessment must be clear and self-explanatory, for example in the form of a dynamic spreadsheet, so that classifications of different projects can be compared, are consistent and are carried out according to the same specifications.
- Against the backdrop of the equal importance of all sustainability issues and the necessary transparency, the aim should be to give equal weighting to the individual assessment criteria in the form of an assessment matrix. Such an assessment matrix requires sufficient flexibility to respond to varying boundary conditions and to take these into account in the weighting process. For example, the Federal Transport Infrastructure Plan (BVWP) implements clear prioritisations of individual criteria. A sustainability methodology that is also to be applied to the structures of the federal trunk road network must therefore be capable of arriving at the same results as the BVWP in specific cases.
- An assessment matrix must be structured in such a way that, as the planning progresses, the sustainability assessment can also be updated without discarding the previous results. This should allow for only certain areas to be addressed and evaluated in greater detail, with areas that will be subject to more detailed planning at a later date (in many cases, the operational equipment used in underground construction) being integrated at a later stage once further information is available.

Various approaches can be formulated to meet these requirements. For example, the a-priori definition of targets with corresponding degrees of fulfilment would be conceivable, or a structured combination of common assessment approaches. The following section therefore explains the basics of assessment methods that are already in use today in this or similar contexts.

5.3 Fundamentals of Assessment Methods

5.3.1 General

An assessment is understood to be a comparison of two situations that differ only in terms of the project under investigation or the measure to be applied (ceteris paribus condition). As a rule, this means that for an object to be assessed, there is a “with” and a “without” case, whereby the effects of the respective measure on the overall result are assessed comparatively. The basis for such a comparison is usually the classic three-phase model of assessment:

- **Phase 1:** The target system, which defines what is to be achieved with the projects/measures under consideration.
- **Phase 2:** The indicators used as metrics for achieving the respective target.
- **Phase 3:** The aggregation of the individual indicator values using an assessment procedure, for example a value synthesis procedure.

When it comes to objectives (Phase 1), a distinction must be made between performance objectives and impact objectives. A performance target is, for example, a specified strength value for an inner lining that must be achieved technically. The impact targets based on this describe the effects at the end of the impact chain, e.g. CO_2 emissions saved by switching from cement-bound to cement-free systems in concrete.

Indicators are defined to "measure" the achievement of objectives (Phase 2). Their values can be collected or measured empirically ex post, after realisation of a project, and/or alternatively calculated or estimated ex ante on the basis of models or assumptions. The calculation of the indicators or their empirical recording is referred to as impact assessment. When running the evaluation algorithms, it is important to distinguish between:

- Quantitative indicators (e.g. direct costs of a measure or its GHG balance)
- Quantitative indicators for which values are available (e.g. travel hours with an hourly rate/monetary value)
- Qualitative indicators that can only be described verbally (e.g. beautification of the landscape by moving the infrastructure underground)
- Qualitative indicators that can be converted into a points system (similar to the procedure used in qualitative risk analyses for construction projects)

Value synthesis methods (Phase 3) enable users to combine individual indicator values into an overall statement. The best-known value synthesis method is cost-benefit analysis (CBA), which is also used, for example, in Standardised Assessment. Other well-known and important value synthesis methods are utility analysis (UA) and multi-criteria analysis. A detailed description of the three-phase model can be found in [77].

Sustainability assessments can be carried out in various ways, whereby very often an assessment is not made by comparing two states of the same object under consideration, but rather the classification is formulated taking into account a global standard. In this case, not only is a target system required at the level of the assessment criteria, but also a global assessment of how sustainability ultimately manifests itself. This can take the form of an aggregated assessment figure, for example, which is then used to determine the classification with the aid of an assessment scale. This requires a comprehensible genesis of such an assessment scale.

5.3.2 Cost-Benefit Analysis (CBA)

A cost-benefit analysis (CBA) compares all monetary costs of a project with the monetisable project consequences (benefits) incurred by this project. In this way, all effects – including external costs and benefits – are monetised, i.e. expressed in monetary units. This requires the determination of monetary values for the partial effects available in quantitative form according to the individual indicators. The CBA is the most widely used method for assessing the direct monetary and monetisable effects of a project and is often used to determine the economic efficiency of a project. By using ideally scientifically derived cost rates, the CBA does not require any weighting for the aggregation of the various indicators.

It is possible to carry out the assessment on the basis of a static or a dynamic analysis. In the case of a static CBA, only one specific year in the life cycle of the structure is considered, whereas in the case of a dynamic CBA, all time-varying costs and benefits as well as the later effects of the project are taken into account. Effects occurring later are discounted accordingly. Methods of life cycle cost calculation can be used for this purpose, as formulated by the DAUB in its corresponding recommendations [2].

A dynamic cost-benefit analysis therefore allows a much more reliable examination of the effects of a project than a static CBA, although the inherent uncertainties in the system, primarily due to the sometimes long observation periods, must be taken into account.

Advantages and disadvantages of the CBA

The most important advantage of the CBA is the direct comparability of different effects through the monetisation of the evaluation variables. Each effect is expressed directly in a measurable unit and can be compared with the object of comparison. At the same time, this advantage is also the greatest weakness of the CBA: variables that cannot be monetised or quantified cannot be integrated into the analysis using this approach. Relying solely on the results of the CBA therefore leads to an incomplete project assessment, especially in the case of underground infrastructure structures with major socio-cultural impact. Another disadvantage is that the requirement for monetisation means that even those impacts for which no market prices exist, or for which monetisation is possible but ethically problematic, are assessed in fiscal terms. A special case of this problem can be found in the monetisation of life, for example in the form of the reduction of accident victims through a measure. Nevertheless, the CBA is now widely accepted as an important part of project assessment and used extensively in many cases, for example in the course of Standardised Assessment.

5.3.3 Utility Analysis (UA)

Utility analysis (UA) is a decision-making method that is often used to systematically evaluate and compare different courses of action. It is particularly useful when decisions should not be based on a single key figure (such as cost or profit), but several qualitative and quantitative criteria must be taken into account, i.e. also aspects that cannot be monetised or quantified.

As with the CBA, the first step is to identify and describe the various alternatives or options to be assessed. Each alternative represents a possible solution or course of action and can be described by a list of criteria. These criteria are then used to assess the alternatives. As a rule, each criterion is assigned a weight, which reflects its relative importance compared to the other criteria. The weighting can be determined by expert opinions, surveys or by a discursive method. In the course of the assessment, either quantified variables or qualitatively assessable aspects can be evaluated. While the quantitative assessment is similar in principle to the procedure used in the CBA, various concepts are used for the assessment of qualitative aspects.

For each non-quantifiable criterion, a scale is developed on which the alternatives can be assessed. These scales can be nominal (categorical), ordinal (rank-based) or cardinal (metric). Cardinal scales allow for a detailed quantitative assessment via conversion, while ordinal and nominal scales remain qualitative assessments. In order to measure the achievement of objectives, a utility function is created for each non-quantifiable criterion, which measures the utility depending on the characteristics of the criteria. A basic distinction is made between three different types of utility functions:

- **Linear utility function**s assume that utility increases linearly with the characteristic of the criterion.
- **Non-linear utility functions** are used when the utility does not increase linearly with the characteristic of the criterion. This can be, for example, a convex or concave function that represents different degrees of preference for certain values.
- **Discrete utility functions** are also known, for example, from qualitative risk analyses, whereby discrete utility values can be assigned to qualitative criteria using a predefined scale (e.g. from “weak” to “strong” to “very strong”).

The alternatives are then assessed using the scales and utility functions developed. Each alternative is assigned a utility value for each criterion, which is calculated using the corresponding utility function. The individual utility values of the criteria are then aggregated to calculate an overall utility value for each alternative. This is often done by a weighted sum of the utility values. After aggregating and evaluating the alternatives, a sensitivity analysis can be carried out to verify the robustness of the decision. This involves analysing how sensitive the results are to changes in the weightings and utility functions. The alternative with the highest overall utility value is identified as the best choice. This decision can then be further supported by qualitative considerations or additional analyses.

Advantages and disadvantages of the UA

UA offers a structured and comprehensible approach to evaluating and selecting alternatives. Its great advantage lies in ability to take both qualitative and quantitative criteria into account, which makes decision-making more comprehensive and realistic. By explicitly presenting the assessment criteria and their weighting, the decision-making process becomes transparent and comprehensible and, with sufficient documentation, can also be retraced at a later date. The method is flexible and can be adapted to different decision-making situations and contexts. In addition, UA is well suited for group decisions, as it promotes discussion and consensus-building and assessments can be aggregated and carried out consensually.

However, the assessment of the alternatives and the weighting of the criteria are often subjective and can be influenced by the personal preferences of the decision-makers. In addition, conducting a UA is very time-consuming and often involves resource-intensive processes for the assessor. This particularly true when there are many criteria and alternatives to consider, which makes it difficult to handle and also requires a wide range of skills in order to correctly assess criteria that are primarily qualitative in nature. Since the development of rating scales and utility functions is often based on empirical processes and so-called expert knowledge, it can also be difficult for outsiders to scale and compare the assessments of the different criteria in a meaningful way. Basically, here too, the quality of the assessment depends heavily on the availability and reliability of the data on which it is based and which is used to assess the alternatives.

5.3.4 Multi Criteria Methods

Multi criteria decision making (MCDM) methods are methods for supporting decision-making that take into account several, often contradictory, criteria. These methods are particularly useful in complex decision-making situations in which both qualitative and quantitative factors play a role. Multi-criteria decision-making systems can basically be divided into two groups: multi-objective methods and multi-attribute methods.

Multi objective methods (multi objective decision making, MODM) primarily deal with problems whose solution space is continuous. This means that these are problems with several specified objectives that must be achieved while complying with restrictions. For this reason, these decisions are often solved with the help of linear programming.

In comparison, the solution space in multi attribute decision making (MADM) methods is discrete, i.e. a goal is pursued on the basis of a defined number of attributes. There are numerous methods that can be used for MADM problems. One way of classifying them is based on the degree of information to the decisionmaker. **Figure 5-3** below provides an overview of the various methods.

The utility analysis already explained also belongs to the MADM methods in a broader sense. The principles formulated in **Chapter 5.3.3** therefore also apply to the MADM methods. All of these methods require that the decision-maker has a clear idea about the utility and weighting of criteria characteristics and how these are to be interpreted in a decision-making process. In contrast to the MADM methods mentioned above, outranking methods are based on the assumption that it is not possible for the decision-maker to define his preferences with regard to the criteria at the outset. The decision-making process generates a structure for the decision-making situation. The result is that, in most cases, a larger selection of suitable alternatives for action is generated, so that it is not necessarily possible to identify only one optimal alternative.

Advantages and disadvantages of multi criteria methods

The explicit presentation and weighting of the criteria make the decision-making process transparent and comprehensible. This facilitates communication and justification of the decision or the assessment result. MADM methods are particularly well suited for complex decision-making and assessment problems where several factors must be taken into account. The methods can be adapted to different assessment and decision-making contexts as well as specific requirements, whereby different MADM techniques can be used as needed. Some MADM methods – such as the Analytical Hierarchy Process – can take into account uncertainties and ambiguities in the data and preferences of the assessment, which increases the robustness of the decision-making. In principle, these methods are therefore a good basis for dealing with complex assessment situations and arriving at stringent decisions and assessment results.

The disadvantages of these methods lie primarily in their complexity, which increases disproportionately, especially when there are a large number of alternatives and criteria. This often results in the need for extensive data analysis and modelling, combined with the corresponding effort for the person performing the task. The selection, weighting and assessment of the criteria are also subject to a high degree of subjectivity and are often influenced by the personal preferences and assessments of the evaluator. The application of MCDM also often requires specific expertise and experience in the methodology, which may require additional training and resources.

5.4 Potential Assessment Methods for Underground Infrastructure

5.4.1 General

The following section presents a selection of sustainability assessment methods that are currently in use or under development. This is a heterogeneous selection of methodological approaches, each with its own advantages and disadvantages in terms of ap-

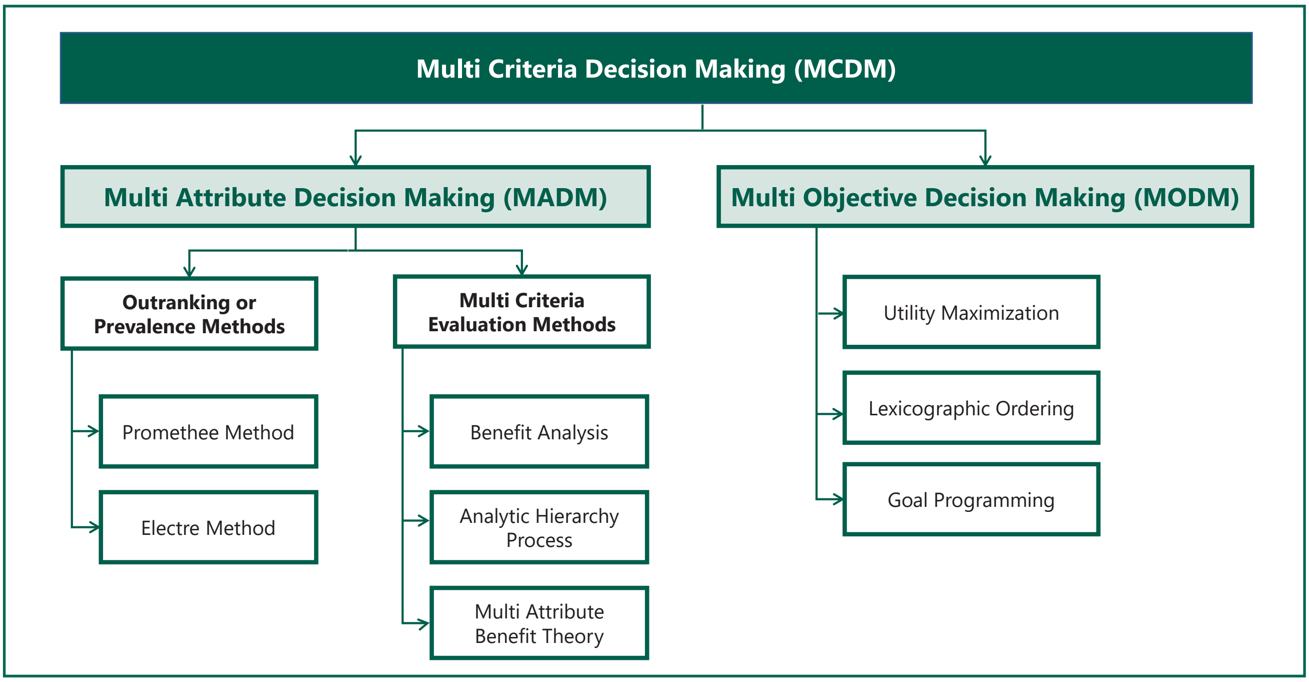


Figure 5-3 *Multi criteria decision making methods in the assessment of alternatives [70]*

plication. The basic idea behind the methodology is presented and the advantages and disadvantages of its application are formulated from the DAUB's perspective. Finally, a classification is made with regard to the theoretical principles of assessment methods (cf. **Chapter 5.4.8**).

5.4.2 BREEAM Infrastructure

BREEAM Infrastructure, formerly known as CEEQUAL (Civil Engineering Environmental Quality Assessment and Award Scheme), is an assessment and certification system for sustainable infrastructure projects and is distributed by the BRE Group. BREEAM stands for Building Research Establishment Environmental Assessment Method and is one of the world's leading sustainability assessment systems, which is currently also used in the field of underground construction, primarily in Scandinavia and English-speaking countries. BREEAM Infrastructure is aimed specifically at infrastructure projects such as roads, bridges, tunnels, hydraulic structures, energy infrastructure and other large-scale civil infrastructure projects.

It assesses the sustainability performance of infrastructure projects in various phases, from planning and design to construction and operation. The system developed for this purpose comprises 8 criteria and 221 associated indicators from the three sustainability pillars, which are included in the assessment with a specified weighting in the overall result and a predefined maximum number of points (credits) that can be achieved per criterion by the project. The number of credits is based on the performance of the project against predefined standards and is determined by the respective evaluator – who has been trained in the application of the algorithm by BREEAM.

In total, taking into account the prioritisation of the individual criteria, this results in an overall assessment based on a predefined assessment scale. The criteria and indicators are defined a priori by BRE, as is the prioritisation of the individual criteria and indicators among themselves. In addition, BRE provides the corresponding points system and formulates the corresponding certification levels, which range from "Pass" to "Good", "Very Good" and "Excellent" to "Outstanding". The assessment algorithm is based on the basic principles of a utility analysis, as the assessments per indicator are converted into points using predefined utility functions, resulting in a final assessment of the entire project via an aggregated discrete point value.

Advantages and disadvantages of the methodology

In principle, the BREEAM system helps to integrate sustainability principles into the planning and construction process, which can lead to more environmentally friendly and socially compatible infrastructure. In Norway, BREEAM is sometimes used as a project management methodology to optimise the sustainability of the project during the design and construction phase, for example by changing the design or replacing materials. By taking a wide range of sustainability criteria into account, projects can theoretically gain in quality and be made more economical and resource-efficient in the long term. The structured assessment process and the clear criteria promote transparency in project assessment. The less flexible contractual structures in Germany do not allow this approach to be implemented immediately.

BREEAM Infrastructure certification involves considerable costs and administrative effort, especially for smaller projects. The application of the assessment methodology requires a high level of expertise and experience, which may necessitate training and specialised consultants. To this end, BRE trains certified evaluators, who are trained in the application of the methodology in internal courses. Despite standardised criteria, subjective interpretations may arise during the assessment, which could impair the comparability and consistency of the results. Furthermore, it is not clear whether the defined standards and the associated utility functions can be readily transferred to, for example, German-speaking countries.

In general, the assessment process and the compilation of the respective criteria are rather opaque to outsiders, as there is no description of the indicators and the origin of the stored utility functions is not documented. It should also be considered that although BREEAM Infrastructure is already used for tunnels, it was actually developed for bridges and other infrastructure structures and therefore does not fully reflect the tunnel-specific constraints of sustainability assessment.

5.4.3 Envision

Envision is a comprehensive assessment system developed by the Institute for Sustainable Infrastructure (ISI) in the USA to measure and promote the sustainability of infrastructure projects. Since its introduction in 2012, the third version of this assessment method is now available. It is designed to help review evaluate and improve large infrastructure projects in the areas of transport, water, energy and waste management in particular. The procedure follows a clearly structured evaluation process, with the methodology designed to allow flexible adaptation to different project phases and requirements. Projects can choose between two evaluation paths: Path A (planning and follow-up) or Path B (follow-up). The division into these two paths theoretically facilitates the integration of the system into different project phases.

The assessment and evaluation are based on five criteria that are intended to cover the various dimensions of sustainability and are or can be themselves underpinned by various subcategories or indicators. The criteria are weighted differently in the determination of the overall result, with "Nature" accounting for the largest share at 23.2 %. These are the following variables (their share in the weighting of the overall result is shown in brackets):

- Quality of Life (20 %)
- Leadership (8.2 %)
- Resource distribution (19.6 %)
- Nature (23.2 %)
- Climate and Resilience (19 %)

The Envisions assessment methodology defines target values, the achievement of which is measured by the respective evaluator using a points system. Similar to the BREEAM approach, target achievement values can be determined across all categories and finally aggregated into an overall assessment of the project, whereby no discrete numerical values from the project are used directly but are transformed into qualitative variables by the evaluator using the target functions. In the context of a final assessment, a certificate can then be obtained for the project, with four so-called "award levels" achievable, from "Verified" to "Platinum", as the best possible certificate from a target achievement rate of 50 %.

Advantages and disadvantages of the methodology

In theory, the Envision Framework promotes the integration of sustainability principles throughout the entire life cycle of infrastructure projects – from planning and construction to operation and maintenance. It covers a wide range of aspects based on the three pillars of sustainability and promotes an integrated approach to ecological, social and economic objectives. The framework also helps, when applied in a concerted manner, to reduce environmental impacts through strategies such as resource conservation, waste reduction and the protection of ecosystems. By also taking into account social dimensions such as job creation and improving the quality of life in the community, it helps to maximise the social benefits of infrastructure projects.

In contrast to BREEAM, which was explicitly developed for ex-post assessments, Envision can also be used to carry out ex-ante assessments, although the application of the framework generates additional costs and greater administrative effort. This applies both in the planning phase and during the implementation of the project: certified evaluators trained by the ISI must be commissioned for this purpose.

Envision was also not explicitly developed for the boundary conditions of underground construction and may therefore sometimes cause adaptation problems, especially given the long lifespan of the structures. As with BREEAM, the stored benefit functions and the threshold values corresponding to the assessments of the criteria are not transparent and therefore not comprehensible. This also applies to the basis for weighting the criteria.

5.4.4 Standardised Assessment

Standardised Assessment is a procedure for the uniform and transparent assessment of projects in the public transport sector, in particular infrastructure projects such as the construction of new railway lines or the improvement of existing transport systems. In Germany, Standardised Assessment is mainly used in the context of local public transport to determine the economic viability and eligibility of projects for funding. Its main features lie, on the one hand, in the use of a defined assessment procedure based on uniform criteria. This enables a comparable assessment of different projects. On the other hand, Standardised Assessment focuses on a cost-benefit analysis, whereby the monetary and non-monetary costs of a project are weighed against the expected benefits.

Since Standardised Assessment was not primarily developed to evaluate the sustainability of a project, the focus is primarily on criteria that describe the effectiveness of urban local public transport, such as travel time savings, operating costs, environmental impacts, safety, spatial planning or aspects of urban development. The result of the assessment is expressed in a benefit-cost indicator (BCI). A BCI greater than 1 means that the expected benefits exceed the costs and the project is economically viable.

Advantages and disadvantages of the methodology

The Standardised Assessment method is an established assessment procedure that has been gradually refined over the years and is indispensable, especially in the area of assessing the economic aspects of public transport projects. This results in a number of advantages for the user or the client: Since the procedures for data collection and recording are well known and widely used, and therefore do not represent anything new, this is a reliable methodology that produces comprehensible and transparent results. In addition, the large number of economic criteria ensures a comprehensive view of the project.

However, with regard to the holistic assessment of sustainability aspects, some weaknesses in the methodology inherent in the system can be identified. On the one hand, the criteria are designed for the assessment of public transport projects and the corresponding monetisation methods have been developed accordingly. For this reason, transferability to other modes of transport, in particular to road infrastructure projects, is problematic at this stage. In addition, the focus of the Standardised Assessment is on the economic criteria of the project, which is not considered sufficient, especially with regard to tunnel construction and its sustainability assessment.

5.4.5 Methodology of the German Sustainable Building Council (DGNB)

The German Sustainable Building Council (DGNB) has developed a comprehensive and recognised certification system for assessing and promoting the sustainability of buildings and neighbourhoods. Work is currently underway to extend the validity of the system to infrastructure projects in general and tunnel projects in particular. The DGNB system is characterised by a holistic view of all essential sustainability aspects and offers flexible application to different building types and construction projects. In addition to the sustainability assessment based on the three main dimensions of ecological, economic and socio-cultural or functional quality, the technical quality, process quality and location of the construction project are also taken into account. The methodology used is based on multi-criteria assessments of the respective pillars, whereby here, too, in the sense of a scoring system, degrees of fulfilment are defined by stored utility functions, which can then be aggregated to form an overall assessment of the project. DGNB certification is awarded in four levels, based on the total score achieved:

- Platinum: Highest award, for projects with a very high total score
- Gold: High total score, very good fulfilment of the criteria
- Silver: Good fulfilment of the criteria
- Bronze: Basic fulfilment of the criteria

The DGNB trains so-called auditors to carry out the assessment. These define the necessary scope of data to be procured for the project participants and then check the provided documents for completeness and coherence and carry out the assessment using the DGNB methodology. The DGNB provides software solutions for data collection, which are designed to standardise data collection and simplify it for those involved in the project.

Advantages and disadvantages of the methodology

The DGNB methodology has proven itself in a large number of applications and represents a tried-and-tested, functional assessment procedure for sustainability assessment. As at the time of writing this recommendation the development of the assessment methodology for infrastructure buildings, and in particular for tunnels, is still under development, only a vague assessment of its advantages and disadvantages can be made at present. It will be particularly important here to also integrate the benefits of underground structures into the assessment, as this is where the greatest asset for clients and users lies in terms of the building's life cycle.

5.4.6 Methodology of the Swiss Sustainable Building Standard (SNBS)

The sustainability assessment system "Swiss Sustainable Building Standard (SNBS) – Infrastructure" is a comprehensive assessment tool that was developed by the Swiss Sustainable Building Network to promote sustainable construction in Switzerland. It was based on the system developed for building construction and further developed for infrastructure construction and takes equal account of ecological, economic and social aspects for a holistic assessment of construction projects. To this end, the SNBS uses a detailed catalogue of criteria that defines specific requirements and assessment standards for each criterion in the three dimensions. Based on the methodological approach of a classic utility analysis, each criterion is assessed based on stored utility functions with points and the total score of a project is ultimately aggregated from the sum of the points in all criteria. A minimum score must be achieved in each dimension for the project to be considered sustainable overall.

Due to its modular structure, the SNBS can be adapted to different types of construction projects (e.g. buildings, infrastructure, etc.) thus enabling flexible application of the system. During the assessment, data on the individual criteria is collected and analysed, whereby, in addition to traditionally available data such as energy consumption, material selection or construction costs, user surveys and their results can also be integrated. Based on the collected data, each criterion is then assessed, and the corresponding points are awarded. The assessment is carried out according to defined standards and benchmarks, which are clearly presented in the respective description of the corresponding criterion. The total score and the achievement of the minimum requirements in each dimension ultimately determine the sustainability level of the project. Successful projects receive corresponding certification according to the SNBS.

Advantages and disadvantages of the methodology

With its methodology, the NNBS presents a very mature and easy-to-use methodology, that is particularly impressive due to the completeness of the criteria across all pillars of sustainability. Extensive documentation describing the criteria is available, which, in addition to the assessment of sustainability, also contains a clear description of the requirements of the criterion or the indicator. In addition, the description of the criteria also shows the extent to which and for which area the respective criterion applies, for example with regard to the phase of the life cycle of the structure for which the criterion is valid.

One disadvantage of the method is that, for example, in terms of economic aspects, the actual costs of the project are not taken into account, but only the question of whether and to what extent, for example, life cycle costs for the project are levied. For example, if such a survey is carried out, this is considered positive, regardless of the actual amount of the life cycle costs. In general, all criteria are assessed using a three-stage assessment scheme. Against this background, improvements within the planning can only be reflected to a limited extent and do not consistently lead to an assessment that differs from the original assessment.

5.4.7 Sustainability Indicators for Road Infrastructure Projects (NISTRA)

NISTRA was developed by the Swiss Federal Roads Office (ASTRA) and is tool designed to enable the assessment of road infrastructure projects taking sustainability goals into account. NISTRA assesses a project on the basis of 42 pre-selected indicators from the areas of direct costs, traffic quality, safety, urban development, the environment, and realisation and coherence. Some of these indicators are monetised in Swiss francs, while others are quantified via target functions and converted into effectiveness points. However, some of the indicators remain purely qualitative and are converted and presented using specific scales.

NISTRA thus maps the sustainability assessment using a mixed calculation, combining a cost-benefit analysis with a cost-effectiveness analysis and a qualitative analysis. The individual assessments thus remain largely in their units or are consistently converted to such units and not aggregated into a single assessment figure. The aim here is to highlight conflicts of interest and thus to provide decision-makers with a basis that can be used for the political deliberation process.

The NISTRA assessment method and the associated Excel calculation file (eNISTRA) have been used by ASTRA since 2003 for major construction and expansion projects on national and main roads – since 2023 in the latest version, NISTRA 2022.

Advantages and disadvantages of the methodology

NISTRA enables a comprehensive assessment of road infrastructure projects by incorporating ecological, economic and social criteria. This means that the sustainability of a project is assessed across all three pillars, rather than just the purely technical or monetary aspects. The aim is to promote the use of environmentally friendly materials and processes and to protect natural resources. In theory, its application minimises the environmental impact of road projects, for example by taking CO_2 emissions and resource consumption into account.

NISTRA takes into account not only the acquisition and construction costs, but also the long-term costs of a road, including maintenance and demolition. The method considers social impacts, such as the effects on the quality of life of local residents, road safety and accessibility for different population groups. The use of standardised sustainability indicators allows projects to be objectively assessed and compared with each other, promoting transparent decision-making. By focussing on social and ecological impacts, the methodology can also help to increase public acceptance of infrastructure projects, as it highlights the benefits to society.

However, the heterogeneity of the approach also contributes to its complexity. Assessment according to NISTRA requires extensive data collection and detailed analysis, which can be both time-consuming and costly. The administrative effort can be considerable, especially for large or complex projects. Furthermore, the system was not developed with a focus on underground infrastructure, meaning that its application to underground structures is possible but would need to be examined on a case-by-case basis. A complete and accurate assessment according to NISTRA often requires specific and extensive data, which may not always be available in the required form or quality, especially in the early stages of a project.

In projects with complex environmental and social impacts, it can also be difficult to determine the correct weighting for each sustainability indicator, as NISTRA gives users considerable freedom in this regard. There is therefore a risk that some aspects will be weighted too heavily or too lightly, which can lead to distorted results and essentially requires a subsequent sensitivity analysis. This means additional effort and further increases the complexity.

5.4.8 Summary of the Assessment Methods Considered

Table 2 lists the assessment methods considered above and assigns them to their theoretical background. It should be noted that such an assignment is not always entirely clear-cut, as some theoretical approaches are mixed together. The following classification therefore represents the predominantly underlying methodology.

5.5 Recommendation for the Selection of Criteria, Indicators, and Target Systems for Sustainability Assessment in Underground Construction

The previous explanations in the recommendation have shown two things in particular with regard to the criteria to be used:

- Underground construction differs in some respects significantly from general infrastructure construction in terms of its impact on the built environment and the other societal effects. Against this background, specific criteria and indicators must be included in the assessment that can reflect these effects and describe them adequately.
- As each tunnel project is very specific, there can be no "complete" list of criteria that would be universally applicable to all other projects.

Against this background, **Appendix A** provides a list of basic criteria that can be used to evaluate ecological, economic and social aspects. This serves as a basis and, when applied, can be expanded to include project-specific influencing factors.

5.6 Recommendations for Conducting Project Assessments for Underground Structures

5.6.1 General

Conducting a sustainability assessment for underground construction projects involves a systematic and methodical process that aims to comprehensively assess the environmental, social and economic aspects of a construction solution. The boundary conditions specific to underground construction play a particularly important role in this context, such as the comparatively long service life of the structures and the direct and indirect effects of the construction measures on the surrounding area.

The following section outlines an example of how such an assessment is carried out and highlights the specific aspects that are of particular importance for underground construction.

5.6.2 Conducting the Assessment

5.6.2.1 Initialisation Phase

At the outset, the project is defined in terms of its basic parameters, including the project objectives, scope and essential requirements. The objectives of the sustainability assessment are also defined at this stage, which serve as the basis for all further steps.

A suitable assessment framework must be selected for this purpose, such as the DGNB system or a comparable methodology. The selection of the framework is generally based on the specific requirements and objectives of the project as well as national and international standards. For underground construction, particular consideration must be given to the following:

- The assessment framework must cover all essential criteria necessary for the assessment of underground construction.
- The methodology underlying the assessment framework must be capable of reflecting the effects of the construction and operation of the object over a time frame of at least 100 years. When selecting a methodology, care must therefore be taken to ensure that transient criteria and indicators, i.e., those that may be subject to change over time are appropriately embedded in the methodology and that their variability can be taken into account over the life cycle. This applies, for example, to environmental factors of the project, if, for example, there is a successively increasing improvement in the quality of life in the in the area surrounding the project over the lifespan of the structure.
- The methodology must be flexible enough to allow for both "with" and "without" scenarios can be taken into account. This applies, for example, to the comparison of material technology solutions that lead to a reduction in GHG emissions. Here, it is important to be able to test substitutes against the original products in terms of their impact.
- The methodology should not be based purely on a cost-benefit analysis, so that aspects of underground construction that are difficult to quantify (for example, effects on the surface) can also be taken into account and given equal consideration. Ideally, the methodology should be based on a combination of utility analyses and/or multi-criteria approaches.
- It is important to be able to assess projects ex ante, i.e. to to be able to look into the future. Some proprietary approaches can only provide an ex post view, which may not be effective, especially for underground construction.

5.6.2.2 Data Collection Phase

In this phase, all data required for the assessment are collected. This includes structural data, material lists, energy consumption forecasts, life cycle cost analyses and environmental information such as emission data and waste management plans.

The collected data are systematically documented and processed. Here, special emphasis is placed on providing evidence to ensure the transparency and traceability of the data. This includes technical reports, certificates for building materials, energy calculations and other relevant documents.

Due to the complexity of underground infrastructure structures, a methodology is recommended here that offers structured collection of data, ideally with software support. Thanks to the BIM master plan for motorway construction [71] now specified by the BMV, some of the information is already available today in a structured form. A suitable methodology is ideally able to extract essential information via interfaces to the BIM models.

5.6.2.3 Assessment Phase

The collected data are analysed and assessed based on the criteria of the selected assessment framework. Each criterion is considered on the basis of specific benchmarks and requirements, and corresponding scores are assigned or assessments made.

The individual assessments of the individual criteria are aggregated to determine an overall assessment of the project. Here, care is taken to ensure that all three dimensions of sustainability (ecological, social and economic) are given equal consideration.

5.6.2.4 Audit and Verification Phase

An external audit is carried out during which independent auditors review the collected data collected and the assessment carried out. The aim of the audit is to confirm the accuracy and completeness of the assessment and to identify any discrepancies.

The audit is followed by a verification and validation of the results. This includes the rectification of any identified deficiencies and final confirmation of the assessment by the certifying body.

5.6.2.5 Post-assessment Phase

After the assessment, the project is continuously monitored to ensure that the sustainability standards are maintained throughout the entire service life of the structure. Regular reports document progress and identify potential for improvement.

Re-evaluation may be necessary at regular intervals to confirm that the project continues to meet the defined sustainability standards. This includes renewed data collection, assessment and auditing.

The sustainability assessment of underground infrastructure is a complex process that places very high demands on all parties involved and should, in principle, cover all phases of the of the structure's life cycle. In addition to selecting the appropriate criteria and indicators, choosing the optimal assessment methodology also plays a decisive role in the outcome.

With a view to future developments, DAUB makes recommendations on the selection of an assessment methodology but does not prefer any particular methodology so as not to exclude others.

6 Open Questions regarding Sustainability Assessment and Conclusion

6.1 Assessment of the Current State of Knowledge

6.1.1 Regarding Sustainability Assessment and this Recommendation

The explanations in the previous chapters have shown that, for a variety of reasons, a comprehensive, complete, and reliable assessment of the sustainability of underground infrastructure projects is currently hardly possible. Essential social and ecological aspects still elude an equivalent quantified assessment. The medium-term goal must be to enable all stakeholders involved in construction to do so.

With this recommendation, DAUB has now developed various principles for achieving such an objective. In addition to a blueprint for complete GHG balances (in Part 2 of these recommendations [1]) for various construction methods in tunnelling, the boundary conditions of underground infrastructure in the context of sustainability assessments are outlined and basic guidance on the selection of assessment methods and the implementation of sustainability assessments is formulated.

Nevertheless, DAUB still sees substantial hurdles and problem areas that currently still make such comprehensive assessments difficult. The following section therefore identifies the problem areas and provides guidance on how to shed light on them. These areas can be assigned to the following topics:

- Adjustment of political and administrative constraints
- Further development of the methodological approaches to assessment procedures
- Prioritisation and weighting of criteria and indicators

6.1.2 Notes on Adjusting Political and Administrative Constraints

Sustainability and ensuring it is achieved is a challenge for everyone involved in construction, which must be lived and implemented throughout all phases of the life cycle. Ideally, therefore, the earliest phases of the project should already involve examination of the structure and its construction, the collection and provision of the necessary data and information, and the development of a concept for integrating sustainability considerations into the planning process. This is the only way to achieve the greatest possible effect in reducing GHG emissions and mobilising the benefits of the structure. This principle gives rise to a number of necessary prerequisites for the interaction between clients, planners, and contractors, which are not yet apparent at this stage:

- The political and regulatory framework conditions must be formulated in such a way that there is sufficient scope for the implementation of innovative measures. This is a particular challenge for ministries, district governments, licensing authorities and infrastructure.
- The creation of the project-specific framework conditions is the responsibility of the client, who must first define and formulate the sustainability goals in the form of concrete specifications for his structures. This requires, especially in the case of large infrastructure operators, a conceptual idea of which sustainability goals can and should be achieved, how, to what extent, and with what concrete effects for the environment.
- The planning of the structures must be based on these objectives. This includes, on the one hand, the definition of specific targets, for example, in terms of GHG savings. On the other hand, future planning concepts must open up opportunities for competition between bidders, with the award of contracts being decided not only on the basis of price, but also the specific fulfilment of these predefined targets. Ideally, the planning should leave room for the implementation of innovative solutions, for example, through novel construction methods or new material concepts.
- This also highlights the need to amend and adapt the current contract structures and award procedures. As things stand today, it can be assumed that the rather rigid concept of the VOB/A, for example, is hardly suitable for reflecting and systematically implementing tenders that are based on sustainability principles. What is needed here are concrete and specific guidelines, that not only focus on the economic efficiency of the project but also enable sustainability objectives to be taken into account, for example, by evaluating bids on the basis of various weighted criteria, without, however, reducing the transparency and legal certainty of the award process.

6.1.3 Notes on the Further Development of Methodological Approaches of Assessment Systems

The assessment methods currently available have the weaknesses already described in Chapter 5, and so far none of them fully meets the requirements arising from the boundary conditions of underground infrastructure structures. Against this background, however, a requirements profile can be drawn up that can serve as a template for future developments. The most important requirements can be summarised as follows:

- A methodology for holistic sustainability assessment of underground infrastructure must be designed in such a way that it can be used to successfully analyse the project in the early stages of its life cycle phases. Methodologies that only allow for ex-post considerations are not suitable for this purpose.
- The assessment framework must include all essential criteria necessary for evaluating underground construction. This applies in particular to criteria that describe the benefit of the structure for the structural, social, and ecological environment.
- The methodology underlying the assessment framework must be capable of reflecting the effects of the construction and operation of the object over a time frame of at least 100 years. When selecting a methodology, care must therefore be taken to ensure that transient criteria and indicators, i.e., those that are subject to change over time, can be embedded in the methodology accordingly and their variability can be taken into account over the life cycle. This applies, for example, to environmental factors of the project, if, for example, over the lifespan of the structure there is a gradual improvement in the quality of life in the environment surrounding the measure.
- The methodology must be flexible enough to allow for both "with" and "without" scenarios to be taken into account. This applies, for example, to the comparison of material technology solutions that lead to a reduction in GHG emissions. Here, it is important to be able to test substitutes against the original products in terms of their impact.
- The methodology should not be based purely on a cost-benefit analysis, so that aspects of underground construction that are difficult to quantify (for example, effects on the surface) can also be taken into account and given equal consideration. Ideally, the methodology is based on a combination of utility analyses and/or multi-criteria approaches.

At present, there is a particular lack of concrete approaches for correctly and fairly incorporating the effects in the vicinity of the construction measures into an assessment. The DAUB strongly recommends that further research be conducted to establish the necessary knowledge in this area.

6.1.4 Prioritisation and Weighting of Criteria and Indicators

In principle, all criteria should be evaluated equally in sustainability assessments, i.e., ecology, economy,

Table 2 *Overview of the Assessment Methods considered and their Formal Assignment*

Approach	**Methods**		
	Cost-Benefit Analysis (CBA)	**Benefit Analysis (BA)**	**Multi Criteria Decision Making (MCDM)**
BREEAM		Transformation of all Indicators to a Predefined Scale	
Envision		Transformation of all Indicators to a Predefined Scale	
Standardized Assessment	Predominant Monetisation of all Indicators		
Methodology of DGNB		Transformation of all Indicators to a Predefined Scale	
Methodology of SNBS		Transformation of all Indicators to a Predefined Scale	
NISTRA			Mix of CBA, with BA and Purely Qualitative Assessments

and social issues. However, this is difficult to achieve within the criteria – for example, with regard to the various indicators of the "economy" criterion – and is also difficult to reconcile with existing assessment approaches. For example, the methodology used to prioritise infrastructure measures within the framework of the Federal Transport Infrastructure Plan involves a specific weighting of certain factors and parameters. Sustainability assessments cannot therefore be carried out in a "vacuum" but must be coordinated and carried out in a "consensual" manner with other assessment systems. Furthermore, the weighting of indicators and criteria must not be left entirely to the user, so that the overarching objective can be maintained and sustainability assessments do not become completely subjective.

The DAUB therefore recommends coordination between the major infrastructure operators and the definition of assessment horizons, limit values, and weightings against the background of a defined set of criteria and indicators. Here, too, there is an urgent need for action, research and regulation.

6.2 Conclusion

With the present recommendation, DAUB has provided a comprehensive work on the assessment of sustainability issues in underground infrastructure. In addition to reviewing the status quo in the description of sustainable effects in the construction environment, the recommendation goes far beyond previous papers on the subject. The core elements are primarily the development and implementation of an exemplary GHG emissions calculation for various construction methods (see Part 2 of the recommendation) and the description of ways in which underground construction as a whole can become more sustainable. These approaches can be pursued further scientifically and technically and ideally lead to concrete measures on future and current construction sites of underground infrastructure.

In addition, decision-making aids for selecting assessment methods are formulated and aspects are highlighted where underground construction already makes essential contributions to sustainability today. In many cases, these go far beyond what is reflected in existing and available assessment methods for sustainability analysis.

Furthermore, the contributions to sustainability are often not included in the assessment, as other civil engineering structures usually have no effect in this regard, for example with regard to improving the quality of life on the surface by laying a route underground. Conversely, the sustainable effects of underground construction are primarily felt over comparatively long periods of time and also differ substantially from what can be generated by bridges or surface transport routes, for example. Therefore, it is imperative that these contributions be given equal weight in future assessments.

It is therefore a key objective of DAUB to update the recommendation presented and to expand and/

or adapt it with in the knowledge gained in the future. Against this background, one of the central demands of this recommendation is to provide assessment procedures that are based on these boundary conditions and thus enable an objective, comprehensible, and technically sound assessment.

It should be noted that other DAUB recommendations, such as those for determining life cycle costs or for recycling tunnel excavation material, should be seen as complementary to the present paper. They logically supplement the subject matter of this paper with information on economic and ecological issues in sustainability balancing. It is conceivable that this overall picture will be supplemented by further recommendations to follow.

The key finding is that sustainability and the reduction of greenhouse gas emissions are intertwined, but nevertheless far from identical. Structures with higher GHG emissions can, in absolute terms, be more sustainable than competing solutions. The reason for this is that any disadvantages in the area of GHG emissions – which currently dominate public debate – can be offset by economic, social, or other ecological aspects in the context of a holistic sustainability assessment.

Therefore, a holistic sustainability assessment is recommended as early as the selection of the preferred option in the preliminary planning stage.

7 References

[1] Deutscher Ausschuss für unterirdisches Bauen (DAUB); Empfehlungen Nachhaltigkeit im Tunnelbau Teil 2: Treibhausgasbilanzierung für die Herstellungs- und Errichtungsphase, Köln, 2025

[2] Deutscher Ausschuss für unterirdisches Bauen (DAUB); Empfehlungen für die Ermittlung von Lebenszykluskosten für Tunnel, Köln, 2023

[3] Deutscher Ausschuss für unterirdisches Bauen (DAUB); Empfehlung „Verwertung von Tunnelausbruchmaterial", Köln, 2024

[4] Rio-Erklärung über Umwelt und Entwicklung; https://www.un.org/Depts/german/conf/agenda21/rio.pdf

[5] United Nations Framework Convention on Climate Change https://unfccc.int/resource/docs/convkp/conveng.pdf

[6] United Nations Convention on Biological Diversity https://www.cbd.int/doc/legal/cbd-en.pdf

[7] United Nations Climate Change Conference, "The Paris Agreement to the United Nations Framework Convention on Climate Change", COP 21, 2018 https://www.bmuv.de/fileadmin/Daten_BMU/Download_PDF/Klimaschutz/paris_abkommen_bf.pdf

[8] United Nations, "Transforming our world: the 2030 Agenda for Sustainable Developement," Resolution Adopted by the General Assembly, 2015. https://sdgs.un.org/2030agenda

[9] European Commission, Directorate-General for Communication, "European green deal: delivering on our targets", Publications Office of the European Union, 2021. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan_de

[10] Verordnung (EU) 2020/852 des Europäischen Parlaments und des Rates vom 18. Juni 2020 über die Einrichtung eines Rahmens zur Erleichterung nachhaltiger Investitionen und zur Änderung der Verordnung (EU) 2019/2088 https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:32020R0852

[11] Deutsche Bundesregierung, Deutsche Nachhaltigkeitsstrategie, Weiterentwicklung 2021 https://www.publikationen-bundesregierung.de/resource/blob/2277952/1875176/9b7154e-5739ecc19a2d1520d2a94a2c3/deutsche-nachhaltigkeitsstrategie-2021-langfassung-download-bpa-data.pdf?download=1

[12] EU, JRC for policy report, GHG emissions of all world countries, 2023 Report https://edgar.jrc.ec.europa.eu/booklet/GHG_emissions_of_all_world_countries_booklet_2023report.pdf

[13] Umweltbundesamt, Berechnung der Treibhausgasemissionsdaten für das Jahr 2022 gemäß Bundesklimaschutzgesetz, Begleitender Bericht, Kurzfassung vom 15. März 2023, Dessau-Roßlau https://www.umweltbundesamt.de/sites/default/files/medien/361/dokumente/vjs_2022_-_begleitbericht_final_kurzfassung.pdf

[14] Leopoldina, Klimawandel: Ursachen, Folgen und Handlungsmöglichkeiten, Factsheet Version 1.1, 2021

[15] BMBF, Ariadne-Hintergrund, Das deutsche Klimaschutzgesetz: Möglichkeiten einer sektorübergreifenden Klimagovernance, Potsdam 2021 https://ariadneprojekt.de/publikation/klimaschutzgesetz-sektorubergreifende-klimagovernance/

[16] Bundes-Klimaschutzgesetz (KSG) 2019, Bundestags-Drucksache 19/14337 in der mit Bundestags-Drucksache 19/15128 geänderten Fassung

[17] Bundesinstitut für Bau-, Stadt- und Raumforschung (BBSR), Umweltfußabdruck von Gebäuden in Deutschland, BBSR-Online-Publikation Nr. 17/2020

[18] Daten der Treibhausgasemissionen des Jahres 2023 nach KSG, https://www.umweltbundesamt.de/sites/default/files/medien/361/dokumente/2024_03_13_em_entwicklung_in_d_ksg-sektoren_thg_v1.0.xlsx

[19] BAU-Industrie – Aktuelles Zahlenbild, Ausgabe 421

[20] Statistisches Bundesamt DESTATIS, Tätige Personen und Umsatz der Betriebe im Baugewerbe, https://www.destatis.de/DE/Themen/Branchen-Unternehmen/Bauen/Publikationen/Downloads-Baugewerbe-Struktur/personen-umsatz-baugewerbe-2040510227005.xlsx

[21] Schäfer, Martin: Tunnelbau in Deutschland: Statistik (2022/2023), Analyse und Ausblick, Tunnel 1/2024

[22] Verein Deutscher Zementwerke, VDZ (Hrsg.); Dekarbonisierung von Zement und Beton – Minderungspfade und Handlungsstrategien. Düsseldorf, 2020

[23] Höltschi, René; Auch Deutschland setzt auf CO_2-Speicherung, Neue Zürcher Zeitung, 27.02.2024

[24] Umwelt Bundesamt, Abfallbilanz (Abfallaufkommen/-verbleib, Abfallintensität, Abfallaufkommen nach Wirtschaftszweigen), https://www.umweltbundesamt.de/daten/ressourcen-abfall/abfallaufkommen#bau-abbruch-gewerbe-und-bergbauabfalle

[25] Secretariat of the Convention on Biological Diversity – United Nations Environment Programme – 2011 Convention on Biological Diversity (CBD)

[26] World Economic Forum, The Global Risks Report 2023, 18th Edition, Cologny/Geneva https://www.weforum.org/publications/global-risks-report-2023/in-full/1-global-risks-2023-today-s-crisis/

[27] Bundesamt für Naturschutz, Artenschutz-Report 2015 – Tiere und Pflanzen in Deutschland, Bonn https://www.bfn.de/sites/default/files/2021-04/Artenschutzreport_Download.pdf

[28] https://www.bmuv.de/themen/artenschutz/nationaler-artenschutz/ursachen-der-bedrohung#:~:text=Frei%20lebende%20Tier%2D%20und%20Pflanzenarten,Zerschneidung%20und%20Flächenverluste%20natürlicher%20Lebensräume

[29] NABU/BCG, Wirtschaften im Einklang mit der Natur – Handlungswege zur Sicherung der Biodiversität, Berlin, 2020 https://www.nabu.de/imperia/md/content/nabude/biodiv/200923-nabu-bcg-studie-biodiv2.pdf

[30] Europäische Kommission, Fahrplan für ein ressourcenschonendes Europa, Brüssel, 20.09.2011, https://eur-lex.europa.eu/legal-content/DE/TXT/PDF/?uri=CELEX:52011DC0571&from=EN

[31] https://www.umweltbundesamt.de/bild/anstieg-der-siedlungs-verkehrsflaeche

[32] Bundesamt für Naturschutz, Bundeskonzept Grüne Infrastruktur, Fachgutachten TU Berlin und Universität Kassel,2017, https://www.bfn.de/sites/default/files/2023-07/Skript457.pdf

[33] Brennstoffemissionshandelsgesetz (BEHG), §10 Veräußerung von Emissionszertifikaten, Abs. 2

[34] Sustainable Bavaria (o.J.) Ziff. 3: Einpreisung und Bewertung von Klimaauswirkungen. München: Bayerische Ingenieure-Kammer-Bau.

[35] Püstow, M. et al. (2023): Impulspapier Klimaverträgliches Bauen mit einem Schattenpreis für CO_2-Emissionen. Wien: KPMG Law; Berlin: Hauptverband der Deutschen Bauindustrie e. V.

[36] https://www.mass.gov/info-details/the-big-dig-project-background

[37] Massachusetts Turnpike Authority: „Transportation Impacts of the Massachusetts Turnpike Authority and the Central Artery/Third Harbor Tunnel Project", Volume I, February 2006, Boston, USA

[38] https://www.rosekennedygreenway.org/

[39] https://www.umweltbundesamt.de/daten/umweltindikatoren/indikator-landschaftszerschneidung#die-wichtigsten-fakten

[40] https://de.statista.com/statistik/daten/studie/1084696/umfrage/prognose-der-nachfrage-nach-urbanen-mobilitaetsleistungen-weltweit/

[41] VDV (Herausgeber): Stadtbahnsysteme – Grundlagen-Technik-Betrieb-Finanzierung; Buch der blauen VDV-Reihe; Juni 2014; S. 32

[42] Datensatz DB Netz AG, 2022 (nicht veröffentlicht)

[43] Bundesverkehrswegeplan 2030, Stand 03/2016, Bundesministerium für Digitales und Verkehr

[44] Leitfaden für die Planungsentscheidung Einschnitt oder Tunnel, Ausgabe 1998, Bundesministerium für Verkehr

[45] Resch, Daniel; Verwendung von Tunnelausbruchmaterial – Entscheidungsgrundlagen Montanuniversität Leoben, 2012

[46] Thienert C.; Breitsprecher G.; Budach C.; Entsorgungskonzepte für Tunnelausbruchmaterial: Innovative Ansätze für Ressourceneffizienz und Praxisbeispiele, In: Forschung + Praxis, Tagungsband zur STUVA-Tagung 2019, S. 209–215,2019

[47] Haist et al. (Haist, Michael; Bergmeister, Konrad; Curbach, Manfred; Forman, Patrick; Gaganelis, Georgios; Gerlach, Jesko; Mark, Peter; Moffatt, Jack; Müller, Christoph; Müller, Harald; Reiners, Jochen; Scope, Christoph; Tietze, Matthias; Voit, Klaus), Betonkalender 2022, S. 421–531: Nachhaltig konstruieren und bauen mit Beton, Februar 2022

[48] Haist M.; Moffatt J.S.; Breiner R.; Vogel M., Müller H. S.: Ansatz zur Quantifizierung der Nachhaltigkeit von Beton auf der Baustoffebene. Beton- und Stahlbetonbau 111 (2016) Heft 10

[49] Proske T.; Rezvani M.; Palm S.; Müller C.; Graubner C.-A.: Concretes made of efficient multi-composite cements with slag and limestone. Cement and Concrete Composites (2018) 89, S. 107-119

[50] 45 % CO_2-Reduzierung bei der Zementproduktion für Stuttgart-21-Tunnelprojekt. Tunnel 06/2022 (2022)

[51] Vogt O.; Ukrainczyk N.; Koenders E.: Geopolymere als Spezialbaustoff. Nachrichten aus der Chemie 65 (12), S. 1198–1202

[52] Uebachs S.: Geopolymerbeton und seine Eigenschaften. BetonWerk International, 2, 42–46, 2018

[53] Vollmann G., Thienert C., Budnik J., Kleen E.: Entwicklung eines geopolymerbasierten zementfreien Spritzbetons, Tagungsband zur STUVA-Tagung 2021

[54] Coenen, M., Beyer, D., Heipke, C., Haist, M. (2022): "Learning to Sieve: Prediction of Grading Curves from Images of Concrete Aggregate", in: ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences, pp. 227–235.

[55] Thienert, C.; Klaproth, C.; Otterbein, R., Ludwig, F. (2017): „Entwicklung und Erprobung eines Online-Messsystems zur Bewertung der Wiederverwendbarkeit von Zementsuspensionen beim Düsenstrahlverfahren", AZ 32564/01, Deutsche Bundesstiftung Umwelt, Osnabrück

[56] Deutscher Ausschuss für unterirdisches Bauen (DAUB); Empfehlungen für den Entwurf, die Herstellung und den Einbau von Tübbingringen, Köln, 2024

[57] „Innovative use of industrial robots in partially automated segment production" in Geomechanics and Tunnelling 16, No. 2, Ernst & Sohn GmbH, 2023

[58] Bilger C.; Grundlagen/Anforderungen Tunnelabwasserbehandlung, Konferenz der Vorsteher der Umweltämter (Schweiz), 2017, https://www.kvu.ch/getdownloadfile.cfm?filename=180409065659_Bericht_WS_Tunnelausbruchmaterial_2017_Stand_2018_03_08.pdf

[59] Technische Universität München (2018): Leitfaden für klimaorientierte Kommunen in Bayern

[60] Europäische Kommission (2020): EU Biodiversity Strategy for 2030

[61] Schweizer Radio und Fernsehen (SRF, 2023): Gotthardtunnel: Ausbruchmaterial wird in Urnersee gekippt

[62] Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMUV, 2014): Das Bundesprogramm Wiedervernetzung

[63] Bayrisches Landesamt für Umwelt (LfU, 2006): Darstellung und Analyse der Landschaftszerschneidung in Bayern (Endbericht)

[64] Land Baden-Württemberg (2010): Verordnung des Umweltministeriums über die Anerkennung und Anrechnung vorzeitig durchgeführter Maßnahmen zur Kompensation von Eingriffsfolgen (Ökokonto-Verordnung, ÖKVO)

[65] OECE (2002): Handbuch zur Bewertung der biologischen Vielfalt: Ein Leitfaden für Entscheidungsträger

[66] Ril 853.8003: Eisenbahntunnel planen, bauen und instand halten - Richtlinie Instandsetzung, Teil- und Vollerneuerung von Tunnelbauwerken, DB InfraGO AG, Version 1.1, 15.04.2024

[67] https://www.hagen-siegen-hanau.de/der-weg-zu-den-tunnelvarianten

[68] Wittke, Walter; Wittke, Martin: "Einsparungen von CO_2-Emissionen und Kosten mit einschaligen konventionellen Tunnelbauweise" in "8. Felsmechanik- und Tunnelbautag", S. 150), 2023

[69] Gesetz zur Förderung der Kreislaufwirtschaft und Sicherung der umweltverträglichen Bewirtschaftung von Abfällen (Kreislaufwirtschaftsgesetz, KrWG): § 6 Abfallhierarchie

[70] Kamarianakis, Sissis; Dissertation Ruhr-Universität Bochum, 2013: Ein multikriterielles fuzzy- und risikobasiertes Entscheidungsmodell für die Planung unterirdischer Infrastruktur

[71] BMVI, Masterplan BIM Bundesfernstraße, Berlin, 2021

[72] Brilon, Werner; Lemke, Kerstin: Verkehrssicherheit in Straßentunneln. In: Bauingenieur (79), 2004, S. 286-290

[73] Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, Wien, Österreich: Bericht über Brände und Unfälle in Tunnelanlagen 1999–2023, Stand: 18. September 2024

[74] Bundesministerium für Verkehr: Standardisierte Bewertung von Verkehrswegeinvestitionen im öffentlichen Personennahverkehr Version 2016+, Berlin, 2023

[75] Deutsche Gesellschaft für nachhaltiges Bauen: Entwurf zur Nachhaltigkeitsbewertung von Tunneln, unveröffentlicht, 2024

[76] BRE-Group: BREEAM Infrastructure – Technical Manuals (Version 6), Watford, England, 2025

[77] Forschungsgesellschaft für Straßen- und Verkehrswesen – Arbeitsgruppe Verkehrsplanung: Hinweise zu Einsatzbereichen von Verfahren zur Entscheidungsfindung in der Verkehrsplanung (2010)

Appendices

APPENDIX A: Criteria and Indicators for Sustainability Assessments

The following tables summarise indicators for the three pillars/criteria of sustainability "Ecology, Economy, and Social Issues", which must be taken into account during consideration and evaluation. These are to be supplemented with project-specific local effects and assessments but in this form provide a basic framework for the assessment process. The following points should be taken into account:

- As already explained in the main part of the recommendation, some indicators can already be sufficiently underpinned by appropriate models to quantify the specific impact on sustainability precisely. Others cannot currently be represented, or only to a very limited extent, and will also only be quantifiable to a limited extent in the long term. The combined consideration of both types therefore requires both an appropriately adapted methodology and with a thorough examination of the softer indicators and suitable modelling of their characteristics.
- Some indicators describe effects that may extend beyond the scope of the respective criteria. For example, improving the quality of life in the vicinity of a construction project can have repercussions in terms of economic aspects, such as land prices in urban areas. Here, a clear distinction must be made between purely monetary aspects and softer aspects such as the well-being of local residents.
- Sustainability assessments are not conducted in isolation from legislative and normative requirements. Against this background, the indicators sometimes need to be adapted to the requirements of the legislator or the infrastructure operator. For example, some indicators correspond to those of the Federal Transport Infrastructure Plan, which is binding for civil engineering structures in transport infrastructure. In this specific case, consistency with these requirements must be ensured in order to avoid deviating or varying assessments for particular indicators.
- As already explained in the main part of the recommendation, some of the aspects can be clarified by DAUB recommendations that have already been published. This applies in particular to the areas of determining life cycle costs and recycling of tunnel excavation material. It is strongly recommended that the assessment process be based on these recommendations.

Table 3 *Ecological Indicators for a Sustainability Assessment of Underground Infrastructure*

Ecology		
Indicator	**Indicator Level 2**	**Unit**
Emissions	Noise Dust Vibrations	dB(A) g/m^3 mm/s
Waste	Contaminated Uncontaminated	t t
Excavation 1)	Utilisation on the Construction Site Utilisation with other Ecological Benefits Disposal	t t t
Land Use Influence	Usable Land and Forests Fragmentation Soil Sealing	ha ha ha
Water Balance	Groundwater Contamination Influence on the Groundwater Table Water Consumption	[–] 2) [–] 2) m
GHG Emissions	Manufacturing and Construction Phase Utilisation phase	t CO_2e/a t CO_2e/a
Energy Consumption	Manufacturing and Construction Phase Utilisation Phase	kWh kWh
Species Protection	Influence on Habitats Influence on Flora and Fauna	[–] 2) [–] 2)
1) See also [3] 2) For a precise recording and description of the influences, consultation of the relevant specialist literature is recommended.		

Table 4 *Economic Indicators for a Sustainability Assessment of Underground Infrastructure*

Economy		
Indicator	**Indicator Level 2**	**Unit**
Life Cycle Costs of the Structure 3)	Manufacturing and Construction Phase Utilisation Phase Investments	€ € €
Increased Attractiveness	Property Prices Additional Tax Revenues	€ €
Impact on Traffic	Reduction of Travel Times Reduction of Congestion Risks	€/h €/h
Secondary effects from traffic redistribution	Reduction in Maintenance Costs Revenue from Infrastructure Use	€ €
3) See also [2]		

Table 5 *Social Indicators for a Sustainability Assessment of Underground Infrastructure*

Social		
Indicator	**Indicator Level 2**	**Unit**
Attractiveness Variance	Impact on the Landscape Impact on Monument Protection Change in Quality of Life in the Surroundings Change in Attractiveness of the Region Change in Land Availability	[–] [–] [–] [–] [–]
Traffic Risk Management	Impact on Property Damage Impact on Personal Injury	€ n/a
Employment Situation	Impact on the Commercial Economy Impact on the Number of Available Jobs	[–] [–]
Risk Management Surroundings	Impact on Crime Impact on Cosiness	[–] [–]

APPENDIX B: Project Examples with Contributions to Improved Sustainability

Tunnel Baaker Mulde

Project Purpose: Conversion of existing tunnel into a bat roost

Project Location: Bochum-Linden

Construction Period: 1894

Affected SDGs:

Project Characteristics: Former railway tunnel of the Baaker Mulde coal mine

Brief Description of the Sustainability Aspect:

The former railway tunnel of the Baaker Mulde coal mine has been filled in along most of its length. An oxygen transport pipeline, which is still in operation, runs through the backfilled tunnel. At the southern portal, part of the tunnel remained unfilled and was closed off with an end wall and converted into a bat tunnel. Due to the expansion of the city’s cycle path infrastructure, there is now also interest in possibly making the tunnel usable again for a cycle path.

Bat tunnel Baaker Mulde in Bochum-Linden (Source: City of Bochum)

Thyssen-Krupp Industrial Tunnel

Project Purpose: Conversion of existing tunnel into a cycle tunnel

Project Location: Alleestraße in Bochum

Construction Period: —

Affected SDGs:

Project Characteristics: Former double-track industrial railway tunnel

Brief Description of the Sustainability Aspect:

The former double-track industrial railway tunnel (rectangular cross-section) under Alleestraße in Bochum, owned by Thyssen Krupp connected two originally separate parts of the plant north and south of Alleestraße and would have had to be dismantled or filled after it was taken out of service. The western tunnel tube was filled in, and a corrugated steel pipe was installed in the eastern tube, after which the annular space was filled in. The measure also involved shortening of the tunnel by 20 m and constructing a ramp system and today forms an important part of the cycle network, which will also include the RS1 cycle highway.


Alleestraße tunnel before and after (cycle tunnel) in Bochum (Photos: City of Bochum)

Schulenberg Tunnel

Project Purpose: Conversion of existing tunnel into a footpath and cycle tunnel

Project Location: Hattingen, North Rhine-Westphalia

Construction Period: 1884

Affected SDGs:

Project Characteristics: 195-meter-long, former railway tunnel

Brief Description of the Sustainability Aspect:

The Schulenberg Tunnel is a 195-meter-long, former railway tunnel in Hattingen, North Rhine-Westphalia. It was opened in 1884 as a so-called coal railway on the Wuppertal–Wichlinghausen–Hattingen railway line for mixed traffic. After about 100 years, first passenger transport was discontinued in 1979, followed by freight transport in 1984. It was not possible to restore this line for railway transport. Thus, conversion work on the former railway tunnel began in 1989. The reopening took place on September 23, 2008. Since then, the tunnel has served as a footpath and cycle path.

Schulenberg Tunnel Hattingen (Source: Olschowy)

Zierenberg Tunnel

Project Purpose: Conversion of existing tunnel into a bat roost

Project Location: Zierenberg, Kassel

Construction Period: 1897

Affected SDGs:

Project Characteristics: 815-meter-long, former railway tunnel

Brief Description of the Sustainability Aspect:

The Zierenberg Tunnel is located on the Kassel–Korbach line and was opened in 1897. Renovating the existing structure was not economically viable, which is why a new, approx. 900 m long parallel tunnel was built. The portals of the old Zierenberg Tunnel are to be treated as cultural monuments under the Hessian Monument Protection Act and must therefore be preserved. For this reason, it was decided to fill the old Zierenberg Tunnel with around 30,000 tonnes of material after completion of the new structure in 2018. Where possible, suitable excavated material from the new tunnel was used for this purpose. In addition, entrances were left in the area of the east portal so that a bat colony could be established here.

East portal Zierenberg Tunnel (Source: DB InfraGO AG, Stephan Nink)

Emscher Sewage Canal

Project Purpose: Renaturation of the Emscher river

Project Location: Ruhr area, Germany

Construction Period: from 2012

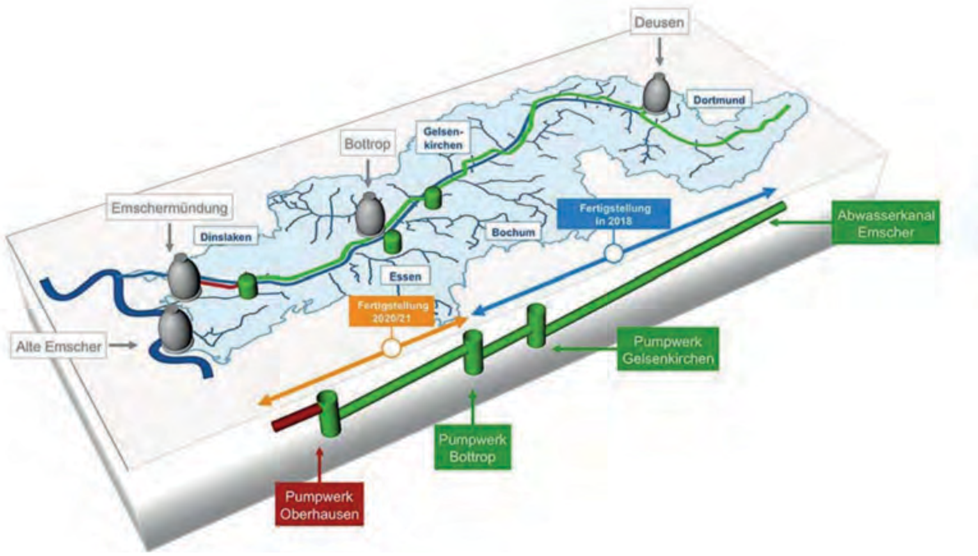
Affected SDGs:

Project Characteristics: A total of approx. 47 km of pipe jacking with diameters between 1.6 and 2.8 m, up to 40 m deep

Brief Description of the Sustainability Aspect:

The Emscher River flows through the Ruhr region between Dortmund in the east and Dinslaken in the west. In the past, this river and its tributaries were used to discharge sewage. The resulting environmental pollution and loss of natural habitats for humans and animals could no longer be tolerated. The numerous projects to renature the Emscher are intended to improve the water quality and to restore it as a habitat for flora and fauna.

In 2016, the Emscher Project was named Environmental Initiative of the Year by the International Tunnelling Association.



(Source: www.eglv.de)

Limmern Pumped Storage Power Plant

Project Purpose: Storage of surplus electricity from off-peak periods and production of peak energy with climate-neutral hydropower

Project Location: Canton of Glarus, Switzerland

Construction Period: 2009 to 2016

Affected SDGs:

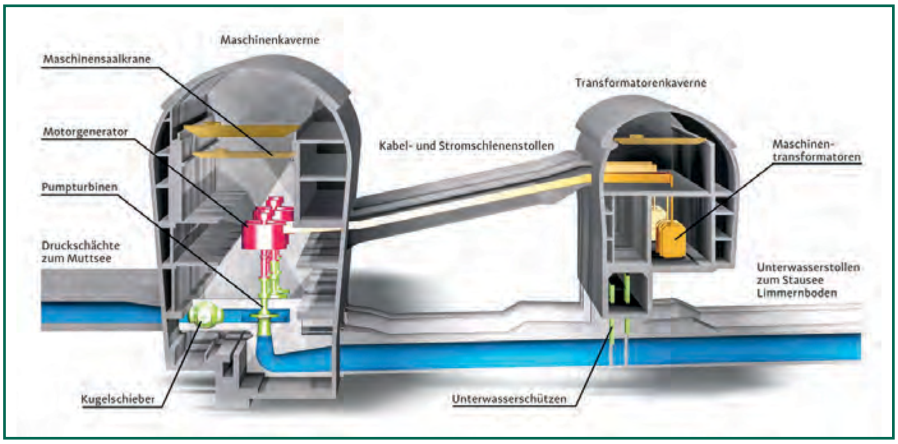
Project Characteristics: Extensive system consisting of tunnels and caverns, incl. a 3.8 km long access tunnel, driven by a hard rock TBM with a diameter of 8.03 m

Brief Description of the Sustainability Aspect:

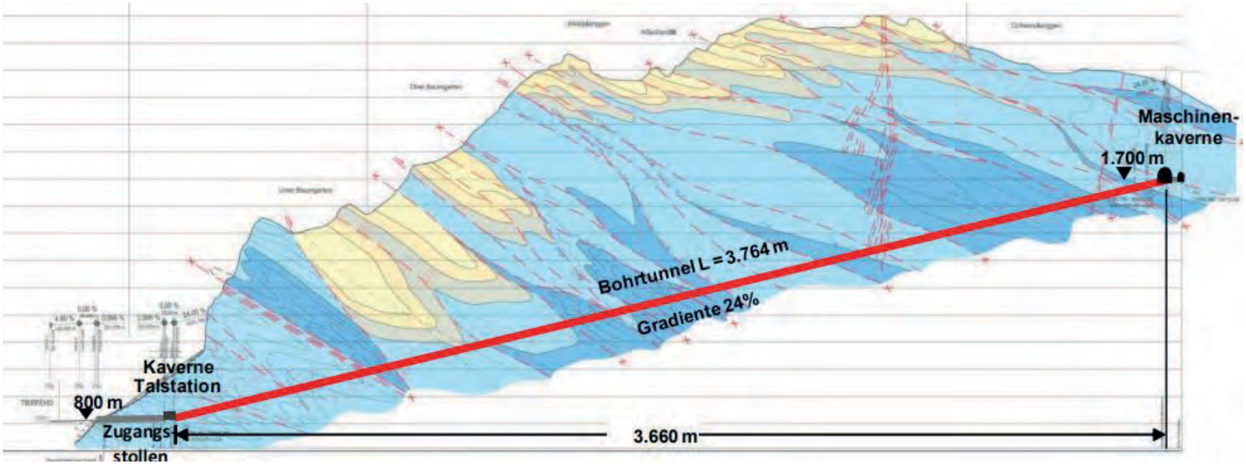
The underground facilities are used to produce climate-neutral electricity.

Access tunnel 1 connects the Linth-Limmern power plant, built 1,700 m above sea level, from the valley floor to enable weather-independent, year-round safe access to the power plant.

(Source: AXPO)



(Source: AXPO)



(Photo: Fridolin Walcher)

Further examples:

Rodund, Limberg III and Kühtai pumped storage power plants in Austria currently under construction

Inn Joint Venture Power Plant

Project Purpose: Climate-neutral electricity production

Project Location: Tyrol, Austria

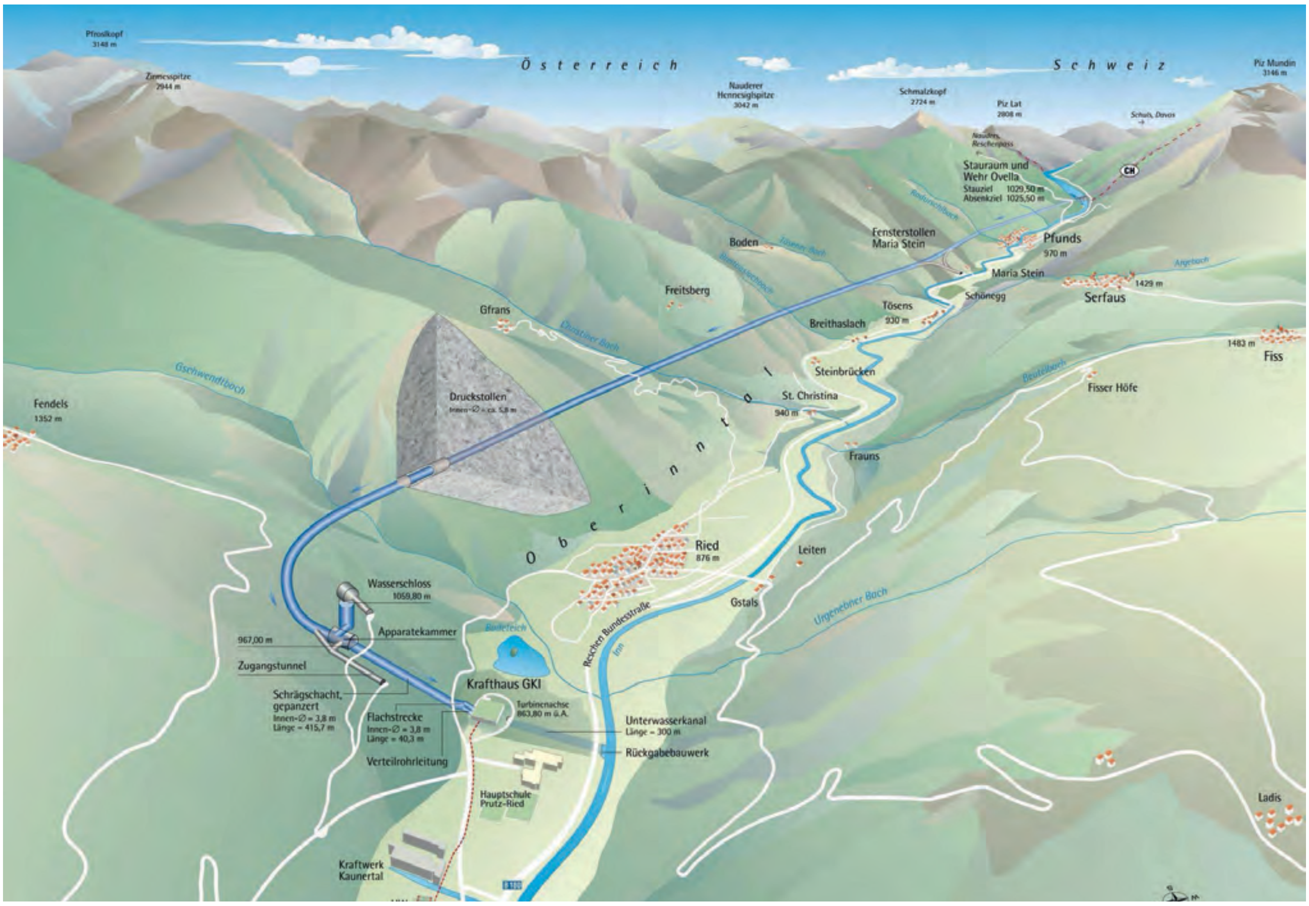
Construction Period: 2015–2022

Affected SDGs:

Project Characteristics: Run-of-river power plant, consisting of a weir, a 21.5 km long headrace tunnel and an underground powerhouse

Brief Description of the Sustainability Aspect:

Production of climate-neutral electricity with a hydropower plant with a high harvest factor. Improvement of the hydropeaking and hydroflushing phenomena in the Inn thanks to a balancing reservoir. Reuse of excavated material for concrete production and landscaping.



(Image: GKI)

London Power Tunnels

Project Purpose: Electrical energy supply

Project Location: London, England

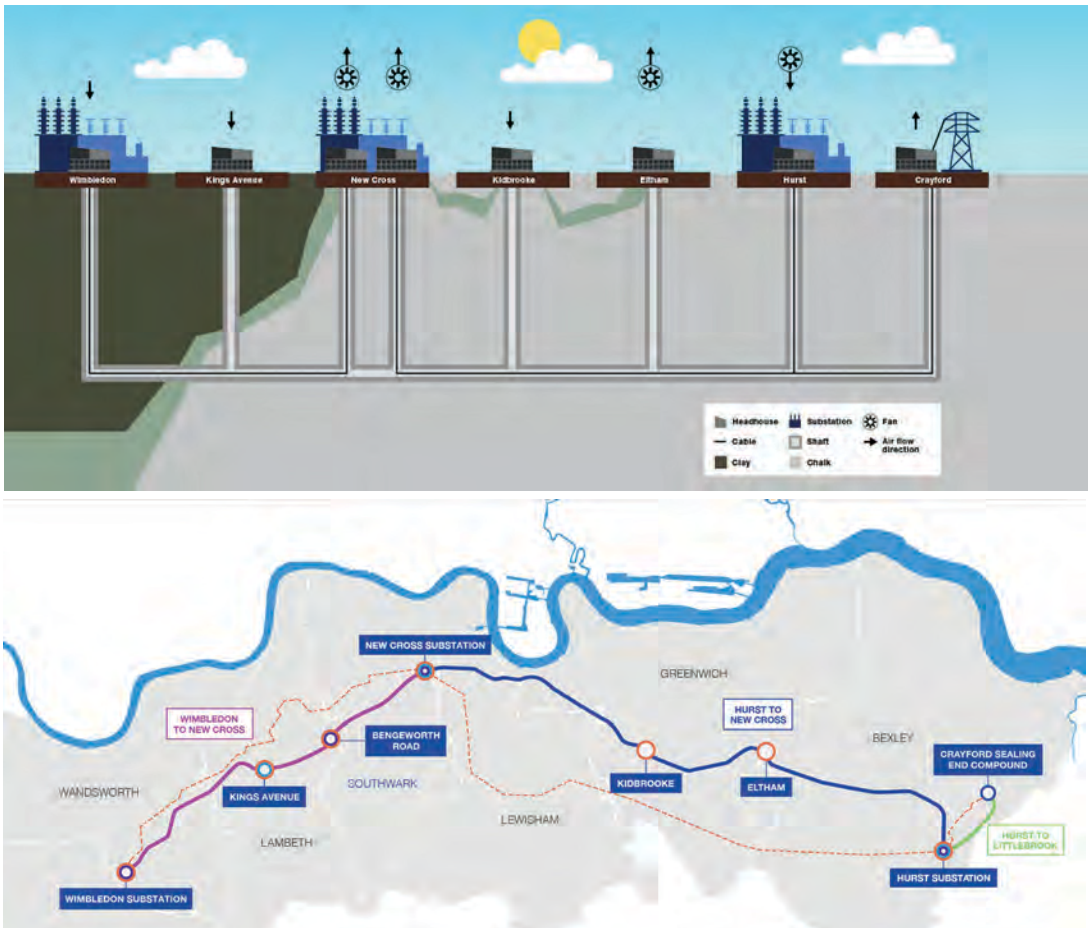
Construction Period: 2020–2026

Affected SDGs:

Project Characteristics: Over 60 km of tunnels with a diameter of 3.0 to 4.0 m, depth up to 60 m below ground level

Brief Description of the Sustainability Aspect:

The construction of the new power grid in tunnels up to 60 m deep will replace ageing, unsafe cables and cover the city's projected electricity demand with climate-neutral in the future.



(Image source: HOCHTIEF)

Corrib Onshore Gas Pipeline

Project Purpose: Electrical energy supply

Project Location: Northwest coast of Ireland

Construction Period: 2011–2015

Affected SDGs:

Project Characteristics: 4.2 km long hydroshield tunnel drive with a diameter of 4.2 m

Brief Description of the Sustainability Aspect:

The local population demanded that the project be planned with particular attention to sustainable and sensitive implementation, with special protection of flora and fauna. To protect the sensitive natural environment, tunnel construction was therefore preferred to land relocation.

During implementation, a maximum construction height of 4 m was specified, the gantry crane was designed with a truss girder, and the bentonite basins were covered. All structures were colour-coordinated with the surroundings and rigorous noise reduction measures were implemented.

(Source: Wayss & Freytag)

Sint-Pieters Woluwe Storage Sewer

Project Purpose: Flood protection

Project Location: Sint-Pieters-Woluwe, Belgium

Construction Period: 2018–2021

Affected SDGs:

Project Characteristics: 375 m EPB tunnel with a diameter of about 5.5 m

Brief Description of the Sustainability Aspect:

Due to increased exceptional rainfall events, storage spaces for temporary intermediate storage must be created more and more often in city centres. During heavy rainfall events, the existing sewerage system in Sint-Pieters-Woluwe was overloaded, resulting in flooding of roads and basements. The tunnel, which was driven under confined space conditions, created an underground temporary storage facility of about 8,000 m³ as flood protection.

(Source: Wayss & Freytag)

SMART-Tunnel: Stormwater Management and Road Tunnel

Project Purpose: Flood protection and road tunnel

Project Location: Kuala Lumpur, Malaysia

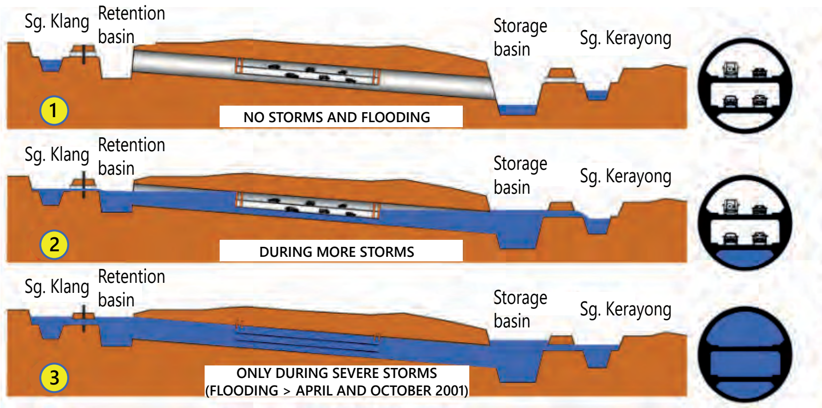
Construction Period: 2018–2021

Affected SDGs:

Project Characteristics: 9,7 m Hydroschild-Tunnel mit Durchmesser etwa 13,2 m

Brief Description of the Sustainability Aspect:

During the monsoon season, the city centre of Kuala Lumpur in Malaysia is sometimes affected by severe flooding as the two rivers, Gombak and Klang, burst their banks. During the planning of the tunnel, the potential for multiple use of the tunnel project, both as a road tunnel and for flood protection, was recognised and combined tunnel use was implemented. The tunnel can be used very flexibly with its 3 operating modes.



Normal conditions:
No floodwater in the system.

During moderate storms:
Floodwater in the lower section of the tunnel; highway section open to traffic.

During severe storms:
Tunnel closed to traffic; floodwater in all sections of the tunnel.

(Source: Wayss & Freytag)

(Source: By cmglee, OpenStreetMap - http://openstreetmap.org/search?query=smart+tunnel, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=101297562)

Gotthard Base Tunnel

Project Purpose: Transport project: Shifting heavy goods traffic across the Alps from road to rail

Project Location: Switzerland

Construction Period: 1996–2016

Affected SDGs:

Project Characteristics: Construction of a 151.1 km long underground system consisting of the tunnel tubes, cross-passages, caverns, shafts and adits for various purposes with a total excavation volume of 10 million m^3.

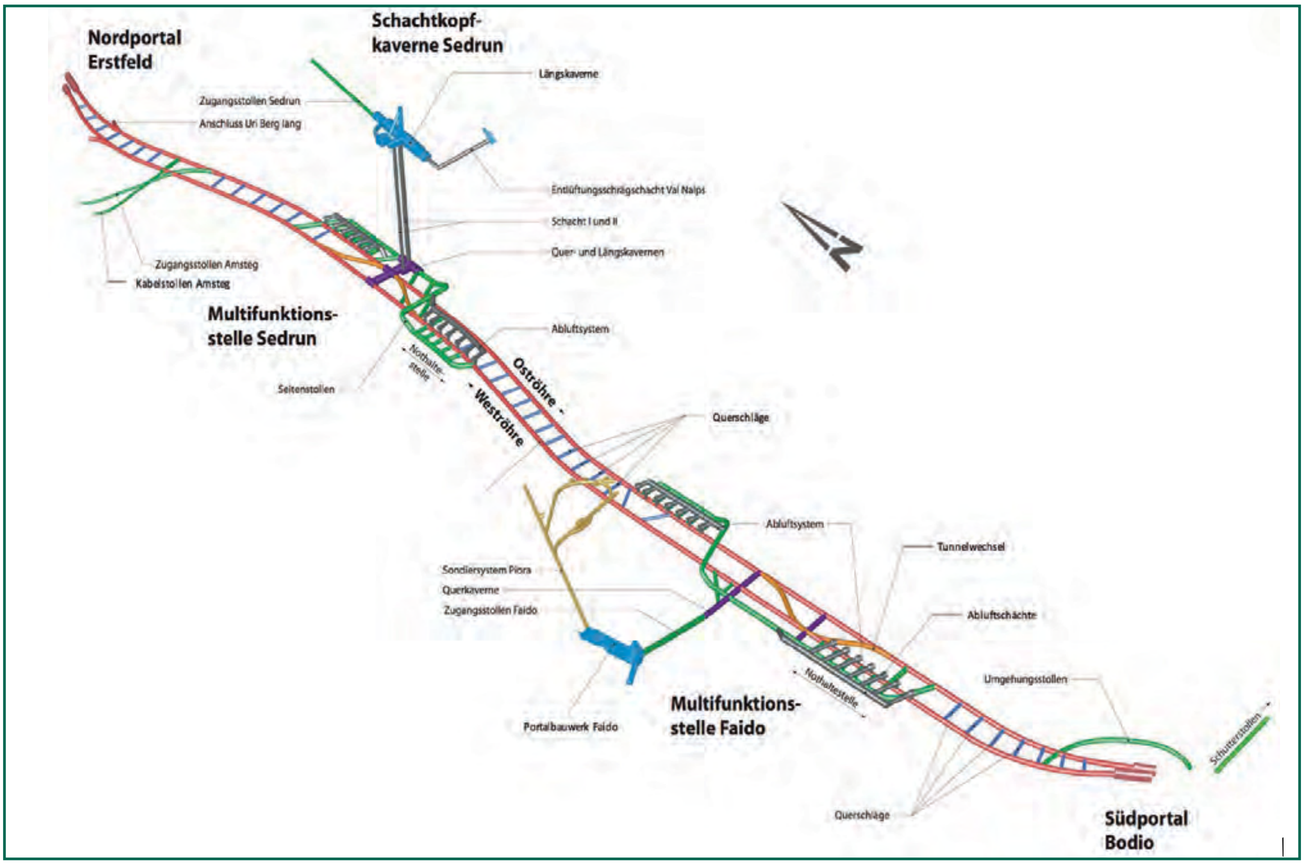
Brief Description of the Sustainability Aspect:

The Gotthard Base Tunnel primarily serves to shift European Alpine transit traffic from road to rail. In Switzerland, the railway is powered by climate-neutral hydropower. By shifting heavy goods traffic to rail, the aim is to relieve the narrow Alpine valleys of the negative consequences of road freight transport (exhaust fumes, accidents). The share of rail in Alpine transit traffic through Switzerland was 72.5 % in 2022.

Sustainability goals were given top priority right from the tunnel construction phase. Only shotcrete and concrete with 100 % aggregate from the excavated material was used for all underground work on the tunnel tubes (TBM and conventional tunnelling). Around 30 % of the excavated material could be reused in this way. Thanks to early close cooperation with industry and innovative techniques, the recycling rate could be maximised.

Around 70 % of the excavated material was used for embankments for track construction and for landscaping. During the landscaping, care was taken to ensure that positive contributions were made to biodiversity, whether for fish and birds in the lake fills in Lake Lucerne or through the creation of new alpine dry meadows on the landscaping from the unavoidable landfill material.

Particulate filters were mandatory on construction sites long before they became a legal requirement, and occupational safety in underground construction was massively improved.



(Source: Amberg Engineering AG)

(Source: Seeschüttung Uri)

ElbX

Project Purpose: Transport of Electrical Energy

Project Location: Glückstadt, Germany

Construction Period: Since 2023

Affected SDGs:

Project Characteristics: Slurry-supported drive under the Elbe, total length about 5.2 km, outer diameter just under 5 m

Brief Description of the Sustainability Aspect:

The 5 km long underpass beneath the Elbe is part of the overall SuedLink project, which involves laying an underground cable between Schleswig-Holstein and Bavaria. The 700 km long overall project aims to improve the supply of renewable energy to 10 million households in Germany.

A water treatment plant is being used in the implementation of the project, which allows water from the Elbe to be used on the construction site and used water to be treated and returned to the Elbe. This process water cycle protects the local drinking water network and treatment system.

Illustration of the cable pulling construction phase in the ElbX project(Source: https://www.tennet.eu/de/projekte/suedlink-planfeststellungs-abschnitt-a2)