ARUP

Life Cycle Assessment

Comparative environmental footprint for future linear colliders CLIC and ILC

Final Report
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Executive summary

Approach

This report evaluates the Life Cycle Assessment (LCA) of the construction of the Compact Linear Collider (CLIC) and the International Linear Collider (ILC). This study has considered the underground facilities construction, covering tunnels, caverns and access shafts only, for the following configuration options:

1. **CLIC Drive Beam**, 5.6m internal diameter, Geneva (380GeV, 1.5TeV and 3TeV)
2. **CLIC Klystron**, 10m internal diameter, Geneva (380GeV)
3. **ILC**, arched 9.5m span, Tohoku Region Japan (250GeV)

The LCA follows the ISO 14040/44 methodology and was carried out using Simapro 9.4.0.2. The ReCiPe Midpoint (H) 2016 method was used to estimate the environmental impacts across 18 impact categories.

A1-A5 Global Warming Potential (GWP) hotspots have been evaluated and possible reduction opportunities have been identified.

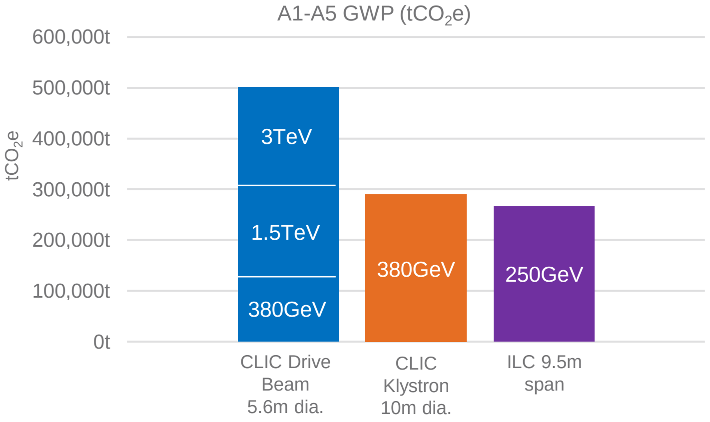
The approach and evaluation has been undertaken in close collaboration with CLIC and ILC teams from CERN and KEK.

A1-A5 Outcomes

A1-A5 considers material, transport and construction environmental impacts only. The A1-A5 GWP (tCO_2e) values are detailed below and constitute a baseline GWP for the current design of the CLIC and ILC.

CLIC Klystron 380GeV and ILC 250GeV have similar A1-A5 GWP of approximately 0.3 $MtCO_2e$. The CLIC Klystron 380GeV has approximately 2 times the A1-A5 GWP than CLIC Drive Beam 380GeV which is due to the increase in cross section of the main linear accelerator tunnel and the shielding wall. The increase in GWP across the 3 CLIC Drive Beam options is a direct function of the increase in tunnel length per increased energy levels.

The options have been evaluated as tunnels, shafts and caverns. The tunnels is the largest A1-A5 GWP contributor across all CLIC and ILC options.



Recommendations

There is an opportunity for material and design optimisation; this includes but is not limited to:

- Consider the use of low carbon concrete technologies
- Reduce the precast concrete segmental lining thickness for CLIC Drive Beam and Klystron options as this can have a significant impact on embodied carbon reduction of the tunnels.
- Replace the shielding wall in CLIC Klystron and ILC with concrete casing and earthworks fill, repurposed from tunnel excavation. This is to be confirmed with CERN and KEK upon shielding wall requirements for experiments.

These reduction opportunities represent a possible 40% embodied carbon reduction for CLIC and ILC, in line with UN Breakthrough Outcomes for 2030.

Consideration of the steel manufacturing process as well as SFRC alternatives such as plant fibres and recycled tyre steel fibres that are lower cost and environmental impact. More generally, partnering with suppliers that are committed to low carbon solutions is recommended.

It is recommended to adopt carbon management principles in accordance with PAS2080:2023 to maximise the carbon reduction potential in the development of these projects and integrate carbon reduction into decision-making driving design, construction and operation of the colliders.

Nomenclature

AAM Alkali-activated Materials

BF Blast Furnace

CEMI Cement that contains 100% Ordinary Portland Cement

CLIC Compact Linear Collider

D&B Drill & Blast

EAF Electric Arc Furnace

EC Embodied Carbon

EIB European Investment Bank

EOFP Photochemical Oxidant Formation Potential: Ecosystems

FA Fly Ash

FEP Freshwater Eutrophication Potential

FETP Freshwater Ecotoxicity Potential

FFP Fossil Fuel Potential

GGBS Ground Granulated Blast-furnace Slag

GWP Global Warming Potential

HOFP Photochemical Oxidant Formation Potential: Humans

HTPc Human Toxicity Potential: Cancer

HTPnc Human Toxicity Potential: Non-cancer

I.D Internal diameter

ILC International Linear Collider

IRP Ionising Radiation Potential

LCA Life Cycle Assessment

LCI Life Cycle Inventory Analysis

LCIA Life Cycle Impact Assessment

LOP Agricultural Land Occupation Potential

MEP Marine Eutrophication Potential

METP Marine Ecotoxicity Potential

O.D Outer Diameter

ODP Ozone Depletion Potential

PMFP Particulate Matter Formation Potential

RICS Royal Institution of Chartered Surveyors

SCM Supplementary Cementitious Materials

SF Silica Fume

SFRC Steel Fibre Reinforced Concrete

SOP Surplus Ore Potential

TAP Terrestrial Acidification Potential

TETP Terrestrial Ecotoxicity Potential

TBM Tunnel Boring Machine

UN United Nations

WCP Water Consumption Potential

For LCA Impact Category terminology refer to: ReCiPe Midpoint (H) 2016.

1

Life Cycle Assessment approach

1.1 Background

Background

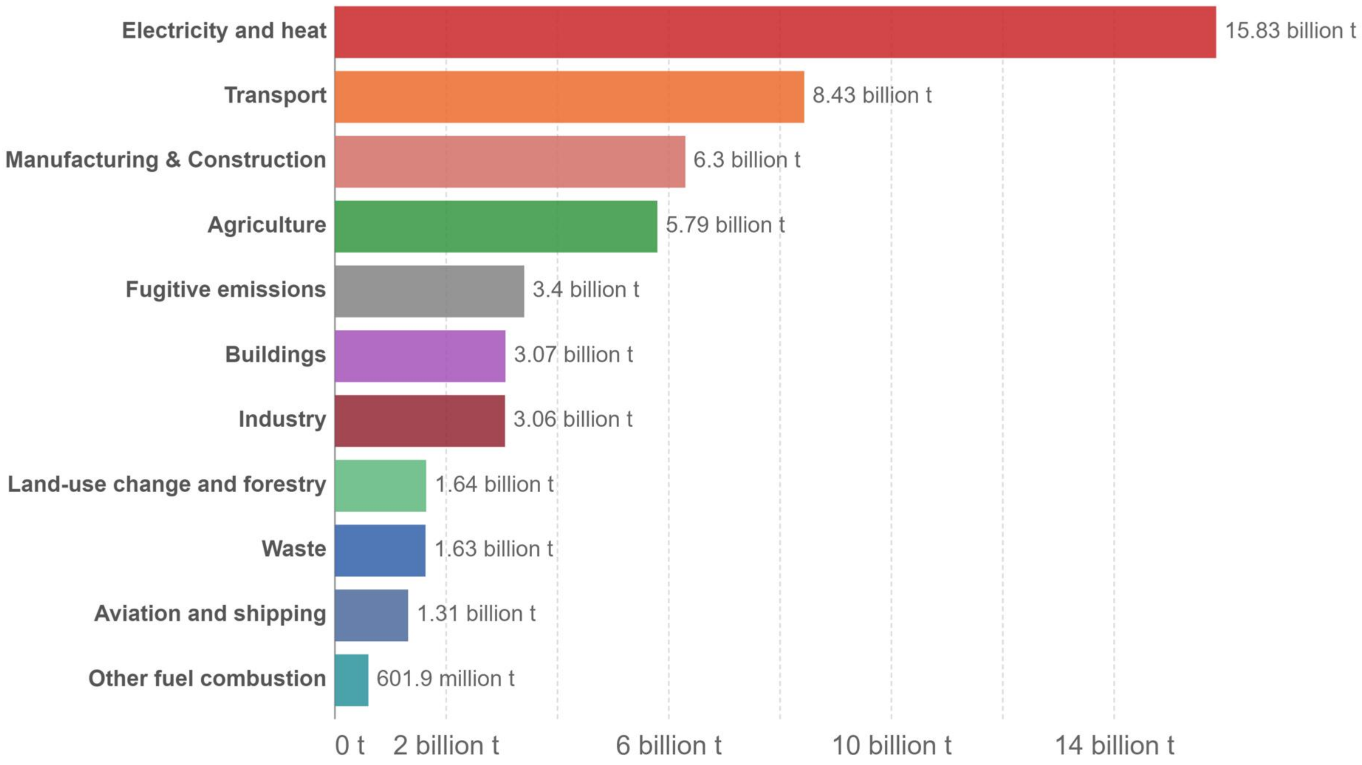
Global context

The manufacturing and construction sector is one of the largest contributors to global greenhouse gas emissions, emitting 6.3 billion tonnes of carbon dioxide equivalents in 2019.

Carbon dioxide, methane, nitrous oxide and fluorinated gases are greenhouse gases, measured as carbon dioxide equivalents.

UN Breakthrough Outcomes for 2030

For the built environment sector, the UN breakthrough outcomes for 2030 detail that 100% of projects due to be completed in 2030 or after are net zero carbon in operation, with at least 40% less embodied carbon compared to current practice. This has been set to make sure the sector is on track for 100% projects to be net zero carbon across the whole life cycle by 2050.



Our World in Data based on Climate Analysis Indicators Tool (CAIT) 2019 (Adapted)

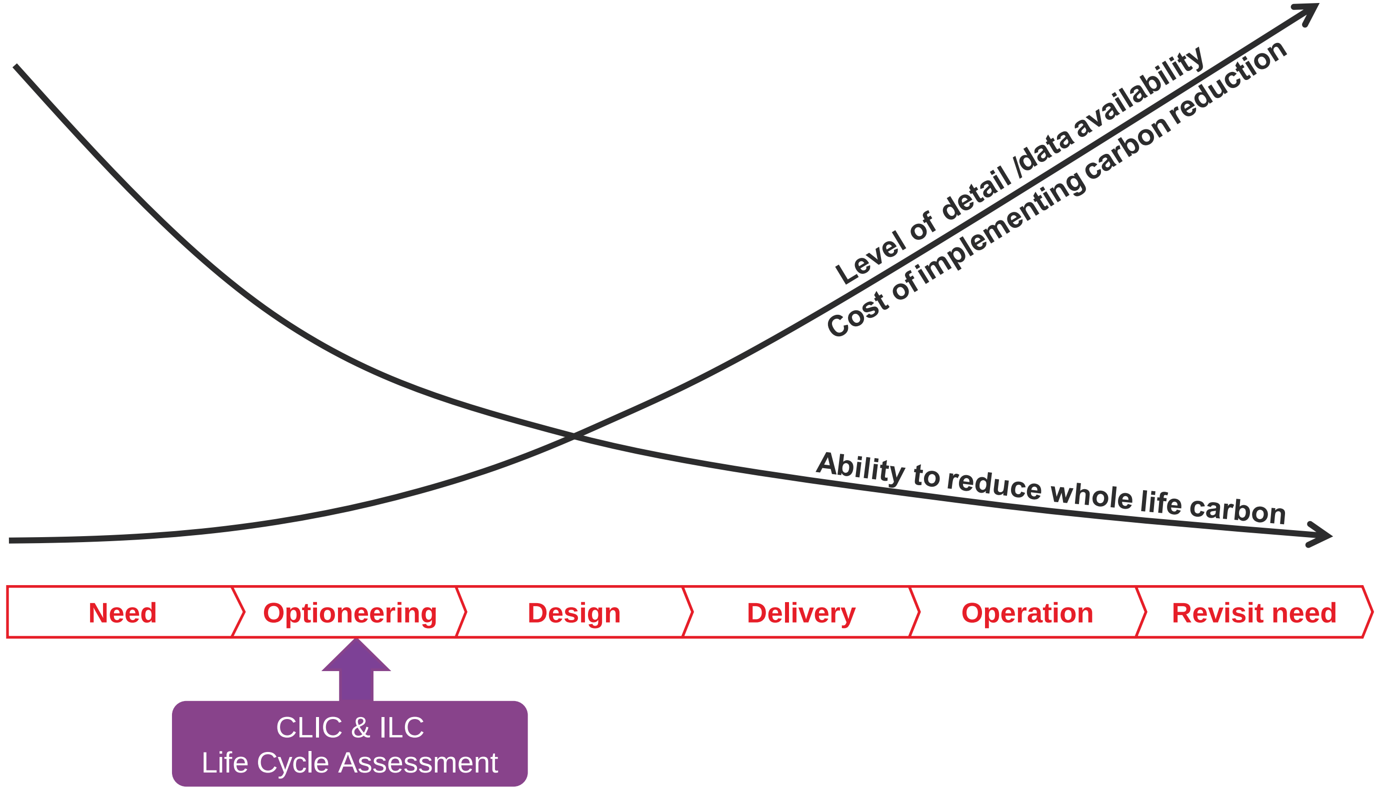
References:
United Nations Framework Convention on Climate Change, 2030 breakthroughs – upgrading our systems together, 2021

Background

Influence

All members of the value chain are able to influence the carbon decisions, which is why collaboration is so important for effective decarbonisation. The ability to reduce whole life carbon diminishes through the project life cycle and the cost of implementing carbon reduction increases towards these later project stages.

We have completed a life cycle assessment for the proposed Compact Linear Collider (CLIC) and International Linear Collider (ILC). Both are at concept design stage, which is the optimum time to be completing a life cycle assessment whilst there is still significant opportunity for carbon and environmental impact reduction.



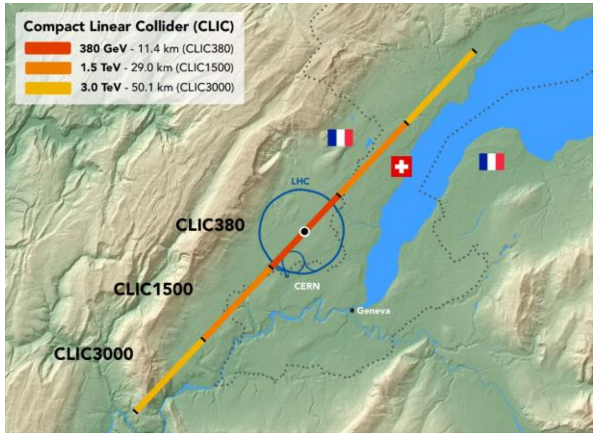
PAS2080:2023 Guidance Document (Adapted)

Background

Compact Linear Collider (CLIC)

The Compact Linear Collider (CLIC) is a proposed accelerator that is being designed as an addition to CERN’s accelerator complex. Its objective is to collide electrons and positrons (antielectrons) at energies of up to several teraelectronvolts (TeV). CLIC is intended to be built and operated in three stages, at collision energies of 380GeV, 1.5TeV and 3TeV.

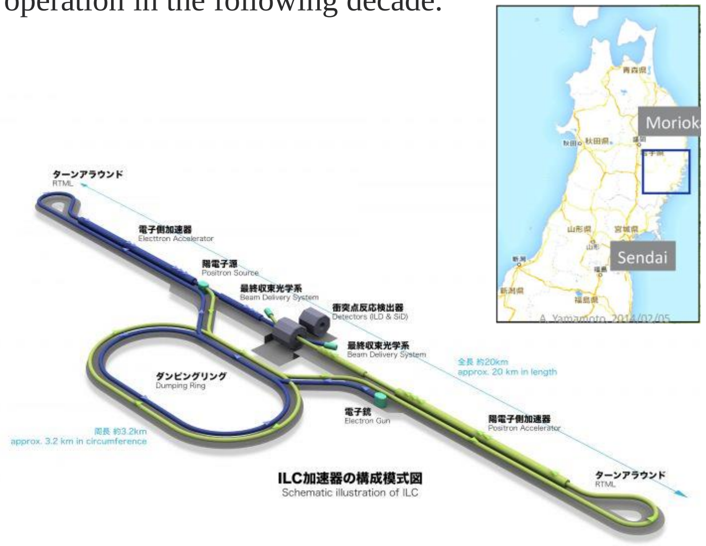
Reflecting the different energies, the site length ranges from 11 to 50 km stretching across the French-Swiss border near Geneva. The construction of the first CLIC energy stage is proposed to start around 2030. This would allow the first beams to be available by 2035 to start the CLIC physics programme spanning the following 25 to 30 years.



International Linear Collider (ILC)

The International Linear Collider (ILC) is a 250 GeV (extendable to 1TeV) centre-of-mass high luminosity linear electron-positron collider, based on 1.3 GHz superconducting radio-frequency (SCRF).

The total footprint of the ILC complex is approximately 33 km long (including damping ring, access tunnels and other tunnels as listed in section 2.3), with a candidate site in the Kitakami mountains in the Tohoku region, about 400 km north of Tokyo, identified as a potential location. The construction is proposed in the 2040s, with operation in the following decade.



Sustainable Linear Colliders

Sustainable development and planning of linear colliders is being studied within the international community and the role that large research infrastructure organisations can take in forming these solutions. Its impact alongside traditional considerations such as technical and cost implications is increasingly important in demonstrating the whole life impacts and contribution of linear collider facilities to the local and wider sustainable efforts.

‘Green-ILC’ studies in the Tohoku area for ILC, and sustainable study workshops, such as the Energy for Sustainable Science workshops at ESRF 2022 are demonstrating the considerations and approaches towards these efforts. This study helps to contribute towards these wider sustainable initiatives, in assessing the environmental impact and carbon footprint of the linear collider underground infrastructure for CLIC and ILC, through a life cycle assessment.

Background

Context

Arup have undertaken a Life Cycle Assessment (LCA) for three proposed linear colliders, considering tunnels, caverns and access shafts only:

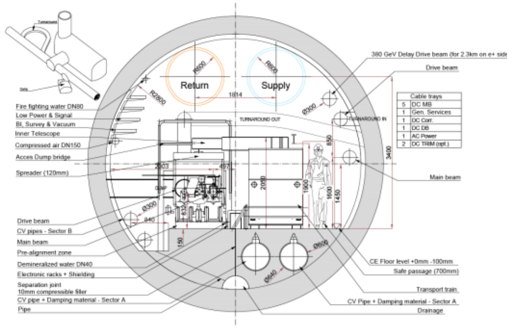
1. **CLIC Drive Beam**, 5.6m internal diameter, Geneva (380GeV, 1.5TeV and 3TeV)
2. **CLIC Klystron**, 10m internal diameter, Geneva (380GeV)
3. **ILC**, arched 9.5m span, Tohoku Region, Japan (250GeV)

CLIC is proposed to be built in 3 stages so that 3 energies can be analysed (380GeV, 1.5TeV, 3TeV). In this LCA CLIC Drive Beam is evaluated for the 3 energies. CLIC Klystron is evaluated for 380GeV only.

A single 250GeV proposal for the ILC has been evaluated in this LCA.

Data sources

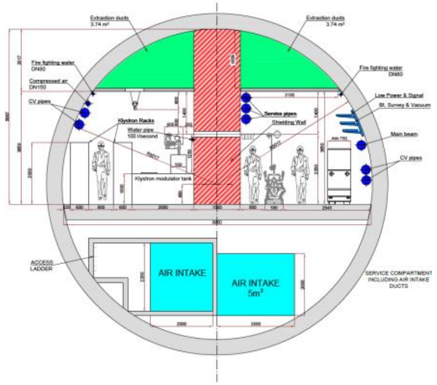
- CLIC Project Implementation Plan 2018 and CERN assumptions and clarifications.
- Tohoku ILC CE Plan 2020 and KEK clarifications in progress meetings.



CLIC Drive beam, 5.6m dia.

Geneva

Energies: 380GeV, 1.5TeV, 3TeV.



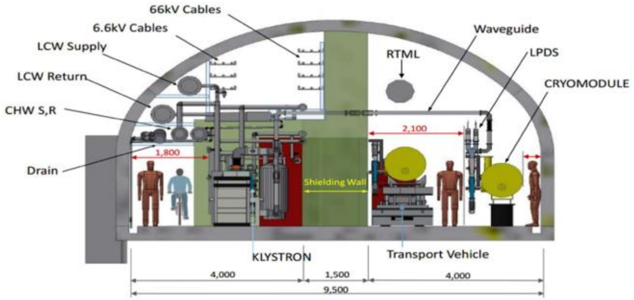
CLIC Klystron, 10m dia.

Geneva

Energies: 380GeV

CLIC Drive Beam and Klystron options are proposed configurations of CLIC to be constructed at the existing CERN site in the Geneva basin, formed predominately of molasse sedimentary rock.

Mechanised tunnelling methods are expected for the main tunnels, with Gripper and Double Shield TBMs historically used across past CERN works within the predominant molasse and limestone ground conditions. A single pass, precast reinforced segmental lining will support the tunnel circular profile.



ILC, 9.5m span

Tohoku Region, Japan

Energies: 250GeV

ILC is proposed to be built in the Kitakami mountains in the Tohoku region. The ILC is proposed to be constructed mainly through Hitokabe, Senmaya, and Orikabe Granite.

Conventional tunnelling methods are expected for the main tunnels, with drill and blast cycles through the predominant hard rock granites. A primary lining typically of rockbolts and shotcrete is expected with a cast in place permanent lining and invert to support the arched profile.

1.2 Life Cycle Assessment

Life Cycle Assessment

Context

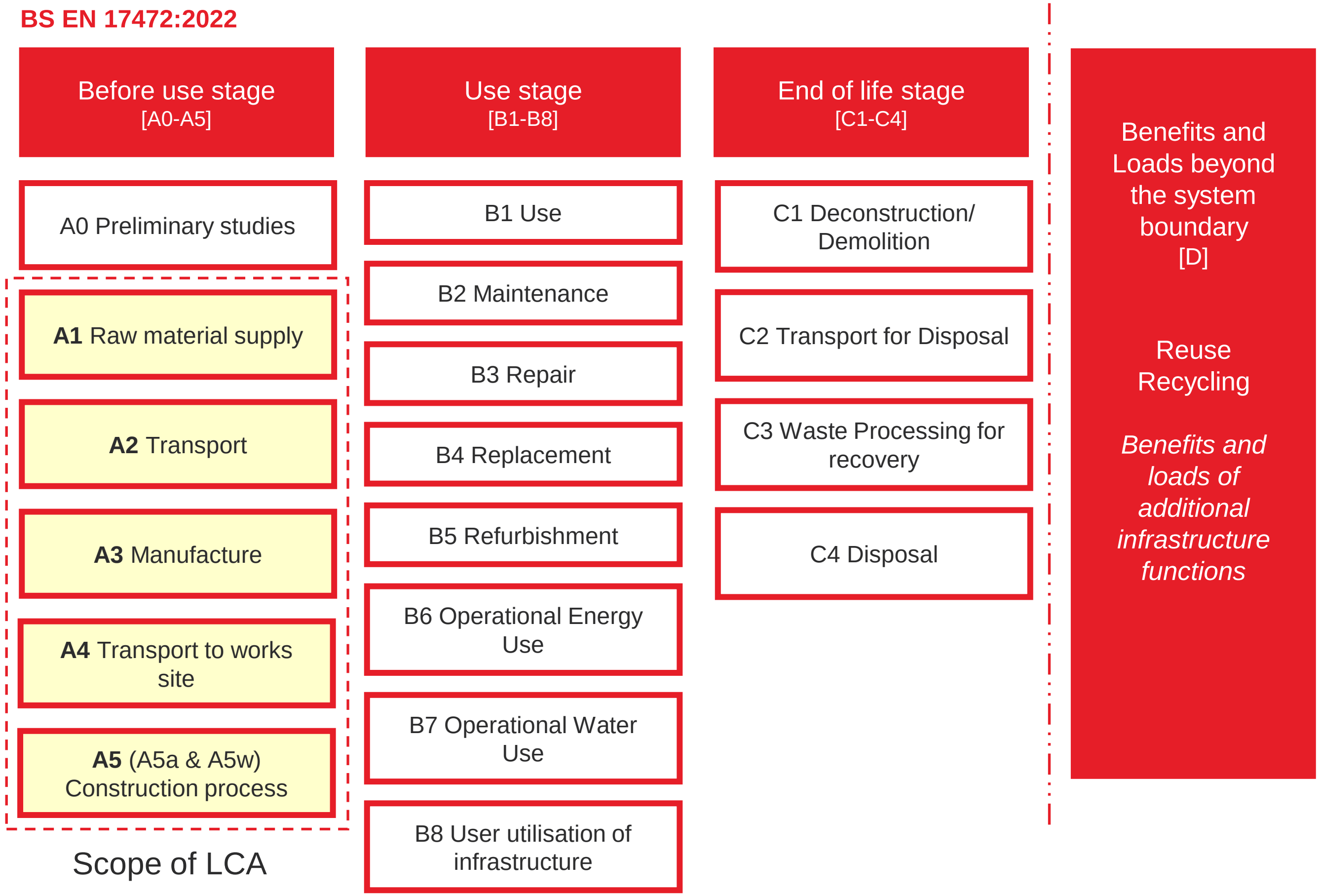
A Life Cycle Assessment (LCA) systematically assesses the environmental impact of a product or asset throughout its life cycle. The purpose of this LCA is to inform a baseline indication of the environmental impact of the underground construction of CLIC and ILC, and to identify opportunities where reductions in environmental impact can be made to help inform decision makers and future design optimisation.

The life cycle is broken down into life cycle modules, as outlined in BS EN 17472:2022.

A LCA can be completed for different parts of the life cycle, most common being A1-A3, A1-A5, and A-C modules.

The scope of this LCA is A1-A5, which includes the raw material extraction to construction activities on site. A5 is split into A5a and A5w, construction activities and material wasted on site, respectively.

This final report evaluates A1-A5 for the three proposed linear colliders as highlighted in section 1.1.



BS EN 17472:2022

Before use stage
[A0-A5]

A0 Preliminary studies

A1 Raw material supply

A2 Transport

A3 Manufacture

A4 Transport to works site

A5 (A5a & A5w) Construction process

Scope of LCA

Use stage
[B1-B8]

B1 Use

B2 Maintenance

B3 Repair

B4 Replacement

B5 Refurbishment

B6 Operational Energy Use

B7 Operational Water Use

B8 User utilisation of infrastructure

End of life stage
[C1-C4]

C1 Deconstruction/ Demolition

C2 Transport for Disposal

C3 Waste Processing for recovery

C4 Disposal

Benefits and Loads beyond the system boundary
[D]

Reuse
Recycling

Benefits and loads of additional infrastructure functions

Life Cycle Assessment

Life Cycle Assessment (LCA)

Within a LCA, there are 4 phases:

1. Goal and scope definition
2. Life cycle inventory analysis (LCI)
3. Life cycle impact assessment (LCIA)
4. Interpretation phase

The LCI is defined as the phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product or asset throughout its life cycle.

The LCIA aims to evaluate the significance of environmental impacts within the stated system boundary. It involves the selection of impact categories, classification and characterisation to achieve results. LCA tools, like Simapro, perform this LCIA. Within a LCIA there are a number of methodologies. Commonly used LCIA methodologies are ReCiPe 2016 and CML 2002. The most appropriate LCIA methodology is chosen to complete the assessment.

Impact categories are environmental issues of concern, for example global warming, eutrophication and acidification.

Limitations

A LCA only addresses the environmental impacts within a stated goal, scope and system boundary. Therefore, within this A1-A5 assessment only a portion of the total environmental impact is evaluated across its life cycle. Within a system boundary there may be assumptions and exclusions; these are clearly stated in section 2.1. This is important to understand the limitations of the study and to enable changes at later design stages.

The accuracy of a LCA is dependent upon the information that is inputted:

- For an early stage design, assumptions are required to fill in design data or construction information gaps.
- LCA databases are in continuous development, therefore there can be varying and limited data for materials across the geographies. Assumptions are required to determine what inventory data is appropriate and representative for that particular material and geography.

Arup approach

Arup has followed the principles set out in ISO 14040/44 and calculation method outlined in BS EN 17472:2022 . The most appropriate LCIA methodology for the LCA was chosen.

A key objective is to have a comparable baseline between CLIC and ILC, with materials and energy mix representative of France and Japan. The environmental data limitations may make this challenging to achieve and so reasonable assumptions are made and clearly stated. The scope of this report is A1-A5, with a focus on Global Warming Potential (GWP).

Arup has provided key conclusions and recommendations associated with material opportunities and design optimisations for CLIC and ILC.

1.3 Desk study

Desk Study

Prior to conducting the LCA, a desk study was undertaken to evaluate existing literature that had completed a LCA for tunnels.
Key summaries and conclusions are identified below:

Rodriguez, R., Perez, F. (2021)

Carbon foot print evaluation in tunnelling construction using conventional methods

- 1km road tunnel, 79.6m^2 cross section
- Location: Spain
- System boundaries: A1-A5 (incl. ventilation & lighting)
- Functional unit: kgCO$_2$e/m of tunnel
- LCIA methodology: Not specified
- Impact categories: GWP
- Construction activities: D&B, uses fuel rates (electric and diesel), machinery required, RMR to calculate construction emissions.
- Results: A1-A3: 85% (80% concrete, 5% steel), A4-A5: 15% (5% from loading and transportation and 10% from generating electricity)

Li, Q et al. (2013)

CO$_2$ emissions during the construction of a large diameter tunnel with a slurry shield TBM

- 6.78km tunnel, outside diameter 14.5m
- Location: China
- System boundaries: A3, A5 (incl. lighting and ventilation)
- Functional unit: kgCO$_2$ per ring
- LCIA methodology: Not specified
- Impact categories: GWP
- Construction activities: TBM, estimated using national standard, literature research, field investigation, engineering experience and machinery data.
- Results: A3: 89.2%, A5: 10.8% (precast of segment, shield driving, segment erection, tunnel inner structures construction and auxiliary)

Huang, L. (2015)

Life Cycle Assessment of Norwegian standard road tunnel

- 3km road tunnel, 67m^2 cross section
- Location: Norway
- System boundaries: A1-A5 incl. ventilation and lighting
- Functional unit: tCO$_2$e/m of tunnel
- LCIA methodology: ReCiPe V1.06
- Impact categories: GWP, ODP, HTP, POFP, PMFP, IRP, TAP, FEP, MEP, TETEP, FETP, METP
- Construction activities: D&B, estimated using a cost database of Norwegian Public Road Administration (NPRA).
- Results: A1-A3: 76%, A4: 15%, A5: 9%. GWP over 100 years: 13 tons CO$_2$e/m tunnel length

Huang, L. (2014)

Environmental impact of drill and blast tunnelling: life cycle assessment

- 3km road tunnel, 67m^2 cross section
- Location: Norway
- System boundaries: A5 (D&B, loading and hauling, scaling)
- Functional unit: tCO$_2$e/m of tunnel
- LCIA methodology: ReCiPe V1.06
- Impact categories: GWP, HTP, POFP, PMFP, TAP, TETP
- Construction activities: D&B, estimated using a cost database of Norwegian University of Science and Technology (NTNU) Tunsim.
- Results: 0.9tCO$_2$e/m tunnel length (D&B 29%, loading and hauling 36%, ventilation 31%).

Desk Study

Schwartzentruber, L.D., Bonnet, R. (2015)

LCA (Life Cycle Assessment) applied to the construction of tunnel

- Cross sections with varying carriageway widths – 7, 8.5 & 11m
- Location: France
- System boundaries: A1-A5
- Functional unit: tCO_2e/m
- Methodology: Discusses LCI and LCIA ISO 14040/44 standards – however not specified.
- Impact categories: EP, CC, PA, PE, ADP, AA, FOP presented.
- Construction activities: D&B and TBM

- Results: D&B materials are responsible of about 60%. 80 to 90% of materials impacts are due to concrete and steel - Concrete and steel represent 80% to 95% of the impacts of materials.

Key takeaways

It is clear from the literature and Arup's experience on other tunnelling projects that there is no consistent approach of completing a LCA for tunnels. This is expected, as the field of LCA for tunnels is in development, and a known challenge within the industry, being actively explored within industry bodies such as ITA working groups.

In the absence of industry standardisation, the approach and methodology, selection should be attuned to the requirements of the project and asset specifics, and in line with best practice guidelines.

System boundaries: System boundaries change depending on the scope of LCA to be evaluated.

LCIA methodology: Where stated, ReCiPe methodology is the most commonly used.

Impact categories: GWP is always reported, but there is no consistency in the reporting of the other impact categories.

Construction activities: There are varying approaches to quantifying the construction activities the LCA - using cost databases, literature and plant machinery energy use and emissions factors.

Functional unit: $kgCO_2e/m$ or tCO_2e/m tunnel length is consistent across majority of studies.

Results: Currently there is no standardised way of assessing GWP from A1-A5. However, from the studies reviewed, it is clear that A1-A3 makes up the largest proportion of GWP in tunnelling projects.

Conclusions

It is key to include GWP in the assessment. Due to lack of consistency in impact categories reported across the literature, this study will report all other impact categories in line with ISO 14040/44 and ReCiPe Midpoint (H) 2016 method.

There is a gap in construction activities and the various methods of evaluation. In the UK, more commonly A5 is evaluated using a project cost equation from the RICS guide (Whole Life Carbon Assessment for the built environment, 2017). Although this provides an estimation, it does not give an idea of the machinery and plant used on site, energy use and duration of construction, particularly when the carbon implications of a TBM are significant compared with more traditional construction plant. Reduction opportunities cannot be harnessed. This study will evaluate the machinery and plant used for CLIC and ILC to provide a more granular and detailed estimation for A5.

1.4 Methodology

Methodology

LCA Methodology

The LCA follows the ISO 14040/44 methodology.

The LCA has been carried out using the LCA tool Simapro 9.4.0.2 which uses Ecoinvent 3.8 database. The ReCiPe Midpoint (H) 2016 method has been used to estimate the environmental impacts across 18 impact categories – see table to the right.

Data for the CLIC and ILC LCA has been gathered from CERN and KEK respectively through drawings and reports, which feeds directly into the Life Cycle Inventory (LCI).

Data quality

Simapro 9.4.0.2 uses Ecoinvent 3.8 database, released in September 2021. Ecoinvent is widely recognised as the largest and most consistent LCI database. Ecoinvent validates the LCI data through ecoEditor software. Ecoinvent reviews the data through manual inspection from at least 3 experts prior to the storage of data in Ecoinvent database (Data quality guideline for the ecoinvent database version 3, 2013).

Goal and Scope of study

The purpose of the study is to calculate the embodied environmental impacts of the civil engineering works associated with the construction of CLIC Drive Beam (380GeV, 1.5TeV, 3TeV), CLIC Klystron (380GeV), and ILC (250GeV).

The A1-A5 results are evaluated to identify hotspots and reduction opportunities across the 3 linear collider options.

System Boundary

The system boundary of this report is A1-A5, raw material extraction to construction activities on site – see section 1.2. Tunnels, caverns and access shafts are evaluated only. Ventilation and lighting during construction are excluded.

Functional Unit

The functional unit for the main accelerator tunnels is tCO_2e/km length. This is to allow comparison between the three collider options. The environmental impacts of each asset as a whole is reported as an absolute value.

ReCiPe Midpoint (H) 2016 Impact Categories

Midpoint Impact Categories	Abbr.	Unit
Global warming	GWP	kg CO_2 eq
Stratospheric ozone depletion	ODP	kg CFC-11 eq
Ionizing radiation	IRP	kBq Co-60 eq
Fine particulate matter formation	PMFP	kg PM2.5 eq
Ozone formation, Human health	HOFP	kg NOx eq
Ozone formation, Terrestrial ecosystems	EOFP	kg NOx eq
Terrestrial acidification	TAP	kg SO_2 eq
Freshwater eutrophication	FEP	kg P eq
Marine eutrophication	MEP	kg N eq
Terrestrial ecotoxicity	TETP	kg 1,4-DCB
Freshwater ecotoxicity	FETP	kg 1,4-DCB
Marine ecotoxicity	METP	kg 1,4-DCB
Human carcinogenic toxicity	HTPc	kg 1,4-DCB
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DCB
Land use	LOP	m^2a crop eq
Mineral resource scarcity	SOP	kg Cu eq
Fossil resource scarcity	FFP	kg oil eq
Water consumption	WCP	m^3

Reference: ReCiPe Midpoint (H) 2016

2

A1-A5 assessment

2.1

Assumptions & exclusions

Detailed for a 2030 construction

Assumptions

A1-A3 materials – 2030 baseline assumptions

General assumptions

Materials:

- CEMI concrete (baseline)
- 80% recycled steel (baseline)

LCIA Factors:

- Global concrete and steel factors from Simapro 9.4.0.2 Ecoinvent 3.8 database (regional concrete and steel factors are not available)

CLIC Drive Beam and Klystron assumptions

The following assumptions were made where design parameters from drawings and reports were not available:

- Shafts and caverns are the same for both CLIC Drive Beam and Klystron options
- Rock bolt diameter 40mm – *DYWIDAG, Rock Bolts and Meshes, GEWI®*
- Rock bolting for the caverns assumed ¾ of the wall heights will require bolting, none in the invert, bolting included in the crown
- Rock bolting shafts, included full wall area

ILC assumptions

The following assumptions were made where design parameters from drawings and reports were not available:

- Shaft steel ribs spaced 1.5m
- Rock bolt diameter 25mm
- Rebar density of insitu permanent lining 50kg/m^3
- RTML tunnels length: 487m (measured in Rhino). Rock bolt number taken from similar sized section (BDS beam tunnel Fig8.2 Tohoku CEP Report)
- AT-DH and AT-DR tunnels length: 1139m (measured in Rhino). Rock bolt number taken from similar sized section (BDS beam tunnel Fig8.2 Tohoku CEP Report)
- All dimensions from BDS section A and D are scaled from BDS sections B and C
- Rock bolt no. for BDS tunnel sections: A= 15no, B = 20no, C=25no, D=38no.
- Peripheral tunnels 8.0m, 6.0m, 4.0m, 3.0m diameter. Total length 717m (measured in Rhino)

Assumptions

A4 transport + A5w material wasted on site – 2030 baseline assumptions

A4

Module A4 covers transport of materials to site**.**

CLIC Drive Beam

Transport of materials to site:

- Concrete: Local by road (50km)
- Steel: European by road (1500km)

CLIC Klystron

Transport of materials to site:

- Concrete: Local by road (50km)
- Steel: European by road (1500km)

ILC

Transport of materials to site:

- Concrete: Local by road (50km)
- Steel: National by road (300km)

LCIA factors:

- Road transport factors from Simapro 9.4.0.2 Ecoinvent 3.8 database

A5w

Module A5w includes the following:

- The % of material wasted during construction and the associated proportions of A1-A3 and A4 of material wasted during construction.
  - Concrete insitu: 5%
  - Precast concrete: 1%
  - Steel reinforcement: 5%
- It considers the transport away from site for disposal, either to landfill or recycling/reuse. It also considers waste processing and disposal of the materials.

Transport of disposal materials off site (Assumptions for CLIC provided by CERN, assumed the same for ILC)

- Concrete and steel recycling: 30km by road
- Concrete and steel landfill: 30km by road
- Spoil: 20km by road

It is assumed that 90% of end of life construction materials are recycled or repurposed and 10% is in landfill (IStructE guidance).

LCIA factors:

- From Simapro 9.4.0.2 Ecoinvent 3.8 database

Assumptions

A5a construction activities – 2030 baseline assumptions

CLIC plant assumptions

Plant operations	Fuel Type
TBM incl. Conveyor	Electricity
MSV	Electricity
Gantry Crane/Hoppit skip/Hoist	Diesel
Roadheader	Electricity
Excavator	Diesel
Dumper	Diesel
Shotcrete rig	Diesel
Shotcrete batching plant	Electricity
Drill and Bolting rig	Electricity
In-situ formwork rig	Electricity
In-Situ Pump	Diesel
Ventilation	Electricity
Site offices (all components)	Electricity
Temporary works*	Electricity
Plant movements	
Excavator	Diesel
Roadheader	Diesel
Bolting Rig	Diesel

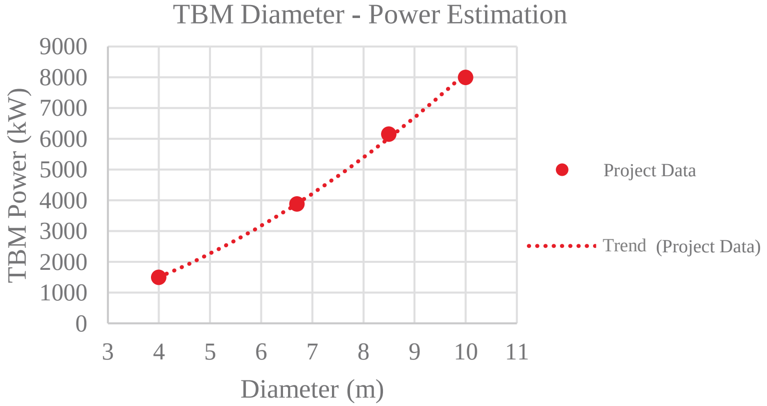
*Additional 20% of total of all other works used to estimate impact of temporary works

Assumption details

The plant machinery has used a baseline of diesel and electricity. There is potential for all plant equipment to convert to electricity in the future, however this has not been considered as the baseline assumption.

The CLIC main tunnels opt for Tunnel Boring Machine (TBM) excavation methods. TBMs have considerable power requirement and typically projects of this scale utilise bespoke TBMs. The embodied carbon of the TBM is currently excluded. It is assumed that the TBM is reused from another tunnel project or reused post CLIC construction, otherwise the embodied carbon of the TBM should be included.

The following graph, informed by other TBM projects helped to provide an estimate of the power requirements for the TBMs used in this LCA.



References

The plant assumptions for CLIC have been informed by the following literature and manufacturers:

- Technical considerations for TBM tunneling for mining projects, D.Brox. Transactions of the Society for Mining, Metallurgy and Exploration,(2013)
- Transformers Magazine. Europe.10 MW to power TBM for high-speed railway construction. (2013)
- Road header excavation performance – geological a geotechnical influences. K.Thuro & R.J. Plinninger, Dept. for General, Applied and Engineering Geology, Technical University of Munich, Germany. (1999)
- Hard Rock Miner’s Handbook, J.de la Vergne, (2014)
- AECOM, A. Spon's Civil Engineering and Highway Works Price Book 2023

Manufacturers:

- Sandvik
- JCB
- Hyundai
- CIFA
- Putzmeister
- Epiroc
- Komatsu

Assumptions

A5a construction activities – 2030 baseline assumptions

CLIC electricity mix

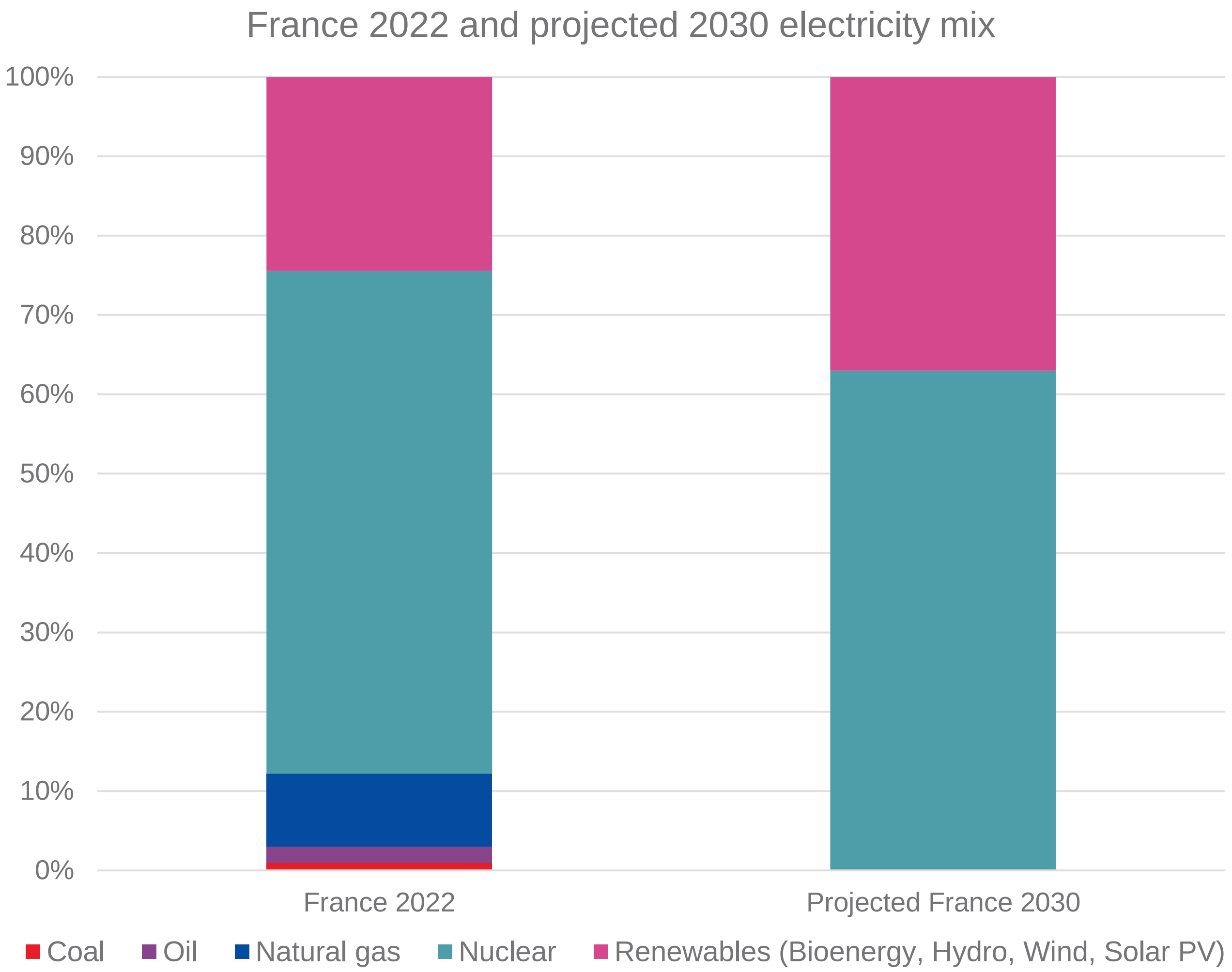
The electricity mix for France in 2022 and projected electricity mix for 2030 is shown.

The baseline assumption for A5a construction activities uses the France electricity mix in 2022, with the projected electricity mix for 2030 evaluated in the reduction opportunities.

France's electricity mix is predominately nuclear, which remains true for the 2030 projection but with an increase in renewables and removal of fossil fuels.

LCIA factors:

- France electricity factor is from Simapro 9.4.0.2 Ecoinvent 3.8 database with the electricity split as detailed:
  - France 2022: Our World in Data
  - France 2030: Energy pathways 2050 key results, RTE 2021
- Diesel factor is global.



Assumptions

A5a construction activities – 2030 baseline assumptions

CLIC GWP/kWh intensity

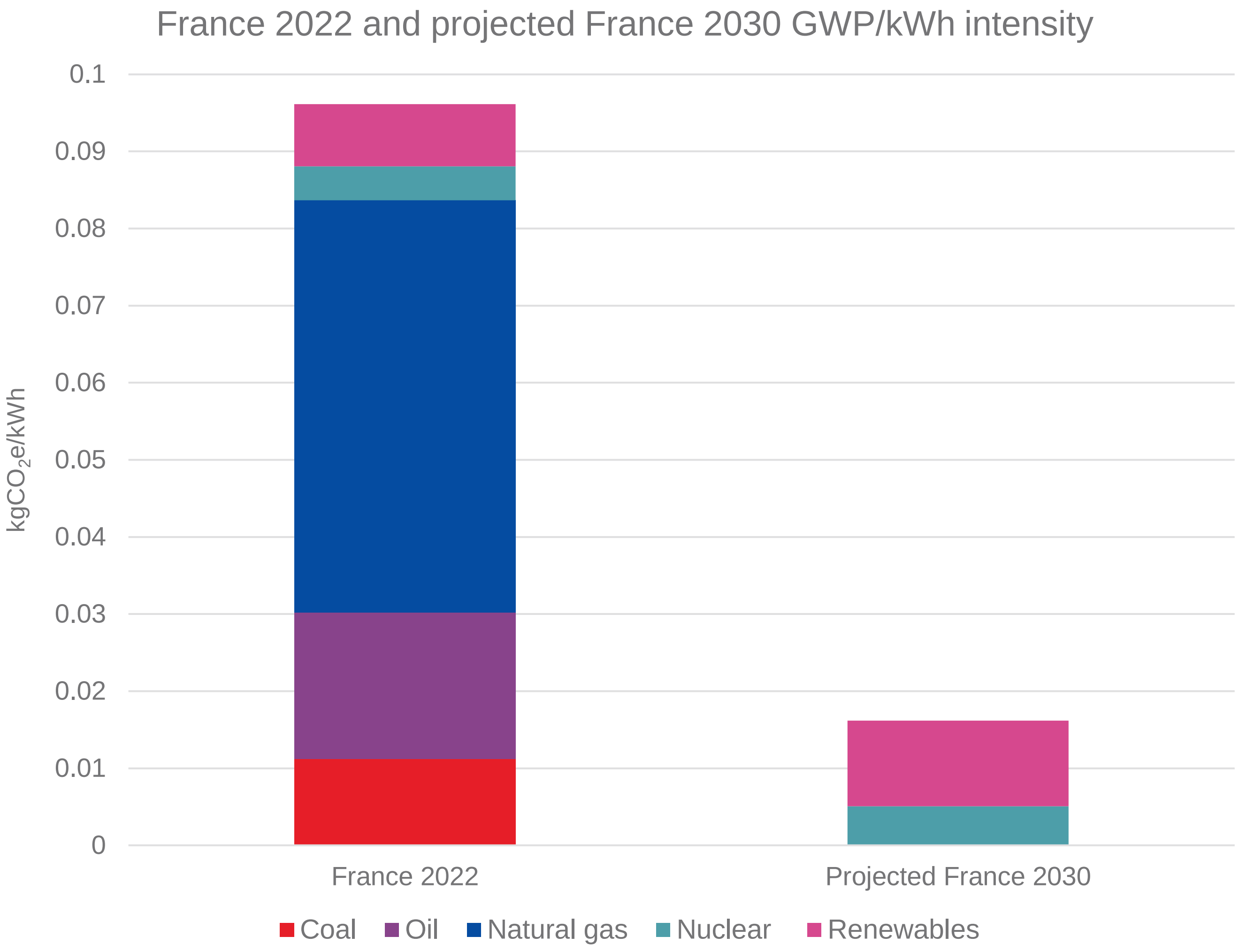
The GWP/kWh intensity for France 2022 and projected 2030 electricity mix is detailed below:

2022: 0.096 kgCO$_2$e/kWh

2030: 0.016 kgCO$_2$e/kWh

(Source: Simapro 9.4.0.2)

The GWP intensity per kWh for coal, oil and natural gas is significant compared to the % in the electricity mix. This emphasises the need of transitioning out fossil fuels from electricity production.



Assumptions

A5a construction activities – 2030 baseline assumptions

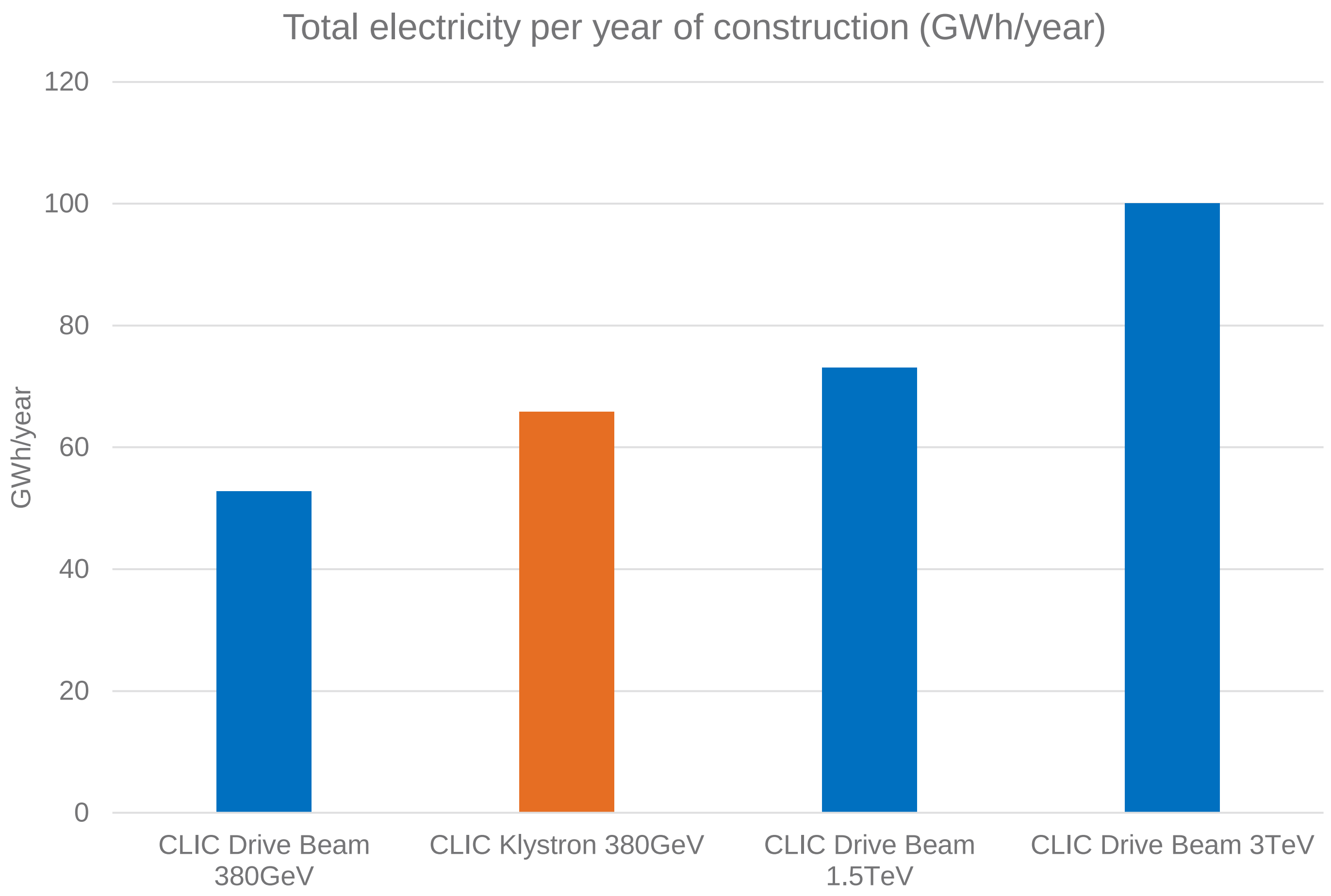
CLIC electricity per year

A5a energy consumption has been informed by construction guidance, literature, and manufacturer plant information.

The electricity consumption per year has been estimated using the total calculated electricity usage by A5a activities for each CLIC option and averaging this across the relevant civil engineering construction periods, provided in the CLIC Project Implementation Plan 2018. ILC A5a electricity usage is not directly comparable to CLIC which is dominated by the TBM operation, therefore ILC is excluded from this comparison.

System	Construction period (years)
CLIC Drive Beam 380GeV	2.25
CLIC Drive Beam 1.5TeV	2.25
CLIC Drive Beam 3TeV	2
CLIC Klystron 380GeV	4.5

The CLIC electricity quantity has been calculated based on plant machinery as outlined on page 24.



Assumptions

A5a construction activities – 2030 baseline assumptions

ILC plant assumptions

Plant operations	Fuel Type
Drilling + Loading Rig	Electricity
Ventilate (vent blasting glasses)	Electricity
Scaling rig	Diesel
Excavator	Diesel
Dumper	Diesel
Bolting rig	Electricity
Shotcrete rig	Diesel
Shotcrete batching plant	Electricity
In-situ formwork rig	Electricity
In-Situ pump	Diesel
Gantry Crane/Hoppit skip/Hoist	Diesel
Ventilation	Electricity
Site offices (all components)	Electricity
Temporary works*	Electricity
Plant movements	
Excavator	Diesel
Scaling	Diesel
Drilling + Loading Rig	Diesel
Bolting Rig	Diesel

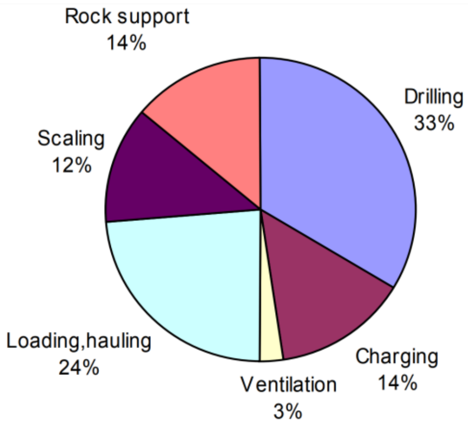
*Additional 20% of total of all other works used to estimate impact of temporary works

Assumption details

The plant machinery has used a baseline of diesel and electricity. There is potential for all plant equipment to convert to electricity in the future, however this has not been considered as the baseline assumption.

Geoguide 4 has been referenced extensively due to the similarities between the ILC geology and the granite geology the guide has been established for use in.

Furthermore, the following figure has been used to approximate plant usage durations.



(S.Zare et al, 2013)

References

The plant assumptions for ILC have been informed by the following literature and manufacturers:

- Estimation Model for Advance Rate in Drill and Blast Tunnelling, S.Zare, A.Bruland (2013).
- Hard Rock Miner’s Handbook, J.de la Vergne (2014).
- Cavern Engineering – Geoguide 4 Geotechnical Engineering Office Civil Engineering and Development Department The Government of the Hong Kong Special Administrative Region (2018).
- Dangers of Toxic Fumes from Blasting. R.Mainiero, M.Harris, J.Rowland III (2007).
- AECOM, A. Spon's Civil Engineering and Highway Works Price Book (2023).

The same manufacturers referenced for CLIC have been utilised in estimating plant power consumption for ILC.

Assumptions

A5a construction activities – 2030 baseline assumptions

ILC electricity mix

The electricity mix for the Tohoku region in 2021 and projected Japan electricity mix for 2030 is shown. In the absence of projected 2030 Tohoku electricity mix, a 2030 projection for Japan is used instead.

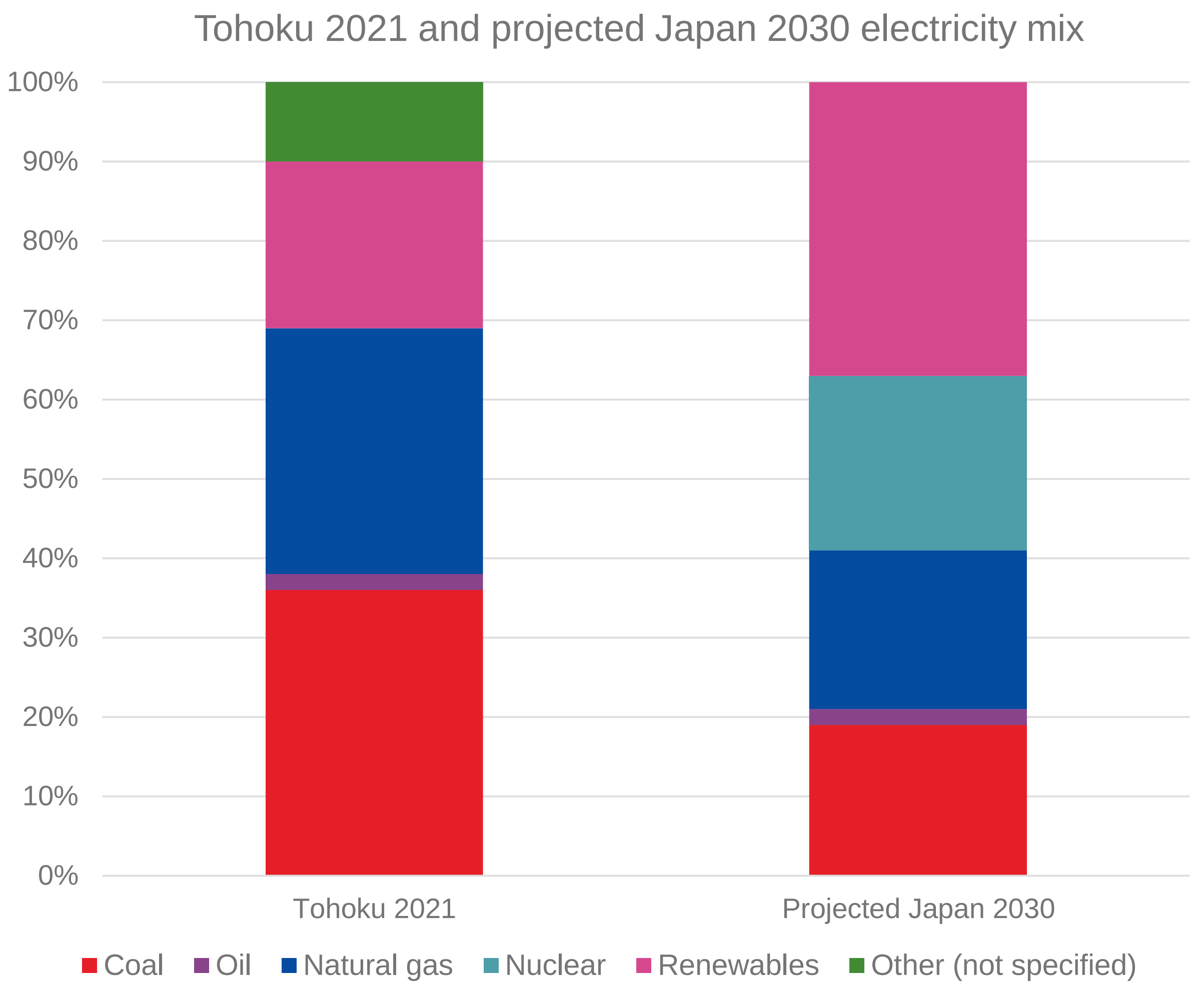
The baseline assumption for A5a construction activities uses the Tohoku electricity mix in 2021, with the projected electricity mix for 2030 evaluated in the reduction opportunities.

Tohoku's electricity mix is predominately coal, oil and gas, with no nuclear. In the projected 2030 Japan scenario, there is a decrease in fossil fuels and an increase in nuclear and renewables.

Note the quantity of electricity required for ILC construction is much less than for CLIC. The drill and blast method uses explosives which emits CO_2, CO, H_2S, NO_x, SO_2 amongst others. The explosives impacts have not been quantified in the ILC LCA due to lack of data.

LCIA factors:

- Electricity factors are from Simapro 9.4.0.2 Ecoinvent 3.8 database with the electricity split as detailed:
  - Tohoku 2021: Tohoku Electric Power Supply, 2021 (https://www.tohoku-epco.co.jp/ir/report/factbook/pdf/fact01.pdf)
  - Japan 2030: 6th Strategy Energy Plan, METI 2021
- Diesel factor is global.



Assumptions

A5a construction activities – 2030 baseline assumptions

ILC GWP/kWh intensity

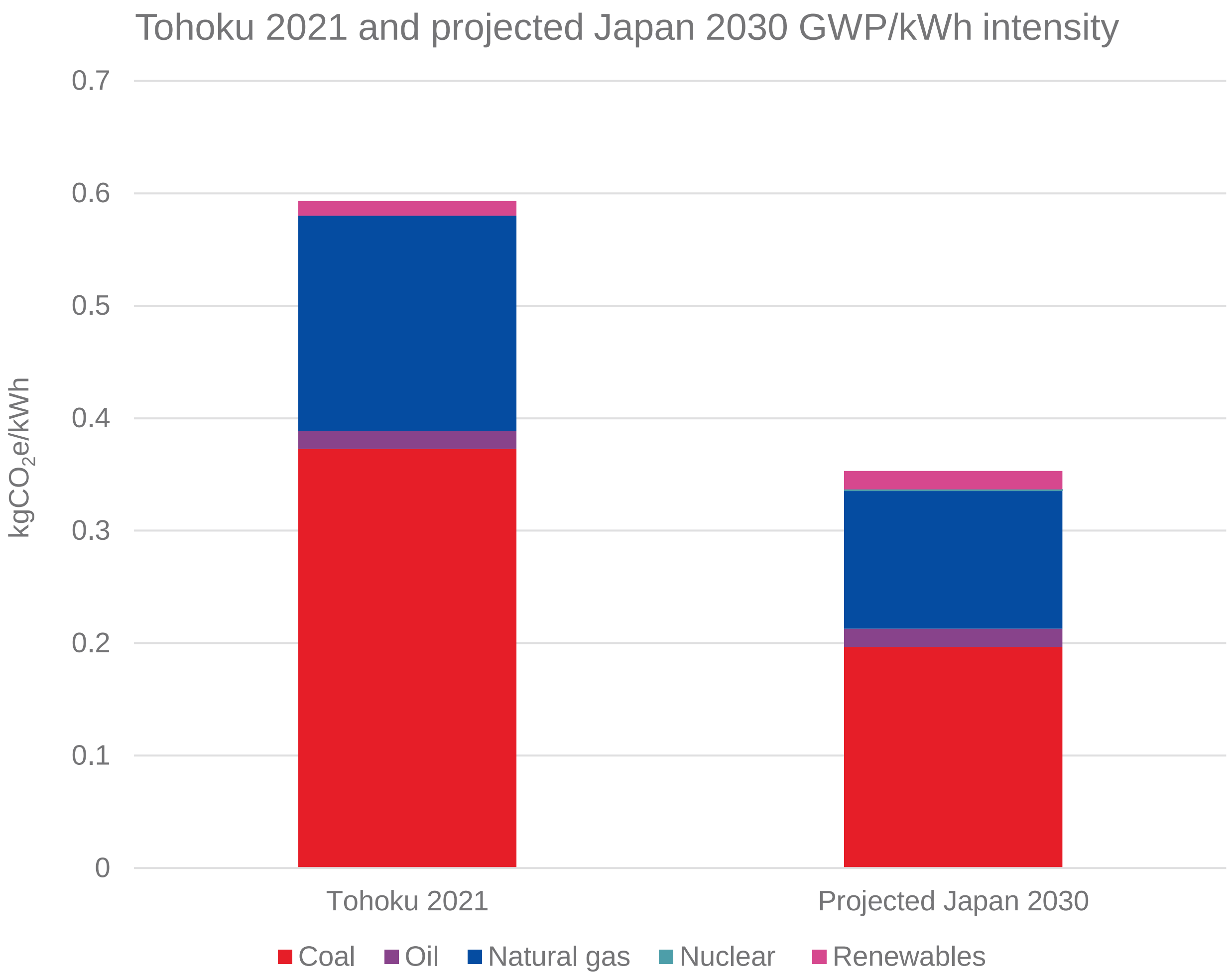
The GWP/kWh intensity for Tohoku region 2021 and projected 2030 electricity mix for Japan is detailed below:

2021: 0.595 kgCO_2e/kWh

2030: 0.356 kgCO_2e/kWh

(Source: Simapro 9.4.0.2)

The GWP intensity per kWh for coal, oil and natural gas is significant. If the quantity of fossil fuels is reduced by 2030, the GWP intensity would reduce by 40%.



Exclusions

A1-A3 materials – 2030 baseline exclusions

General exclusions

This LCA study does not take into account the following:

- Embodied impact of mechanical, electrical and plumbing
- Embodied impact of plant, including TBM
- Embodied impact of waterproofing system
- Embodied impact of invert drainage and survey pipes
- Embodied impact of temporary face support
- Modification to existing CERN facilities
- Drainage fleece and membrane

CLIC Drive Beam and Klystron exclusions

This following civil engineering assets are excluded:

- Injector complex

ILC exclusions

The following civil engineering assets are excluded:

- Drainage tunnel
- BDS service tunnel

Exclusions

A4-A5 transport to works site & construction process – 2030 baseline exclusions

General exclusions

This LCA study does not take into account the manufacturing of equipment, its transport to and from the site, or wear and tear over the course of works.

Further exclusions include:

- Water and electrical supplies
- Heating
- Lighting
- Waterproofing
- Infrastructure (e.g. roads and substations) for construction activities
- Potential delays in construction programme
- Accessibility works
- Transport of workers to construction site
- Offsite construction activities
- Commissioning and waste management
- Landscaping including site clean-up and land remediation
- Site investigation required for the projects. This can be quite different for different depths, length, geology and planning requirements

CLIC Drive Beam and Klystron exclusions

Although the impact of temporary works has been provided the impacts of the following have not been reviewed in detail:

- TBM launching structures, gantries, and cranes.
- Alterations and installations to the power network required to facilitate TBM use
- Segment production facilities, if on site.
- TBM maintenance
- Shaft temporary works e.g. freezing and sinking plant
- Dewatering equipment

ILC exclusions

The explosives impacts have not been quantified in the ILC LCA due to lack of data. It should be noted that explosives used in the drill and blast method typically emit CO_2, CO, H_2S, NO_x, SO_2 amongst other compounds (ratios are dependent on choice of explosive) (R.Mainiero et al, 2007).

2.2 Design parameters

Data Hierarchy

Asset hierarchy

An asset hierarchy was developed for CLIC and ILC to allow the data to be analysed and insights drawn at different levels of granularity.

The hierarchy is defined as follows:

1. System
2. Sub-system
3. Components
4. Sub-components

The hierarchy for CLIC and ILC is displayed in the table on the right.

System	Sub-system	Components	Sub-components
CLIC Drive Beam & Klystron			
	Tunnels		
		Main accelerator tunnel and turnarounds	
			Primary Lining Permanent Lining Invert/shielding wall
	Shafts		
		9-18m dia.	
			Primary Lining Permanent Lining
	Caverns		
		BDS, UTRC, UTRA, BC2, DBD, service cavern, IR cavern, detector and service hall	
			Primary Lining Permanent Lining
ILC 250GeV			
	Tunnels		
		Main accelerator tunnel, loop sections at both ends, damping ring tunnel, access tunnels, BDS beam tunnels, widening sections, reversal pits, peripheral tunnels, RTML tunnels, AT-DR and AT-DH tunnels	
			Primary Lining Permanent Lining Invert/shielding wall
	Shafts		
		Main (18m dia. 70m depth) and utility (10m dia. 70m depth)	
			Primary Lining Permanent Lining
	Caverns		
		Access Hall S/E/M Dome, HE Dome, Detector Hall	
			Primary Lining Permanent Lining

CLIC Drive Beam

A1-A3

Design parameters

CLIC Drive Beam is assessed across 3 energies:

380GeV
- Main accelerator tunnel length: 11470m
- No. beam turnarounds: 10
- No. shafts: 18m at 135m depth, 12m at 135m depth, 9m at 130m depth, 9m at 111m depth.

1.5TeV
- Main accelerator tunnel length: 17564m
- No. beam turnarounds: 20
- No. shafts: 9m at 122m depth, 9m at 70m depth, 9m at 107m depth, 9m at 121m depth.

3TeV
- Main accelerator tunnel length: 21078m
- No. beam turnarounds: 24
- No. shafts: 9m at 88m depth, 9m at 109m depth, 9m at 146m depth, 9m at 181m depth.

Note the main accelerator tunnel length excludes BC2. This is included in the caverns sub-system instead.

Note Waterproofing methods are not defined. This should be evaluated in later stages of design and considered in construction and operation.

Material parameters

System	Sub-system	Components	Sub-components		
			Primary lining	Permanent lining	Invert
CLIC 5.6m dia. 380GeV 1.5TeV 3TeV	Tunnels	Main accelerator tunnel		Grout, 100mm thk, 20MPa Precast concrete, 300mm thk, 50MPa Rebar 80kg/m^3 SFRC 35kg/m^3	Invert insitu concrete 30MPa Rebar 60kg/m^3
		Turnarounds	Shotcrete, 200mm thk, 30MPa Rebar 60kg/m^3 Rock bolt 2.5m (3x3m) 40mm dia.	Insitu concrete, 200mm thk, 40MPa Rebar 100kg/m^3	-
	Shafts	9m – 18m dia.	Shotcrete, 300-500mm thk, 30MPa Rebar 20-50kg/m^3Rock bolts 7m (3x3m) 40mm dia.	Insitu concrete, 300-600mm thk, 40MPa Rebar 60-130kg/m^3	-
	Caverns	BDS, UTRC, UTRA, BC2, service, IR, detector and service hall	Shotcrete, 400mm thk, 30MPa Rebar 55kg/m^3 Rock bolts 10m (3x3m) 40mm dia.	Insitu concrete, 110mm thk, 40MPa Rebar 120kg/m^3	-
		Drive beam dump	Shotcrete, 200mm thk, 30MPa Rebar 55kg/m^3 Rock bolts 10m (3x3m) 40mm dia.	Insitu concrete, 45mm thk, 40MPa Rebar 120kg/m^3	

Note 1.5TeV and 3TeV are calculated as an extension to 380GeV to reflect the 3 build stages. The extension includes the main accelerator tunnel and respective shafts and caverns. The detector hall, BDS caverns, BDS service halls, service and IR caverns are already included in 380GeV calculation and are therefore not included in the 1.5TeV and 3TeV calculation.

CLIC Klystron

A1-A3

Design parameters

CLIC Klystron 380GeV is assessed:

380GeV

- Main accelerator tunnel length: 11470m
- No. beam turnarounds: 10
- No. shafts: 18m at 135m depth, 12m at 135m depth, 9m at 130m depth, 9m at 111m depth.

Note the main accelerator tunnel length excludes BC2. This is included in the caverns sub-system instead.

Note Waterproofing methods are not defined. This should be evaluated in later stages of design and considered in construction and operation.

Material parameters

System	Sub-system	Components	Sub-components		
			Primary lining	Permanent lining	Invert / Shielding wall
CLIC 10m dia. 380GeV	Tunnels	Main accelerator tunnel		Grout, 150mm thk, 20MPa Precast concrete, 450mm thk, 50MPa Rebar 80kg/m^3 SFRC 35kg/m^3	Shielding wall insitu concrete 30MPa, Rebar 40kg/m^3 Invert insitu concrete 30MPa, Rebar 60kg/m^3
		Turnarounds	Shotcrete, 200mm thk, 30MPa Rebar 60kg/m^3 Rock bolt 2.5m (3x3m) 40mm dia.	Insitu concrete, 200mm thk, 40MPa Rebar 100kg/m^3	-
	Shafts	9m – 18m dia.	Shotcrete, 300-500mm thk, 30MPa Rebar 20-50kg/m^3 Rock bolts 7m (3x3m) 40mm dia.	Insitu concrete, 300-600mm thk, 40MPa Rebar 60-130kg/m^3	-
	Caverns	BDS, UTRC, UTRA, BC2, service, IR, detector and service hall	Shotcrete, 200mm thk, 30MPa Rebar 55kg/m^3 Rock bolts 10m (3x3m) 40mm dia.	Insitu concrete, 110mm thk, 40MPa Rebar 120kg/m^3	-
		Drive beam dump	Shotcrete, 200mm thk, 30MPa Rebar 55kg/m^3 Rock bolts 10m (3x3m) 40mm dia.	Insitu concrete, 45mm thk, 40MPa Rebar 120kg/m^3	

ILC

A1-A3 tunnel

Design parameters

ILC 250GeV is assessed:

250GeV

Tunnels	Length (m)
Main accelerator tunnel	13267
BDS beam tunnel section A	400
BDS beam tunnel section B	4700
BDS beam tunnel section C	600
BDS beam tunnel section D	600
Damping ring tunnel	3725
Loop sections at both ends	346
Widening sections	500
Reversal pits	1520
Access tunnel CI	233
Access tunnel CII	3784
Access tunnel DI	740
Access tunnel DIII	330
Access tunnel DI (Emergency Parking Zone)	30
Access tunnel CII (Emergency Parking Zone)	270
Peripheral tunnel 3.0m	183
Peripheral tunnel 4.0m	71
Peripheral tunnel 6.0m	182
Peripheral tunnel 8.0m	255
AT-DH and AT-DR Tunnels	850
RTML Tunnels	456
SUM	33042

Note Waterproofing methods are not defined. This should be evaluated in later stages of design and considered in construction and operation.

Material parameters

System	Sub-system	Components	Sub-components		
			Primary lining	Permanent lining	Shielding wall
ILC 9.5m span 250GeV	Tunnels	Main accelerator tunnel	Shotcrete,100mm thk, 30MPa Rock bolts, L=3m, 25mm dia.	Insitu concrete, 300mm thk, 40MPa Rebar density 50kg/m^3 Roadbed concrete, 400mm thk, 40MPa	Shielding wall 30MPa Rebar 40kg/m^3
		BDS Beam tunnels (Section A, B, C, D)	Shotcrete, 50-150mm thk, 30MPa Rock bolts, L=4m, 25mm dia. Rock bolt no. for sections A= 15no, B = 20no, C=25no, D=38no.	Insitu concrete, 400mm thk, 40MPa Rebar density 50kg/m^3 Roadbed concrete 40MPa	-
		Damping ring, loop at ends, widening, reversal pits, RTML, AT-DH and AT-DR	Shotcrete, 100mm thk, 30MPa Rock bolts, L=3m, 25mm dia.	Insitu concrete, 300mm thk, 40MPa Rebar density 50kg/m^3 Roadbed concrete 40MPa	Shielding wall for widening 30MPa, Rebar 40kg/m^3
		Peripheral tunnels	Shotcrete, 50mm thk, 30MPa Rock bolts, L=3m, 25mm dia.	Shotcrete, 100mm thk, 30MPa Roadbed concrete 40MPa	-
		Access tunnel (CI)	Shotcrete, 100mm thk, 30MPa Rock bolts, L=3m, 25mm dia.	Shotcrete, 100mm thk, 30MPa Roadbed concrete 40MPa	-
		Access tunnel (CII)	Shotcrete, 100mm thk, 30MPa Rock bolts, L=3m, 25mm dia. Steel support H125 per 1.2m	Shotcrete, 150mm thk, 30MPa Roadbed concrete 40MPa	-
		Access tunnel (DI)	Shotcrete, 150mm thk, 30MPa Rock bolts, L=4m, 25mm dia. Steel support H125 per 1.0m	Shotcrete, 150mm thk, 30MPa Roadbed concrete 40MPa	-
		Access tunnel (DIII)	Shotcrete, 250mm thk, 30MPa Rock bolts, L=4m 25mm dia. Steel support H200 per 1m Steel pipe tip, L=12.5m, 114.3mm dia. t=6mm	Insitu concrete, 300mm thk, 40MPa Rebar density 50kg/m^3 Roadbed concrete 40MPa	-

ILC

A1-A3 shafts & caverns

Design parameters

ILC 250GeV is assessed:

250GeV

- Shafts: Main shaft 18m dia. at 70m depth , utility shaft 10m dia. at 70m depth
- Caverns: Access hall S/E/M/HE Dome, Detector hall

Note Waterproofing methods are not defined. This should be evaluated in later stages of design and considered in construction and operation.

Material parameters

System	Sub-system	Components	Sub-components		
			Primary lining	Permanent lining	Shielding wall
ILC 9.5m span 250GeV	Shafts	Main shaft 18m dia.	Shotcrete 30MPa Steel support H200, assumed 1.5m spacing Rock bolts, L=6m, 25mm dia.	Shotcrete 30MPa Rebar 50kg/m^3	-
		Utility shaft 10m dia.	Shotcrete 30MPa Steel support H125, assumed 1.5m spacing Rock bolts, L=3m, 25mm dia.		-
	Caverns	Access hall S/E/M/HE Dome	Shotcrete 30MPa Rock bolts, L=4m, 25mm dia.	Shotcrete 30MPa Roadbed concrete 40MPa	-
		Detector Hall	Shotcrete 30MPa Rock bolts, L= 5m (2x2m), 25mm dia. PS anchors, L=15m (4x4m), 25mm dia.		

2.3 A1-A5 GWP results

A1-A5 GWP Results

Purpose

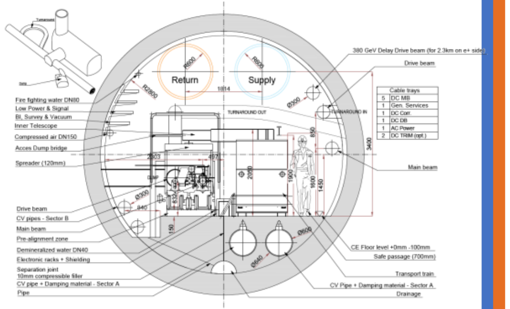
Global Warming Potential (GWP) was analysed as one of the 18 impact categories in the ReCiPe Midpoint (H) 2016 method. The GWP impacts contribute directly to increased greenhouse gas emissions in the atmosphere.

A1-A5 GWP results are reported and analysed for potential reduction opportunities at system and sub-system level only. A1-A3 GWP results are reported for components and sub-components level. The other 17 midpoint impact categories are reported and contrasted in section 2.5.

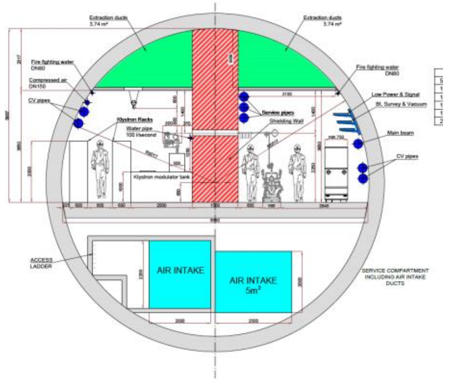
A summary of the A1-A5 GWP is evaluated:

1. **CLIC Drive Beam**, 5.6m internal diameter, Geneva (380GeV, 1.5TeV and 3TeV). Built in 3 stages.
2. **CLIC Klystron**, 10m internal diameter, Geneva (380GeV)
3. **ILC**, arched 9.5m span, Tohoku Region, Japan (250GeV)

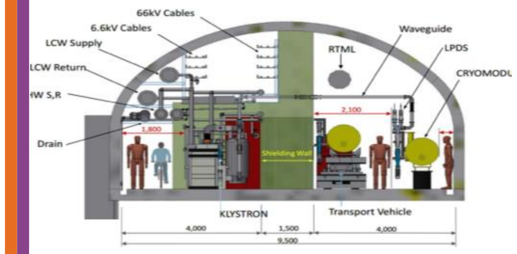
The results are colour coded blue, orange and purple respectively for ease of comparison between the 3 proposed linear collider options.



CLIC Drive beam, 5.6m dia.



CLIC Klystron, 10m dia.



ILC, 9.5m span

A1-A5 GWP Results

A1-A5 absolute GWP

The absolute A1-A5 GWP results are listed below and are reported to 3 significant figures:

CLIC Drive Beam (built in 3 stages):

380GeV	127,000 tCO_2e
1.5TeV	169,000 tCO_2e
3TeV	205,000 tCO_2e

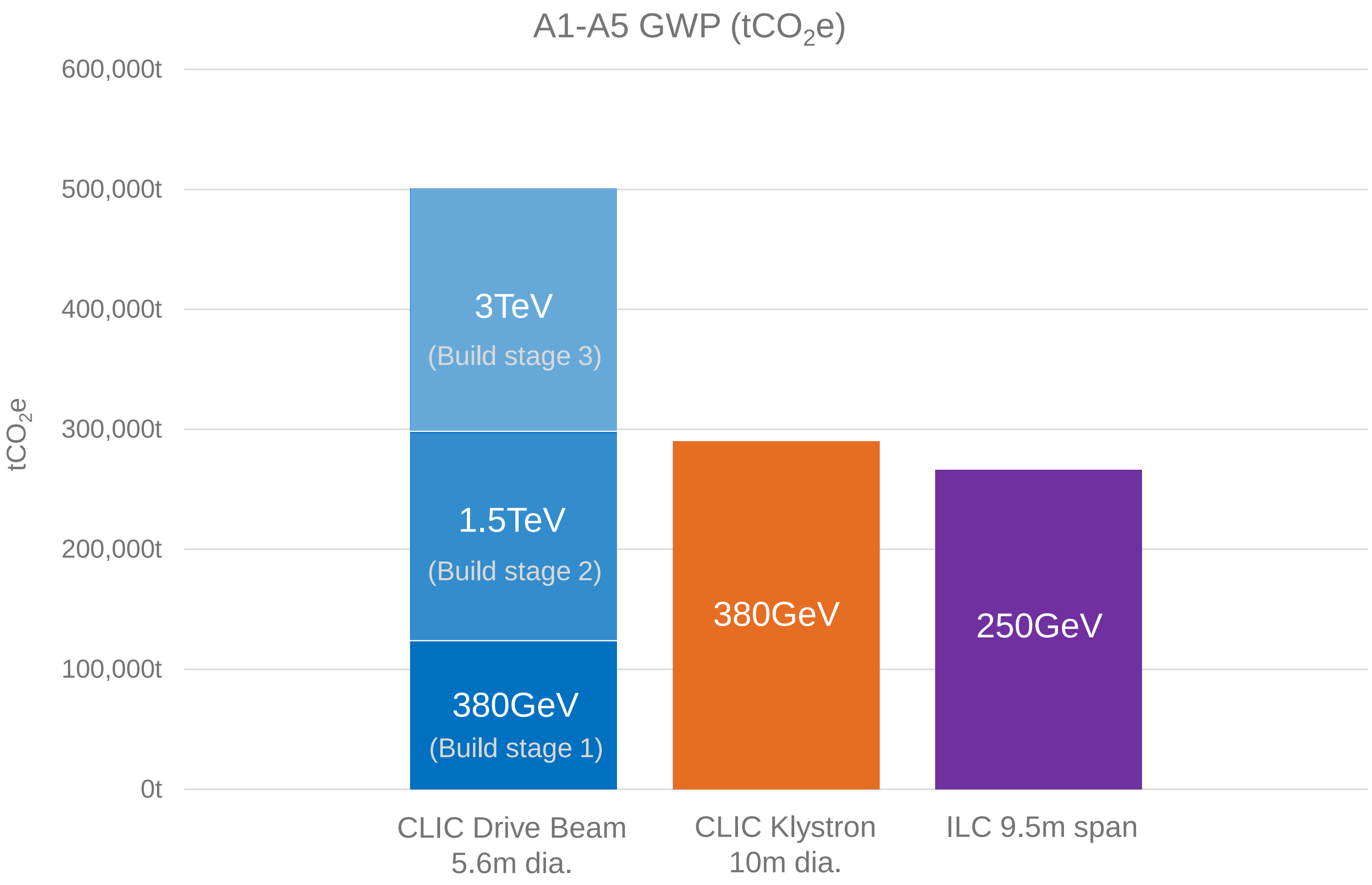
Total CLIC Drive Beam 3TeV: 501,000 tCO_2e

CLIC Klystron:

380GeV	290,000 tCO_2e

ILC:

250GeV	266,000 tCO_2e



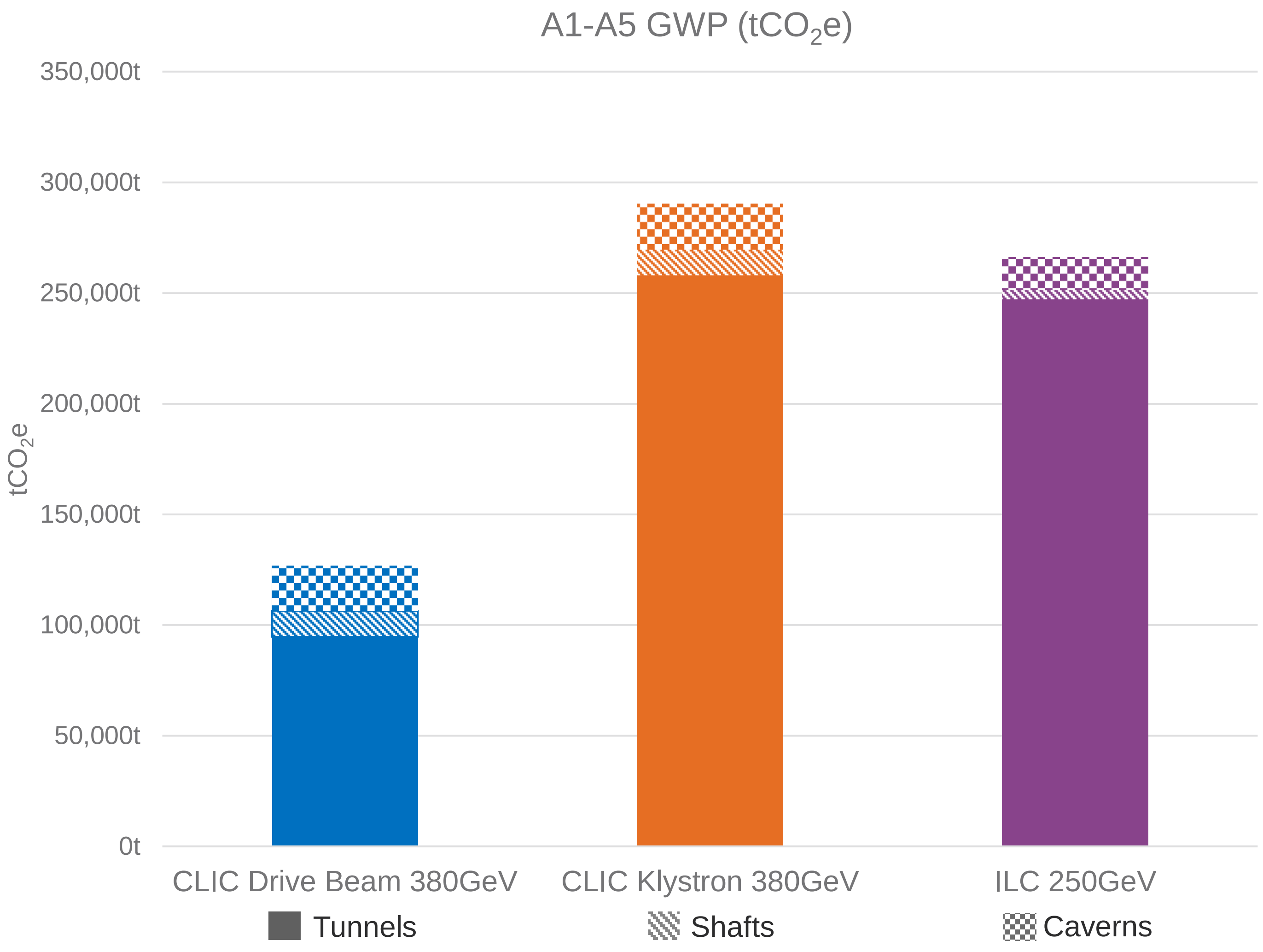
A1-A5 GWP Results

A1-A5 GWP

The tCO_2e is evaluated for tunnels, shafts and caverns for CLIC and ILC.

The full list of tunnel, shafts and caverns that are included in the LCA are detailed in the following section.

The tunnels component is the most significant A1-A5 GWP contributor. The caverns and shafts make up a smaller proportion of the overall A1-A5 GWP impact.

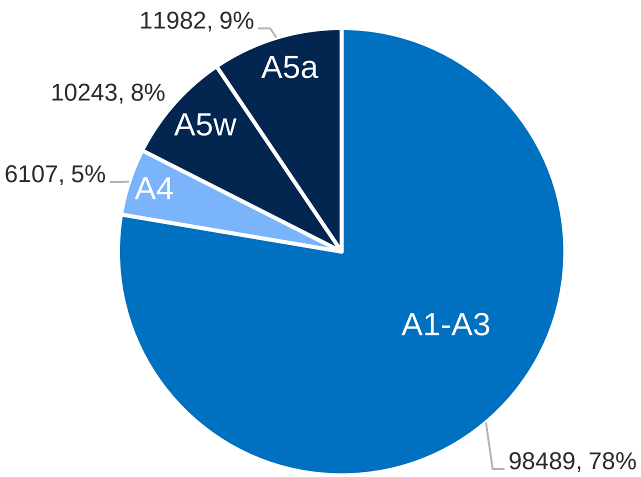


A1-A5 GWP Results

System | Sub-system | Components | Sub-components

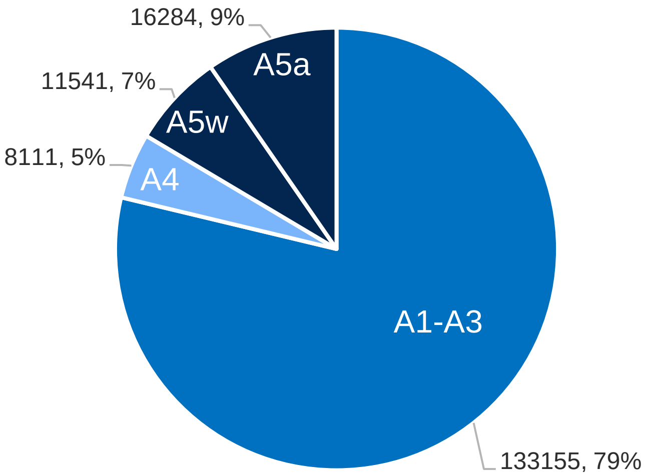
Across modules A1-A5, A1-A3 is the most significant contributor. A4 and A5 are a smaller proportion of the total A1-A5 GWP impact. A5a is defined as the construction activities associated with building the asset and A5w is material wasted on site during construction - see A5a and A5w assumptions in section 2.1.
A1-A3 GWP is evaluated at component and sub-component in the following section to understand what material items contribute the most to this GWP impact.

CLIC Drive Beam 380GeV



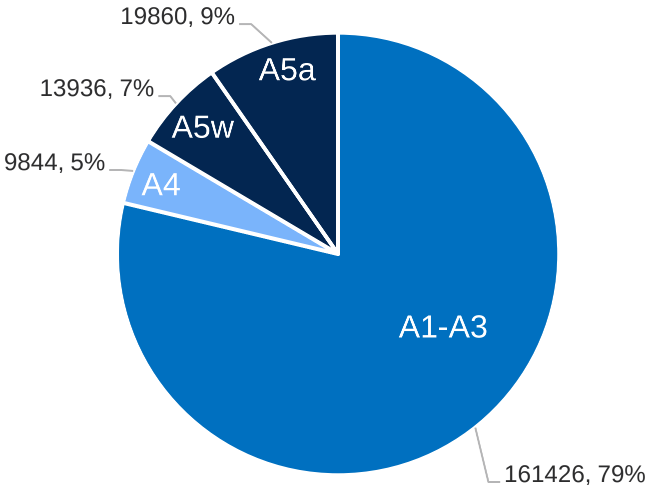
Total A1-A5 GWP: 127,000 tCO_2e

CLIC Drive Beam 1.5TeV



Total A1-A5 GWP: 169,000 tCO_2e

CLIC Drive Beam 3TeV



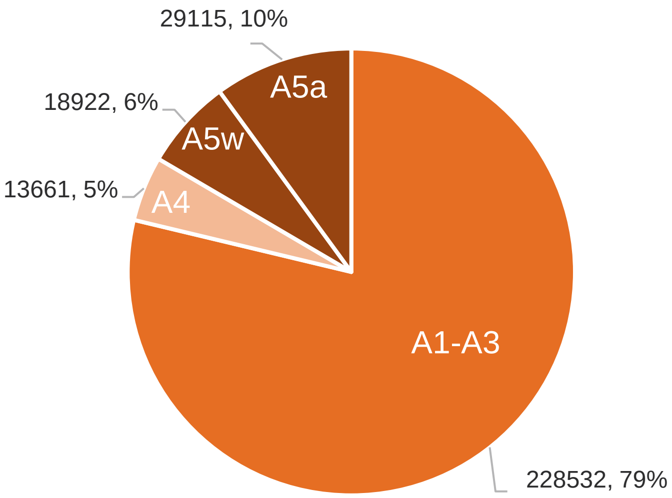
Total A1-A5 GWP: 205,000 tCO_2e

A1-A5 GWP Results

System | Sub-system | Components | Sub-components

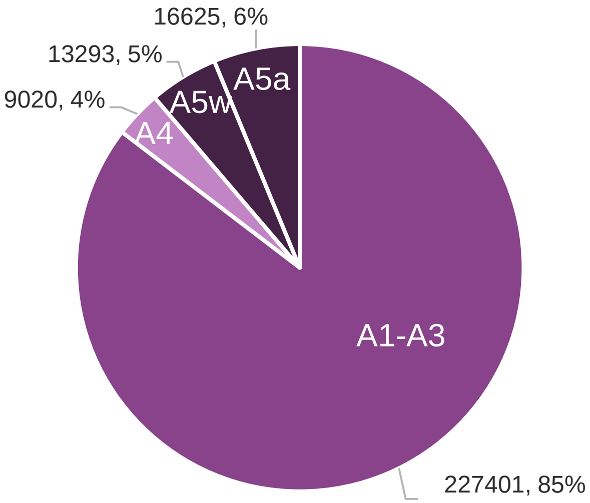
Across modules A1-A5, A1-A3 is the most significant contributor. A4 and A5 are a smaller proportion of the total A1-A5 GWP impact. A5a is defined as the construction activities associated with building the asset and A5w is material wasted on site during construction - see A5a and A5w assumptions in section 2.1.
A1-A3 GWP is evaluated at component and sub-component in the following section to understand what material items contribute the most to this GWP impact.

CLIC Klystron 380GeV



Total A1-A5 GWP: 290,000 tCO_2e

ILC 250GeV



Total A1-A5 GWP: 266,000 tCO_2e

The impact of explosives used in the drill and blast method for ILC is excluded from A5a due to lack of data.

A1-A5 GWP Results

System | Sub-system | Components | Sub-components

Main accelerator tunnel

The tCO_2e/km of the main accelerator tunnel A1-A5 GWP results are listed below to 3 significant figures:

CLIC Drive Beam:

380GeV 8050 tCO_2e/km

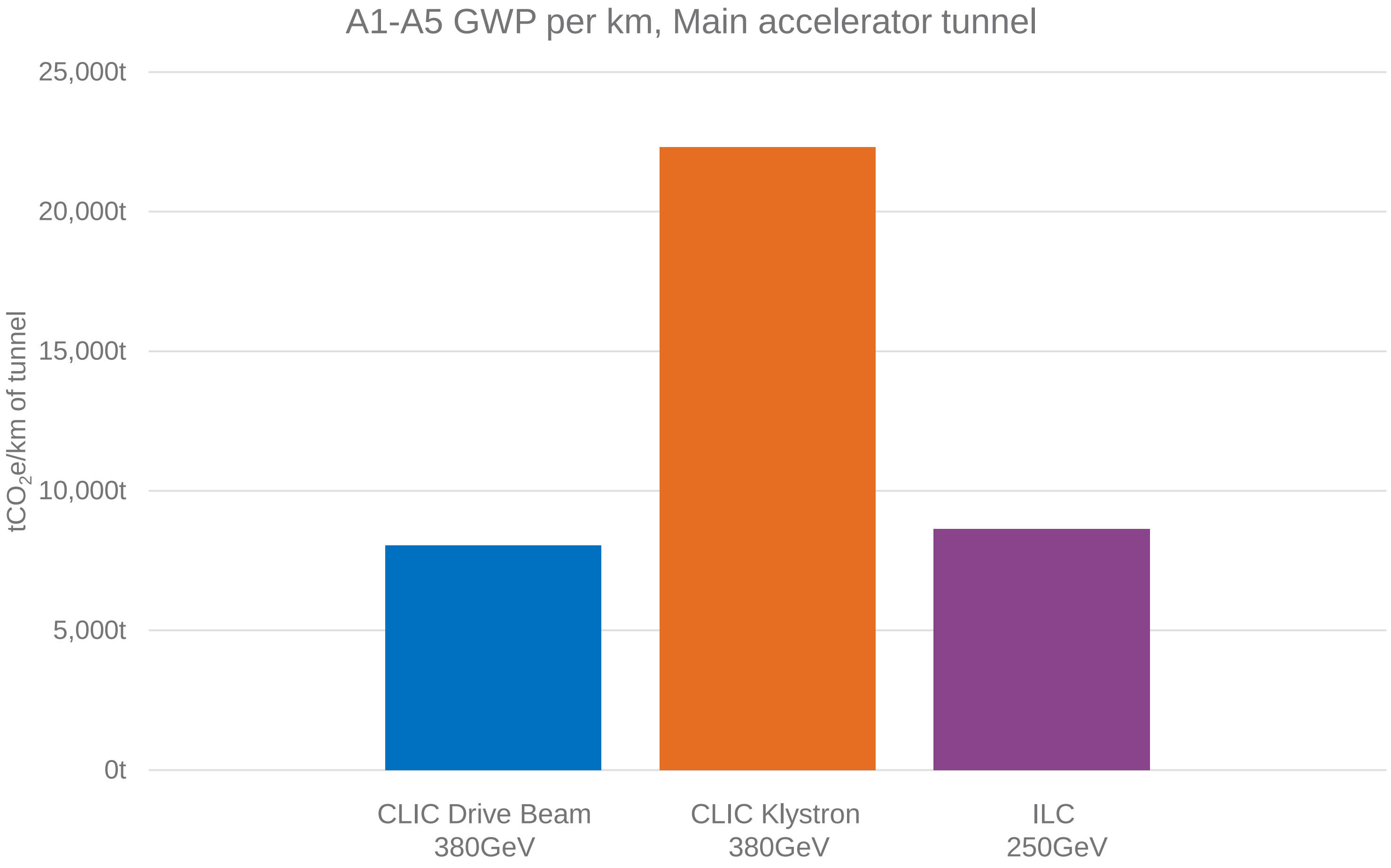
CLIC Klystron:

380GeV 22,300 tCO_2e/km

ILC:

250GeV 8640 tCO_2e/km

CLIC Klystron is approximately 2.5 times the A1-A5 GWP per km compared to ILC. This is predominantly due to the material quantity of CLIC Klystron being much greater than ILC, see the next page for further insights.



A1-A5 GWP Results

CLIC Klystron and ILC main accelerator tunnel

The tCO_2e/km of the main accelerator tunnel for CLIC and ILC is compared across A1-A5.

CLIC Klystron:

380GeV 22,300 tCO_2e/km

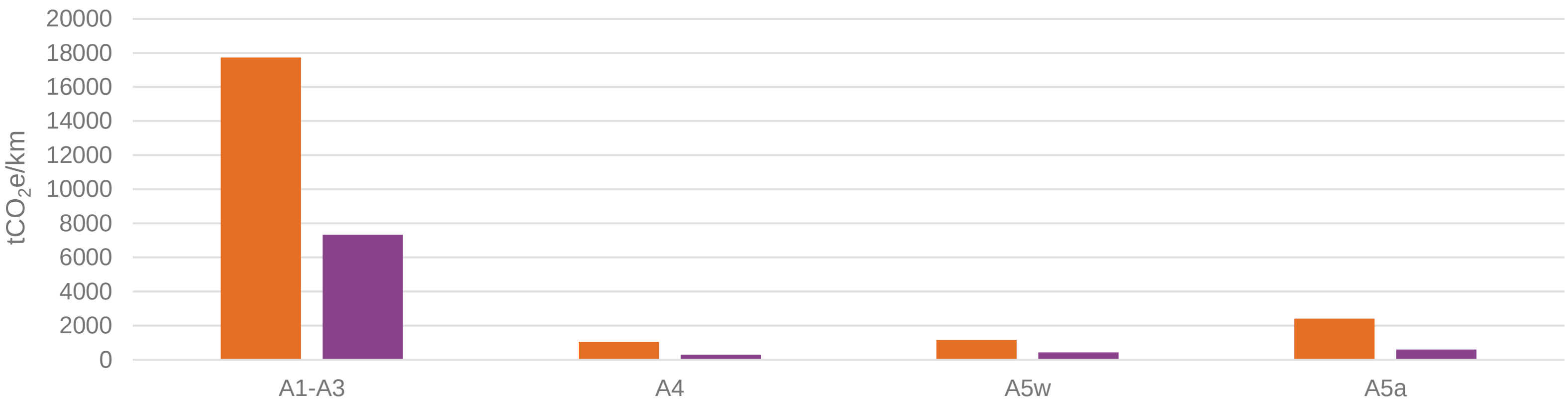
ILC:

250GeV 8640 tCO_2e/km

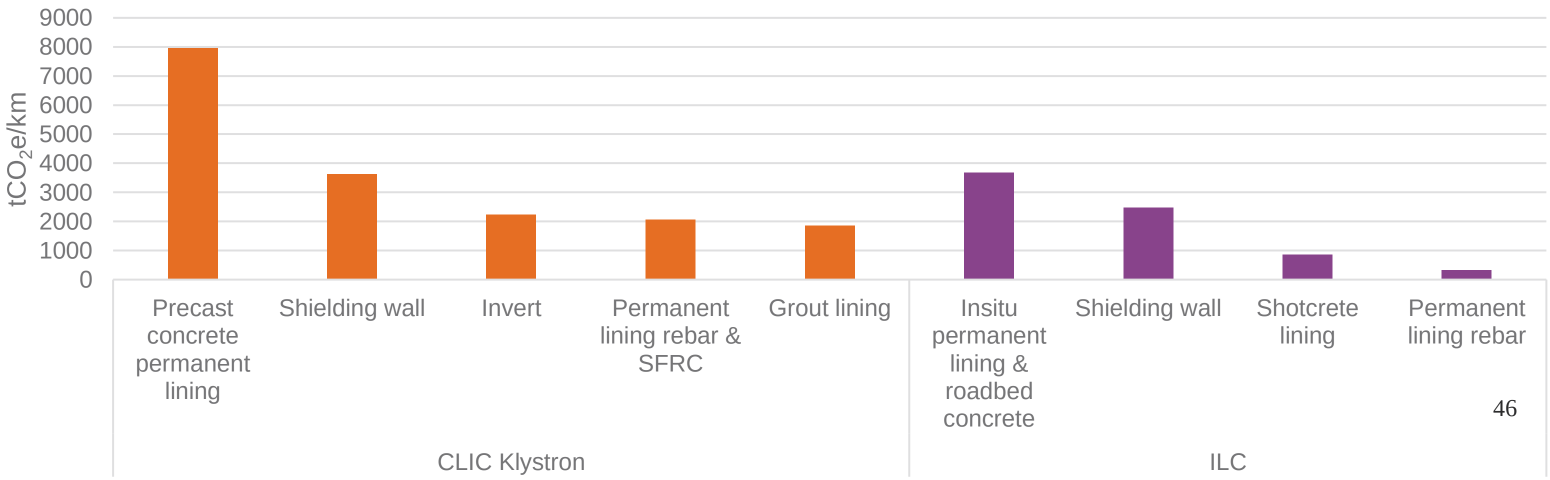
CLIC Klystron has approximately 2.5 times the A1-A5 GWP per km compared to ILC. This is predominantly due to the A1-A3 and A5a stage:

- CLIC Klystron permanent lining thickness is 1.5 times that of ILC (450mm compared to 300mm for ILC).
- CLIC Klystron shielding wall is larger compared with the shielding wall for ILC.
- CLIC Klystron has additional concrete and rebar for the invert, whereas ILC does not require an invert due to the arched span and roadbed concrete.
- CLIC Klystron has 80kg/m^3 rebar density and 35kg/m^3 SFRC density, whereas ILC has 50kg/m^3 rebar density assumed.
- CLIC Klystron has a more electricity intensive construction method (TBM) compared to ILC (D&B). Note the explosives impacts have not been quantified in the ILC LCA due to lack of data.

A1-A5 CLIC Klystron and ILC comparison



A1-A3 CLIC Klystron and ILC comparison



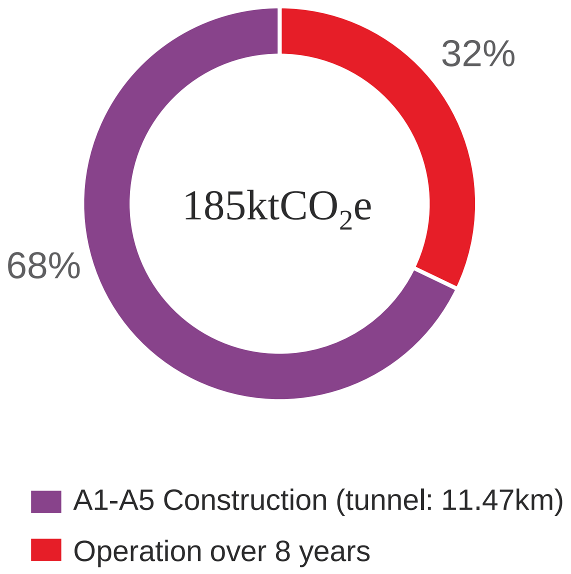
CLIC Drive Beam construction and operational GWP

Operational estimates were provided by CERN for CLIC Drive Beam only, based on a projected electricity mix in 2050 (50% nuclear, 50% renewables). The A1-A5 construction GWP with 2030 baseline assumptions is reported against the operational estimates. A1-A5 construction makes up a significant proportion of the overall GWP, with a decreasing proportion for the higher energies. The scope of this LCA is A1-A5 construction, but this operational estimate emphasises the importance of considering both construction and operational GWP which both have significant impacts. It is important to note that the operational estimates do not include the capital carbon of new infrastructure required to transition the grid away from fossil fuels or the response to the increasing electricity demand. This is important to consider as colliders have a significant impact on the grid.

380GeV

Annual CO$_2$e of operations is 6% of embodied carbon.

A1-A5 GWP is equivalent to 1.7 decades of running accelerator.



1.5TeV

Annual CO$_2$e of operations is 12% of embodied carbon.

A1-A5 GWP is equivalent to 0.8 decades of running accelerator.

3TeV

Annual CO$_2$e of operations is 17% of embodied carbon.

A1-A5 GWP is equivalent to 0.6 decades of running accelerator.

CLIC Drive Beam A1-A3 GWP results

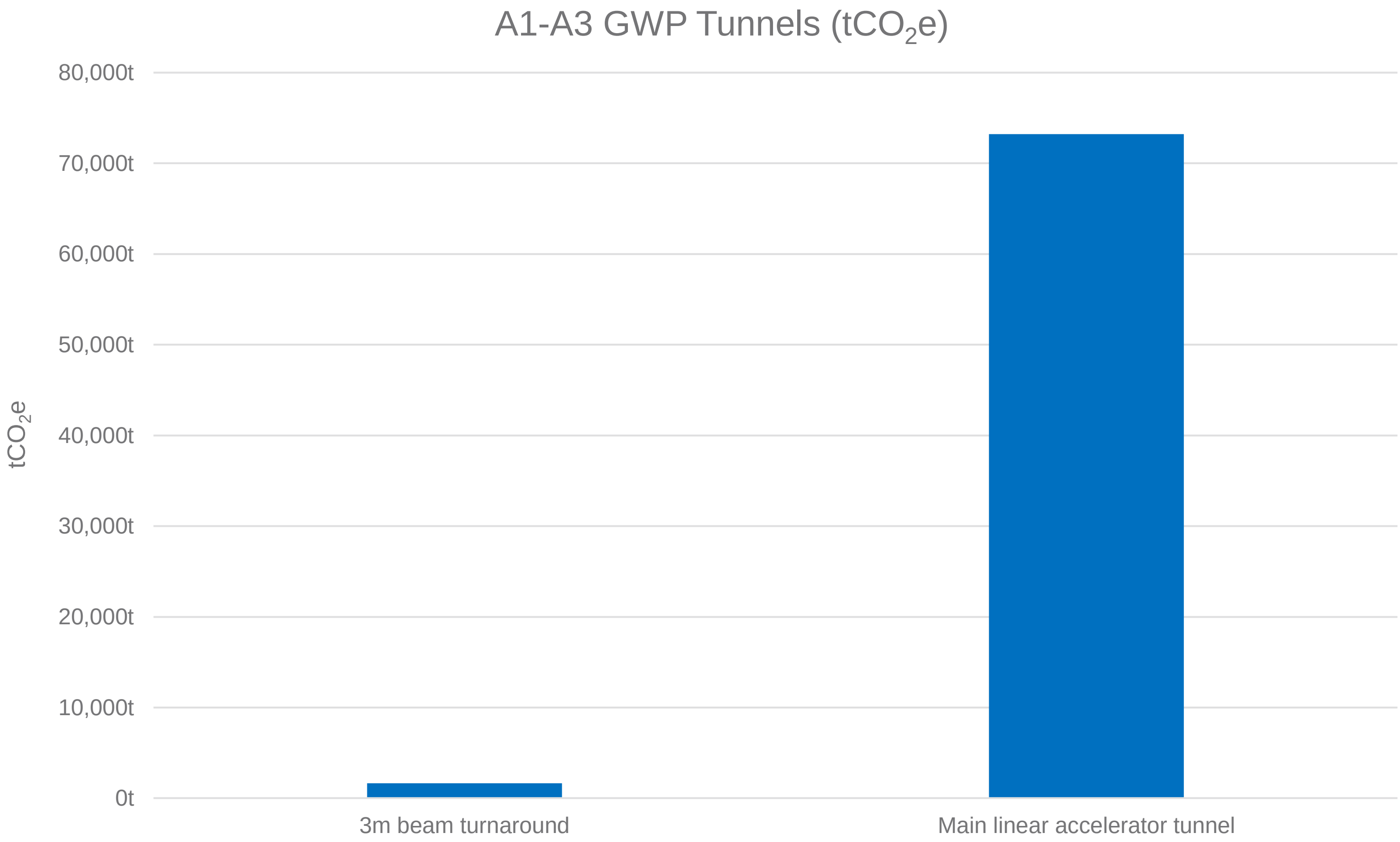
CLIC Drive Beam, 380GeV

Tunnels

Tunnels are inclusive of:

- 11470m 5.6m internal dia. accelerator tunnel
- 10no. 3m internal dia. beam turnarounds

As expected the main linear accelerator tunnel is the largest contributor to GWP.



CLIC Drive Beam, 380GeV

System | Sub-system | Components | **Sub-components**

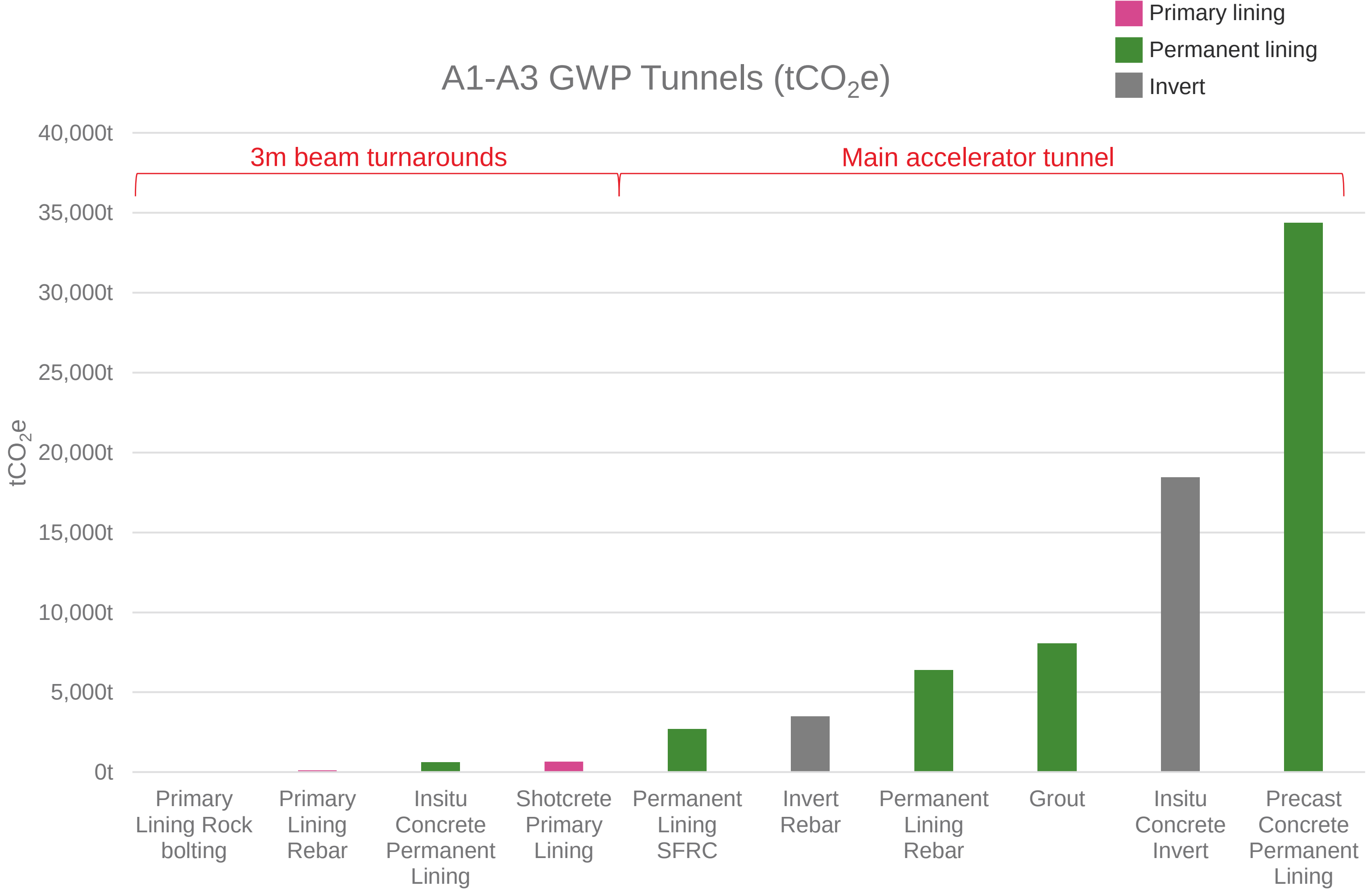
Tunnels

Tunnels are inclusive of:

- 11470m 5.6m internal dia. accelerator tunnel
- 10no. 3m internal dia. beam turnarounds

The main accelerator tunnel is the largest A1-A3 GWP contributor for CLIC Drive Beam 380GeV.

The precast concrete permanent lining of the main accelerator tunnel is the largest A1-A3 GWP contributor for the tunnels sub-component level for CLIC Drive Beam 380GeV, with a lining thickness of 300mm at 50MPa. This is followed by insitu concrete invert (30MPa with 60kg/m^3 rebar) and segmental lining grout (lining thickness 100mm at 20MPa).



* Note primary lining is in reference to beam turnaround design only. Not applicable to main accelerator tunnel.

CLIC Drive Beam, 380GeV

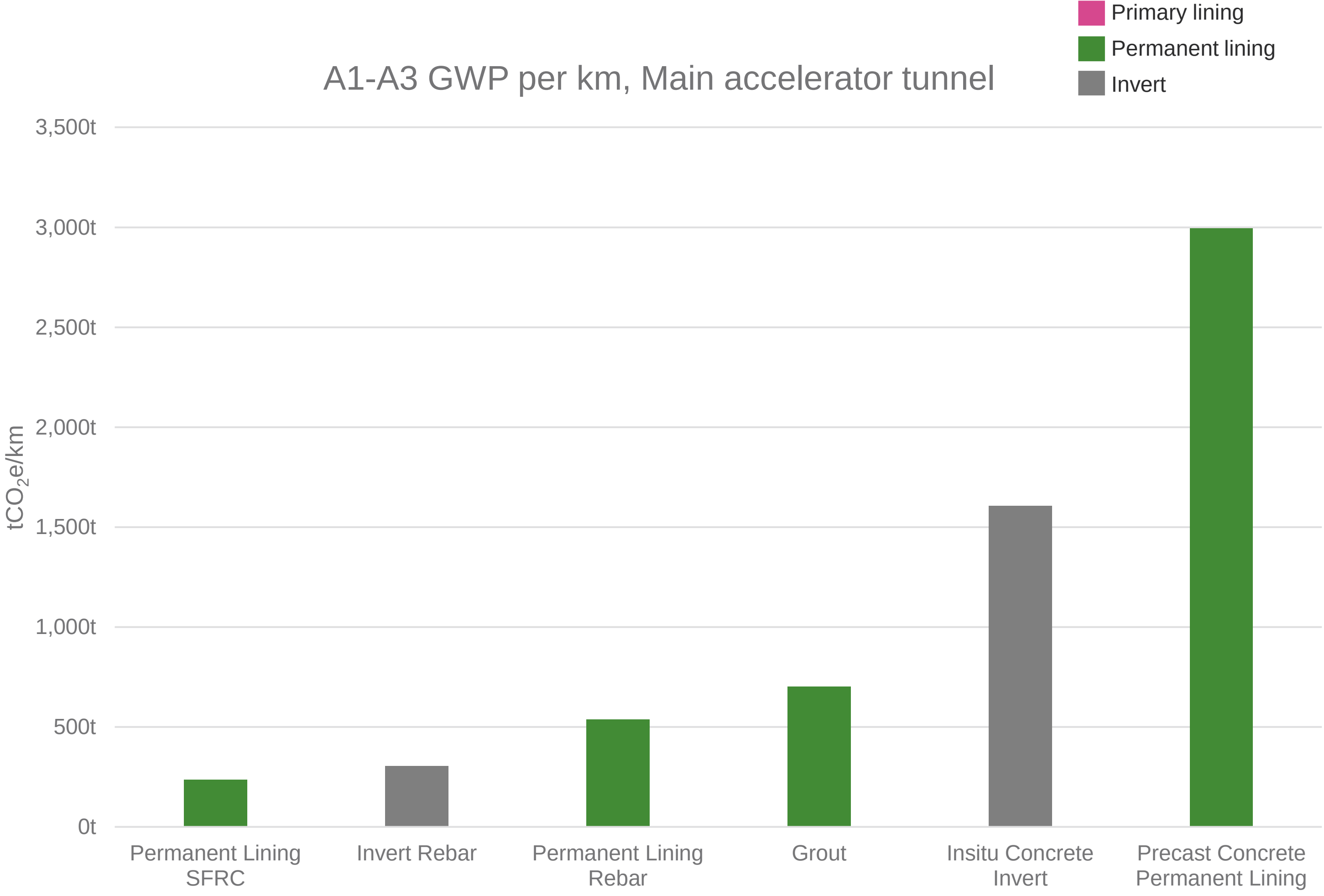
Main accelerator tunnel A1-A3 GWP / km

The main accelerator tunnel has been evaluated at sub-component level for A1-A3 GWP/km to allow comparison between the options.

Design and material parameters are detailed below:

Sub-components	
Permanent lining	**Invert**
Grout, 100mm thk, 20MPa Precast concrete, 300mm thk, 50MPa Rebar 80kg/m^3 SFRC 35kg/m^3	Insitu concrete, 30MPa Rebar 60kg/m^3

The precast concrete permanent lining and invert are the biggest A1-A3 GWP contributors per km of main accelerator tunnel.



CLIC Drive Beam, 380GeV

Shafts

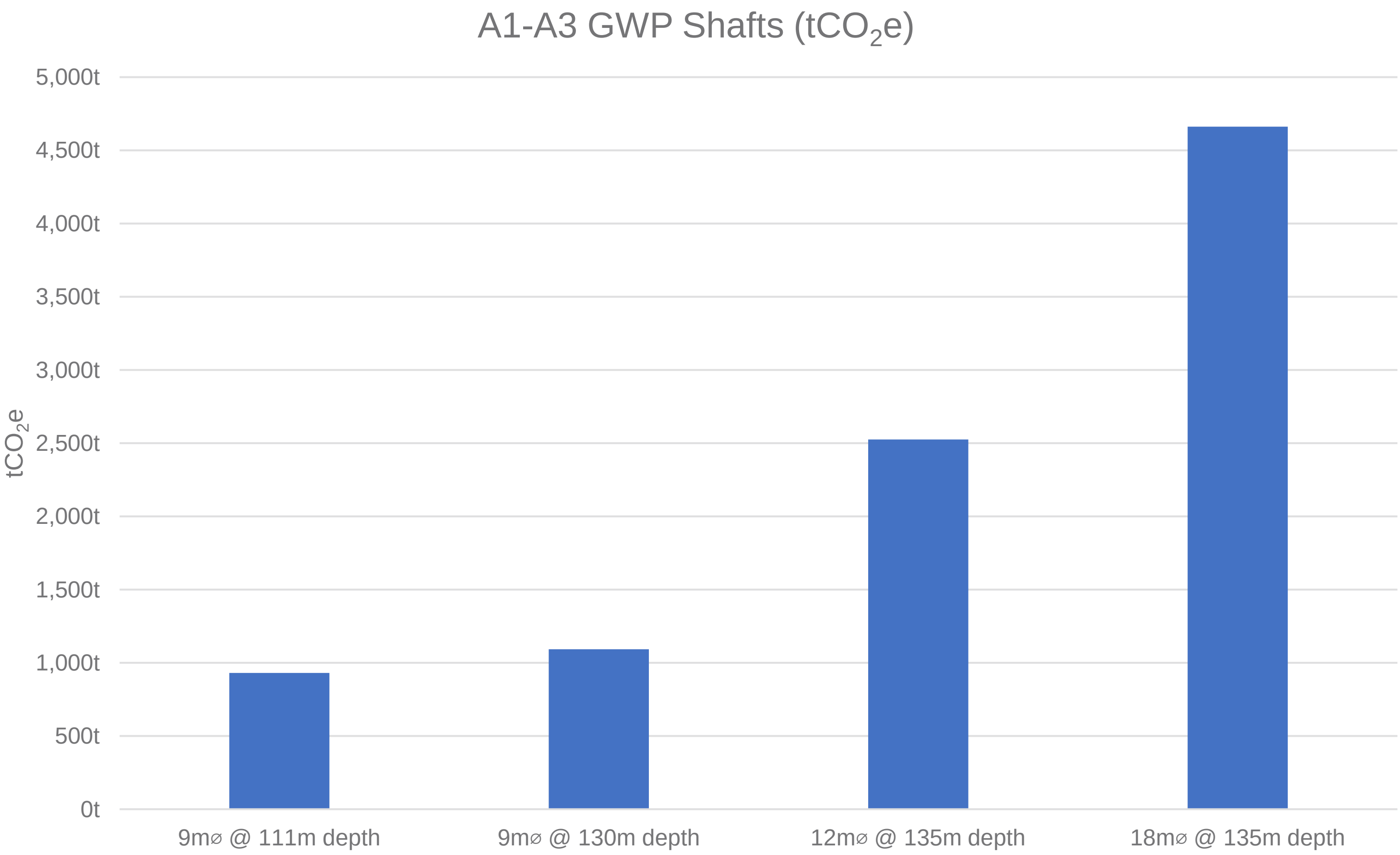
Shafts are inclusive of:

- 1no. 18m dia. at 135m depth
- 1no. 12m dia. at 135m depth
- 1no. 9m dia. at 130m depth
- 1no. 9m dia. at 111m depth

GWP/m:

Shafts	tCO_2e/m
18m dia. at 135m depth	34.5
12m dia. at 135m depth	18.7
9m dia. at 130m depth	8.4
9m dia. at 111m depth	8.4

As expected, the 18m dia. shaft at 135m depth is the biggest contributor to GWP, with a lining thickness of 600mm at 40MPa.



CLIC Drive Beam, 380GeV

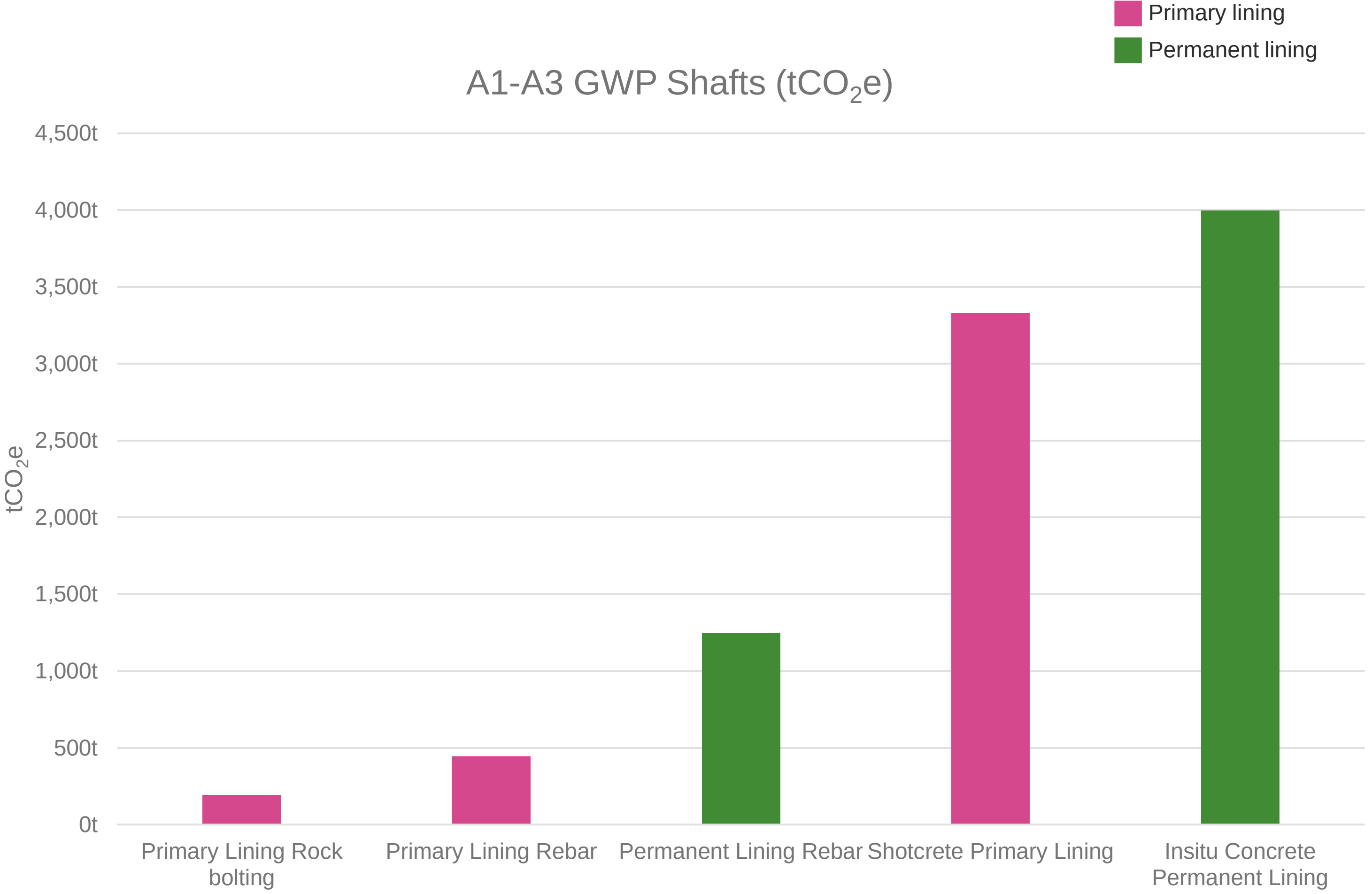
Shafts

Shafts are inclusive of:

- 1no. 18m dia. at 135m depth
- 1no. 12m dia. at 135m depth
- 1no. 9m dia. at 130m depth
- 1no. 9m dia. at 111m depth

Insitu concrete permanent lining is the greatest contributor to A1-A3 GWP for the shafts. 18m, 12m and 9m dia. shafts have a lining thickness of 600mm, 500mm and 300mm respectively.

The shotcrete primary lining has a smaller thickness than the insitu permanent lining.



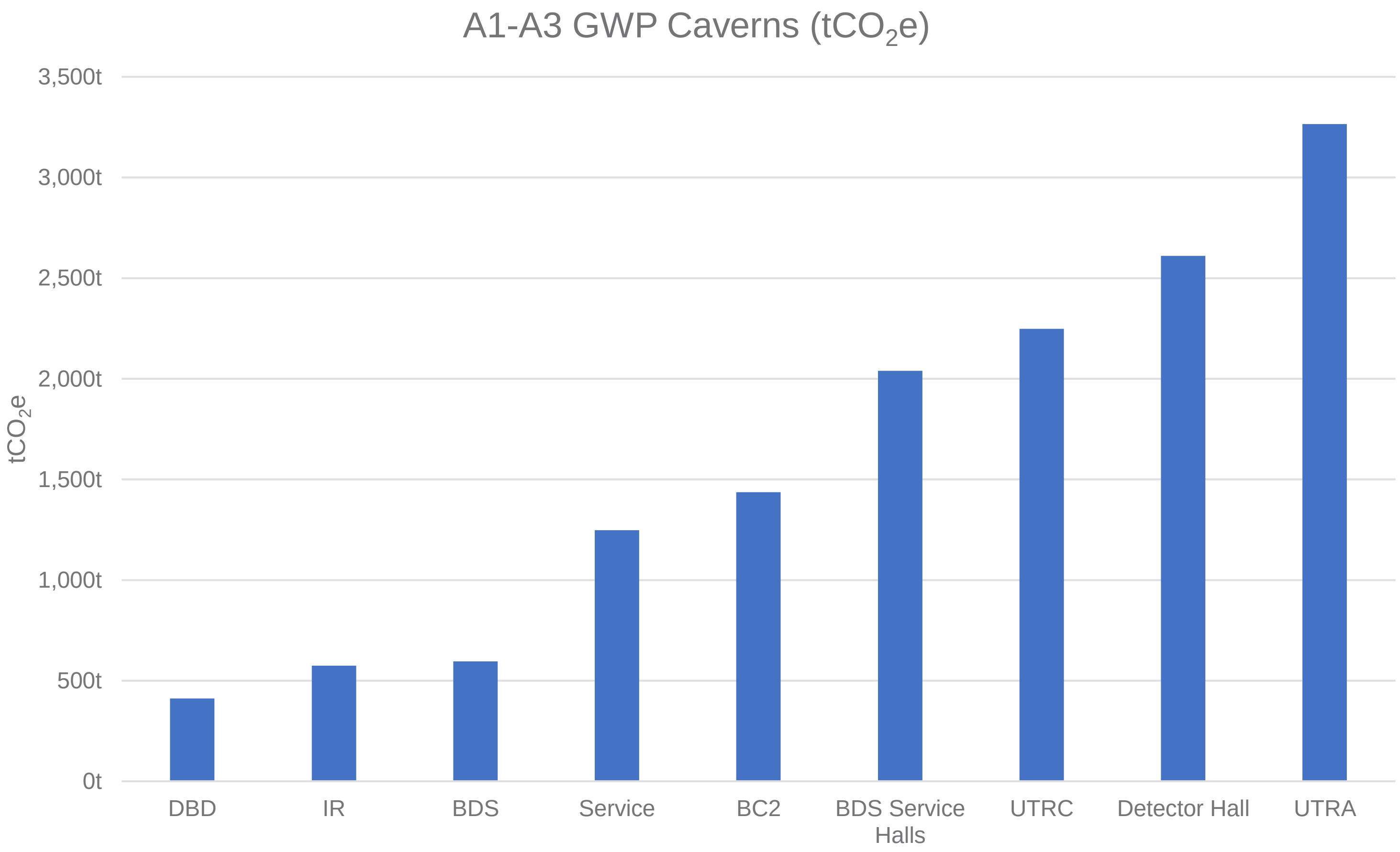
CLIC Drive Beam, 380GeV

Caverns

Caverns are inclusive of:

- 8no. UTRA caverns (40x10x7.2m)
- 1no. Detector hall (62x31.5x33.5m)
- 2no. UTRC caverns (55x15x18m)
- 2no. BDS service halls (49x16x18m)
- 2no. BC2 caverns (100x10x3m)
- 1no. Service cavern (60x20x15m)
- 2no. BDS caverns (20x8x14m)
- 1no. IR cavern (15.5x23x19m)
- 12no. Drive beam dump caverns (6x9x5m)

UTRA is the largest GWP contributor, due to the quantity (8no.) and size of the UTRA caverns (40x10x7.2m).



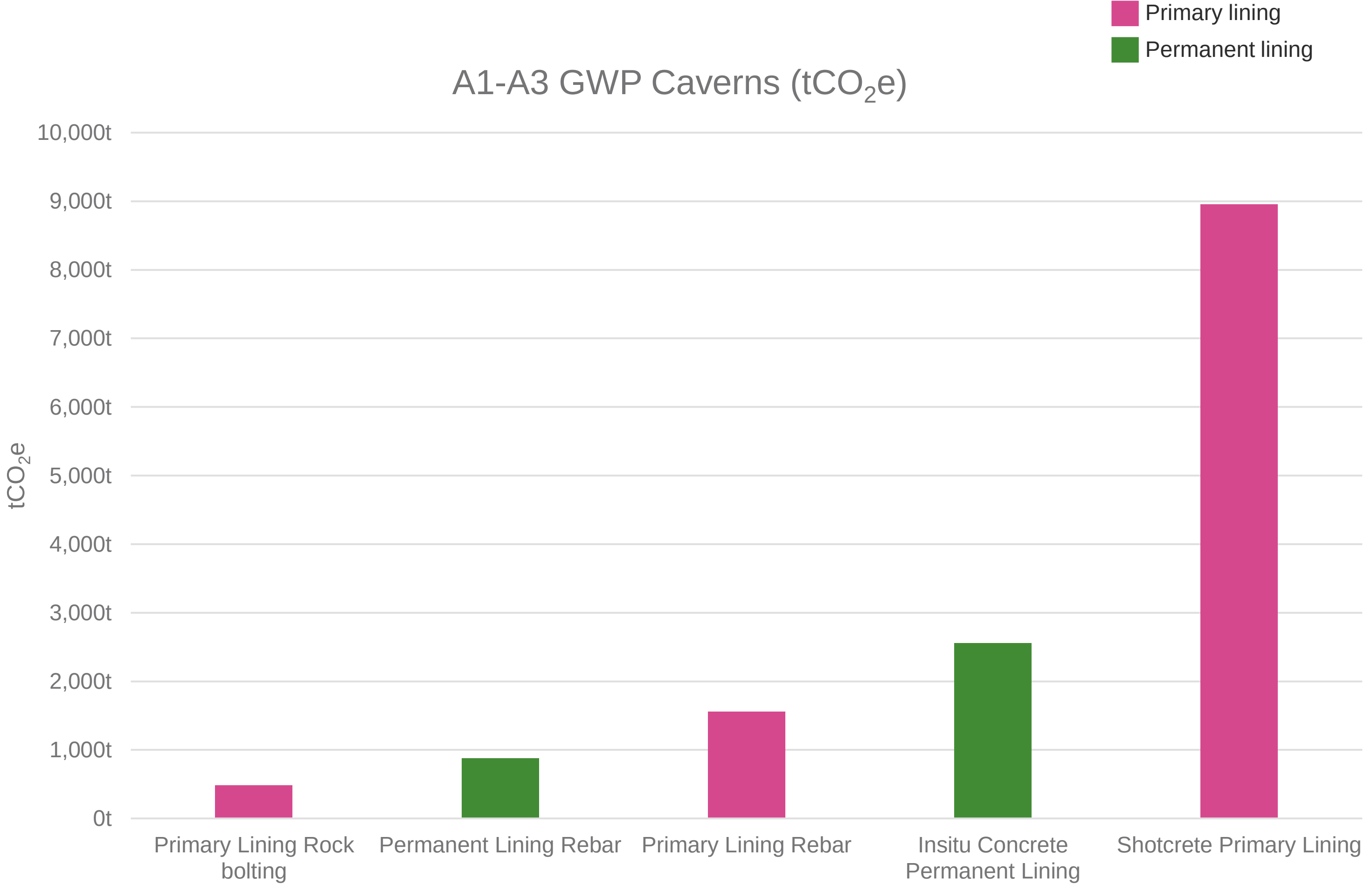
CLIC Drive Beam, 380GeV

Caverns

Caverns are inclusive of:

- 8no. UTRA caverns (40x10x7.2m)
- 1no. Detector hall (62x31.5x33.5m)
- 2no. UTRC caverns (55x15x18m)
- 2no. BDS service halls (49x16x18m)
- 2no. BC2 caverns (100x10x3m)
- 1no. Service cavern (60x20x15m)
- 2no. BDS caverns (20x8x14m)
- 1no. IR cavern (15.5x23x19m)
- 12no. Drive beam dump caverns (6x9x5m)

The shotcrete primary lining is the largest GWP contributor, this is due to the 400mm thick shotcrete primary lining. The permanent lining thickness is 110mm.



CLIC Drive Beam, 1.5TeV

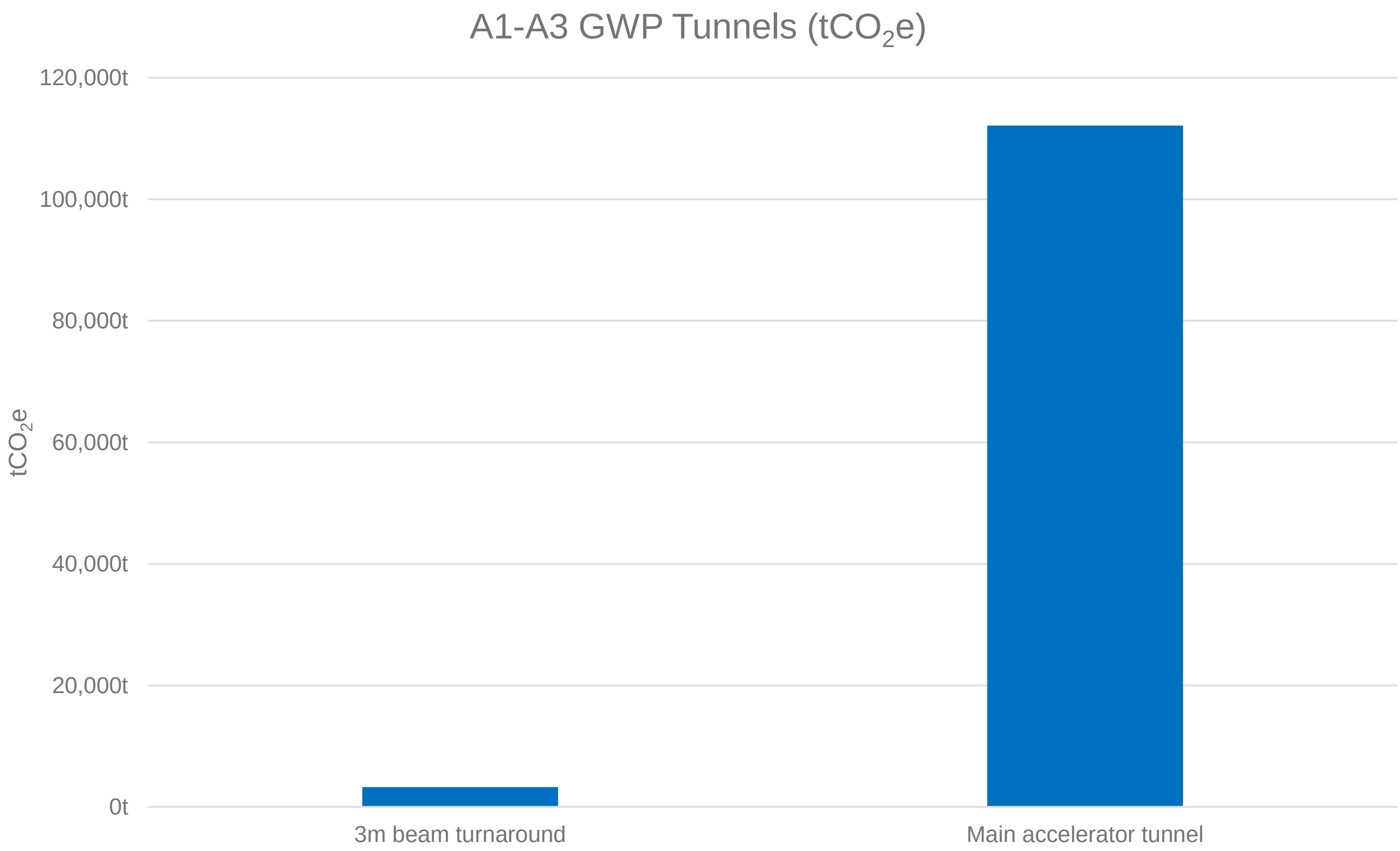
System | Sub-system | **Components** | Sub-components

Tunnels

Tunnels are inclusive of:

- 17564m 5.6m internal dia. accelerator tunnel
- 20no. 3m internal dia. beam turnarounds

As expected the main linear accelerator tunnel is the largest contributor to GWP.



CLIC Drive Beam, 1.5TeV

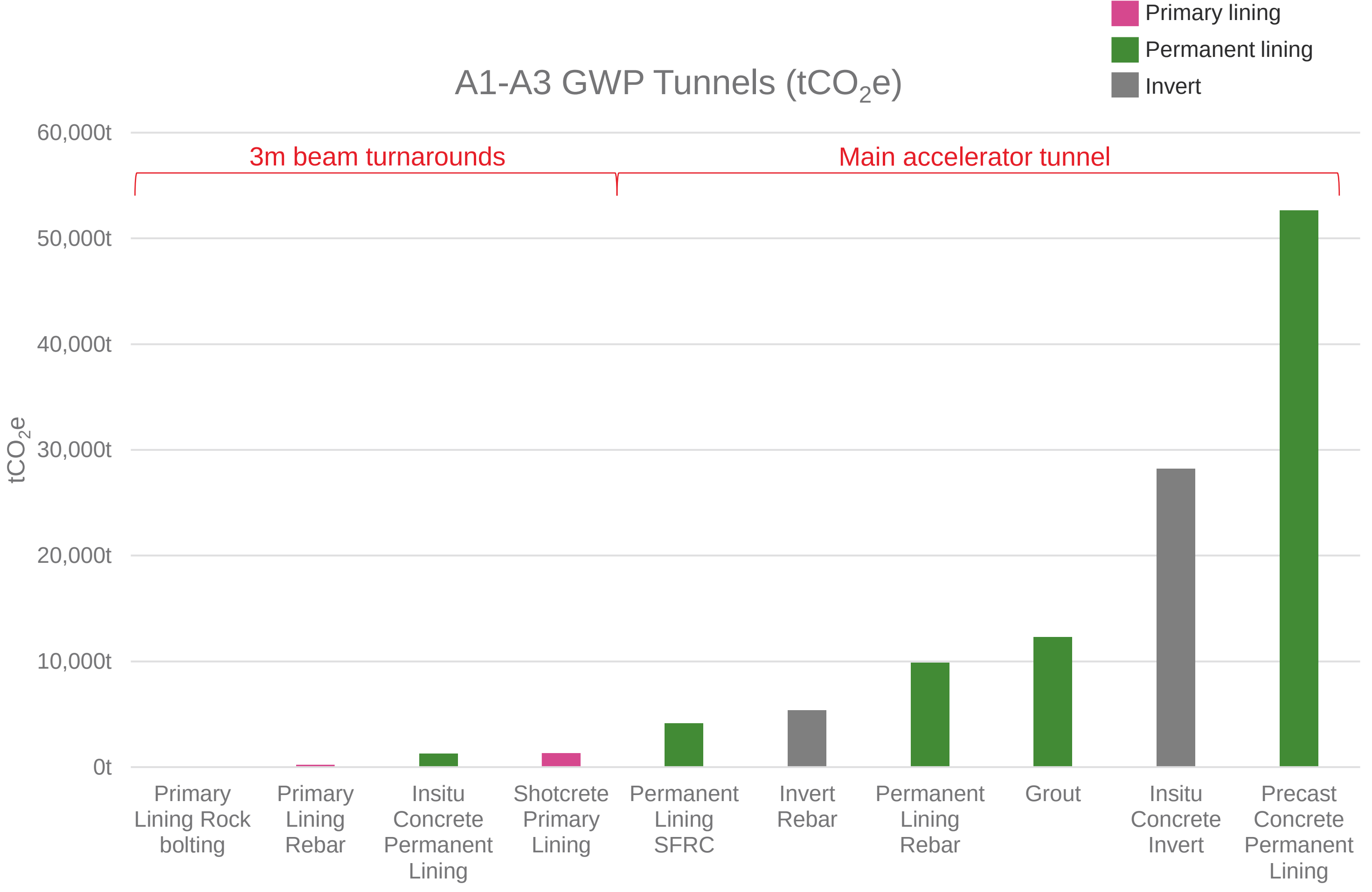
Tunnels

Tunnels are inclusive of:

- 17564m 5.6m internal dia. accelerator tunnel
- 20no. 3m internal dia. beam turnarounds

This is the second extension stage for CLIC 5.6m.

Precast concrete permanent lining is the largest A1-A3 GWP contributor for the tunnels sub-component level for CLIC 5.6m 1.5TeV, with a lining thickness of 300mm at 50MPa. This is followed by insitu concrete invert (30MPa with 60kg/m^3 rebar) and segmental lining grout (lining thickness 100mm at 20MPa).



* Note primary lining is in reference to beam turnaround design only. Not applicable to main accelerator tunnel.

CLIC Drive Beam, 1.5TeV

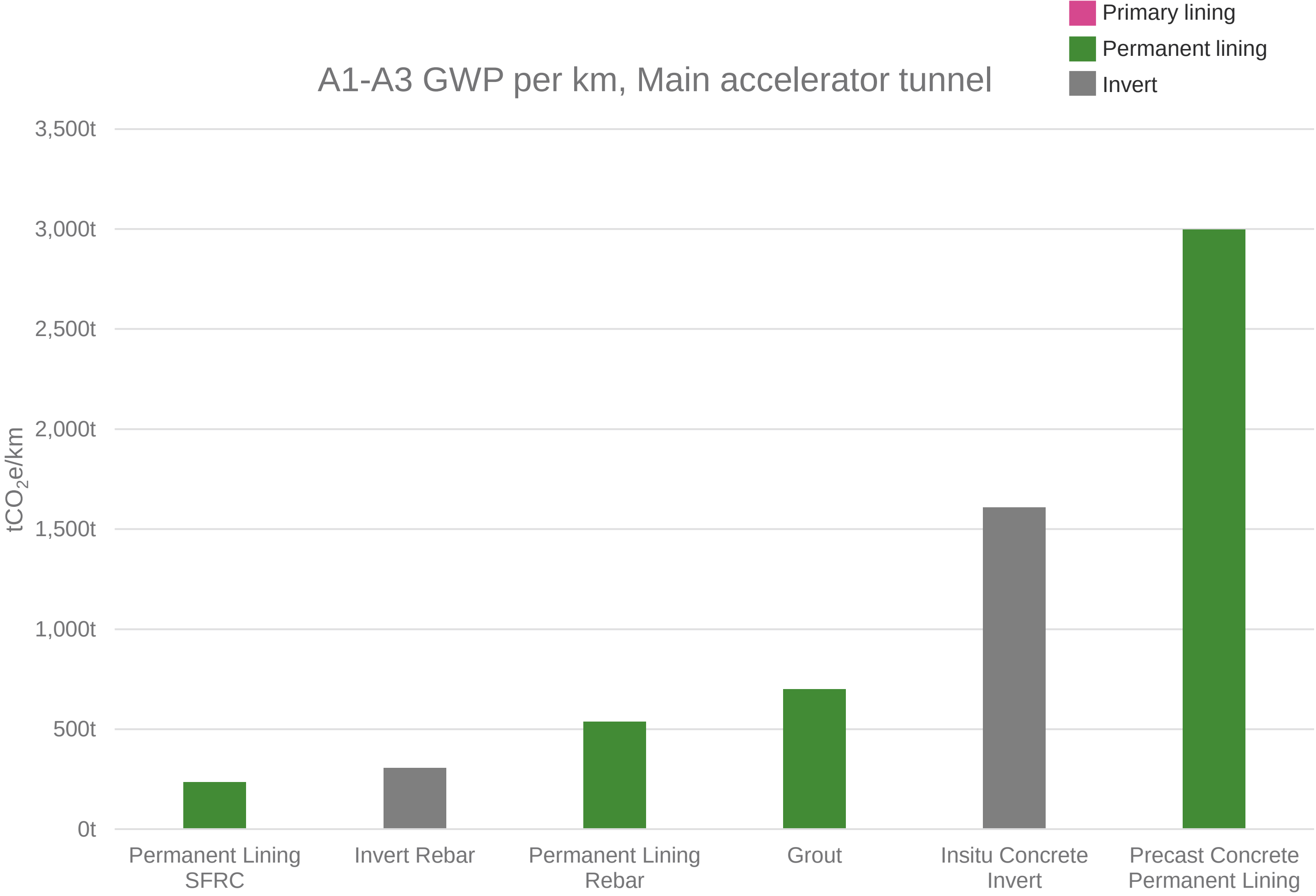
Main accelerator tunnel A1-A3 GWP / km

The main accelerator tunnel has been evaluated at sub-component level for A1-A3 GWP/km to allow comparison between the options.

Design and material parameters are detailed below:

Sub-components	
Permanent lining	**Invert**
Grout, 100mm thk, 20MPa Precast concrete, 300mm thk, 50MPa Rebar 80kg/m^3 SFRC 35kg/m^3	Insitu concrete, 30MPa Rebar 60kg/m^3

The precast concrete permanent lining and invert are the biggest A1-A3 GWP contributors per km of main accelerator tunnel.



CLIC Drive Beam, 1.5TeV

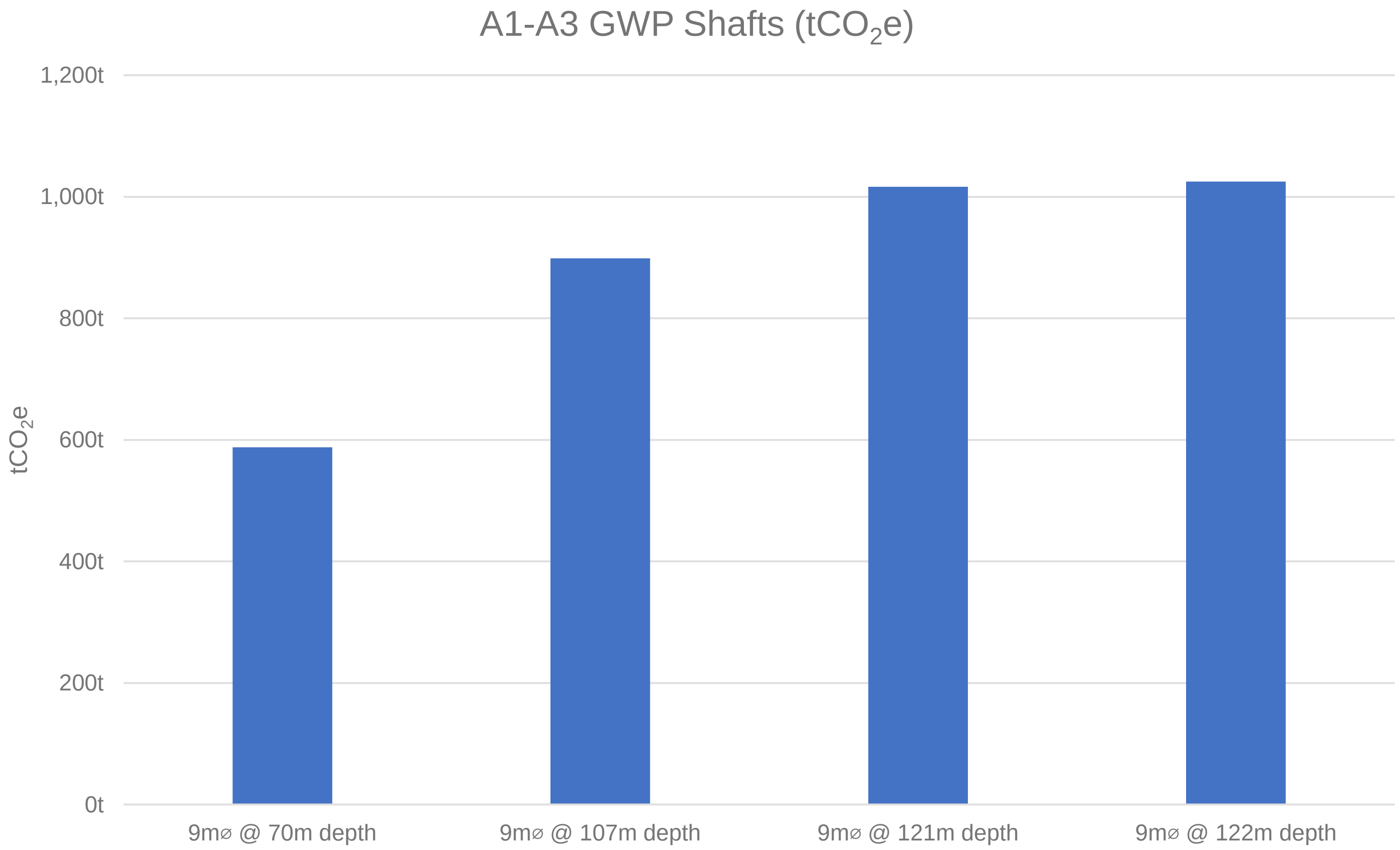
Shafts

Shafts are inclusive of:

- 1no. 9m dia. at 122m depth
- 1no. 9m dia. at 121m depth
- 1no. 9m dia. at 107m depth
- 1no. 9m dia. at 70m depth

GWP/m: 8.4 tCO_2e/m

As expected the 9m dia. shaft at 122m depth is the biggest contributor to GWP, with a lining thickness of 300mm at 40MPa.



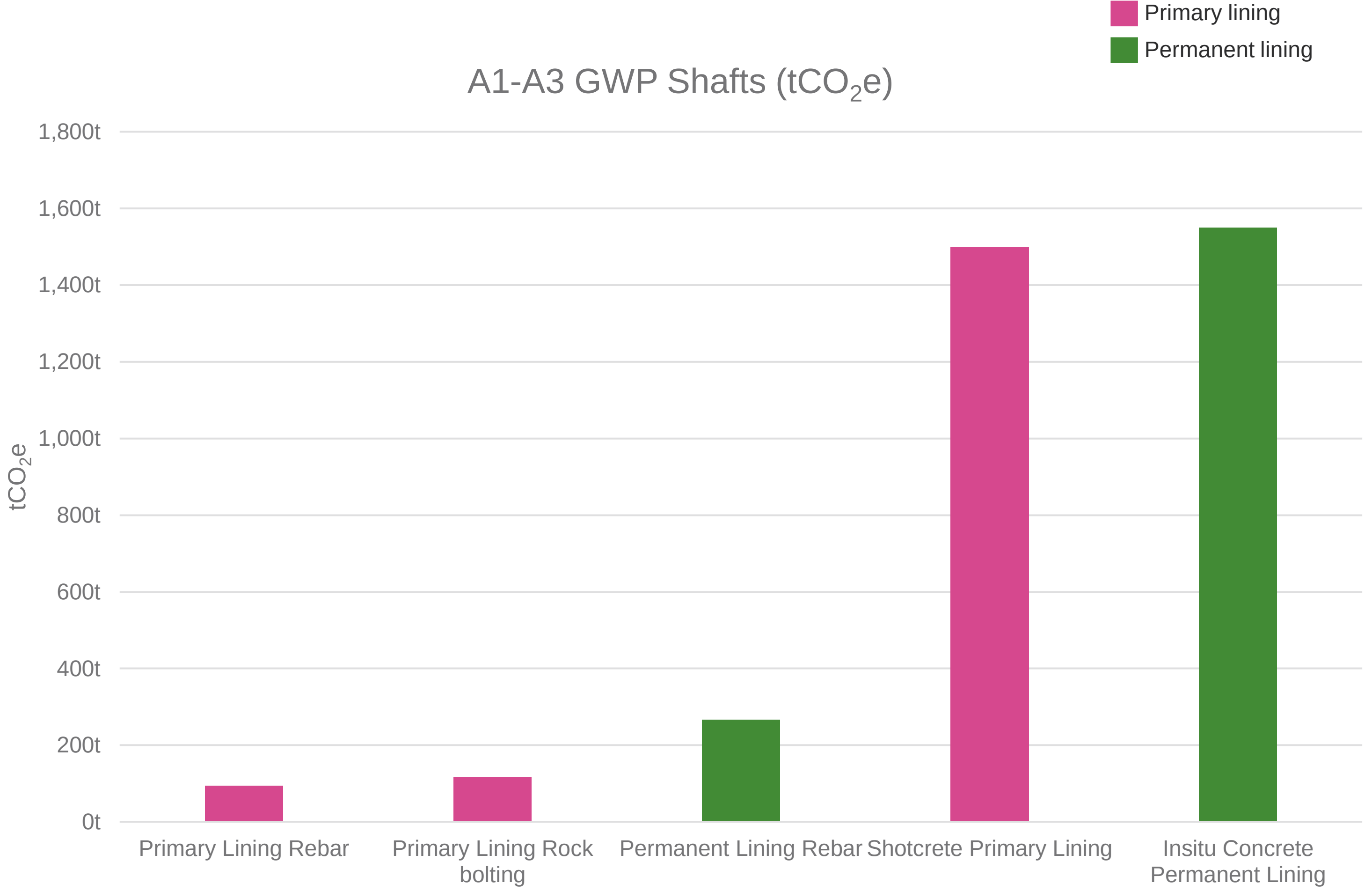
CLIC Drive Beam, 1.5TeV

Shafts

Shafts are inclusive of:

- 1no. 9m dia. at 122m depth
- 1no. 9m dia. at 121m depth
- 1no. 9m dia. at 107m depth
- 1no. 9m dia. at 70m depth

Insitu concrete permanent lining is the greatest contributor to A1-A3 GWP for the shafts, with a lining thickness of 300mm at 40MPa. This is closely followed by shotcrete primary lining, with a lining thickness of 300mm at 30MPa.

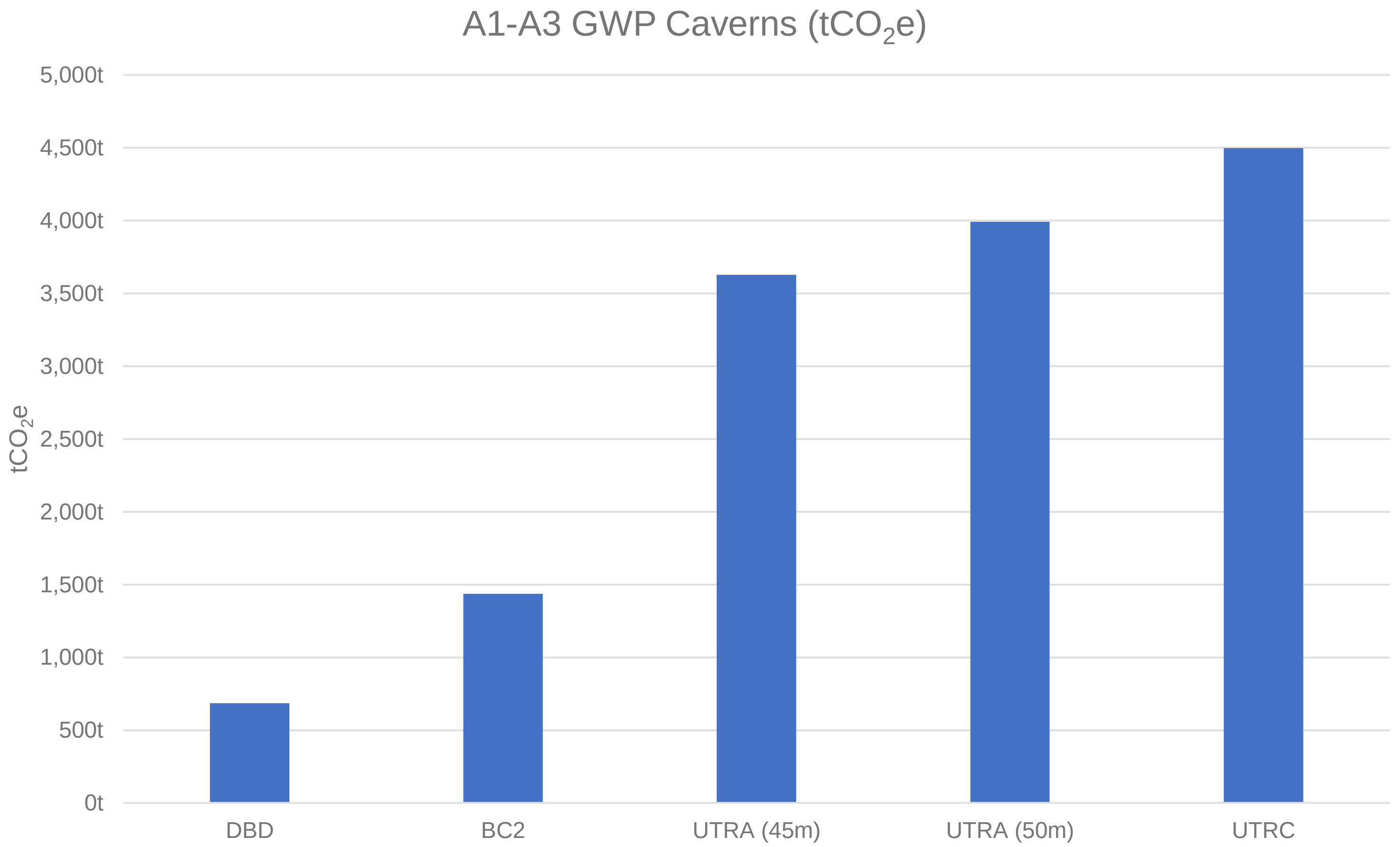


CLIC Drive Beam, 1.5TeV

Caverns

Caverns are inclusive of:
- 4no. UTRC cavern (55x16x18m)
- 8no. UTRA cavern (50x10x7.2m)
- 8no. UTRA cavern (45x10x7.2m)
- 2no. BC2 cavern (100x10x3m)
- 20no. Drive beam dump cavern (6x9x5m)

UTRC cavern has the largest GWP contribution due to the size and number of caverns (4no.).

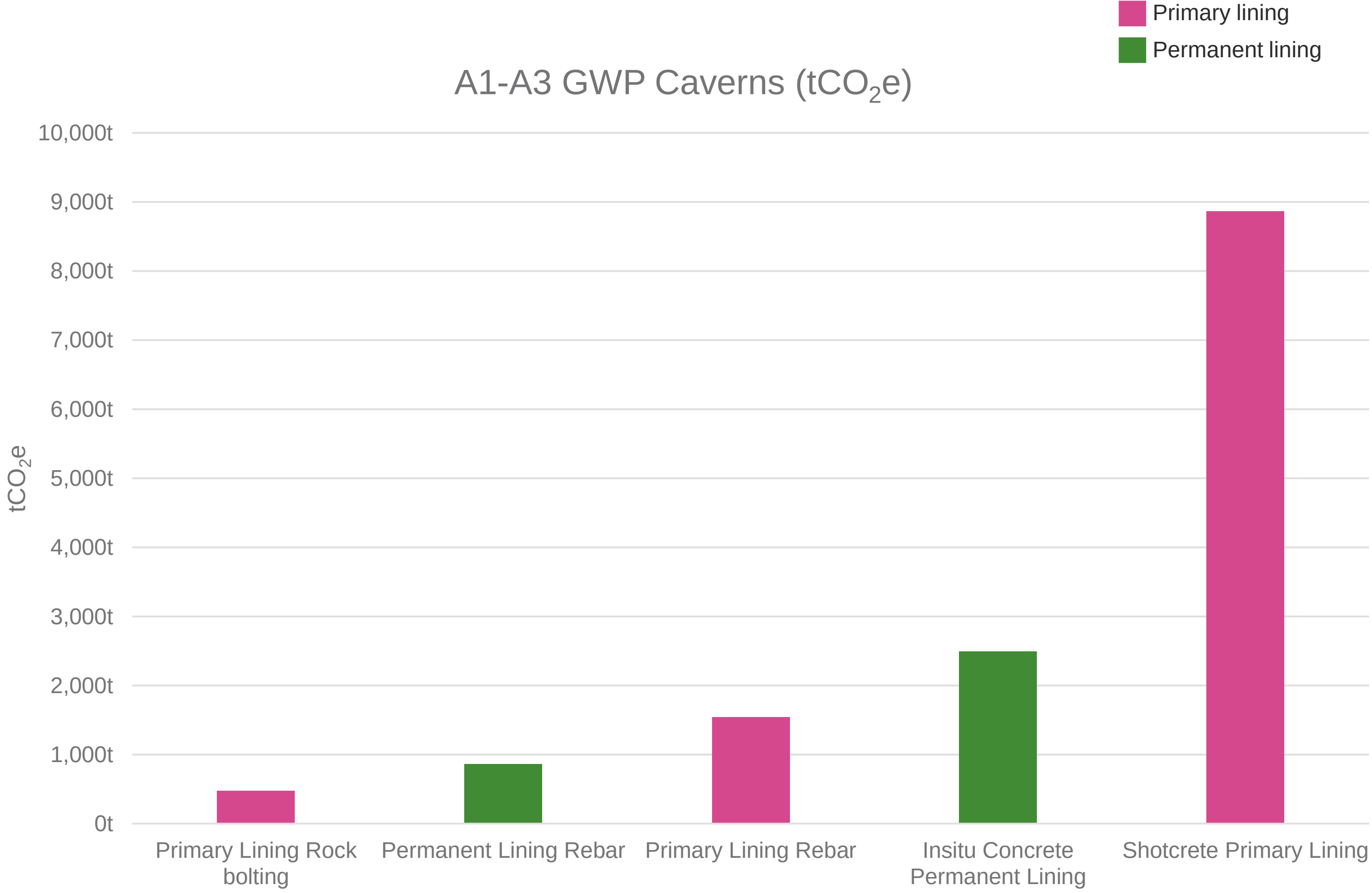


CLIC Drive Beam, 1.5TeV

Caverns

Caverns are inclusive of:
- 4no. UTRC cavern (55x16x18m)
- 8no. UTRA cavern (50x10x7.2m)
- 8no. UTRA cavern (45x10x7.2m)
- 2no. BC2 cavern (100x10x3m)
- 20no. Drive beam dump cavern (6x9x5m)

The shotcrete primary lining is the largest GWP contributor, this is due to the 400mm thick shotcrete primary lining. The permanent lining thickness is 110mm.



CLIC Drive Beam, 1.5TeV

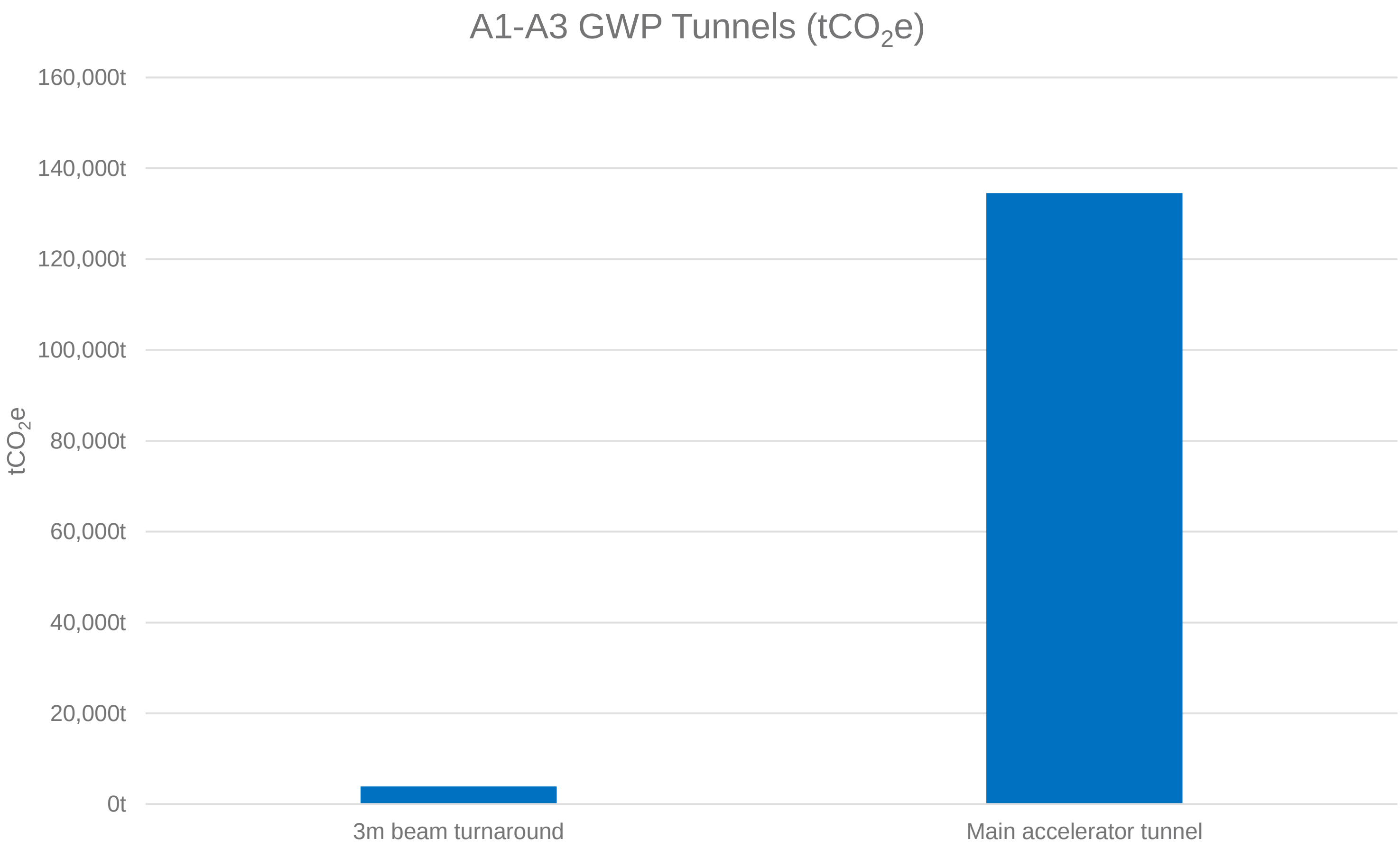
System | Sub-system | **Components** | Sub-components

Tunnels

Tunnels are inclusive of:

- 21078m 5.6m internal dia. accelerator tunnel
- 24no. 3m internal dia. beam turnarounds

As expected the main linear accelerator tunnel is the largest contributor to GWP.



CLIC Drive Beam, 3TeV

System | Sub-system | Components | **Sub-components**

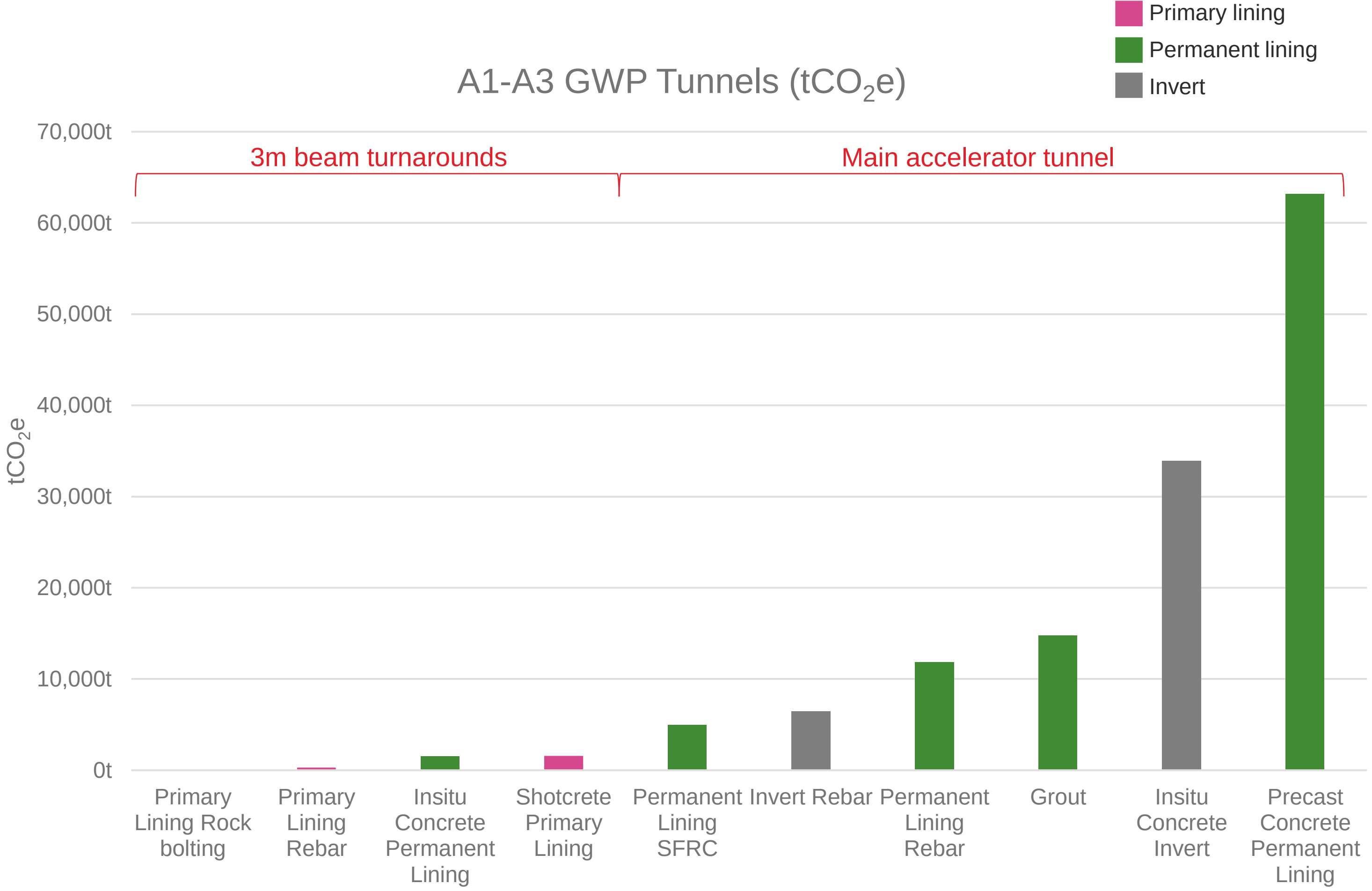
Tunnels

Tunnels are inclusive of:

- 21078m 5.6m internal dia. accelerator tunnel
- 24no. 3m internal dia. beam turnarounds

This is the last extension stage for CLIC Drive Beam.

Precast concrete permanent lining is the largest A1-A3 GWP contributor with a lining thickness of 300mm at 50MPa. This is followed by insitu concrete invert (30MPa with 60kg/m^3 rebar) and segmental lining grout (lining thickness 100mm at 20MPa).



* Note primary lining is in reference to beam turnaround design only. Not applicable to main accelerator tunnel.

CLIC Drive Beam, 3TeV

System | **Sub-system** | **Components** | **Sub-components**

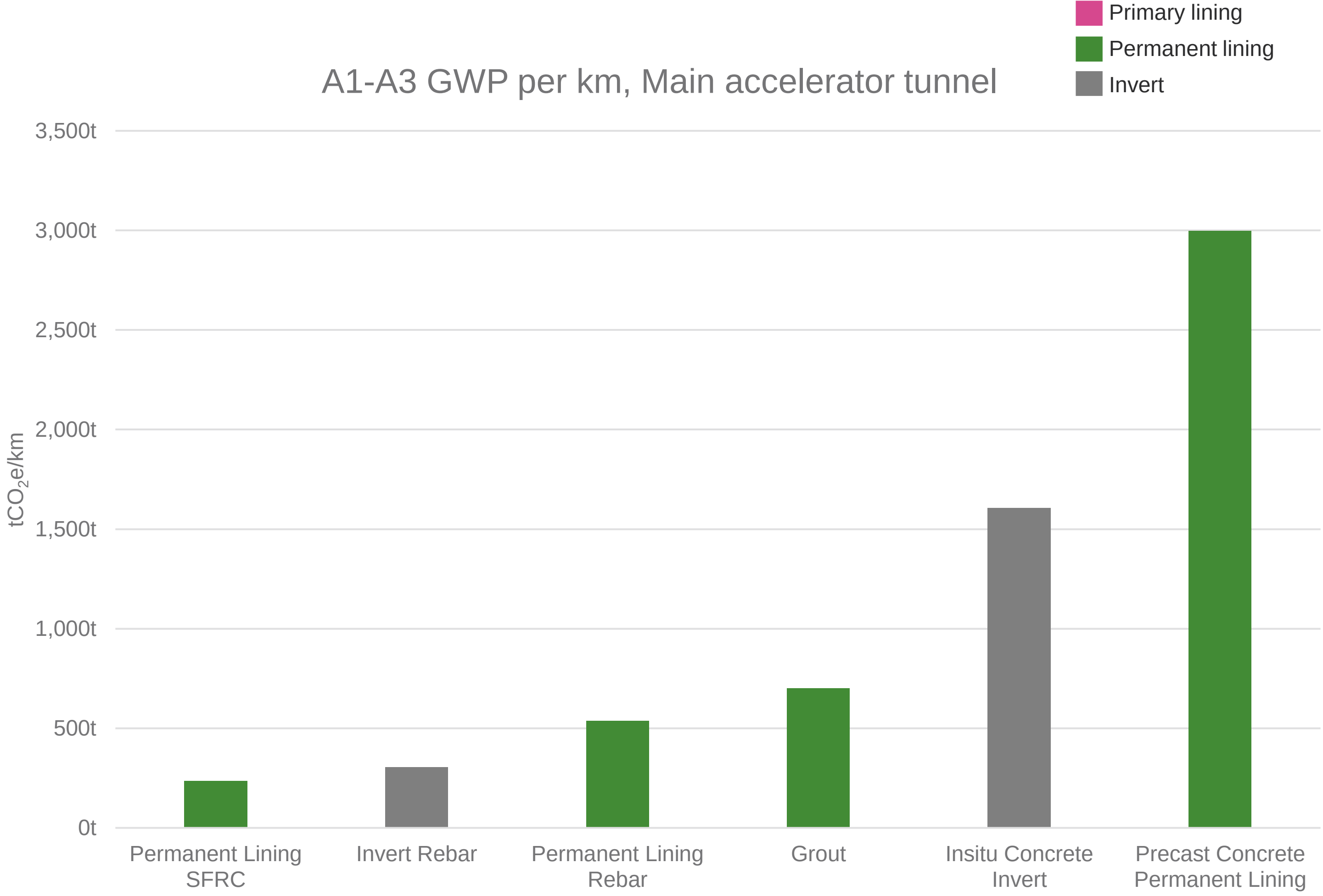
Main accelerator tunnel A1-A3 GWP / km

The main accelerator tunnel has been evaluated at sub-component level for A1-A3 GWP/km to allow comparison between the options.

Design and material parameters are detailed below:

Sub-components	
Permanent lining	**Invert**
Grout, 100mm thk, 20MPa Precast concrete, 300mm thk, 50MPa Rebar 80kg/m^3 SFRC 35kg/m^3	Insitu concrete, 30MPa Rebar 60kg/m^3

The precast concrete permanent lining and invert are the biggest A1-A3 GWP contributors per km of main accelerator tunnel.



CLIC Drive Beam, 3TeV

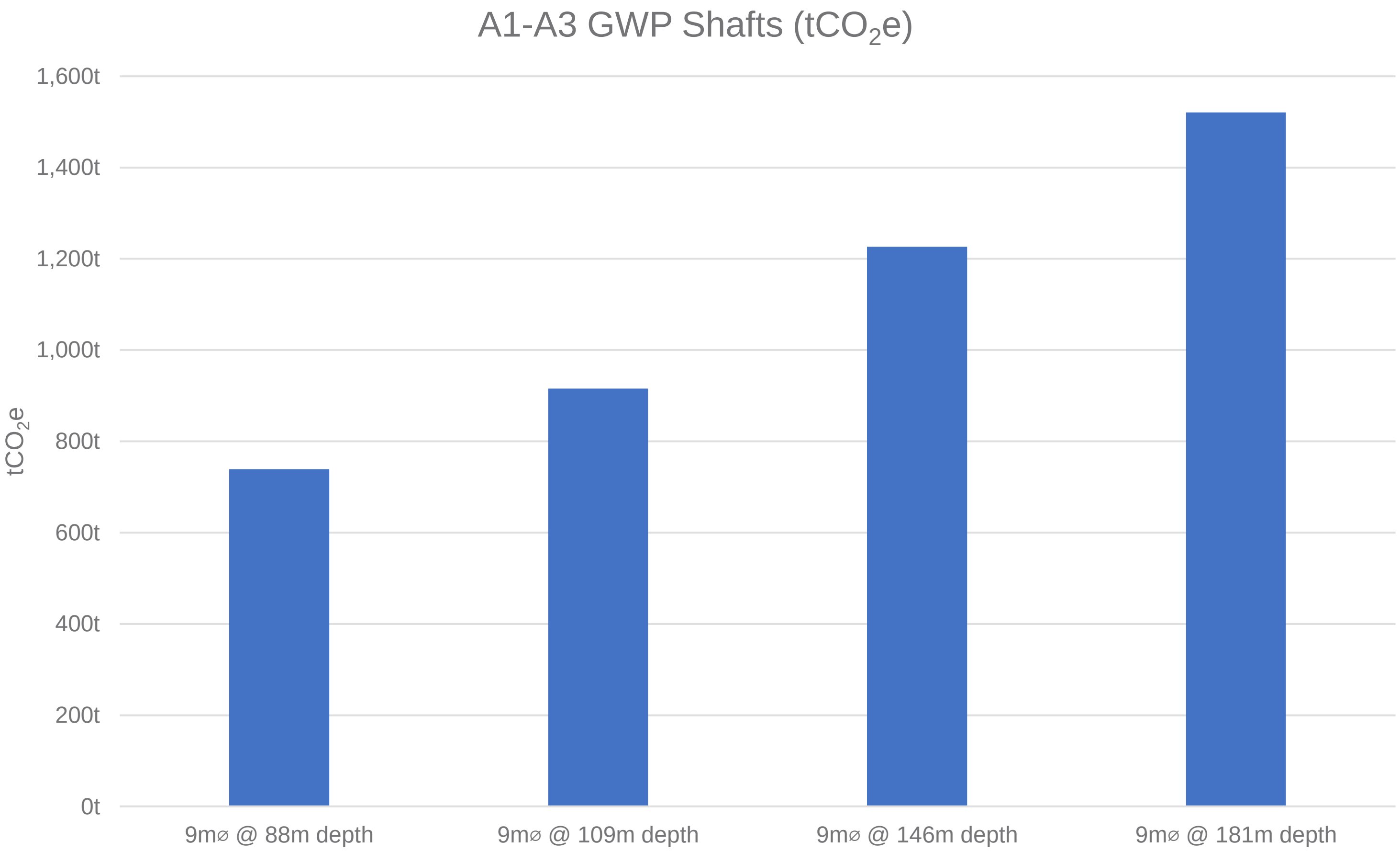
Shafts

Shafts are inclusive of:

- 1no. 9m dia. at 181m depth
- 1no. 9m dia. at 146m depth
- 1no. 9m dia. at 109m depth
- 1no. 9m dia. at 88m depth

GWP/m: 8.4 tCO_2e/m

As expected the 9m dia. shaft at 181m depth is the biggest contributor to GWP, with a lining thickness of 300mm at 40MPa.

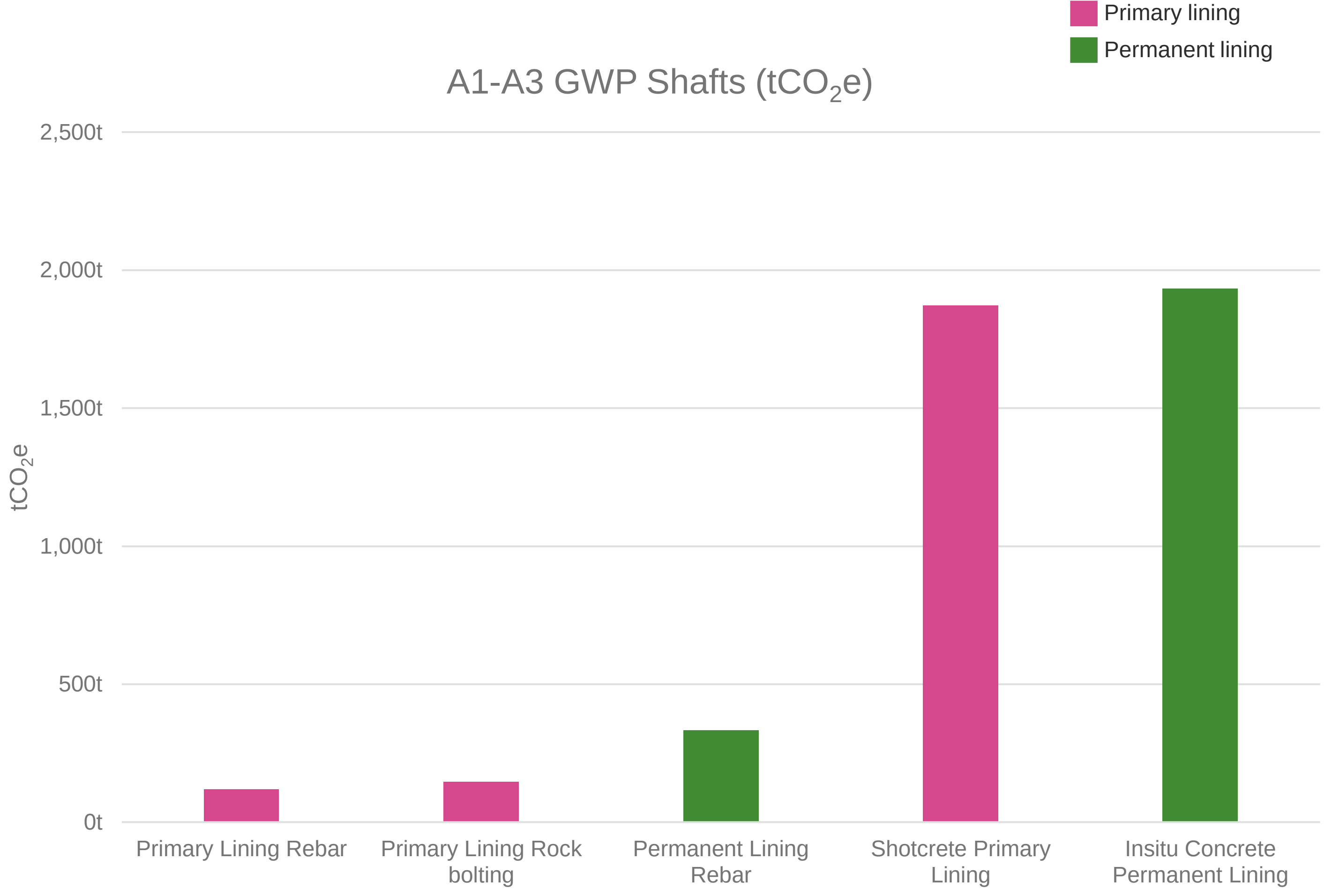


CLIC Drive Beam, 3TeV

Shafts

Shafts are inclusive of:
- 1no. 9m dia. at 181m depth
- 1no. 9m dia. at 146m depth
- 1no. 9m dia. at 109m depth
- 1no. 9m dia. at 88m depth

Insitu concrete permanent lining is the greatest contributor to A1-A3 GWP for the shafts, with a lining thickness of 300mm at 40MPa. This is closely followed by shotcrete primary lining, with a lining thickness of 300mm at 30MPa.



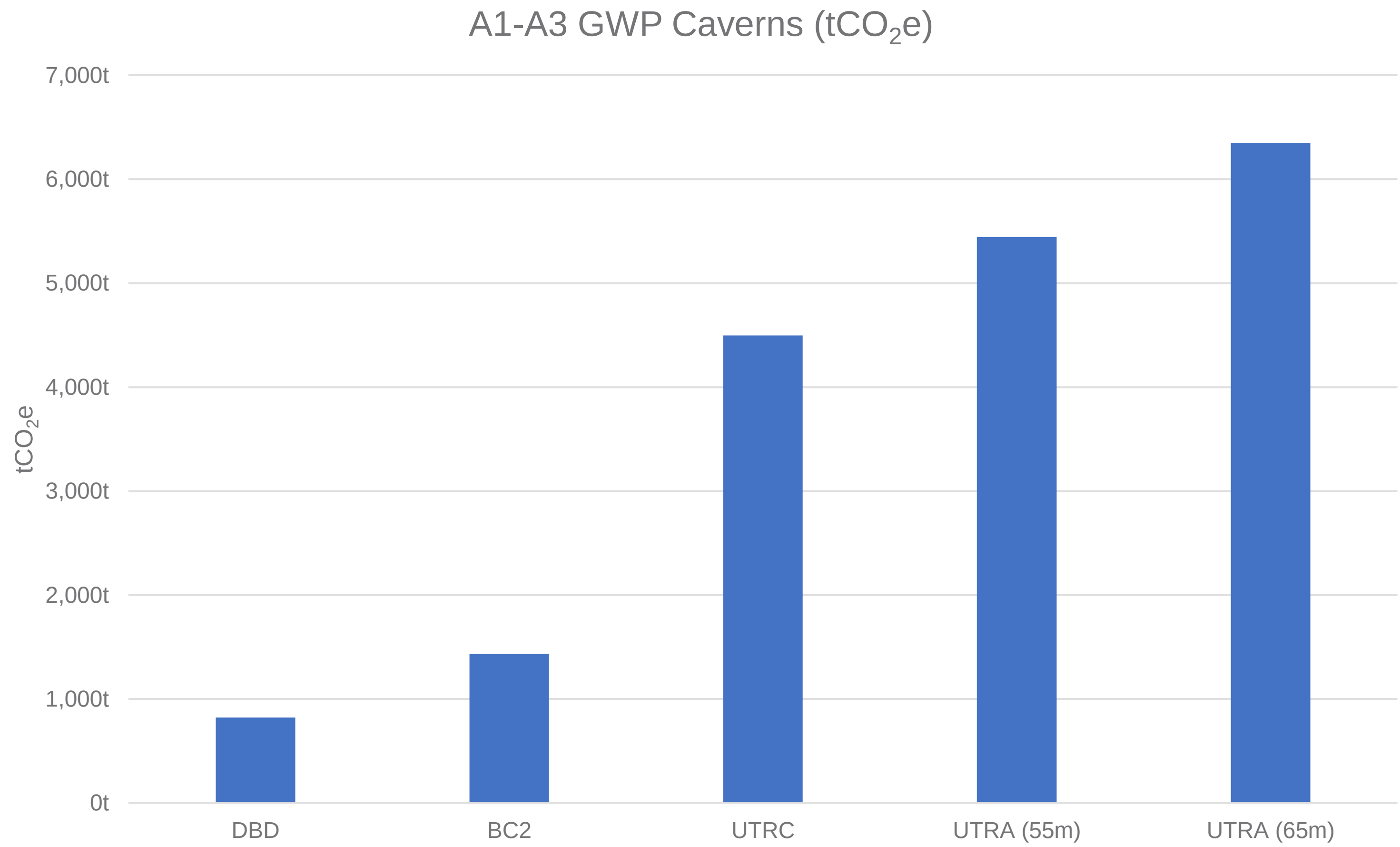
CLIC Drive Beam, 3TeV

Caverns

Caverns are inclusive of:

- 10no. UTRA cavern (65x10x7.2m)
- 10no. UTRA cavern (55x10x7.2m)
- 4no. UTRC cavern (55x16x18m)
- 2no. BC2 cavern (100x10x3m)
- 24no. Drive beam dump cavern (6x9x5m)

UTRA 65m cavern has the largest GWP contribution due to the size and number of caverns (10no.)



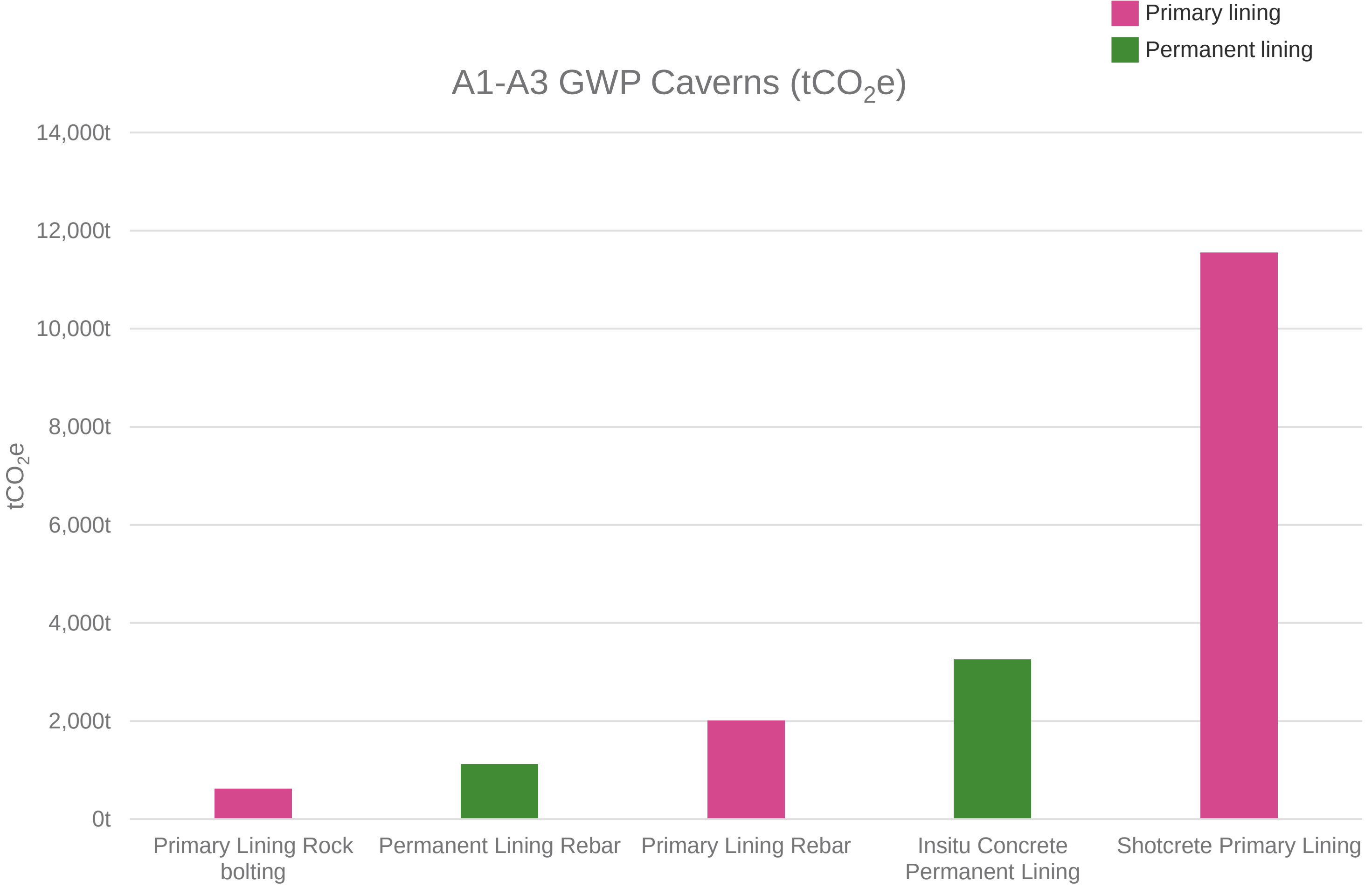
CLIC Drive Beam, 3TeV

Caverns

Caverns are inclusive of:

- 10no. UTRA cavern (65x10x7.2m)
- 10no. UTRA cavern (55x10x7.2m)
- 4no. UTRC cavern (55x16x18m)
- 2no. BC2 cavern (100x10x3m)
- 24no. Drive beam dump cavern (6x9x5m)

The shotcrete primary lining is the largest GWP contributor, this is due to the 400mm thick shotcrete primary lining. The permanent lining thickness is 110mm.



CLIC Drive Beam A1-A3 GWP Results

Conclusions

CLIC Drive Beam is proposed to be built in 3 stages to enable experiments to run at the three energies 380GeV, 1.5TeV and 3TeV.

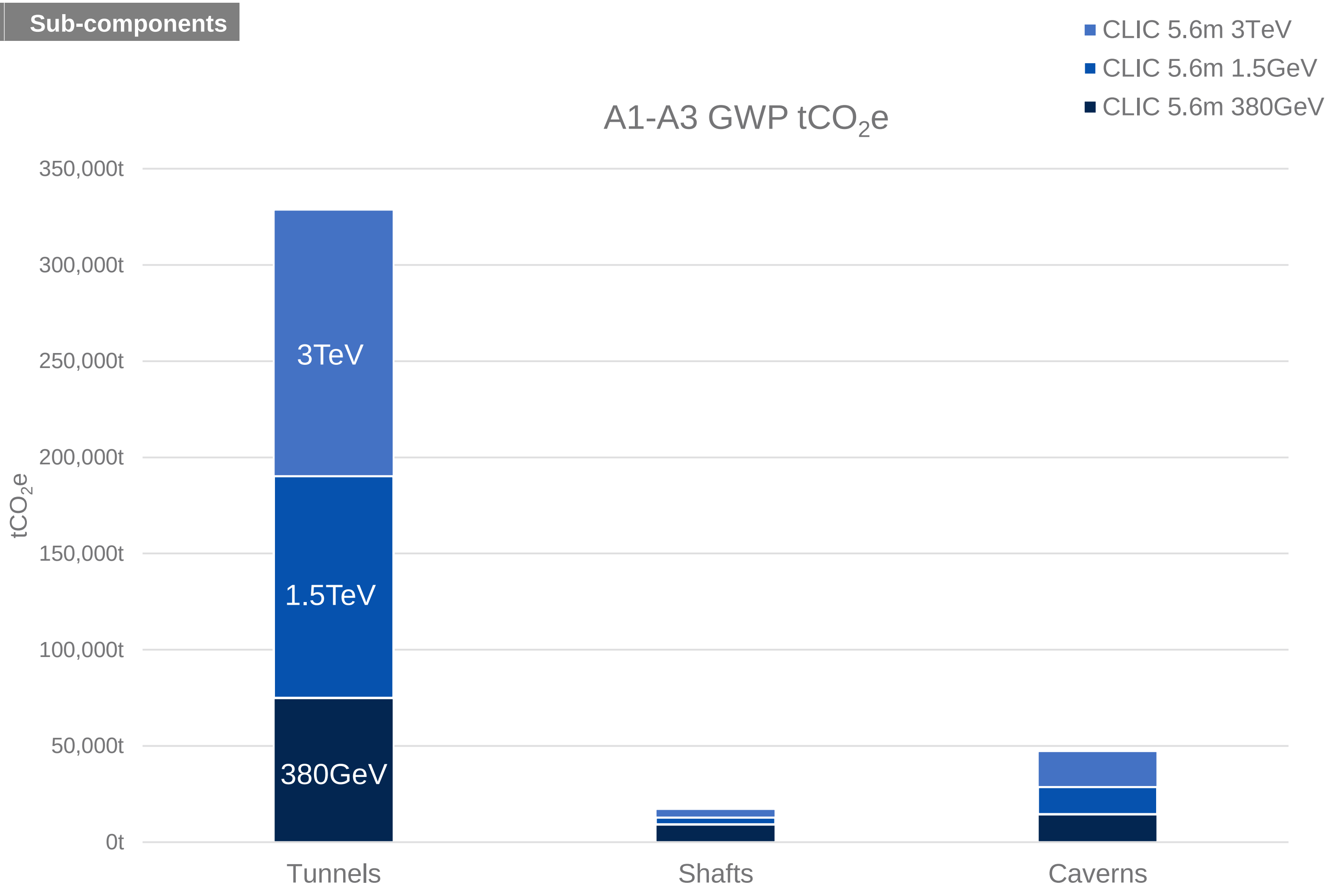
1.5TeV and 3TeV are calculated as an extension to 380GeV to reflect the 3 build stages.

Note The 1.5TeV and 3TeV extensions include the main accelerator tunnel and respective shafts and caverns. The detector hall, BDS caverns, BDS service halls, service and IR caverns are already included in 380GeV calculation and are therefore not included in the 1.5TeV and 3TeV calculation.

The increase in GWP for 1.5TeV and 3TeV compared to 380GeV is due to the increased length of tunnel.

The larger GWP contribution for the shafts for 380GeV energy is due to the larger shafts, 18m and 12m diameter shaft compared to 9m diameter for 1.5TeV and 3TeV options.

Reduction opportunities are highlighted in section 4.



CLIC Klystron A1-A3 GWP results

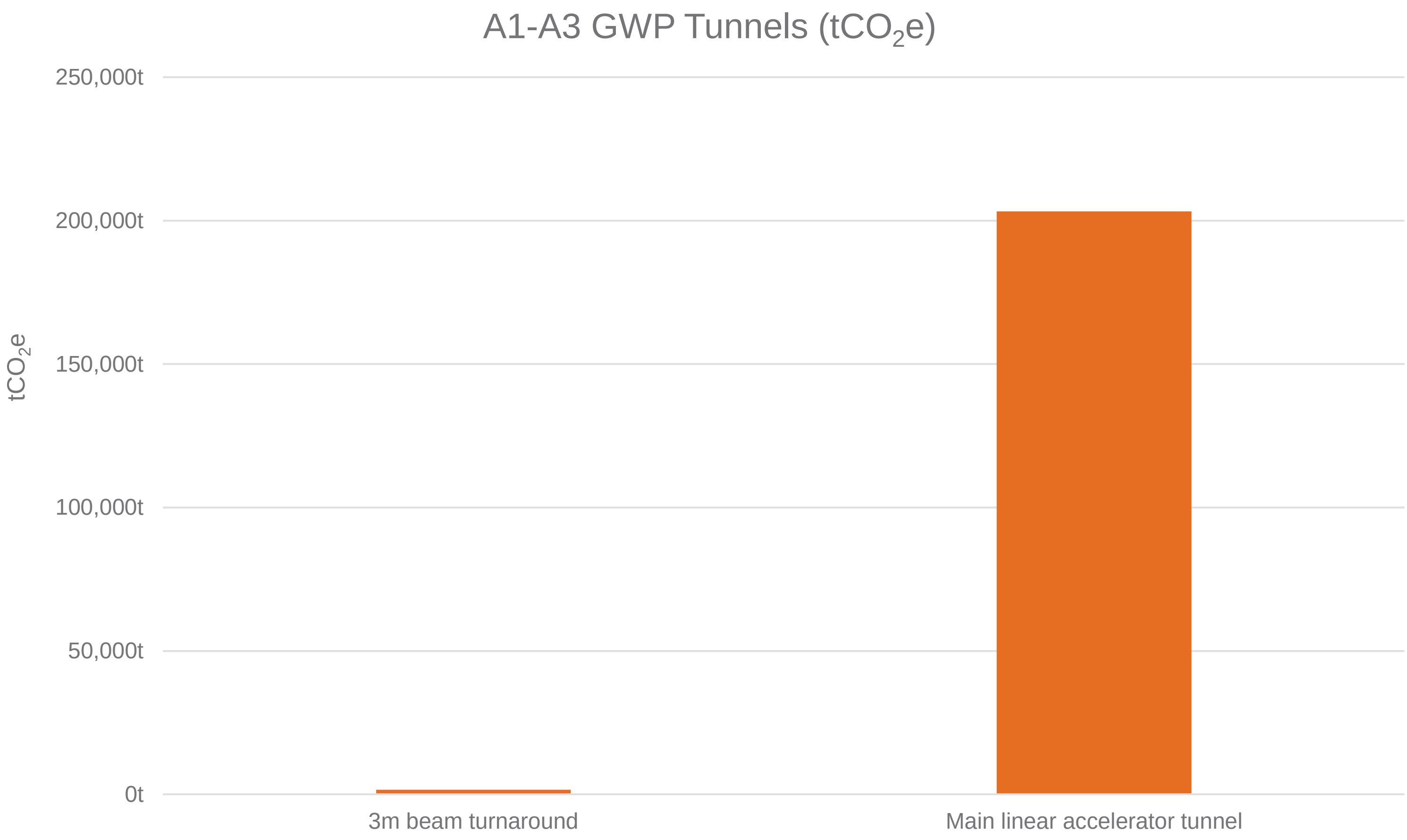
CLIC Klystron, 380GeV

System | Sub-system | **Components** | Sub-components

Tunnels

Tunnels are inclusive of:

- 11470m 10m internal dia. accelerator tunnel and shielding wall
- 10no. 3m internal dia. beam turnarounds



CLIC Klystron, 380GeV

Tunnels

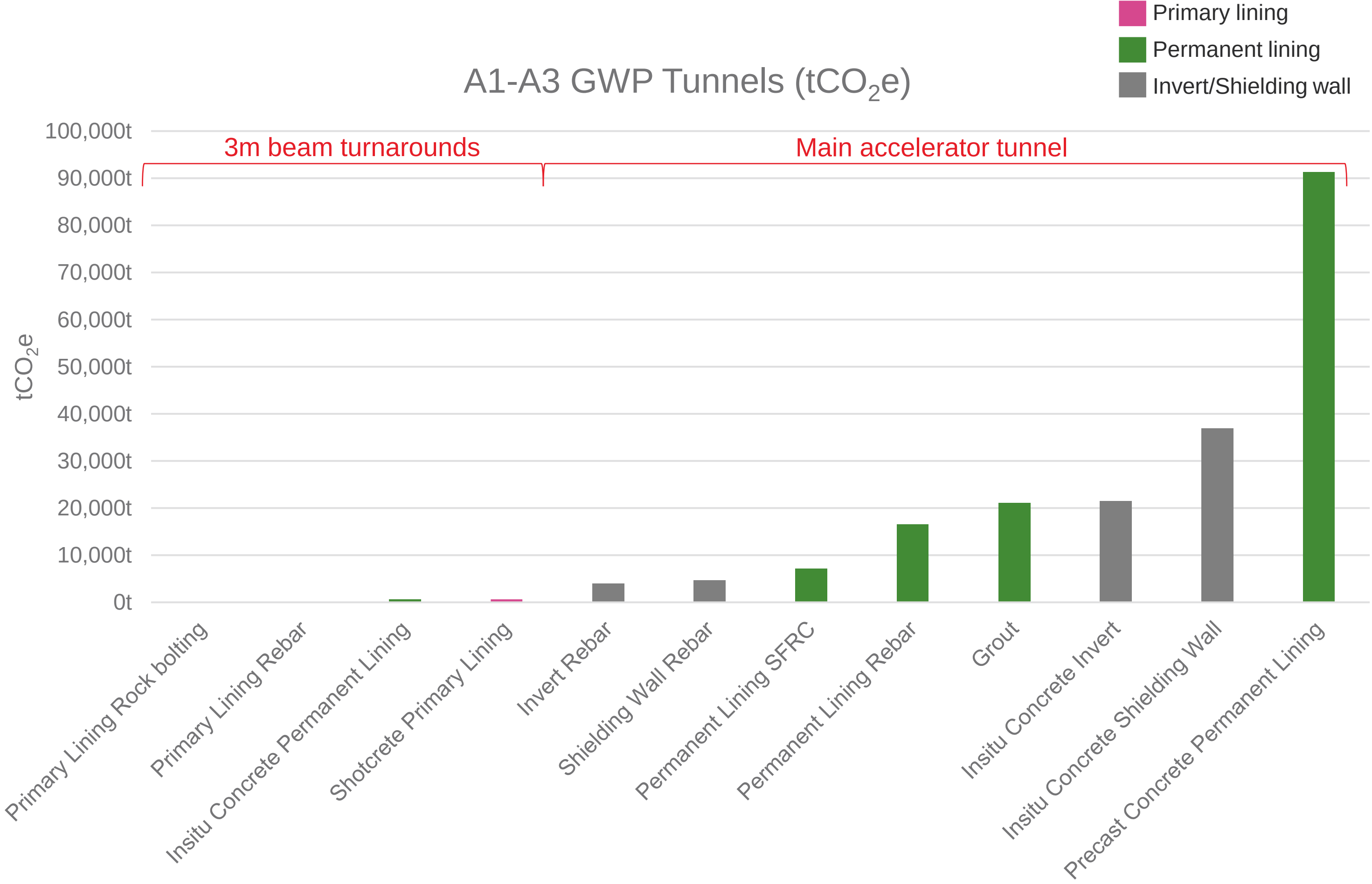
Tunnels are inclusive of:

- 11470m 10m internal dia. accelerator tunnel and shielding wall
- 10no. 3m internal dia. beam turnarounds

Precast concrete permanent lining is the largest A1-A3 GWP contributor for the tunnels sub-component level for CLIC 10m 380GeV.

As the main accelerator tunnel cross section is the only difference between CLIC Drive Beam 5.6m dia. and CLIC Klystron 10m dia. only the tunnel sub-component level is evaluated.

Please refer to CLIC Drive Beam 5.6m dia. A1-A3 GWP results for shafts and caverns.



* Note primary lining is in reference to beam turnaround design only. Not applicable to main accelerator tunnel.

CLIC Klystron, 380GeV

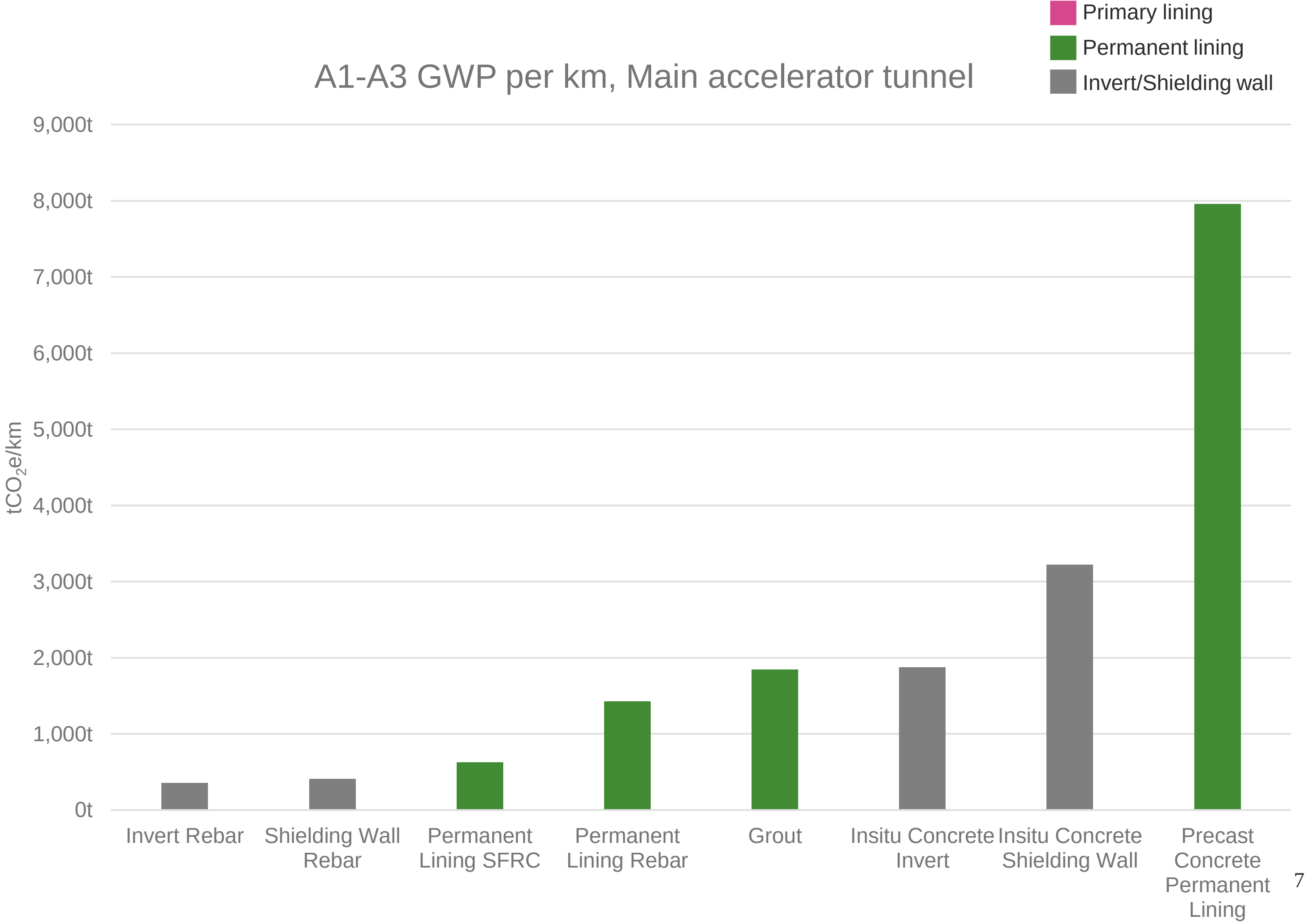
Main accelerator tunnel A1-A3 GWP / km

The main accelerator tunnel has been evaluated at sub-component level for A1-A3 GWP/km to allow comparison between the options.

Design and material parameters are detailed below:

Sub-components	
Permanent lining	**Invert / Shielding wall**
Grout, 150mm thk, 20MPa Precast concrete, 450mm thk, 50MPa Rebar 80kg/m^3 SFRC 35kg/m^3	Invert insitu concrete 30MPa, Rebar 60kg/m^3 Shielding wall insitu concrete 30MPa, Rebar 40kg/m^3

The precast concrete permanent lining, shielding wall and invert are the biggest A1-A3 GWP contributors per km of main accelerator tunnel.



CLIC Klystron A1-A5 GWP Results

System | Sub-system | Components | Sub-components

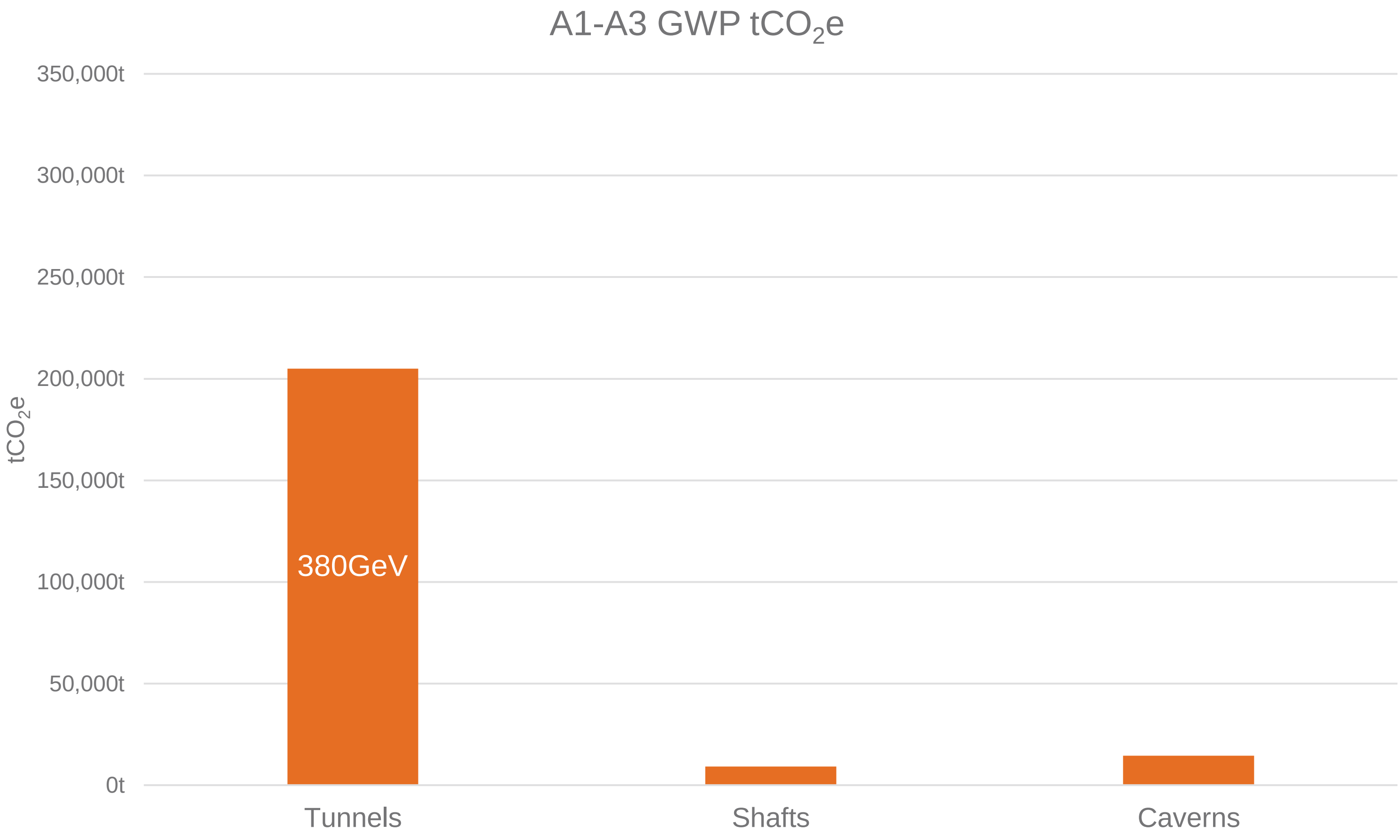
Conclusions

CLIC Klystron 10m diameter 380GeV energy was evaluated.

The shafts and caverns are exactly the same as the CLIC Drive Beam 5.6m diameter, the only difference is the tunnel cross section and diameter. Similarly to the CLIC Drive Beam 5.6m diameter, the tunnels are the largest GWP contributor.

CLIC Klystron 10m diameter 380GeV tunnel GWP is 2.7 times larger than CLIC Drive Beam 5.6m diameter 380GeV. This is due to the increased diameter and shielding wall addition to the CLIC Klystron 10m.

Reduction opportunities are highlighted in section 4.



ILC A1-A3 GWP results

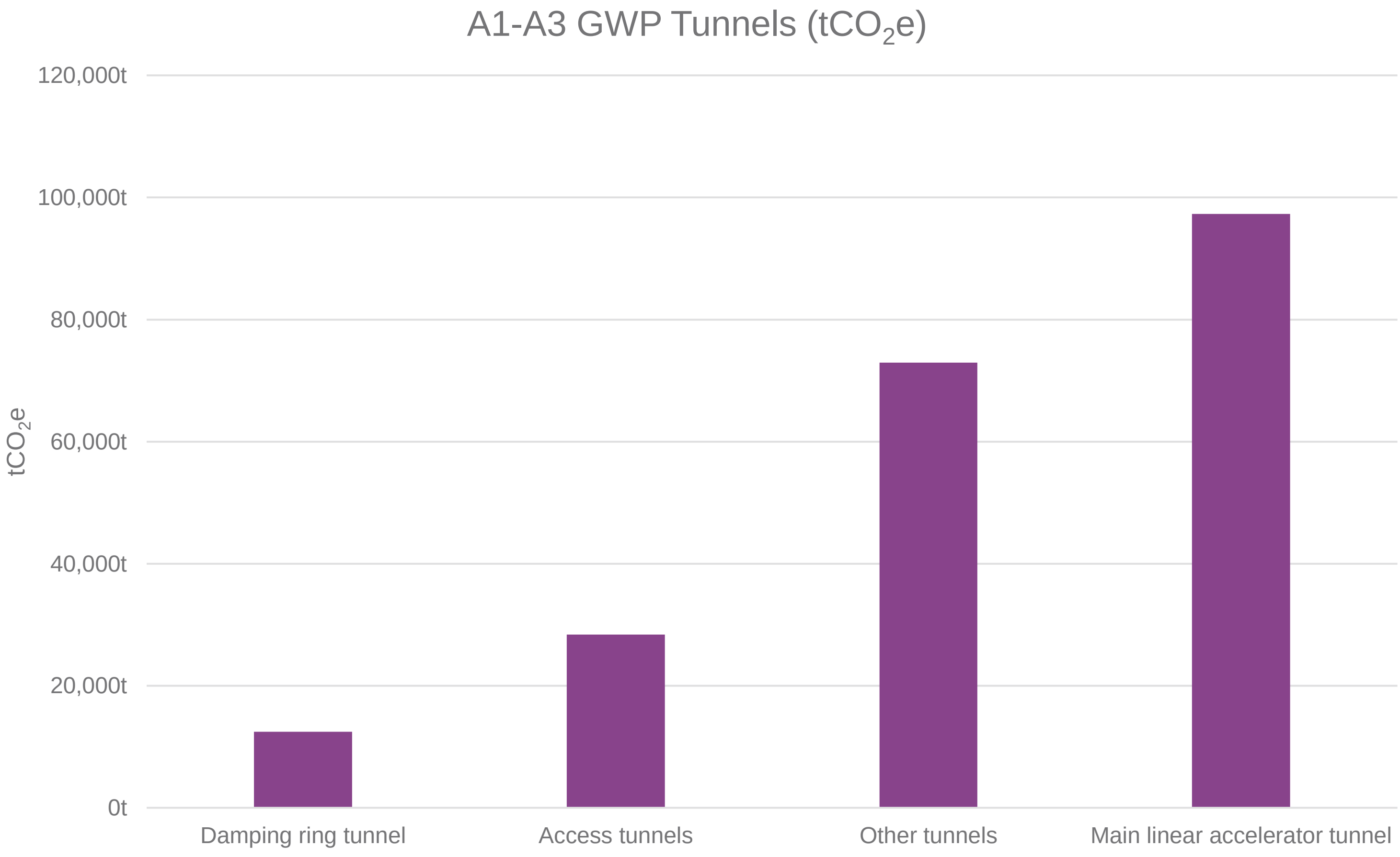
ILC, 250GeV

Tunnels

Tunnels are inclusive of (total length: 33,042m)
Main accelerator tunnel
Damping ring tunnel

Access tunnels:
- Access tunnel CI
- Access tunnel CII
- Access tunnel DI
- Access tunnel DIII
- Access tunnel DI (EPZ)
- Access tunnel CII (EPZ)

Other tunnels:
- BDS beam tunnel Section A w9.5m
- BDS beam tunnel Section B w13m
- BDS beam tunnel Section C w17m
- BDS beam tunnel Section D w25m
- Loop sections at both ends
- Widening sections
- Reversal pits
- Peripheral tunnel 3.0m
- Peripheral tunnel 4.0m
- Peripheral tunnel 6.0m
- Peripheral tunnel 8.0m
- AT-DH and AT-DR tunnels
- RTML tunnels

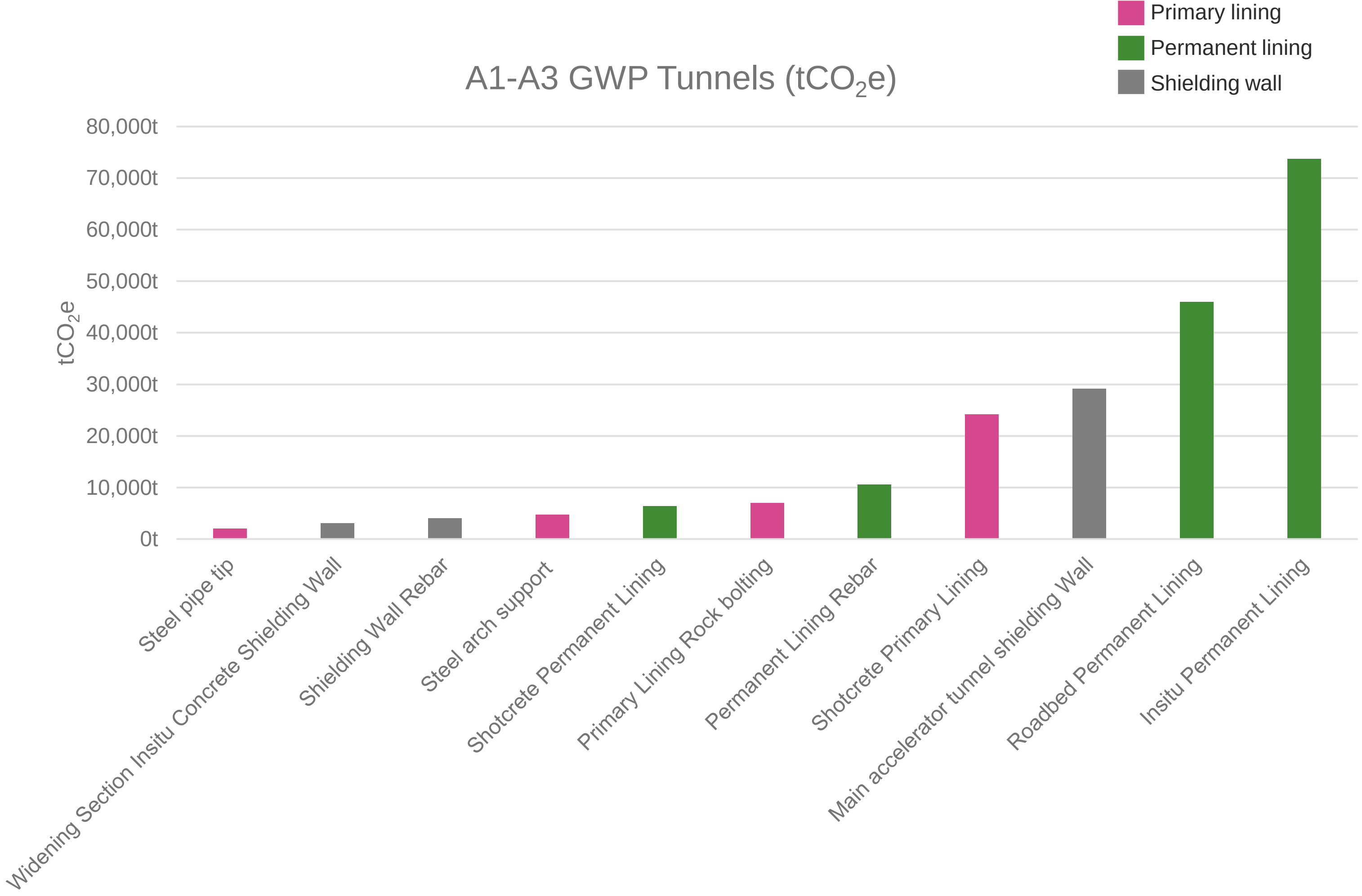


ILC, 250GeV

System | Sub-system | Components | **Sub-components**

Tunnels

Insitu permanent lining is the largest GWP contributor due to its larger thickness compared to the shotcrete primary lining – see ILC design parameters for lining thicknesses for all the tunnels.



ILC, 250GeV

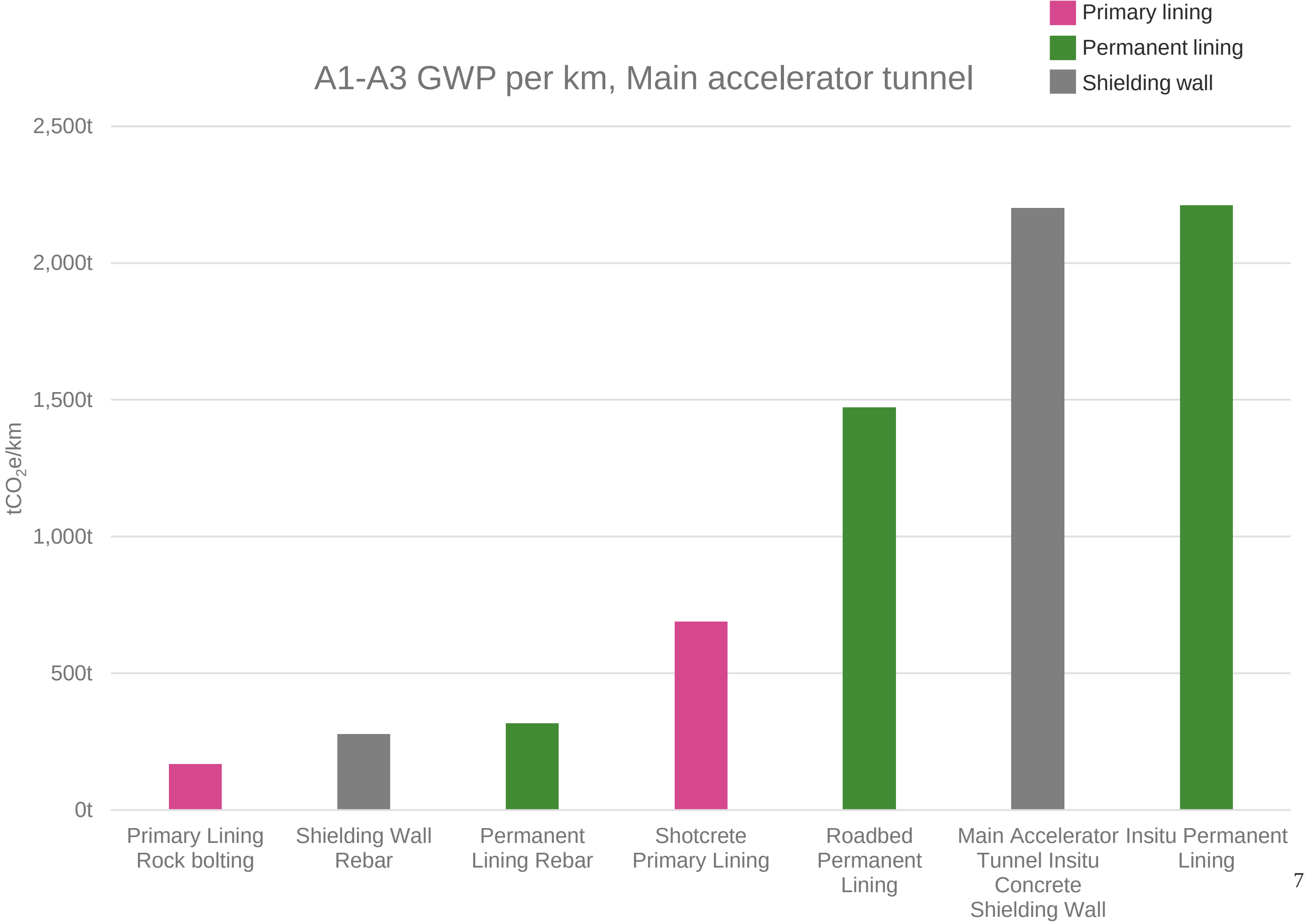
Main accelerator tunnel A1-A3 GWP / km

The main accelerator tunnel has been evaluated at sub-component level for A1-A3 GWP/km to allow comparison between the options.

Design and material parameters are detailed below:

Sub-components		
Primary lining	**Permanent lining**	**Shielding wall**
Shotcrete, 100mm thk, 30MPa Rock bolts, L=3m, 25mm dia.	Insitu concrete, 300mm thk, 40MPa Rebar density 50kg/m^3 Roadbed concrete, 400mm thk, 40MPa	Shielding wall 30MPa Rebar 40kg/m^3

The insitu permanent lining, shielding wall and roadbed permanent lining are the biggest A1-A3 GWP contributors per km of main accelerator tunnel.



ILC, 250GeV

Shafts

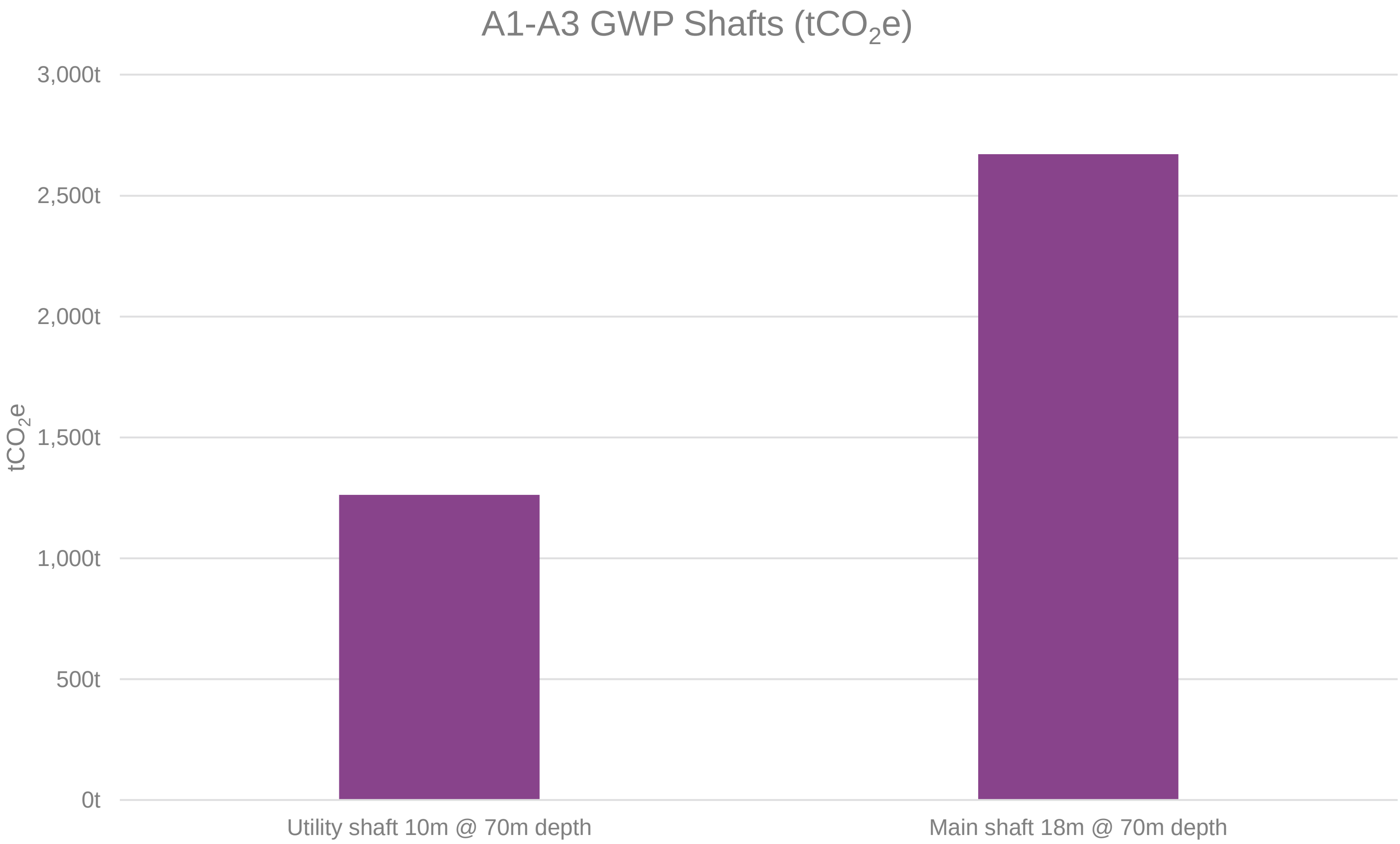
Shafts are inclusive of:

- Main shaft 18m dia. at 70m depth
- Utility shaft 10m dia. at 70m depth

GWP/m:

Shafts	tCO_2e/m
18m dia. at 70m depth	38.2
10m dia. at 70m depth	18.0

As expected the 18m dia. shaft at 70m depth is the biggest contributor to GWP.



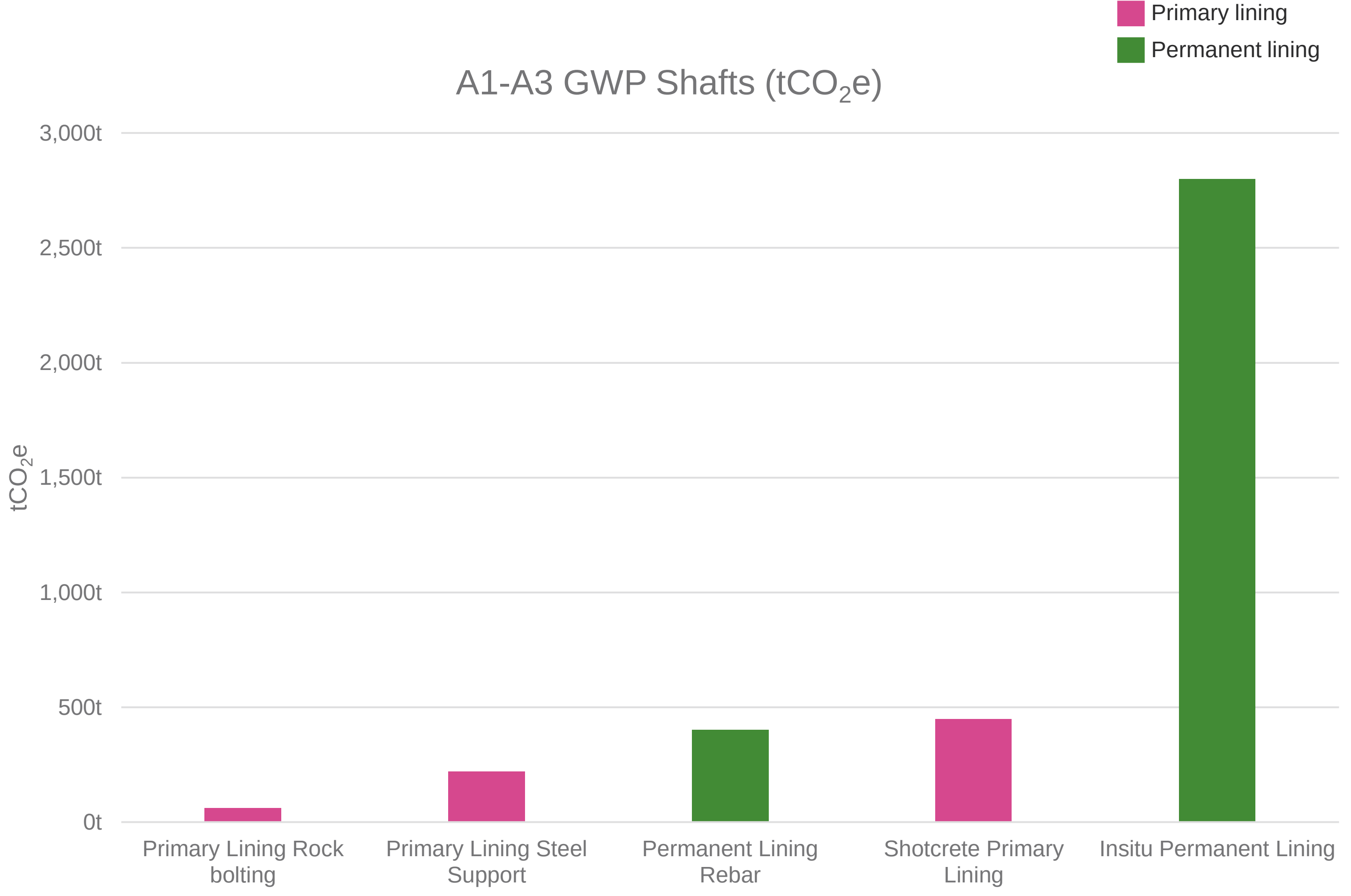
ILC, 250GeV

System | Sub-system | Components | **Sub-components**

Shafts

Shafts are inclusive of:
- Main shaft 18m dia. at 70m depth
- Utility shaft 10m dia. at 70m depth

Insitu concrete permanent lining is the greatest contributor to A1-A3 GWP for the shafts. The insitu concrete permanent lining for 18m shaft is 1000mm thick. The insitu concrete lining for 9m shaft is 800mm thick. The shotcrete primary lining has a smaller thickness than the permanent lining, ranging between 125-200mm.



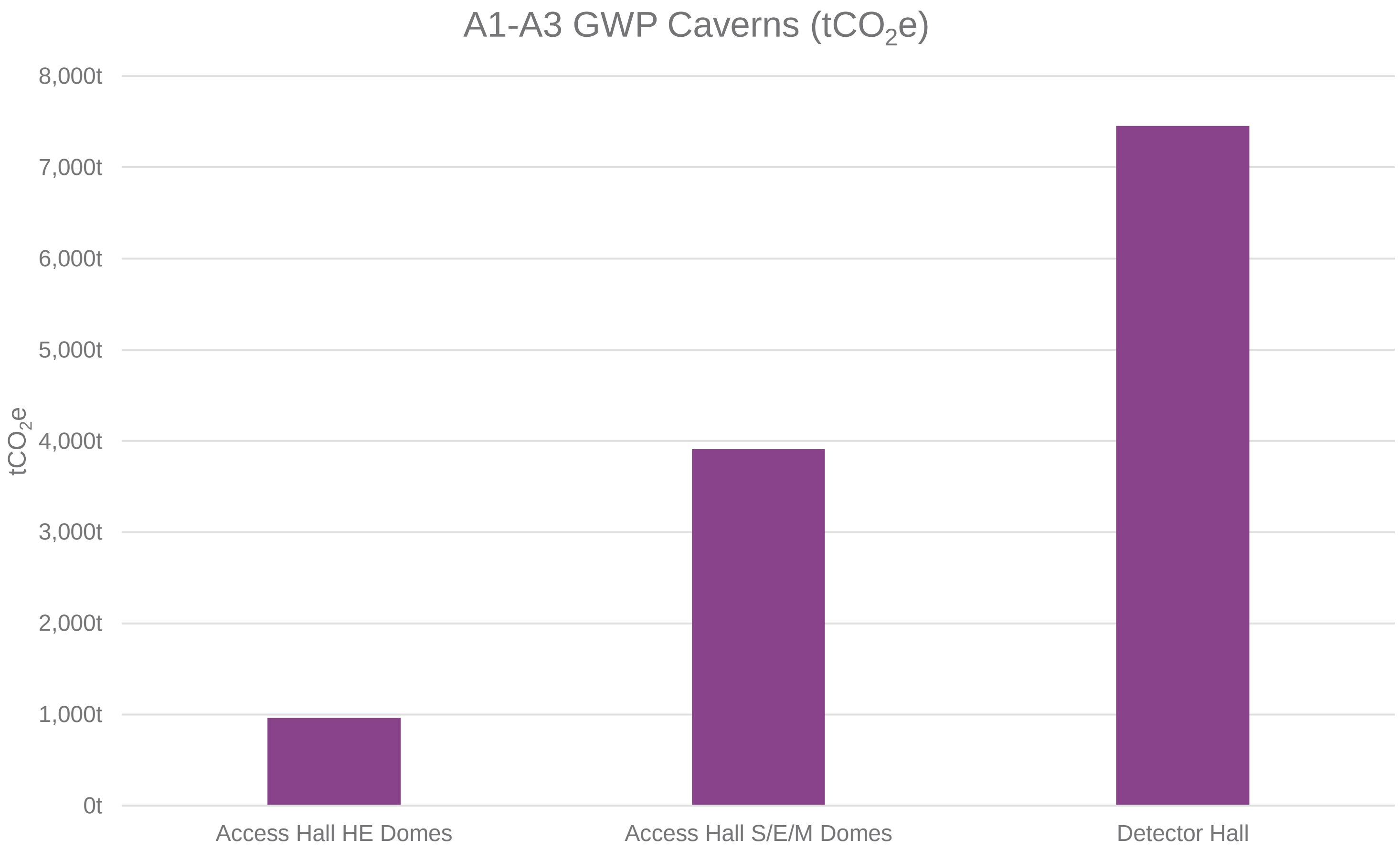
ILC, 250GeV

System | Sub-system | **Components** | Sub-components

Caverns

Caverns are inclusive of:
- Access hall S/E/M Domes
- Access Hall HE Domes
- Detector Hall

The detector hall is the largest GWP contributor compared to the access Hall S/E/M/He Domes.

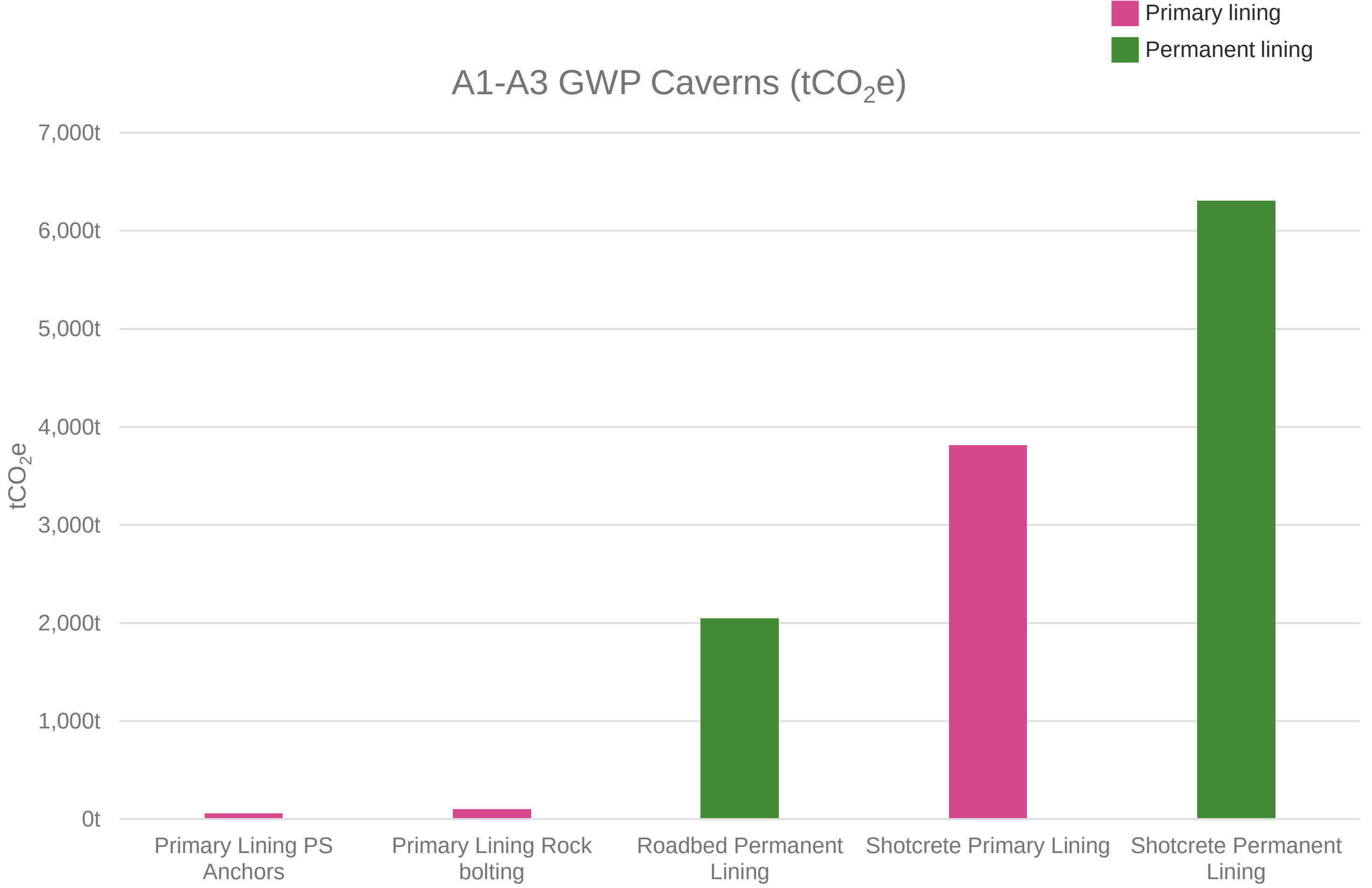


ILC, 250GeV

Caverns

Caverns are inclusive of:
- Access hall S/E/M Domes
- Access Hall HE Domes
- Detector Hall

The shotcrete permanent lining is the largest GWP contributor, this is due to the detector hall having a large volume of shotcrete permanent lining.



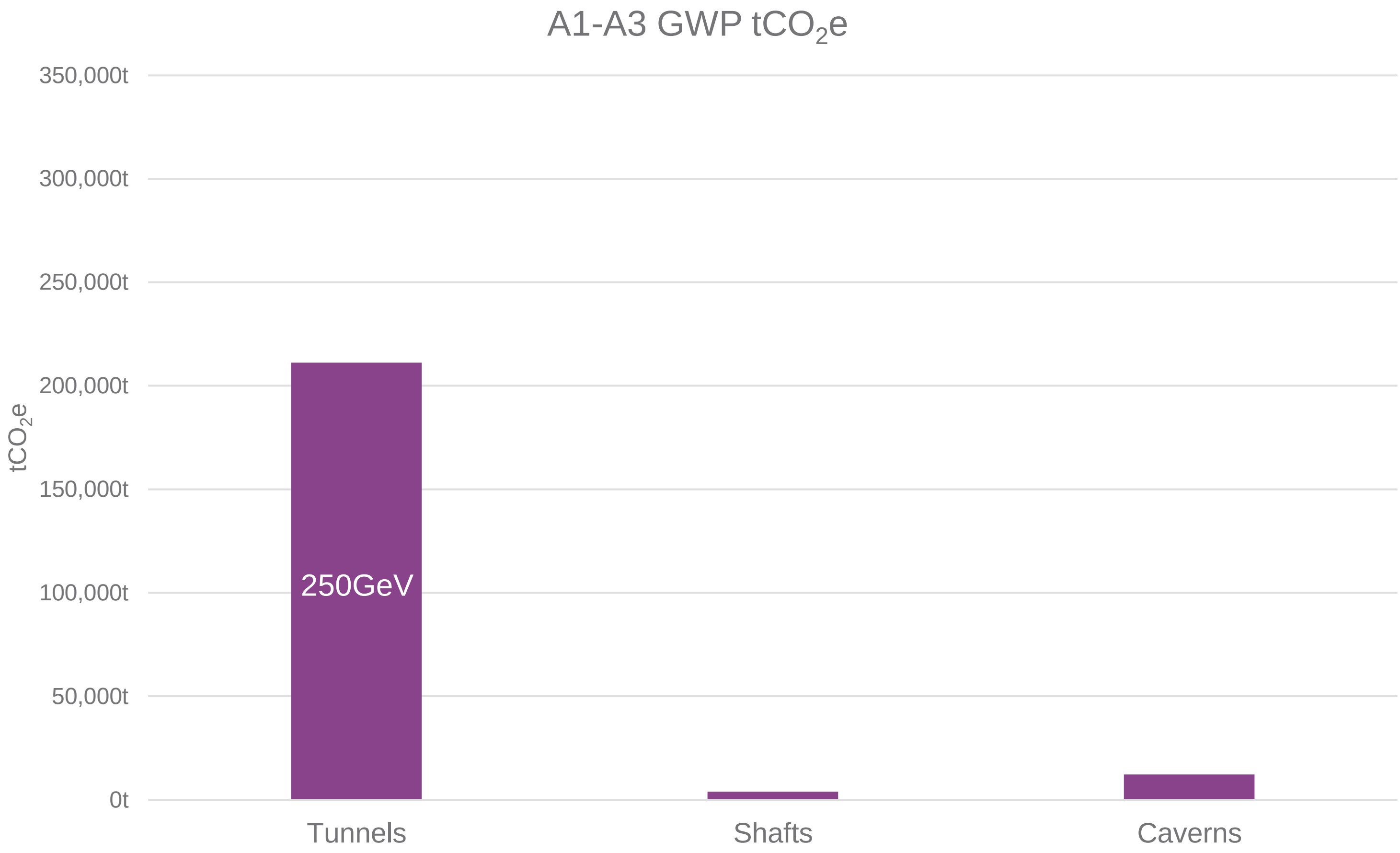
ILC 250GeV GWP Results

Conclusions

ILC 9.5m span 250GeV energy was evaluated.

The tunnels have the largest A1-A3 GWP contribution.

Reduction opportunities are highlighted in section 4.



2.5 A1-A5 Other Midpoint Impact Categories results

Other Impact Categories

Midpoint Impact Categories

In addition to GWP, 17 impact categories have been evaluated through the ReCiPe Midpoint (H) 2016 method.

These other impact categories are useful to evaluate as they detail the wider environmental impacts. GWP is just one aspect of environmental impact which contributes to the increase in greenhouse gas emissions. For example, ozone depletion, acidification and eutrophication impact categories evaluate the A1-A5 impacts on these environmental areas of concern.

All 18 impact categories are reported as relative contribution of A1-A5 to environmental impact.

Midpoint Impact Categories	Abbr.	Unit	Environmental issue measured
Global warming	GWP	kg CO_2 eq	Increased greenhouse gas emissions increases global mean temperature
Stratospheric ozone depletion	ODP	kg CFC-11 eq	Emissions of Ozone Depleting Substances (ODSs) increases UVB radiation
Ionizing radiation	IRP	kBq Co-60 eq	Anthropogenic emissions of radionuclides generated in the nuclear fuel cycle (mining, processing, waste disposal) as well as burning coal. Dispersion is modelled and exposure to population is measured.
Fine particulate matter formation	PMFP	kg PM2.5 eq	Air pollution that causes primary and secondary aerosols in atmosphere which has negative impact on human health. Fine particulate matter with a diameter of less than 2.5 µm (PM2.5) can cause human health problems.
Ozone formation, human health	HOFP	kg NO_x eq	Air pollutants formed as a result of photochemical reactions of NO_x and Non Methane Volatile Organic Compounds (NMVOCs). It is a health hazard for humans as can inflame airways and damage lungs.
Ozone formation, terrestrial ecosystems	EOFP	kg NO_x eq	Air pollutants formed as a result of photochemical reactions of NO_x and Non Methane Volatile Organic Compounds (NMVOCs). It has negative impact on vegetation including reduction of growth and seed production.
Terrestrial acidification	TAP	kg SO_2 eq	Acidification of soils predominately through transformation of air pollutants (NO_x, NH_3 or SO_2) to acids. A serious deviation from optimum acidity level is harmful for that kind of species, and is referred to as acidification.
Freshwater eutrophication	FEP	kg P eq	Discharge of nutrients into soil or freshwater bodies increasing nutrients levels (phosphorus and nitrogen), increasing plant and algae growth. Leads to relative loss of species.
Marine eutrophication	MEP	kg N eq	Discharge of plant nutrients from soil into marine systems increasing nutrients levels (phosphorus and nitrogen). It is assumed N is limiting nutrient in marine waters. Leads to marine ecosystem disturbance and disappearance.
Terrestrial ecotoxicity	TETP	kg 1,4-DCB	Pollutants that are toxic to land-dependent ecosystems.
Freshwater ecotoxicity	FETP	kg 1,4-DCB	Pollutants that are toxic to freshwater ecosystems.
Marine ecotoxicity	METP	kg 1,4-DCB	Pollutants that are toxic to marine ecosystems.
Human carcinogenic toxicity	HTPc	kg 1,4-DCB	Risk increase of cancer disease incidence.
Human non-carcinogenic toxicity	HTPnc	kg 1,4-DCB	Risk increase of non-cancer disease incidence.
Land use	LOP	m^2a crop eq	Relative loss of species due to local land use.
Mineral resource scarcity	SOP	kg Cu eq	Reduction of the global amount of non-renewable raw materials – minerals and metals.
Fossil resource scarcity	FFP	kg oil eq	Describes reduction of the global amount of non-renewable raw materials – fossil fuels.
Water consumption	WCP	m^3	Mains, surface and groundwater consumption leading to reduction in freshwater availability, thus water shortage for irrigation, reduction in plant diversity and changed river discharge.

Reference: ReCiPe Midpoint (H) 2016

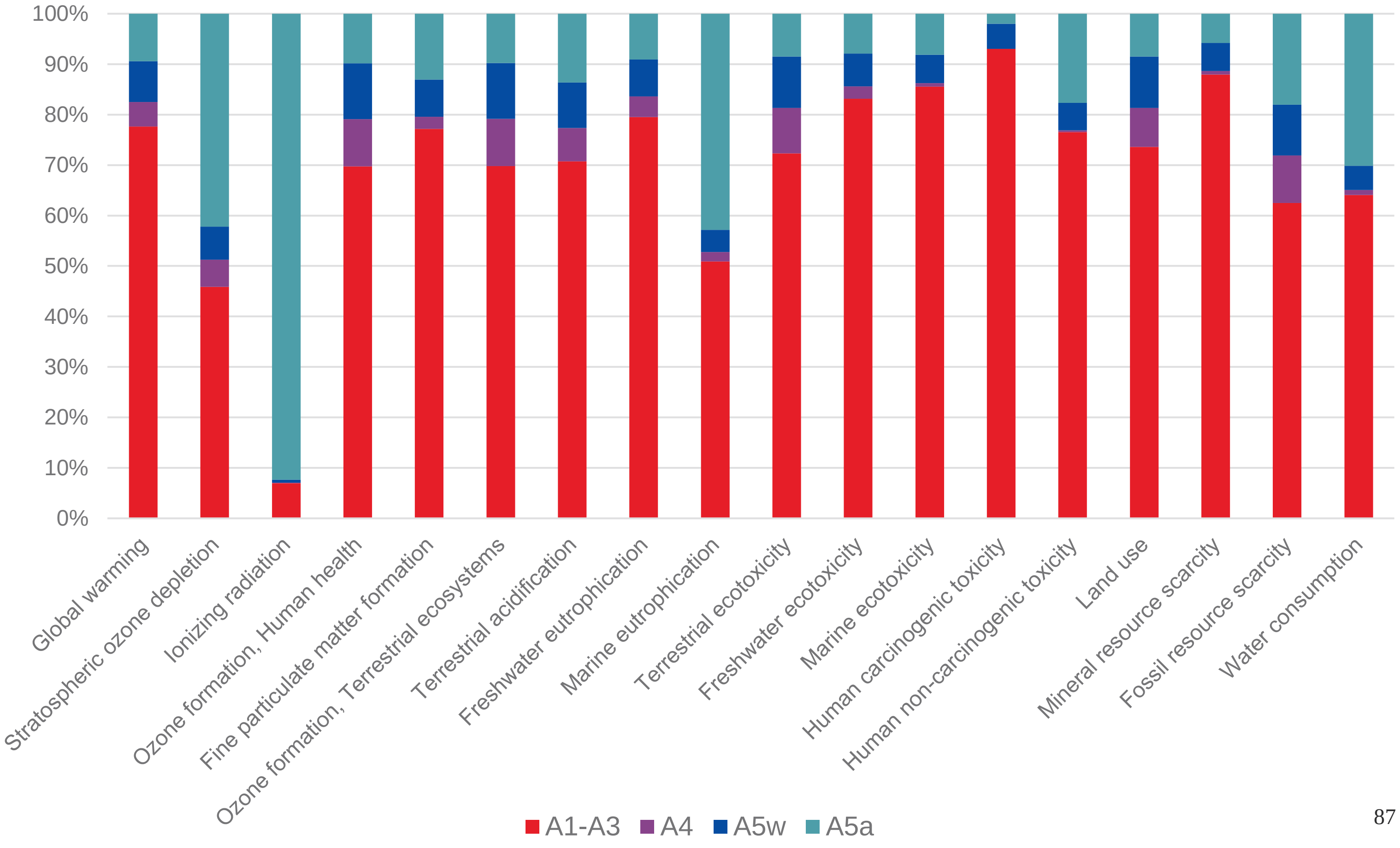
CLIC Drive Beam, 380GeV

A1-A5 results

The absolute values are reported below:

Midpoint Impact Categories	Absolute value	Unit
Global warming	1.27E8	kg CO$_2$ eq
Stratospheric ozone depletion	38	kg CFC-11 eq
Ionizing radiation	5.85E7	kBq Co-60 eq
Fine particulate matter formation	3.21E5	kg PM2.5 eq
Ozone formation, Human health	1.11E5	kg NO$_x$ eq
Ozone formation, Terrestrial ecosystems	3.28E5	kg NO$_x$ eq
Terrestrial acidification	2.84E5	kg SO$_2$ eq
Freshwater eutrophication	2.90E4	kg P eq
Marine eutrophication	3.11E3	kg N eq
Terrestrial ecotoxicity	4.29E8	kg 1,4-DCB
Freshwater ecotoxicity	4.31E6	kg 1,4-DCB
Marine ecotoxicity	5.77E6	kg 1,4-DCB
Human carcinogenic toxicity	3.28E7	kg 1,4-DCB
Human non-carcinogenic toxicity	6.78E7	kg 1,4-DCB
Land use	5.07E6	m^{2}a crop eq
Mineral resource scarcity	1.23E6	kg Cu eq
Fossil resource scarcity	2.14E7	kg oil eq
Water consumption	1.21E6	m^3

CLIC Drive Beam 380GeV | Relative contribution of A1-A5 to environmental impact



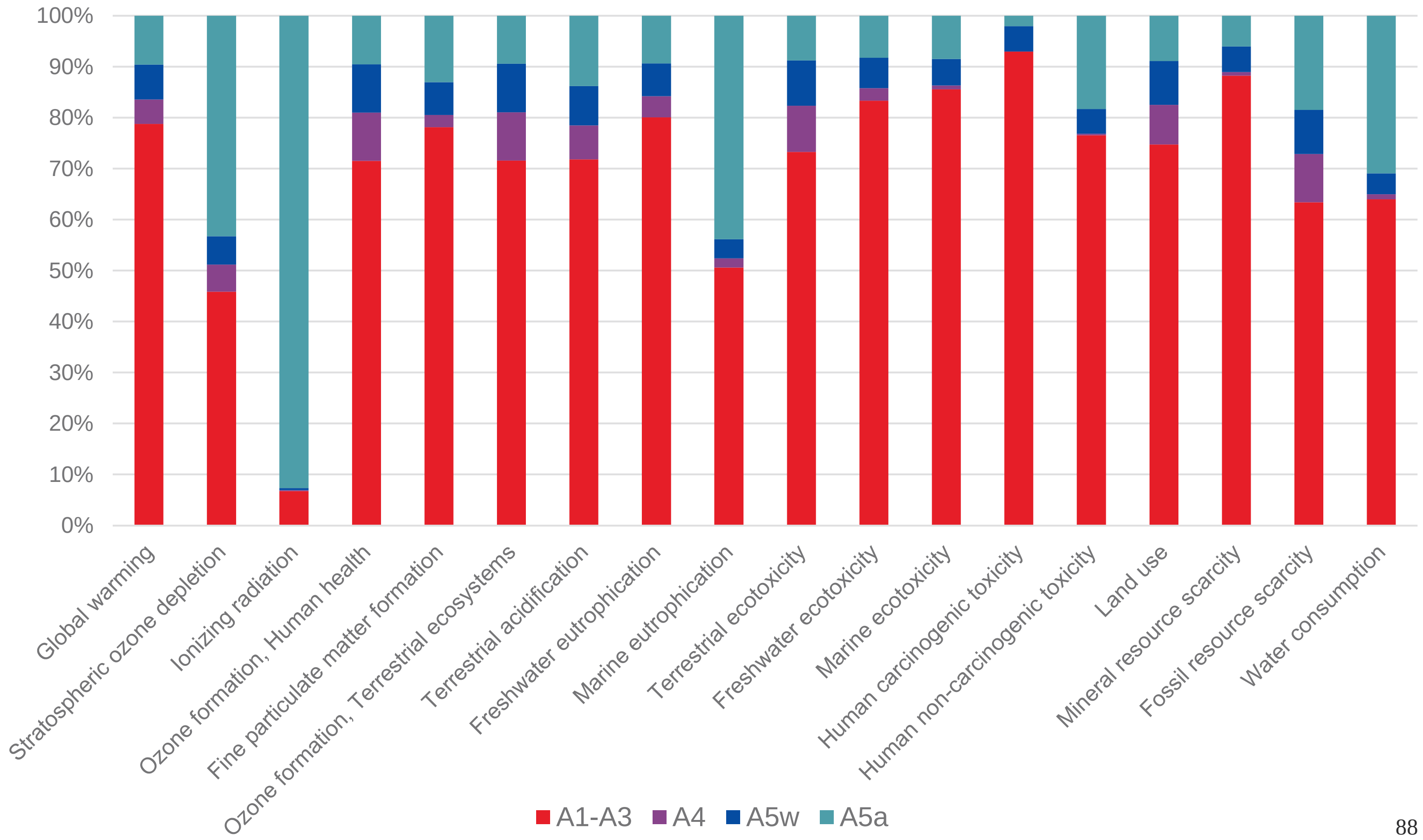
CLIC Drive Beam, 1.5TeV

A1-A5 results

The absolute values are reported below:

Midpoint Impact Categories	Absolute value	Unit
Global warming	1.69E8	kg CO_2 eq
Stratospheric ozone depletion	51	kg CFC-11 eq
Ionizing radiation	8.08E7	kBq Co-60 eq
Fine particulate matter formation	4.21E5	kg PM2.5 eq
Ozone formation, Human health	1.47E5	kg NO_x eq
Ozone formation, Terrestrial ecosystems	4.30E5	kg NO_x eq
Terrestrial acidification	3.76E5	kg SO_2 eq
Freshwater eutrophication	3.84E4	kg P eq
Marine eutrophication	4.20E3	kg N eq
Terrestrial ecotoxicity	5.67E8	kg 1,4-DCB
Freshwater ecotoxicity	5.69E6	kg 1,4-DCB
Marine ecotoxicity	7.63E6	kg 1,4-DCB
Human carcinogenic toxicity	4.31E7	kg 1,4-DCB
Human non-carcinogenic toxicity	9.04E7	kg 1,4-DCB
Land use	6.67E6	m^{2}a crop eq
Mineral resource scarcity	1.63E6	kg Cu eq
Fossil resource scarcity	2.84E7	kg oil eq
Water consumption	1.63E6	m^3

CLIC Drive Beam 1.5TeV | Relative contribution of A1-A5 to environmental impact

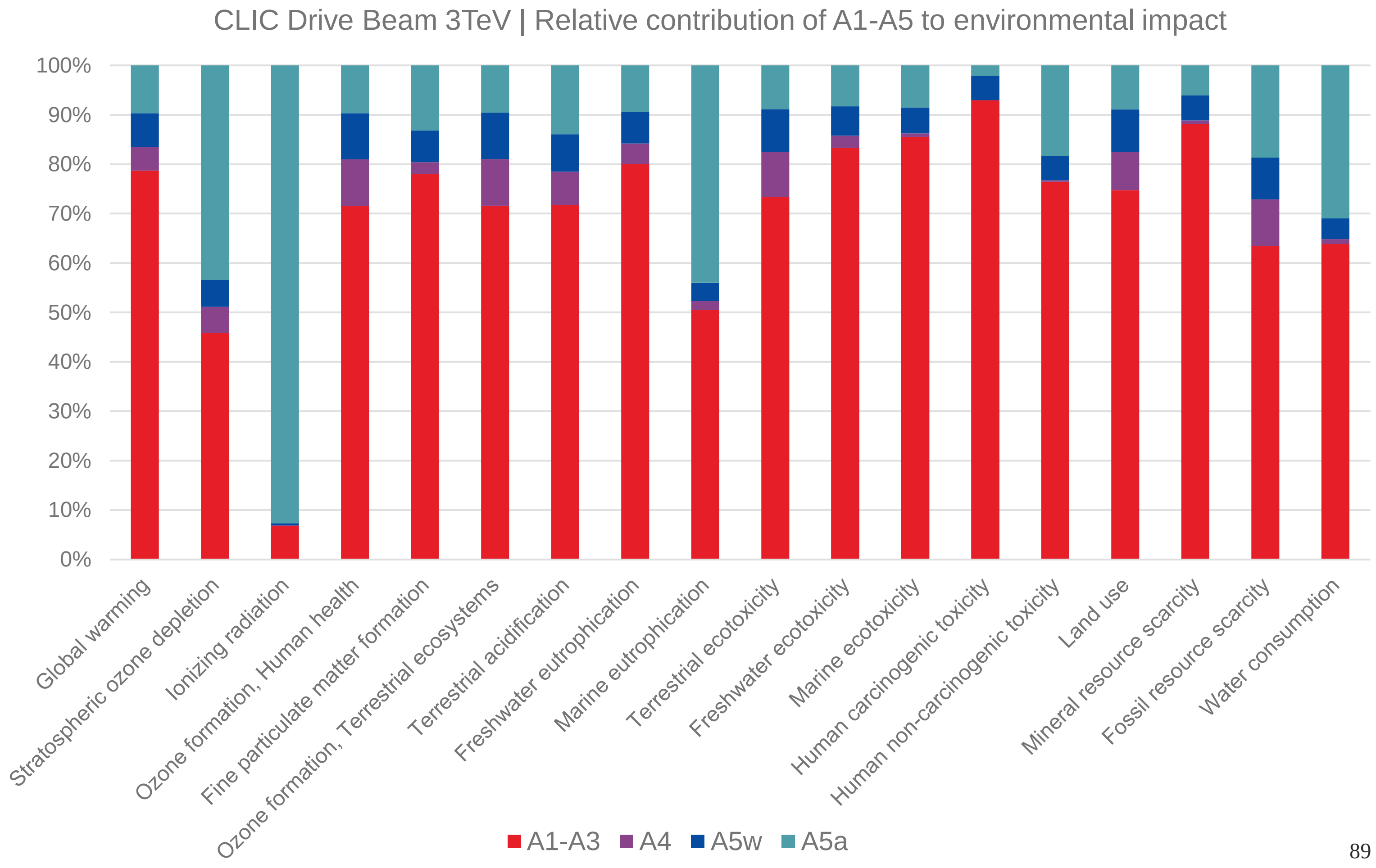


CLIC Drive Beam, 3TeV

A1-A5 results

The absolute values are reported below:

Midpoint Impact Categories	Absolute value	Unit
Global warming	2.05E8	kg CO$_2$ eq
Stratospheric ozone depletion	62	kg CFC-11 eq
Ionizing radiation	9.83E7	kBq Co-60 eq
Fine particulate matter formation	5.10E5	kg PM2.5 eq
Ozone formation, Human health	1.79E5	kg NO$_x$ eq
Ozone formation, Terrestrial ecosystems	5.21E5	kg NO$_x$ eq
Terrestrial acidification	4.56E5	kg SO$_2$ eq
Freshwater eutrophication	4.66E4	kg P eq
Marine eutrophication	5.10E3	kg N eq
Terrestrial ecotoxicity	6.86E8	kg 1,4-DCB
Freshwater ecotoxicity	6.90E6	kg 1,4-DCB
Marine ecotoxicity	9.27E6	kg 1,4-DCB
Human carcinogenic toxicity	5.23E7	kg 1,4-DCB
Human non-carcinogenic toxicity	1.10E8	kg 1,4-DCB
Land use	8.09E6	m^{2}a crop eq
Mineral resource scarcity	1.98E6	kg Cu eq
Fossil resource scarcity	3.44E7	kg oil eq
Water consumption	1.99E6	m^3

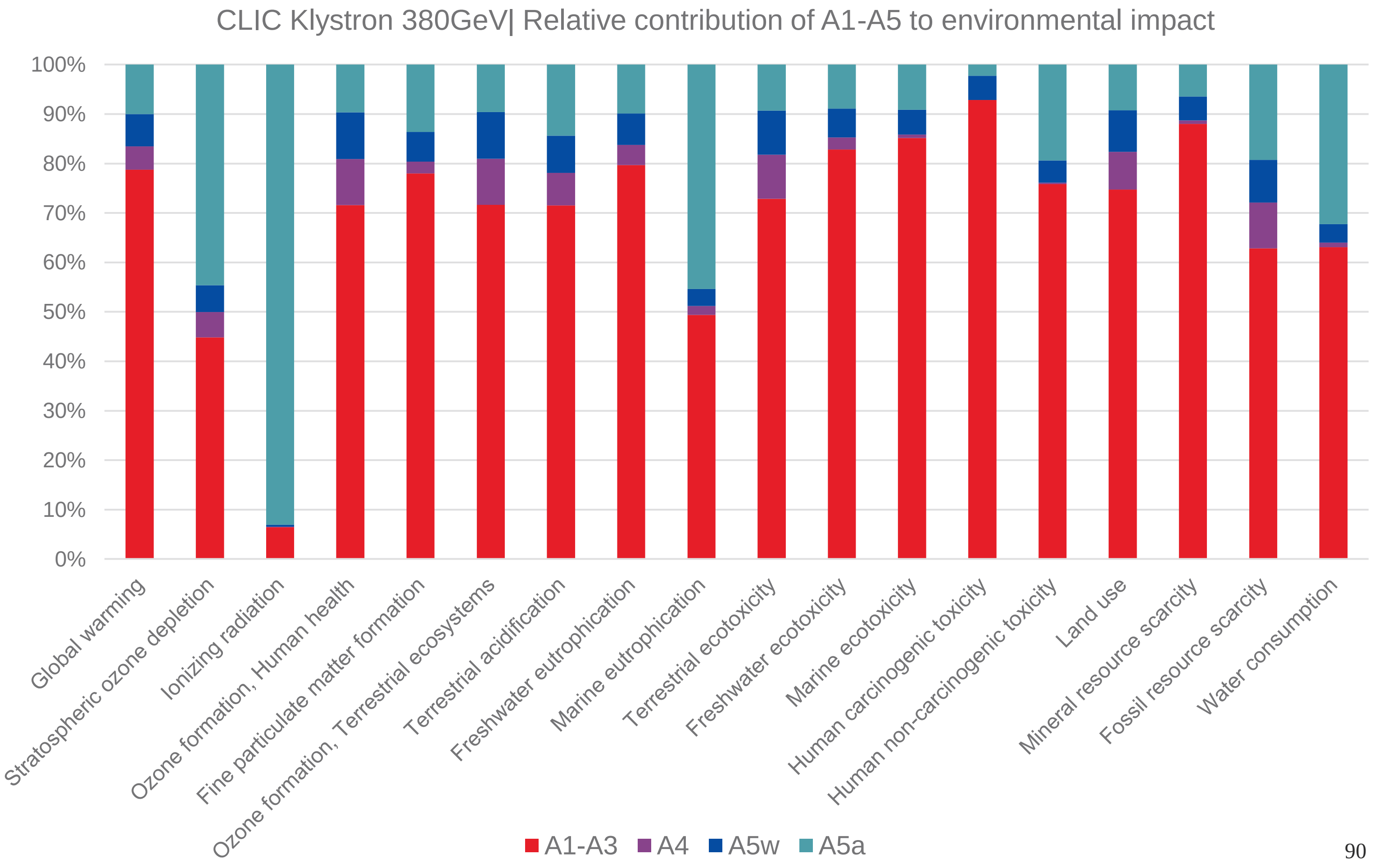


CLIC Klystron, 380GeV

A1-A5 results

The absolute values are reported below:

Midpoint Impact Categories	Absolute value	Unit
Global warming	2.90E8	kg CO$_2$ eq
Stratospheric ozone depletion	89	kg CFC-11 eq
Ionizing radiation	1.45E8	kBq Co-60 eq
Fine particulate matter formation	7.20E5	kg PM2.5 eq
Ozone formation, Human health	2.50E5	kg NO$_x$ eq
Ozone formation, Terrestrial ecosystems	7.35E5	kg NO$_x$ eq
Terrestrial acidification	6.45E5	kg SO$_2$ eq
Freshwater eutrophication	6.50E4	kg P eq
Marine eutrophication	7.31E3	kg N eq
Terrestrial ecotoxicity	9.65E8	kg 1,4-DCB
Freshwater ecotoxicity	9.51E6	kg 1,4-DCB
Marine ecotoxicity	1.28E7	kg 1,4-DCB
Human carcinogenic toxicity	7.07E7	kg 1,4-DCB
Human non-carcinogenic toxicity	1.54E8	kg 1,4-DCB
Land use	1.15E7	m^{2}a crop eq
Mineral resource scarcity	2.74E6	kg Cu eq
Fossil resource scarcity	4.87E7	kg oil eq
Water consumption	2.82E6	m^3


CLIC Klystron 380GeV| Relative contribution of A1-A5 to environmental impact

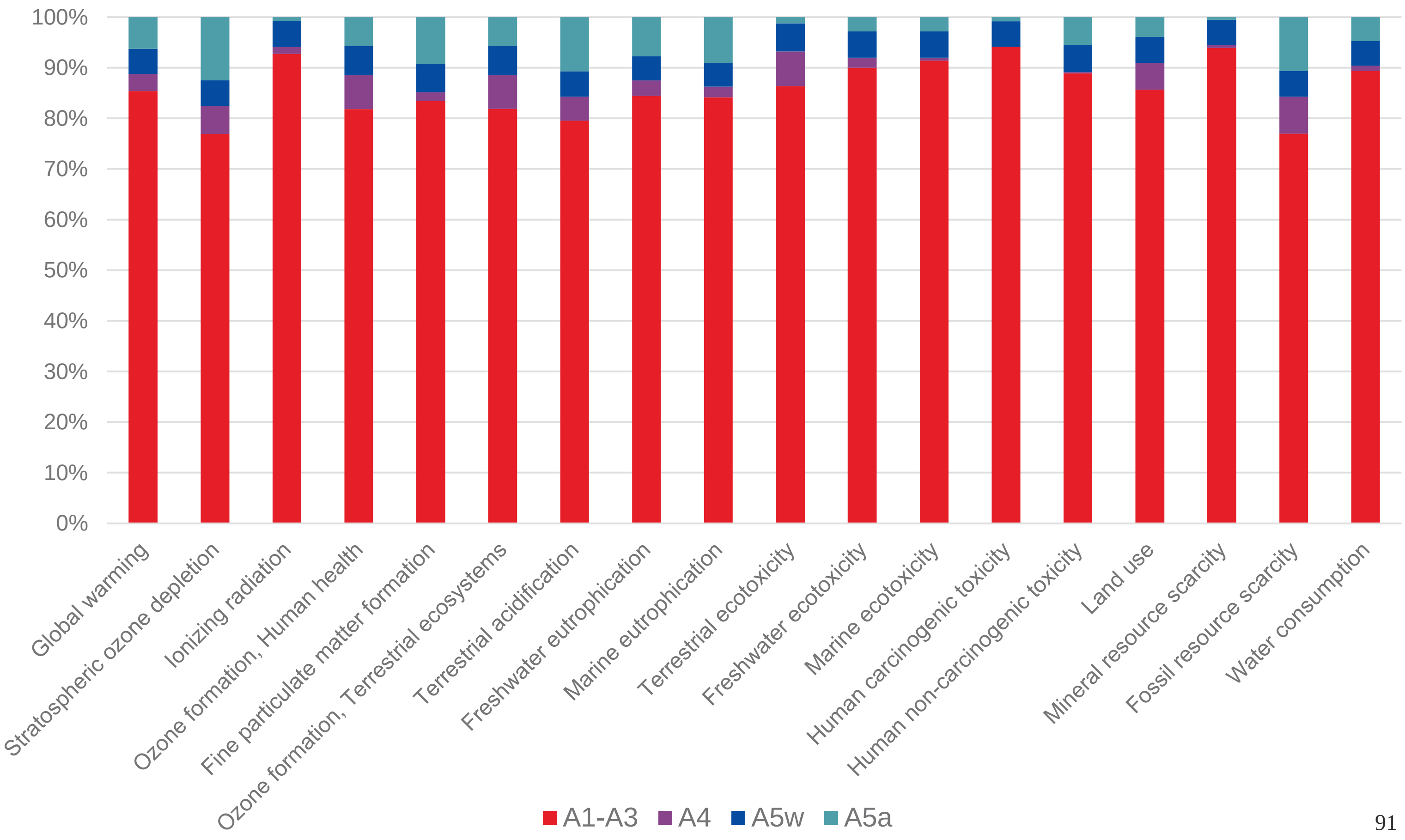
ILC, 250GeV

A1-A5 results

The absolute values are reported below:

Midpoint Impact Categories	Absolute value	Unit
Global warming	2.66E8	kg CO_2 eq
Stratospheric ozone depletion	55	kg CFC-11 eq
Ionizing radiation	9.55E6	kBq Co-60 eq
Fine particulate matter formation	6.56E5	kg PM2.5 eq
Ozone formation, Human health	2.34E5	kg NO_x eq
Ozone formation, Terrestrial ecosystems	6.70E5	kg NO_x eq
Terrestrial acidification	5.90E5	kg SO_2 eq
Freshwater eutrophication	5.79E4	kg P eq
Marine eutrophication	4.18E3	kg N eq
Terrestrial ecotoxicity	8.36E8	kg 1,4-DCB
Freshwater ecotoxicity	7.78E6	kg 1,4-DCB
Marine ecotoxicity	1.06E7	kg 1,4-DCB
Human carcinogenic toxicity	5.62E7	kg 1,4-DCB
Human non-carcinogenic toxicity	1.26E8	kg 1,4-DCB
Land use	1.09E7	m²a crop eq
Mineral resource scarcity	2.28E6	kg Cu eq
Fossil resource scarcity	4.09E7	kg oil eq
Water consumption	1.69E6	m³

ILC 250GeV | Relative contribution of A1-A5 to environmental impact



Other Impact Categories

Conclusions

Absolute values and relative contribution of each A1-A5 stage across the 18 impact categories as detailed in ReCiPe Midpoint (H) 2016 method were evaluated.

CLIC Drive Beam and Klystron

A5 has a significant contribution to stratospheric ozone depletion, ionising radiation and marine eutrophication due to the quantity of electricity used to power the Tunnel Boring Machine (TBM).

The electricity mix in France is predominately nuclear which is the reason for the significant A5 relative contribution to ionising radiation specifically.

ILC

The drill and blast method uses significantly less electricity than the TBM for CLIC, therefore the A5 contribution is not as significant across the impact categories. It should be noted that explosives have not been included due to lack of data, and if this was included it might change the A5a contribution.

The electricity mix in Tohoku region is predominately coal, oil and gas, and no nuclear, so ionising radiation for A5 stage is not a significant relative contributor. The A1-A3 materials stage remains the biggest contributor to all impact categories.

A4 and A5w have contribute the smallest amount to each impact category.

The total kWh electricity required for CLIC is greater than ILC to power the TBM, thus the A5 contribution across the impact categories is larger, with A5 more onerous in some impact categories more than others.

Limitations

A number of limitations were found during the LCA of the other 17 impact categories:

- The 17 impact categories (excluding GWP) are not widely reported across the industry. Thus baselines and reduction opportunities are harder to determine.
- There is no available project data benchmarks for the other 17 impact categories for tunnel projects. The only benchmarks are from literature and academic studies.

3

Benchmarking

Benchmarking

Purpose

A benchmarking exercise was undertaken to review the existing A1-A5 GWP calculations for tunnelling projects. The results of which can inform the validity of the LCA undertaken for the CLIC and ILC options.

A tCO_2e/km comparison was completed for CLIC, ILC and the benchmark tunnelling projects listed below.

Benchmark Example Projects

- **Thames Tideway** – concept stage
- **Railway Tunnel** (Internal Arup Study) – concept stage
- **Californian High-speed Rail System** – proposed scheme
- **Channel Tunnel Rail Link High Speed 1** – as built, estimate of embodied energy
- **Crossrail** – as built, estimate of embodied energy

All the studies presented in this section are from tunnelling projects from a range of design stages, utilising various methods of calculation.

Limitations

A number of limitations were found during the A1-A5 benchmarking exercise:

- The carbon assessment of the structures were often completed at early project stages (feasibility/concept) and therefore it was difficult to determine the quality of the estimation compared to actual emissions once the projects had been completed.
- The percentage uncertainty in embodied emissions estimates, as disclosed by authors, can be as large as 50%.
- In one study (Channel Tunnel Rail Link High Speed 1) A4 only considered local transport on site, impacting the reliability of the A1-A5 composition
- In some studies, A5 calculations appeared to use cost values to estimate carbon emissions. It should be noted that project cost estimates themselves are prone to large levels of uncertainty which would heavily impact the reliability of these estimates – especially in the case of concept stage studies.

Benchmarking

Data from tunnel projects

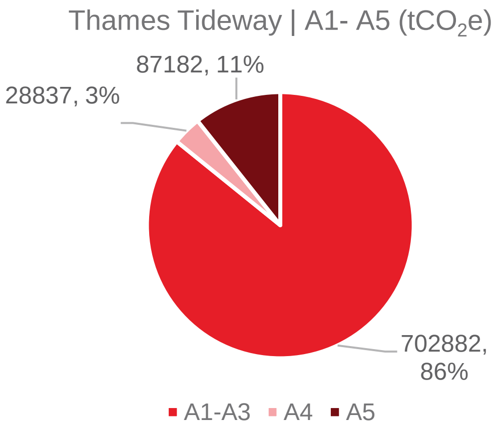
Thames Tideway, UK

Concept stage

The Thames Tideway project features segmentally lined TBM tunnels running under the river Thames. As part of the application for development consent an Energy and Carbon Footprint report was produced.

This reviewed:

- 25km, 6.5m-7.2m I.D Main Tunnel
- 1.1km 3m I.D & 4.6km and 5m I.D connection tunnel
- Permanent above ground infrastructure



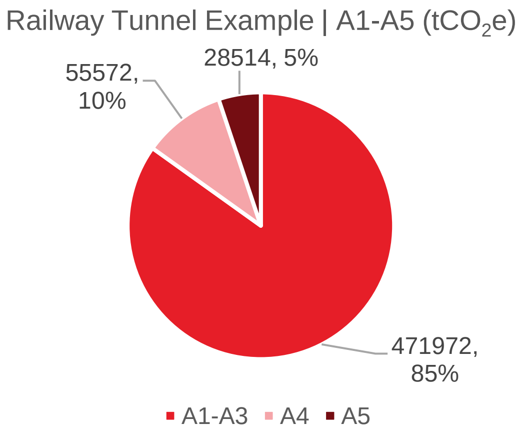
Total A1-A5 GWP: 819,000 tCO$_2$e

Railway Tunnel (Arup Internal Example)

Concept stage

An internal A1-A5 carbon calculation was completed for a 9.75m diameter (O.D), 10km long rail tunnel. This exercise using IStructE, National Highways and BEIS Guidance.

Note: the A5 value was informed by overall project costs as opposed to a bottom-up approach evaluating plant usage.



Total A1-A5 GWP: 112,000 tCO$_2$e

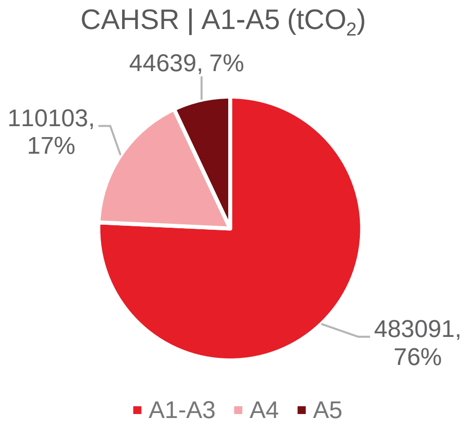
Californian High-speed Rail System (CAHSR), USA

Proposed scheme

49km of twin-bore 9m I.D New Austrian Tunnelling Method (NATM) tunnel

Estimation of lifecycle GHG emissions from construction of a proposed high – speed rail tunnel.

Note: Data is reported as CO_2 but is reasonable to compare against CO_2e.



Total A1-A5 GWP: 638,000 tCO$_2$

Reference: Thames Tideway Tunnel, Thames Water Utilities Limited, Application for Development Consent, Energy and Carbon Footprint Report, (2013).

Reference: Arup Railway Tunnel Carbon Calculation internal study, (2022).

Reference:
Understanding the contribution of tunnels to the overall energy consumption of and carbon emissions from a railway J. A. Pritchard , J. Preston, Transportation Research Group, University of Southampton, (2018).

Benchmarking

Data from tunnel projects

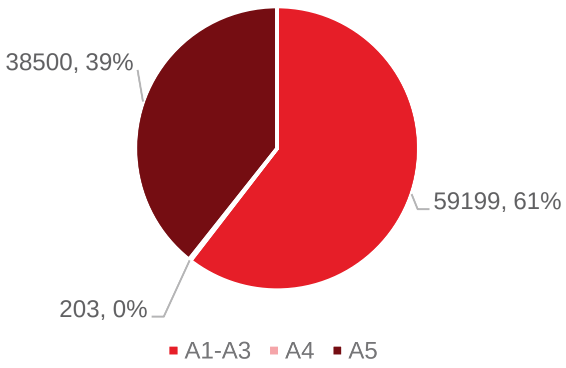
Channel Tunnel Rail Link HS1 (CTRL HS1), UK

As built - Retrospective evaluation

7km of twin-bore 7.15m I.D TBM tunnel

Evaluation of embodied energy of a built section of UK Channel Tunnel Rail Link HS1 (CTRL HS1), contract 220.

Channel Tunnel Rail Link HS1 (Contract 220) | A1-A5 (tCO_2e)



Total A1-A5 GWP: 97,900 tCO_2

References:
Embodied energy evaluation for sections of the UK Channel Tunnel Rail link, Geotechnical Engineering, vol.165 Chau, Soga, O'Riordan and Nicholson (2011).
Understanding the contribution of tunnels to the overall energy consumption of and carbon emissions from a railway J. A. Pritchard , J. Preston, Transportation Research Group, University of Southampton, (2018).

Crossrail, UK

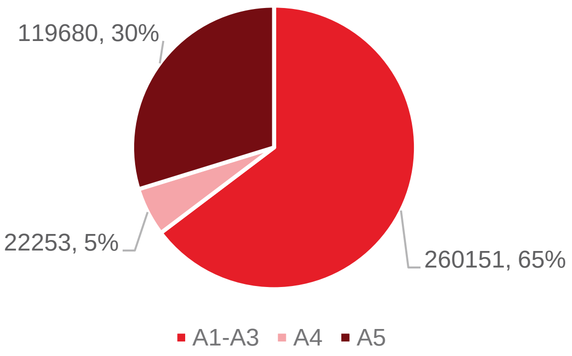
As built

17km total length of 5x twin-bore 6.2m I.D TBM tunnel

Evaluation of data for five twin-bore tunnel sections on the Crossrail project.

Note: Data is reported as CO_2 but is reasonable to compare against CO_2e.

Crossrail sample of tunnel sections| A1-A5 (tCO_2)



Total A1-A5 GWP: 402,000 tCO_2

Reference:
Understanding the contribution of tunnels to the overall energy consumption of and carbon emissions from a railway J. A. Pritchard , J. Preston, Transportation Research Group, University of Southampton, (2018).

Benchmarking Conclusions

Data from tunnel projects

Conclusions

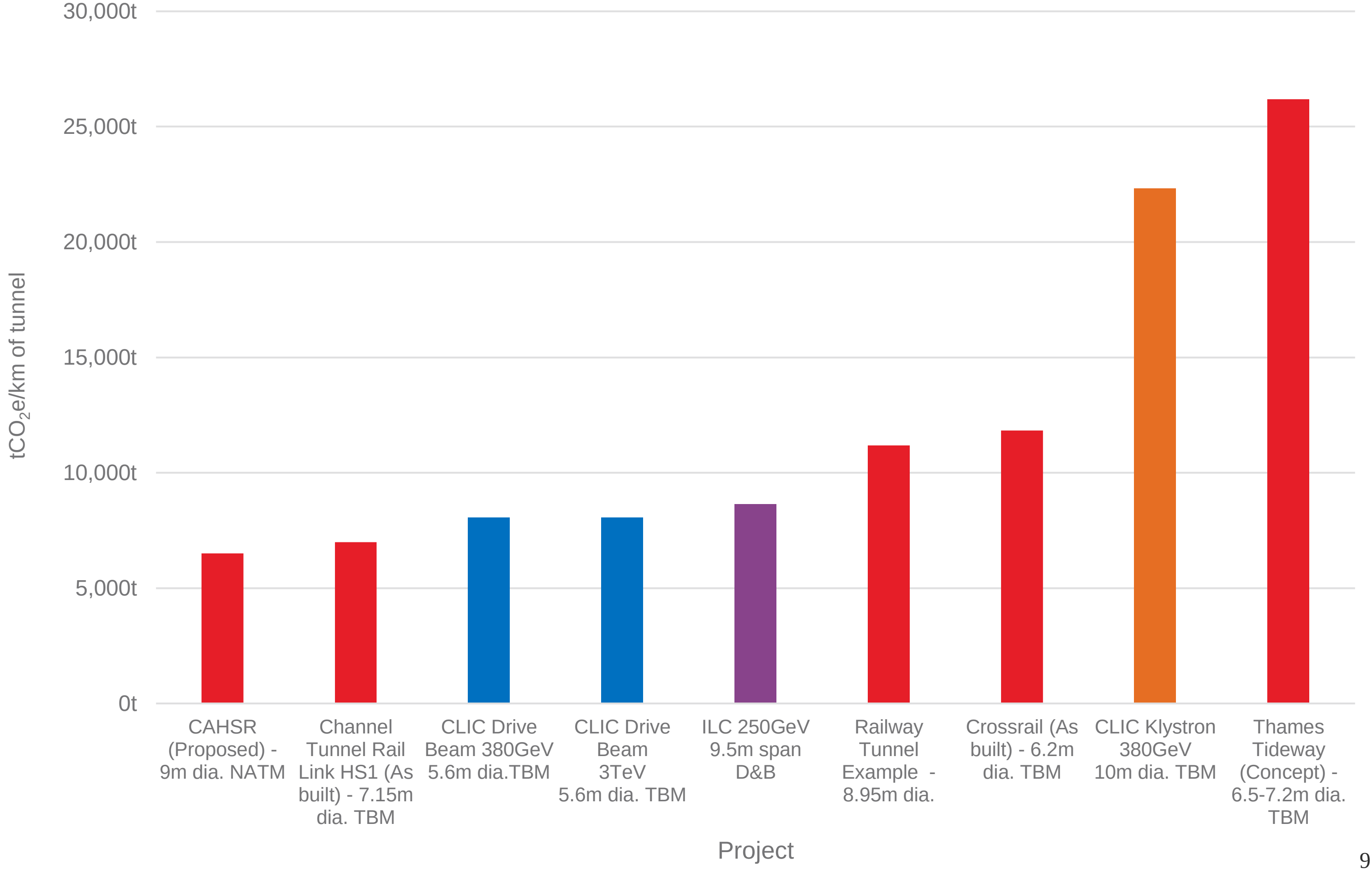
It can be concluded that A1–A5 tCO_2e/km results for the CLIC Drive Beam, CLIC Klystron and ILC tunnels are in good agreement with the GWP estimates calculated in the other studies on major tunnelling projects, see graph to the right.

CLIC Drive Beam tCO_2e/km estimate is within -15 to 45% of as built benchmarks Channel Tunnel Rail Link HSI (CTRL HS1) and Crossrail, both with similar tunnel internal diameters, TBM construction method and estimated A5 using plant emissions. CLIC Drive Beam tCO_2e/km falls in the middle of these two A1-A5 GWP benchmark estimates. CTRL HS1 is likely an underestimate as it has not considered transport of materials to site, only on-site transport.

CLIC Klystron 380GeV tCO_2e/km estimates are within -50 to 20% of the railway tunnel example and concept stage benchmark Thames Tideway, both with a similar internal diameter. The railway tunnel example uses the RICS formula to calculate A5a whereas Thames Tideway evaluates plant emissions. This could further contribute to the % variance.

ILC 250GeV tCO_2e/km estimate is within 25% of similar internal diameter NATM tunnelling project, Californian High-speed Rail System (proposed scheme). A5 was calculated using plant emissions.

A1-A5 GWP Benchmarks Comparison (tCO_2e/km of tunnel)



4

Sensitivities & reduction opportunities

4.1 Sensitivity analysis & cost impact of carbon

Sensitivity analysis

A sensitivity analysis was completed for A1-A3 to understand the sensitivity of steel quantity and GWP impact.

Steel & concrete

The embodied carbon impact of steel is significant even with small steel quantities. The charts on the right demonstrate this.

Both CLIC and ILC options have assumed CEMI concrete and 80% recycled steel as the baseline.

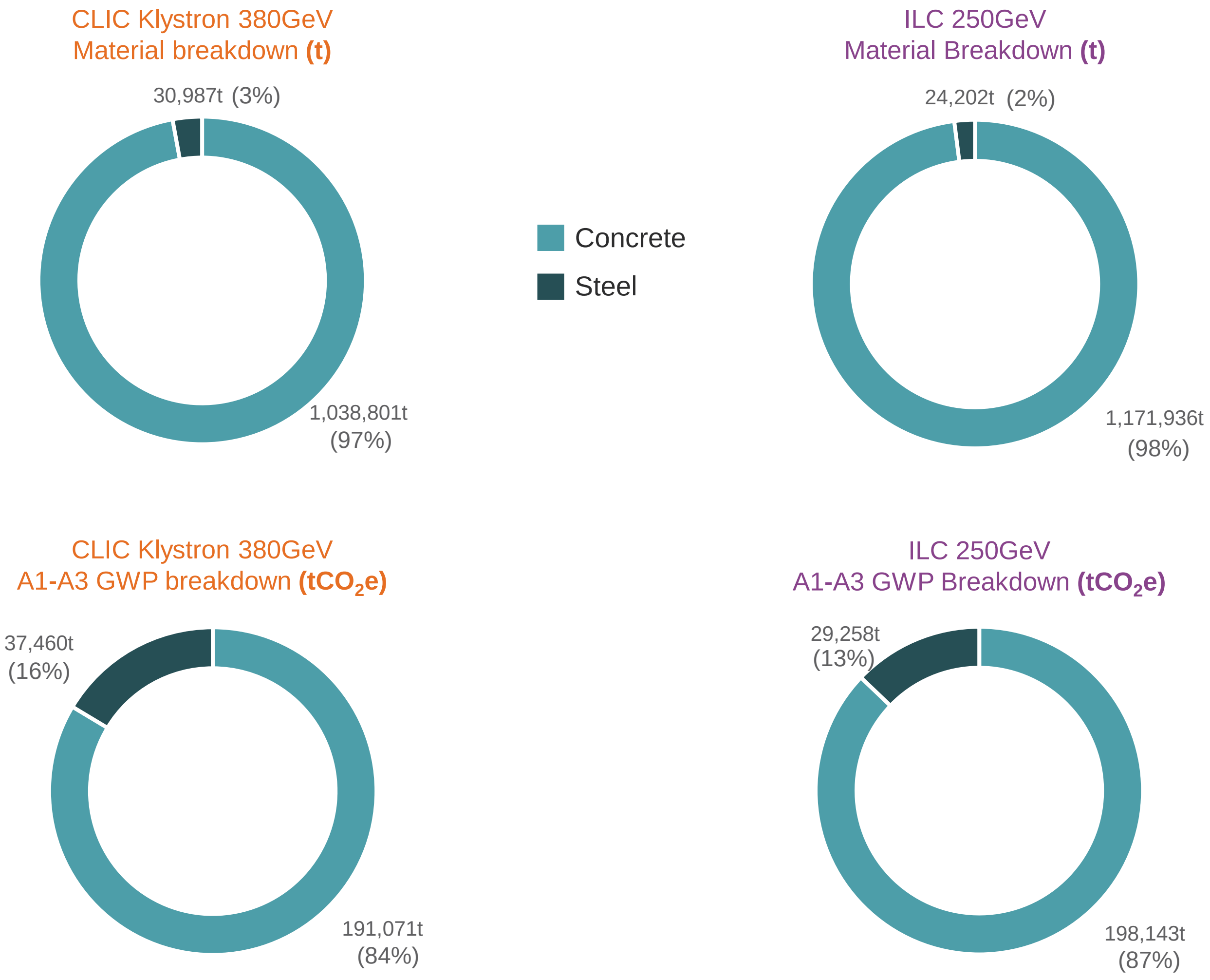
ILC 80% recycled steel baseline is potentially optimistic for steel manufacturing in Japan. However for comparison between the options steel was taken to be 80% recycled content.

If the steel for ILC was manufactured using a Blast Furnace (BF) with a small scrap content (2%), the A1-A3 GWP split is as follows:

- Concrete, 200,000 tCO_2e (80%)
- Steel, 50,000 tCO_2e (20%)

Design optimisation

There are possible value engineering opportunities for both CLIC and ILC options. A number of high level design optimisations have been identified and the GWP reduction opportunities evaluated.



CLIC Klystron 380GeV
Material breakdown **(t)**

ILC 250GeV
Material Breakdown **(t)**

CLIC Klystron 380GeV
A1-A3 GWP breakdown **(tCO_2e)**

ILC 250GeV
A1-A3 GWP Breakdown **(tCO_2e)**

Check against A5a cost formula

A benchmarking exercise was completed for A5a to check the difference between evaluating discrete plant emissions and using the RICS formula.

A5a construction activities

A5a can be calculated using a formula based on project cost in the absence of site specific data, as outlined in the RICS guide 'Whole Life Carbon Assessment for the built environment, 2017'. The project cost is multiplied by a Construction Activities Emissions Factor (CAEF) of 1,400kgCO_2e per £100,000 construction cost for a whole building. A clear limitation is that this formula was developed for building construction, rather than infrastructure.

For this LCA, we have evaluated the plant required for constructing CLIC and ILC from experience, manufacturers data and literature.

Within the benchmark data, A5 varies between 4-39%, which can be attributed to the design stage as well as A5a calculation method. It is useful to understand the sensitivities of A5a calculated from plant emissions and from the RICS formula at this stage of design to see how this might impact the A5 contribution.

RICS formula:

Embodied Carbon A5a (EC_{A5a})= CAEF x Project Cost/£100k

where, CAEF = 1,400 kgCO_2e/£100,000

CLIC Drive Beam, 380GeV

CLIC Drive Beam and Klystron civil engineering construction costs are given in the CLIC Project Implementation Plan (2018), where costs are detailed with an uncertainty of +/- 25%.

Construction elements	Construction price	
Civil engineering	1300	million CHF
Total £ (1 CHF to 0.89 £)	1163	million £

RICS formula: EC_{A5a} = 16,200,000 kgCO_2e

Construction plant (LCA): EC_{A5a} = 12,000,000 kgCO_2e

The RICS formula estimates 35% more GWP compared to evaluating the plant emissions.

CLIC Klystron, 380GeV

Construction elements	Construction price	
Civil engineering	1479	million CHF
Total £ (1 CHF to 0.89 £)	1323	million £

RICS formula: EC_{A5a} = 18,400,000 kgCO2e

Construction plant (LCA): EC_{A5a} = 29,100,000 kgCO_2e

The RICS formula estimates 37% less GWP compared to evaluating the plant emissions.

ILC, 250GeV

ILC civil engineering construction cost is given in the Tohoku Civil Engineering Plan (2020).

Construction elements	Construction price	
Access tunnels	24700	million yen
Accelerator tunnel, DR, BDS, end loop sections	64400	million yen
Detector hall and peripheral tunnels	13400	million yen
Drainage is excluded		
Total yen	102500	million yen
Total £ (1 yen to 0.006 £)	615	million £

RICS formula: EC_{A5a} = 8,610,000 kgCO_2e

Construction plant (LCA): EC_{A5a} = 16,700,000 kgCO_2e

The RICS formula estimates 50% less GWP compared to evaluating the plant emissions.

Summary

The RICS estimate varies between 35-50% compared to construction activities calculated from discrete plant emissions. Using site specific data to evaluate plant emissions is the preferred approach used in this LCA.

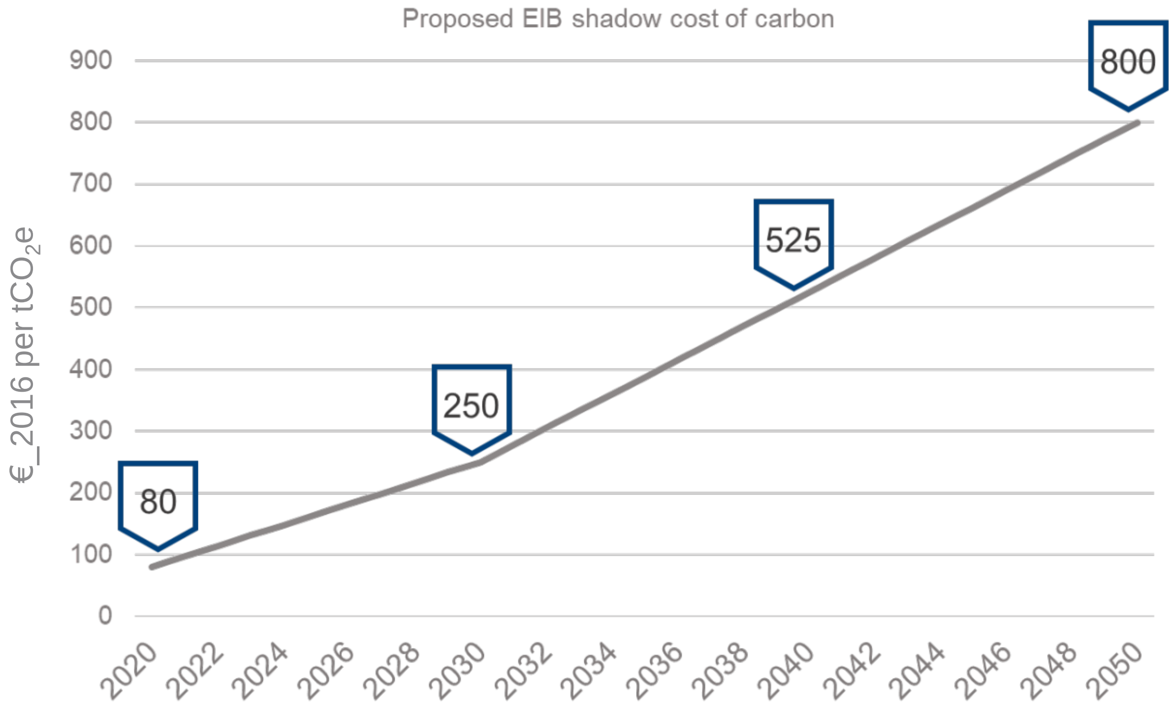
Cost impact of carbon

Shadow cost of carbon

The shadow cost of carbon is a parameter used to estimate the full value to society when the emission of $1tCO_2e$ is avoided.

Since 2021, the European Investment Bank (EIB) has clearly stated that they will not support projects that are not aligned with the Paris Agreement. They have reflected this in the shadow carbon pricing they have adopted, starting from €80 per tCO_2e in 2020, rapidly increasing to €800 per tCO_2e by 2050.

This is a much higher carbon price than previously used and signals a step change in the investor community driven by international decarbonisation commitments.



Climate Bank Roadmap 2021-2025, EIB Group 2020 (Adapted)

References:
Sustainability Report, EIB 2021
Climate Bank Roadmap 2021-2025, EIB Group 2020

4.2 Material opportunities

Concrete

Concrete opportunities are evaluated.

Concrete opportunities

The embodied carbon impact of concrete is mostly due to the amount of portland cement that it contains, which accounts for 75-90% of the overall embodied carbon impact of concrete. Portland cement is the most common type of cement used globally. Limestone, clay and other raw materials are processed in a kiln at significant temperatures (c.1500°C) to form clinker. The clinker is ground with gypsum to become portland cement. The high thermal energy and CO_2 released during the chemical decomposition of limestone into lime are the largest embodied carbon emissions of portland cement.

As such, there are several avenues that can be considered for reducing carbon footprint of concrete as a material, this includes, but is not limited to:

1) Partially replacing Portland cement (CEMI) with Supplementary Cementitious Materials (such as fly ash, GGBS, limestone powder, calcined clay and others)
2) Totally replacing Portland cement with “Portland cement-free” materials (such as alkali-activated materials / geopolymers)
3) Carbon sequestering in concrete (such as carbon negative aggregates and carbon injection in concrete)

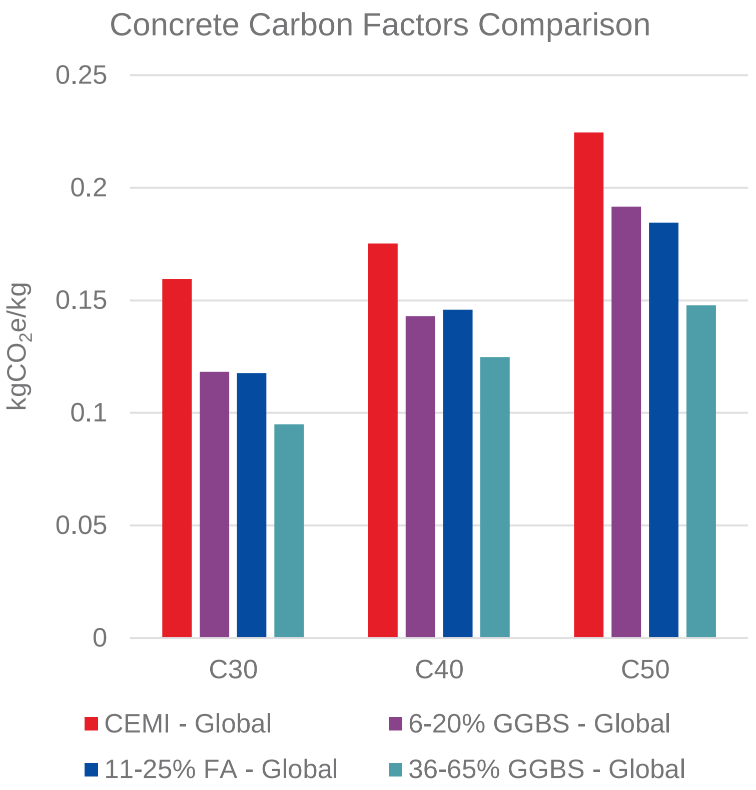
There are more emerging novel technologies but these are still in development stage and are beyond the scope of this report. The following concrete opportunities focus on precast segmental concrete lining.

1) Partial replacement of Portland cement

Supplementary Cementitious Materials (SCMs) have been used for decades in concrete to enhance performance and to reduce embodied carbon impact by replacing the portland cement content. SCMs normally include widely used industrial by-products such as Ground Granulated Blast-furnace Slag (GGBS), Fly Ash (FA), and Silica Fume (SF).

The concrete carbon factors in the graph on the right detail GGBS and FA SCM replacement options. With an increased quantity of SCM the embodied carbon $kgCO_2e/kg$ of concrete is reduced.

Precast segmental linings may encompass specific early-strength requirements to enable quick production of the segments in the precast concrete factory. This should be considered when choosing the % SCM replacement. GGBS and FA have been used for several years in concrete and can normally replace up to 50% of CEMI in precast concrete segments. Where early strength gain is critical, the replacement is limited to up to 20%.



Reference: Simapro (Ecoinvent 3.8 database 2021)

Concrete

Concrete opportunities are evaluated.

Concrete opportunities

2) Total replacement of Portland cement

Alkali-activated materials (AAMs) are those known in the industry as “cementless” or “cement free” concrete technologies. There have been certain AAMs commercially available, for example:

1) Cemfree (DB Group; GGBS-based)
2) LowCem (C-Probe; GGBS-based)
3) Earth friendly concrete (Capital Concrete; GGBS and fly ash - based)
4) Vertua (Cemex; GGBS-based)
5) ECOPact (Aggregate Industries; GGBS-based)
6) Tarmac and other manufacturers are working on similar proprietary products

These materials are largely based on GGBS and fly ash and include high quantities of chemical activators that are used to activate the binding reaction and strengthen the concrete. The replacement of Portland cement with GGBS and fly ash, can be as high as 100%, however, as the chemical activators used can be quite carbon intensive, the embodied carbon of these materials/concretes may not be as low as anticipated.

The commercialised products are somewhat available globally; however, they might be less available in certain parts of the world and could require transportation from elsewhere which can add up to their carbon footprint. Generally, AAMs are known to exhibit excellent resistance to sulfates and chlorides, however, are more prone to carbonation and to strength gain issues related to curing.

One of the main issues with specifying and using these materials is the lack of standardisation. Currently, these materials are only covered by PAS 8820 in the UK and possibly ASTM C1157 in the Americas region, which are documents that provide recommendations for performance-based testing of AAMs and other non-standard concretes for use in concrete construction. As AAMs are not covered by national or European specification and design standards, there are risks and liabilities associated with their use which should be accepted by one of the associated parties, e.g., client, contractor designer. In any case, a performance-based testing regime will have to be design for using AAMs in structural elements. However, they could be more easily used in non-structural elements.

3) Carbon sequestering technologies

Most recently, carbon sequestering concrete technologies have emerged in the wider market but are mostly in developmental stage. Those most relevant to precast concrete tunnel lining are listed below:

- Concrete4change. This technology is based on carbon sequestration during the production of a cementitious binder (cement). This technology is emerging and still at developmental stage.
- Seratech. This technology is based on carbon sequestration during the production of a cementitious binder (cement). This technology is emerging and sill at developmental stage.
- Carbon Upcycling. This technology is based on pressurising captured carbon on SCMs reducing considerably their carbon footprint.

The market readiness of the above is generally low, the barrier of standardisation is also an issue with these technologies.

Concrete

Concrete risks are evaluated.

Concrete risks

There are some risks associated with SCMs, highlighted below.

Availability of SCMs

Due to the high demand and decarbonisation of steel manufacturing and coal-related energy production sectors, there can be limited availability of GGBS and FA, respectively.

Cost impact

While it used to be the case that FA and GGBS were cheaper compared to Portland cement, due to the current drive for sustainability, these materials are high demand and can have comparable prices to CEMI.

Market readiness

There is adequate understanding of GGBS and FA behaviour in concrete thus where these materials are available they can be used in concrete with no issues.

It is noted that Japan and Europe concrete practices share similarities; i.e. similar % GGBS or FA can be used in precast segment linings.

Steel

Steel opportunities and risks are evaluated.

Steel opportunities

Steel embodied carbon impacts vary depending on the % of recycled content and manufacturing process - Electric Arc Furnace (EAF) or Blast Furnace (BF). BF is a fossil fuel production process that produces steel from mostly virgin iron ore, compared to scrap metal. EAF is powered by the electricity grid and can produce steel made with very high recycled content.

The business as usual manufacturing process for steel in Europe uses EAF with a high recycled content. Reuse of sections without melting should also be considered.

The Responsible Steel standard provides performance levels to be achieved globally for the steel manufacturing industry. Partnering with suppliers that are committed to net zero steel production will help in achieving these performance levels.

There are benefits of repurposing steel at the end of life of the asset which contribute to the avoided emissions for other projects that require steel. This should be evaluated as a potential end of life scenario for CLIC and ILC along with repurposing the assets for another use. This is outside the scope of this study but should be considered in the future.

The graph on the right details the kgCO$_2$e/kg of steel reinforcement bars and rolled open sections with varying % recycled content. This is 6-10 times greater than the kgCO$_2$e/kg for concrete.

Steel risks

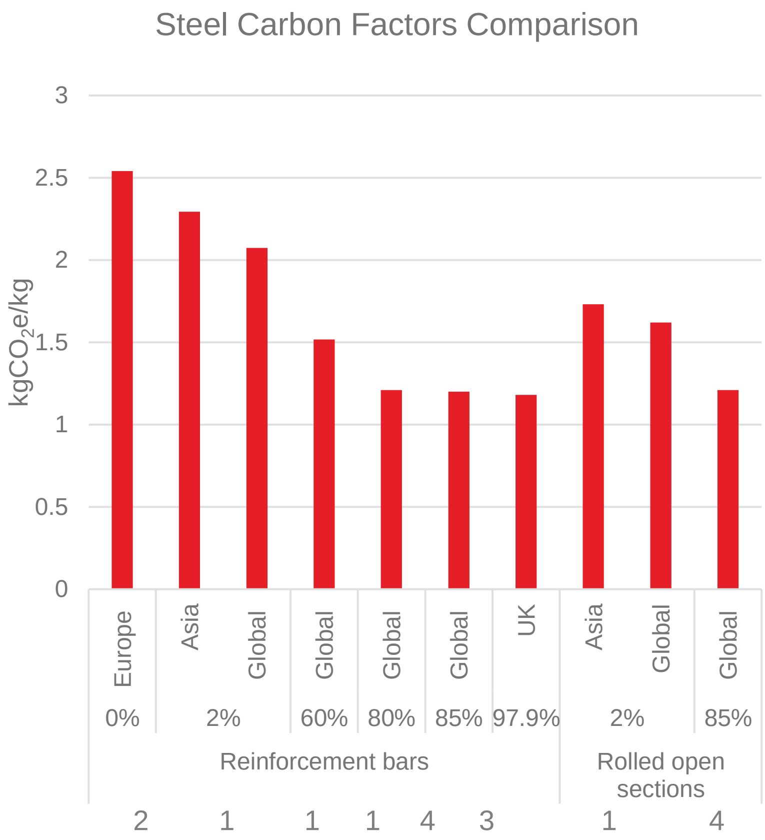
There are some risks associated with the production of low carbon steel:

Scrap steel is a constrained resource

Moving away from BF manufacturing relies on a high percentage of scrap steel, which is a constrained resource. Therefore using a higher % scrap content doesn't necessarily equate to reduced GHG emissions as steel from virgin iron ore will still need to be produced elsewhere globally.

Manufacturing process

BF manufacturing is highly carbon intensive due to the CO$_2$ emitted during the production of steel from virgin iron ore. As EAF is business as usual, further carbon reduction savings should be investigated through lower carbon manufacturing processes, like the use of green hydrogen to produce HYBRIT, a SSAB Fossil-free™ steel, for example. Limitations of this technology are scale of production.



1. Simapro 9.4.0.2 (Ecoinvent 3.8 database 2021)
2. BRE Carbon Steel Reinforcing Bar EPD, 2022
3. BRE Carbon Steel Reinforcing Bars (scrap) EPD, 2020
4. ICE Database 2019

Steel Fibre Reinforced Concrete (SFRC)

SFRC alternatives are evaluated.

SFRC alternatives

SFRC is commonly used in precast concrete segmental tunnel lining. The production process of fibres consumes a significant amount of fossil fuels and therefore there is increasing interest in the use of alternatives, such as plant fibres and recycled tyre steel fibres.

Plant fibres

Plant fibres are low cost, biodegradable, abundant, renewable, and non-toxic raw materials which makes it an attractive alternative to SFRC. However they have the following limitations:

- High water absorption: It requires pre-treatment for use in cement composites. Compatibilizers and water repellents could be used to control the water absorption and enhance the bond between the plant fibres and cement matrix.
- Compatibility: A severe limitation is the compatibility of natural fibres and interfacial bond strength. However, through treatment and heating this has the potential to be overcome.
- Durability: The degradation and weathering of plant fibres should be thoroughly investigated to assess durability. Packing or drying composite sealing or substituting Portland Cement with granulated blast-furnace slag could improve durability.

In summary, plant fibres could be an alternative to SFRC in the future but investigation around fire performance and the use in marine environments is required, as well as decreasing water absorption, enhancing compatibility and durability.

References:

Zhao K, et al. Application of Natural Plant Fibers in Cement-Based Composites and the Influence on Mechanical Properties and Mass Transport. Materials (Basel). 2019 Oct 25.

Labib WA. Plant-based fibres in cement composites: A conceptual framework. Journal of Engineered Fibers and Fabrics. 2022.

Recycled tyre steel fibres (RTSF)

Rubber tyres do not decompose naturally and thus need to be recycled so that they do not end up in landfill. Currently there are more than 500 million tonnes of used tyres stored as landfill. Used tyres are made up of rubber, textile and steel cords, of which steel constitutes 13-27%.

Purification of the steel cords, with limited contamination from rubber, textile and steel dust is required to achieve effective reinforcement capabilities. The irregular dimensions and geometry of the fibres are beneficial in achieving effective microcracking control, reported to be better than SFRC or rebar.

A higher density of RTSFs are required to achieve similar flexural strength and fracture toughness. Good adhesion of the fibres to the cement matrix was observed with purified RTSF.

It is reported that the use of RTSF reduces the carbon footprint by up to 95% and the cost by up to 50% compared to SFRC. If treated to remove contaminants, there is great potential to use RTSF in replacement of SFRC.

References:

Michalik A, Chyliński F, Bobrowicz J, Pichór W. Effectiveness of Concrete Reinforcement with Recycled Tyre Steel Fibres. Materials (Basel). 2022 Mar 26

Zero Waste Works. (2020). Recycled Steel Tyre Microfibres. Retrieved from https://www.zerowasteworks.co.uk/recycled-steel-microfibres

Material opportunities conclusions

The material opportunities in relation to CLIC and ILC are evaluated.

Concrete

There is no "silver bullet" to the problem of carbon in concrete and multidisciplinary actions are required to reduce the CO_2 emissions of precast concrete segments for tunnelling operations. The following recommendations are given towards the reduction of embodied carbon of precast concrete segments:

- Consideration of high replacement levels of CEMI (Portland cement) in concrete with SCMs. These can preferably be through ternary and quaternary binders which combine different SCMs together. In the case where ternary and quaternary binders are not available, high GGBS, fly ash and even calcined clay mixes can be considered.
- AAMs and carbon sequestering technologies can be considered if there is scope for project specific materials testing to validate concrete properties.
- Consider resource efficiency and responsible resourcing, i.e. utilise locally available materials.
- Savings can arise from geometry optimisation and reduction in section thicknesses.
- Relaxation of crack widths as necessary can result in reductions of crack control reinforcement, where applicable.

Steel

Although steel makes up a relatively small proportion of the materials for the CLIC and ILC tunnels, shafts and caverns, its GWP impact should not be dismissed. Depending on the % scrap content, 1kg of steel can have 6-10 times the GWP impact compared to 1kg of concrete. Therefore careful consideration of steel quantities in design is required. The following recommendations are given:

- Consider the steel manufacturing route for CLIC and ILC. The manufacturing route will determine the % scrap steel content possible. Although a higher % of scrap steel attributes to a lower environmental impact, scrap steel is a constrained resource and thus a higher % scrap content doesn't necessarily equate to reduced GHG emissions. This is because the steel from virgin iron ore will still need to be produced elsewhere globally.
- Consider using steel suppliers that are committed to net zero steel production will help in achieving the performance levels outlined in the Responsible Steel standard.

SFRC alternatives

The current precast concrete segmental lining design for CLIC Drive Beam and Klystron has a SFRC density of 35kg/m^3. Across the 50km length of tunnel for CLIC Drive Beam 3TeV, this equates to ~10,000t steel. The production process of SFRC is fossil fuel intensive and thus alternatives are explored.

Some emerging alternatives, but not limited to, are plant fibres and recycled tyre steel fibres (RTSF). The potential use of RTSF appears more advanced than plant fibres, with products listed at Zero Waste Works. RTSF have a lower cost and GWP impact compared to SFRC.

It is recommended for RTSF to be considered as an alternative to SFRC for CLIC options. The properties of RTSF should be evaluated to check it meets design requirements for when the accelerator is in operation.

4.3 CLIC & ILC reduction opportunities

CLIC & ILC reduction opportunities

A1-A5 GWP

Reduction opportunities

As highlighted in A1-A5 GWP results in section 2.3, for CLIC and ILC options the tunnels are the biggest contributor to GWP impact. The permanent lining followed by the invert/shielding wall are the biggest portions of this. Therefore, the reduction opportunities focus on these areas. Reduction opportunities are also reported for shafts and caverns.

With consideration to the material opportunities highlighted in section 4.2 and the 2030 projected electricity mix detailed in section 2.1, the A1-A5 GWP reduction opportunities for CLIC and ILC evaluated are:

- Replace Portland cement (CEMI) with 50% GGBS content.
- Design optimisation of precast concrete segmental tunnel lining for CLIC options using ITA segmental tunnel lining guidance, 2019.
- Replace concrete shielding wall with concrete casing filled with compact earthworks from excavation.
- 2030 projected electricity mix (less fossil fuels and increased renewables) for A5a construction activities.

Note steel remains the same as the baseline at 80% recycled scrap content.

It is recommended for further carbon reduction opportunities for the CLIC and ILC designs to be investigated.

The reduction opportunities for CLIC and ILC are not limited to this list. As highlighted in the material opportunities, there is possibility for further reductions. This provides insight into the possible scale of reduction by considering these 4 material and design optimisation opportunities.

CLIC Drive Beam, 380GeV

A1-A5 GWP

Reduction opportunities

Tunnels *(41% possible A1-A5 GWP reduction)*

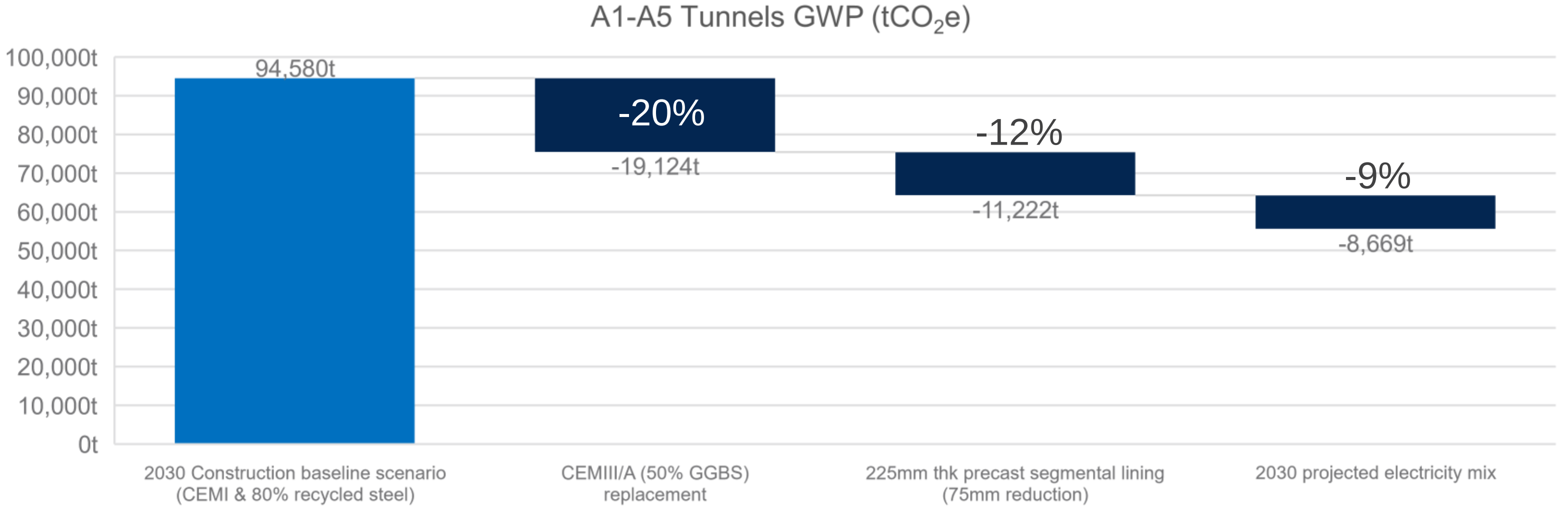
- Replace CEMI with CEMIII/A (50% GGBS).
- Reduce the existing design precast concrete segmental lining thickness from 300mm to 225mm thickness. This is in line with the lower bound value detailed in the ITA segmental tunnel lining guidance, 2019.
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.

Shafts *(22% possible A1-A5 GWP reduction)*

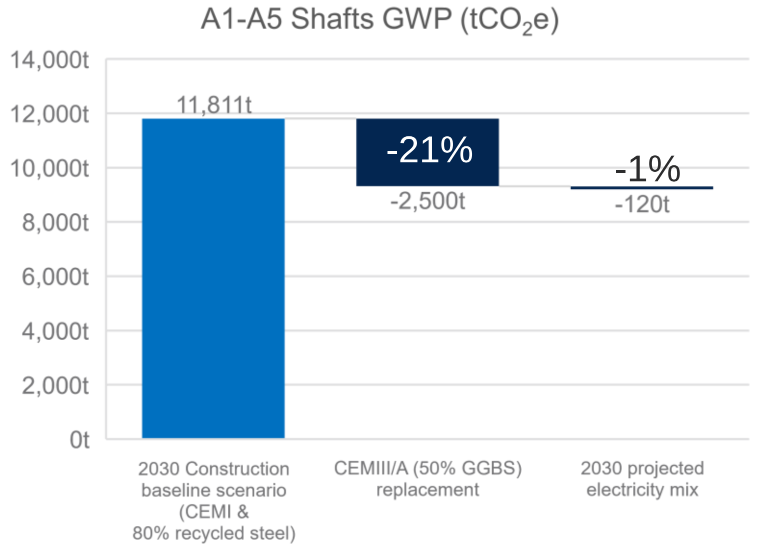
- Replace CEMI with CEMIII/A (50% GGBS).
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.

Caverns *(24% possible A1-A5 GWP reduction)*

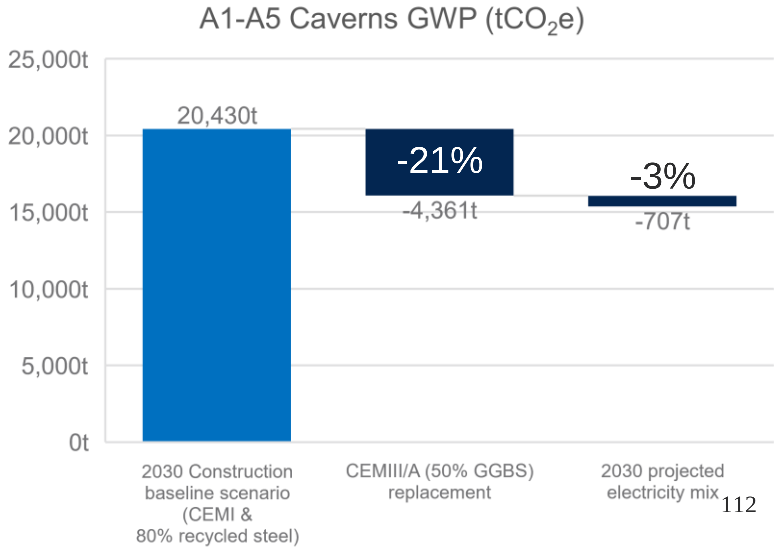
- Replace CEMI with CEMIII/A (50% GGBS).
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.



A1-A5 Tunnels GWP (tCO_2e)



A1-A5 Shafts GWP (tCO_2e)



A1-A5 Caverns GWP (tCO_2e)

CLIC Drive Beam, 1.5TeV

A1-A5 GWP

Reduction opportunities

Tunnels *(41% possible A1-A5 GWP reduction)*

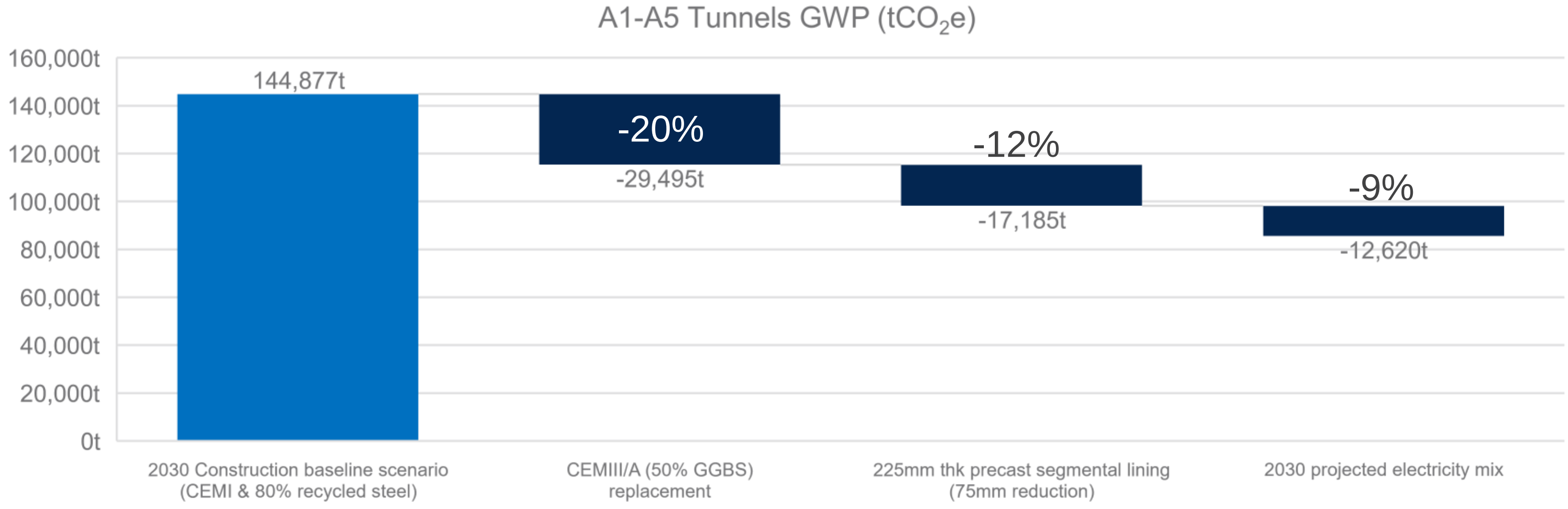
- Replace CEMI with CEMIII/A (50% GGBS).
- Reducing existing design precast concrete segmental lining thickness from 300mm to 225mm thickness. This is in line with the lower bound value detailed in the ITA segmental tunnel lining guidance, 2019.
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.

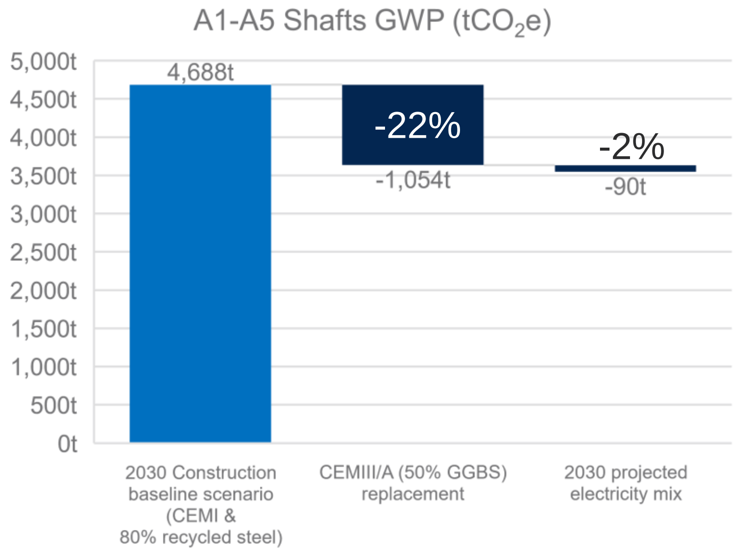
Shafts *(24% possible A1-A5 GWP reduction)*

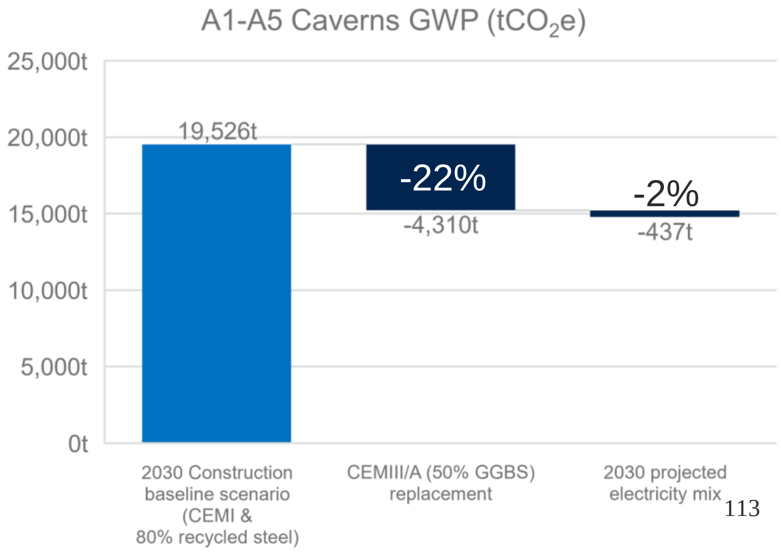
- Replace CEMI with CEMIII/A (50% GGBS).
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.

Caverns *(24% possible A1-A5 GWP reduction)*

- Replace CEMI with CEMIII/A (50% GGBS).
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.







CLIC Drive Beam, 3TeV

A1-A5 GWP

Reduction opportunities

Tunnels *(41% possible A1-A5 GWP reduction)*

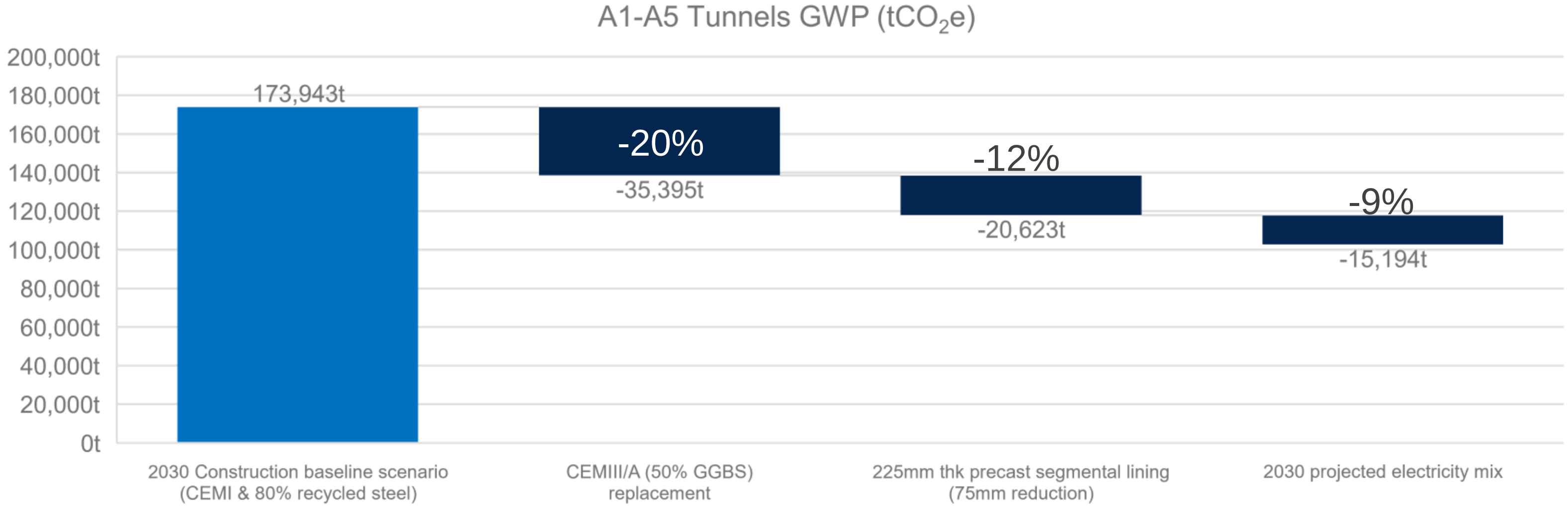
- Replace CEMI with CEMIII/A (50% GGBS).
- Reducing existing design precast concrete segmental lining thickness from 300mm to 225mm thickness. This is in line with the lower bound value detailed in the ITA segmental tunnel lining guidance, 2019.
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.

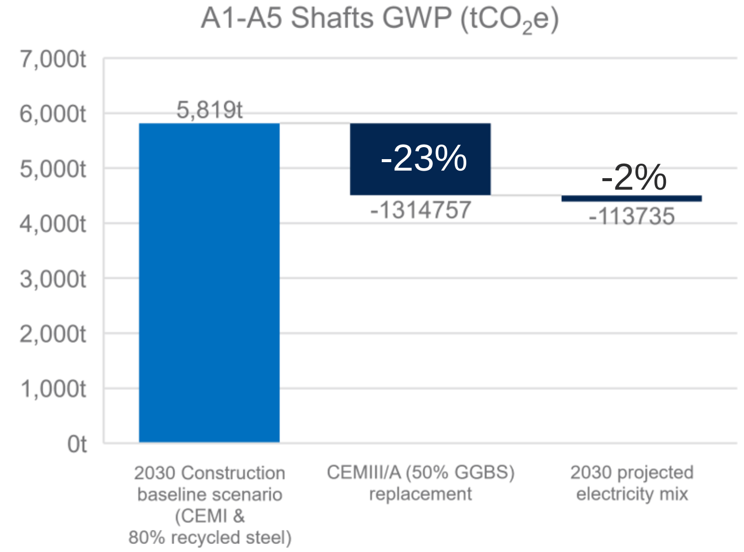
Shafts *(25% possible A1-A5 GWP reduction)*

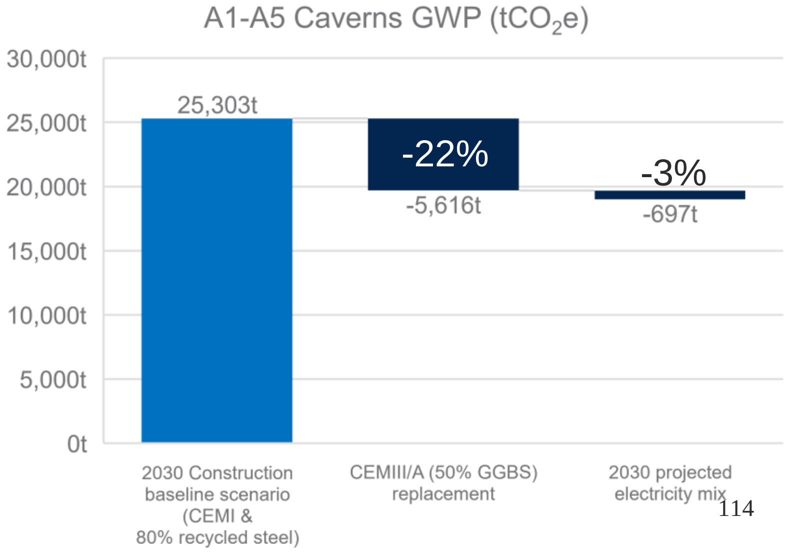
- Replace CEMI with CEMIII/A (50% GGBS).
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.

Caverns *(25% possible A1-A5 GWP reduction)*

- Replace CEMI with CEMIII/A (50% GGBS).
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.


A1-A5 Tunnels GWP (tCO_2e)


A1-A5 Shafts GWP (tCO_2e)


A1-A5 Caverns GWP (tCO_2e)

CLIC Klystron, 380GeV

A1-A5 GWP

Reduction opportunities

Tunnels *(46% possible A1-A5 GWP reduction)*

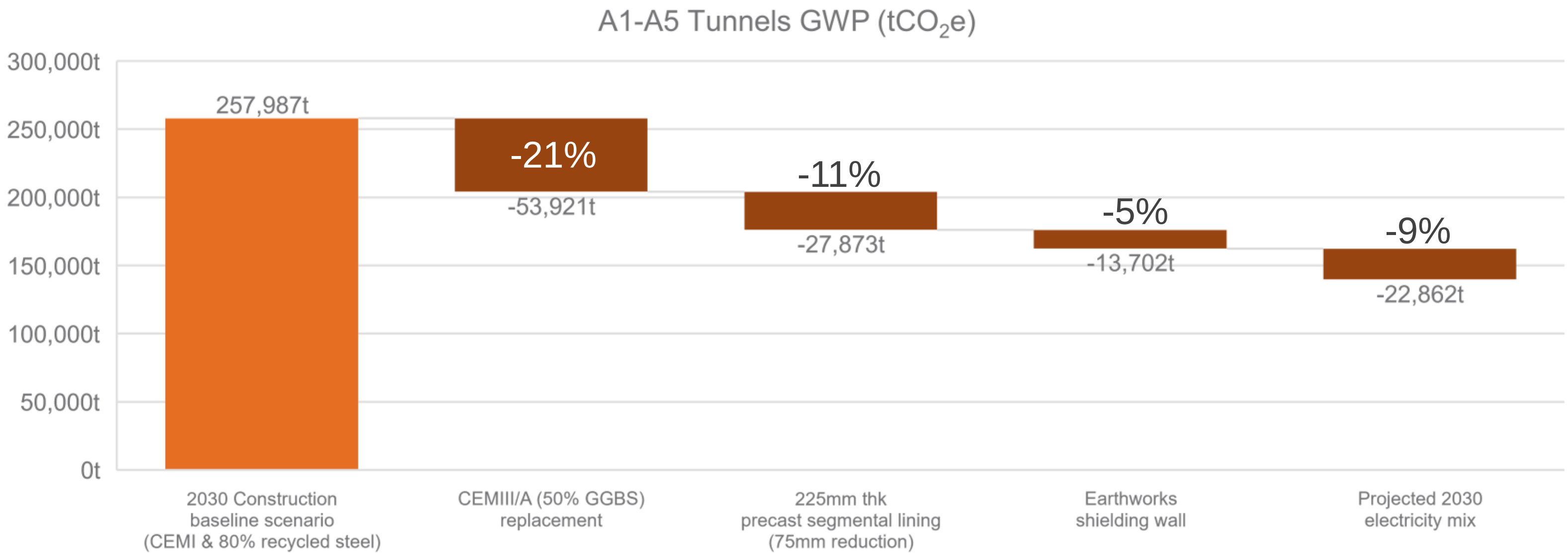
- Replace CEMI with CEMIII/A (50% GGBS).
- Replace concrete shielding wall with 250mm concrete casing, 0.2% rebar, filled with compact earthworks from excavation.
- Reducing existing design precast concrete segmental lining thickness from 450mm to 400mm thickness. This is in line with the lower bound value detailed in the ITA segmental tunnel lining guidance, 2019.
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.

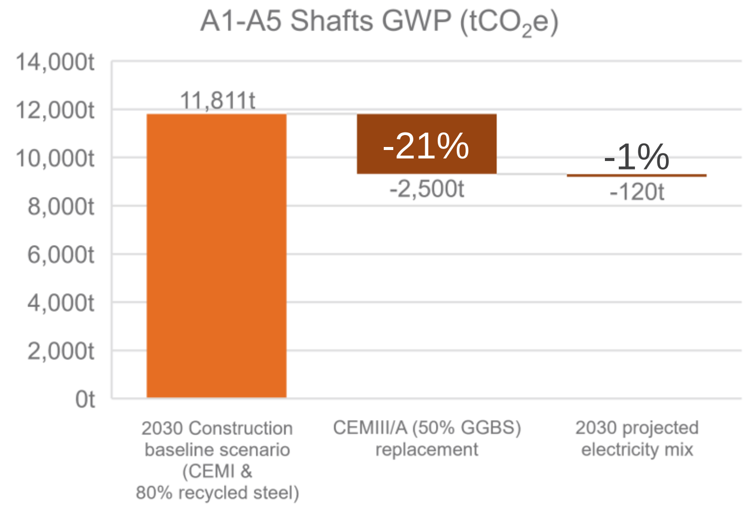
Shafts *(22% possible A1-A5 GWP reduction)*

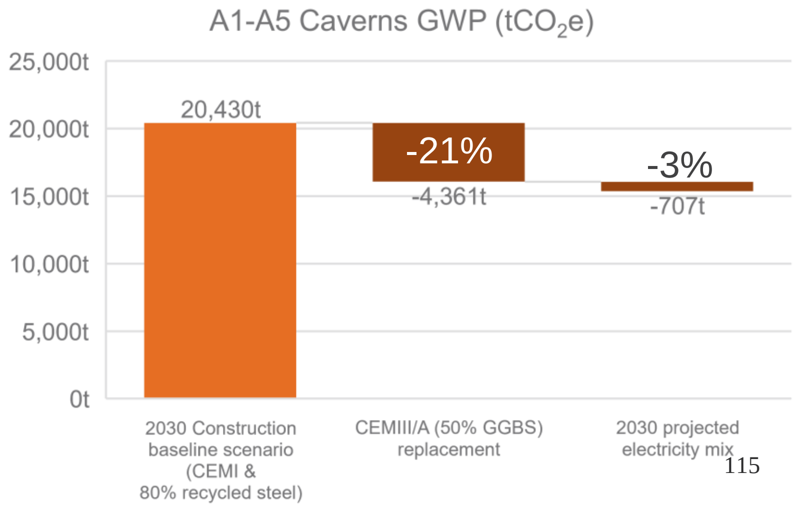
- Replace CEMI with CEMIII/A (50% GGBS).
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.

Caverns *(24% possible A1-A5 GWP reduction)*

- Replace CEMI with CEMIII/A (50% GGBS).
- 2030 projected electricity mix in France for construction activities as detailed in section 2.1.







ILC, 250GeV

A1-A5 GWP

Reduction opportunities

Tunnels *(41% possible A1-A5 GWP reduction)*

- Replace CEMI with CEMIII/A (50% GGBS).
- Replace concrete shielding wall with compact earthworks from excavation (assumed no concrete casing is required as excavated material is granite).
- 2030 projected electricity mix in Tohoku region for construction activities as detailed in section 2.1.

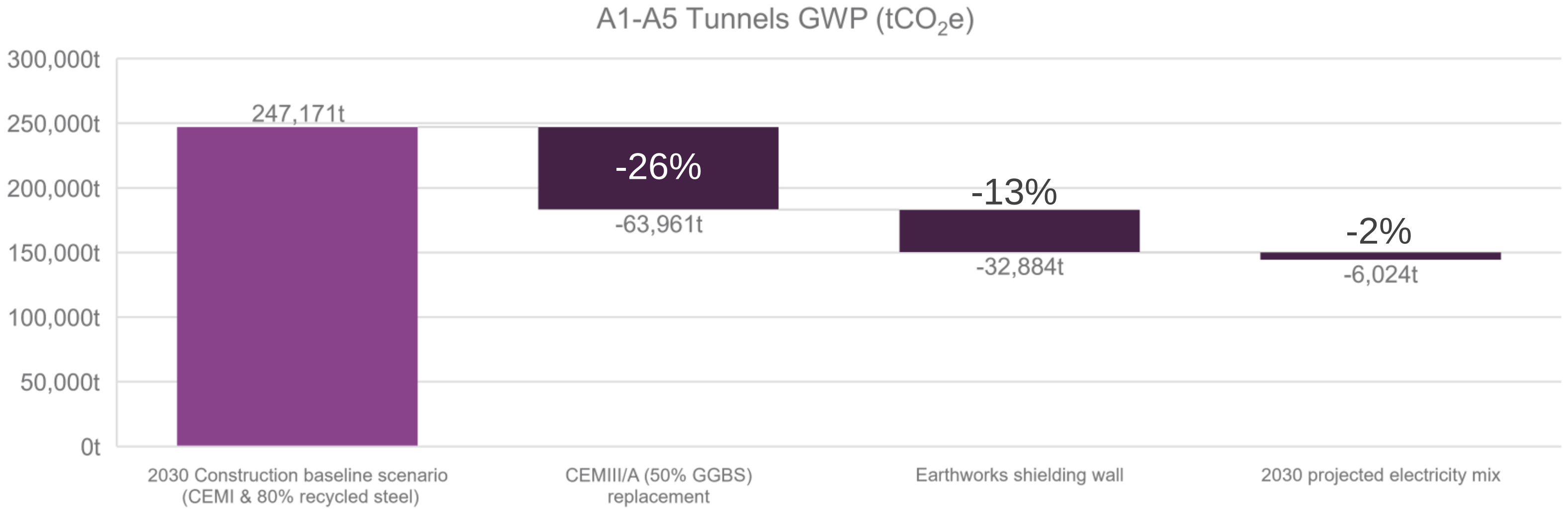
Note The LCA has evaluated the design in the Tohoku ILC Civil Engineering Plan 2020. The lining thickness of the tunnel has not been changed.

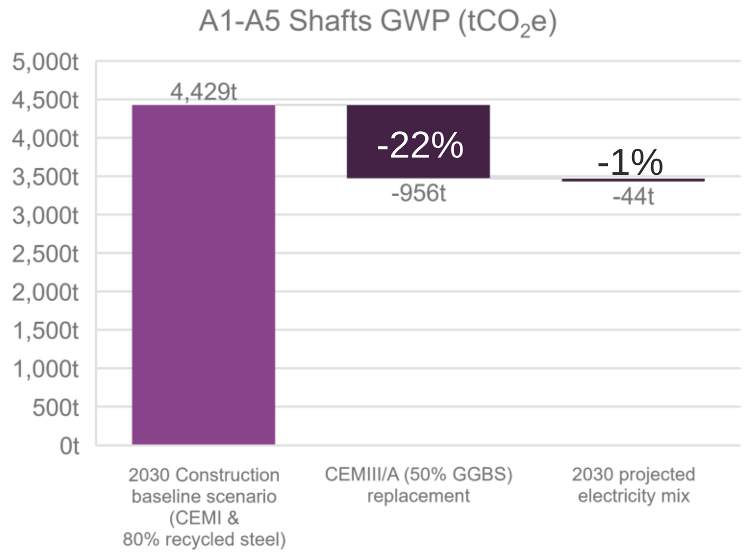
Shafts *(23% possible A1-A5 GWP reduction)*

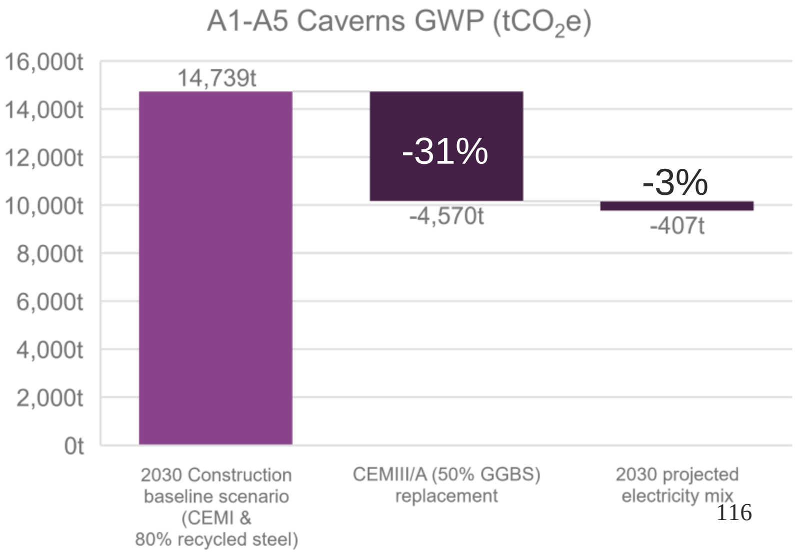
- Replacement of CEMI with CEMIII/A (50% GGBS).
- 2030 projected electricity mix in Tohoku region for construction activities as detailed in section 2.1.

Caverns *(34% possible A1-A5 GWP reduction)*

- Replacement of CEMI with CEMIII/A (50% GGBS).
- 2030 projected electricity mix in Tohoku region for construction activities as detailed in section 2.1.







Reduction opportunities conclusions

A1-A5 GWP possible reduction

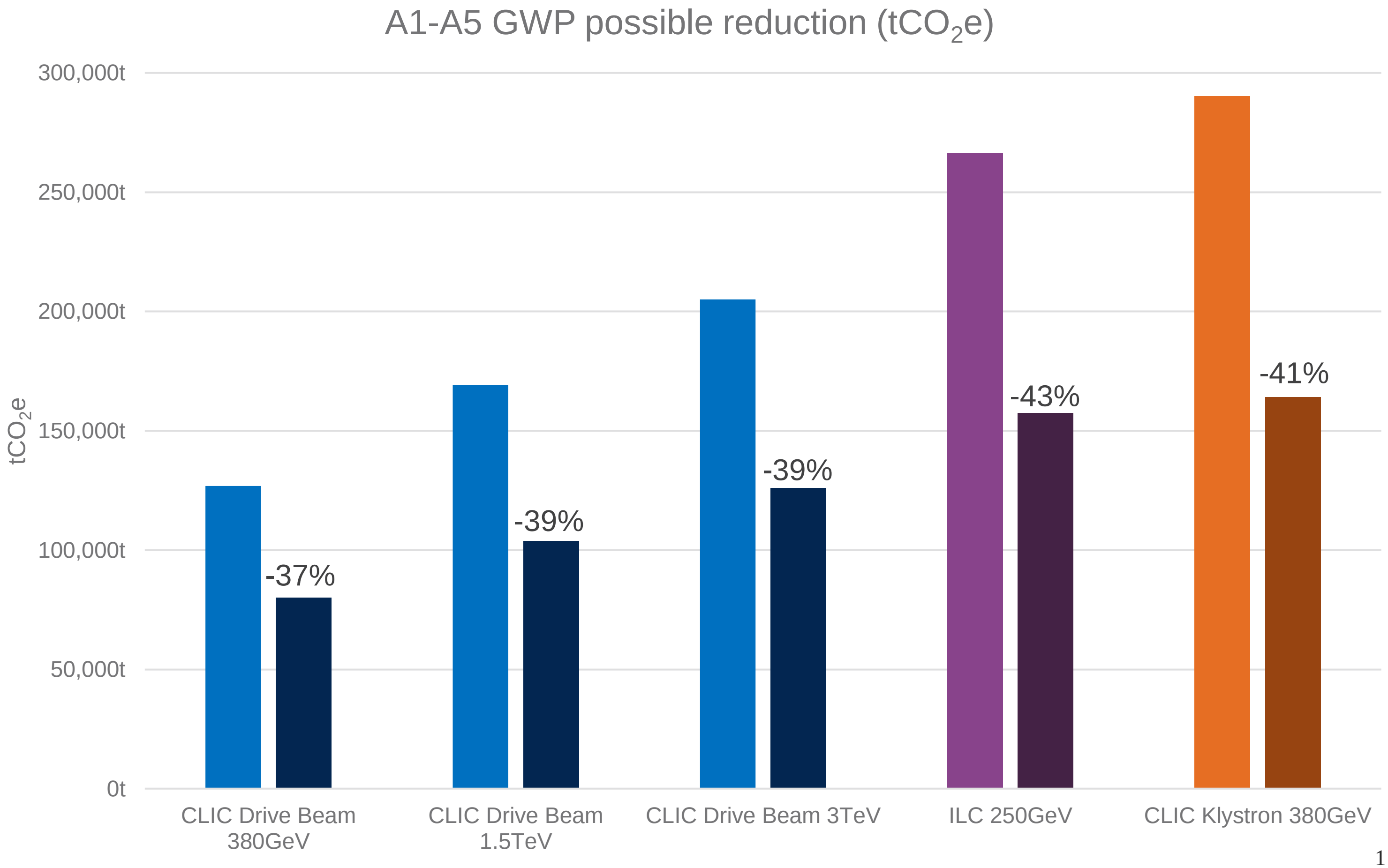
The following reduction opportunities were quantified for CLIC and ILC:

- Replace CEMI with CEMIII/A (50% GGBS).
- Replace concrete shielding wall with concrete casing filled with compact earthworks from excavation.
- Reduce existing design precast concrete segmental lining thickness in line with the lower bound value detailed in the ITA segmental tunnel lining guidance, 2019.
- 2030 projected electricity mix for France and Japan.

In relation to ILC, Huang, L. et al (2014)* recommends that improvements to blasting efficiency and reduced consumption of explosives can significantly reduce environmental impacts of D&B.

Note that these are not exhaustive, more carbon reduction opportunities can be identified if a consistent carbon management process is integrated in the project development – see PAS2080:2023.

A summary of the possible A1-A5 GWP reduction for CLIC and ILC options (tunnel, shafts and caverns combined) are summarised in the chart to the right. A 40% embodied carbon reduction is theoretically achievable for CLIC and ILC, in line with UN Breakthrough Outcomes for 2030 as detailed in section 1.1.



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* Huang, L. et al. Environmental impact of drill and blast tunnelling: life cycle assessment, Norwegian University of Science and Technology, 2014

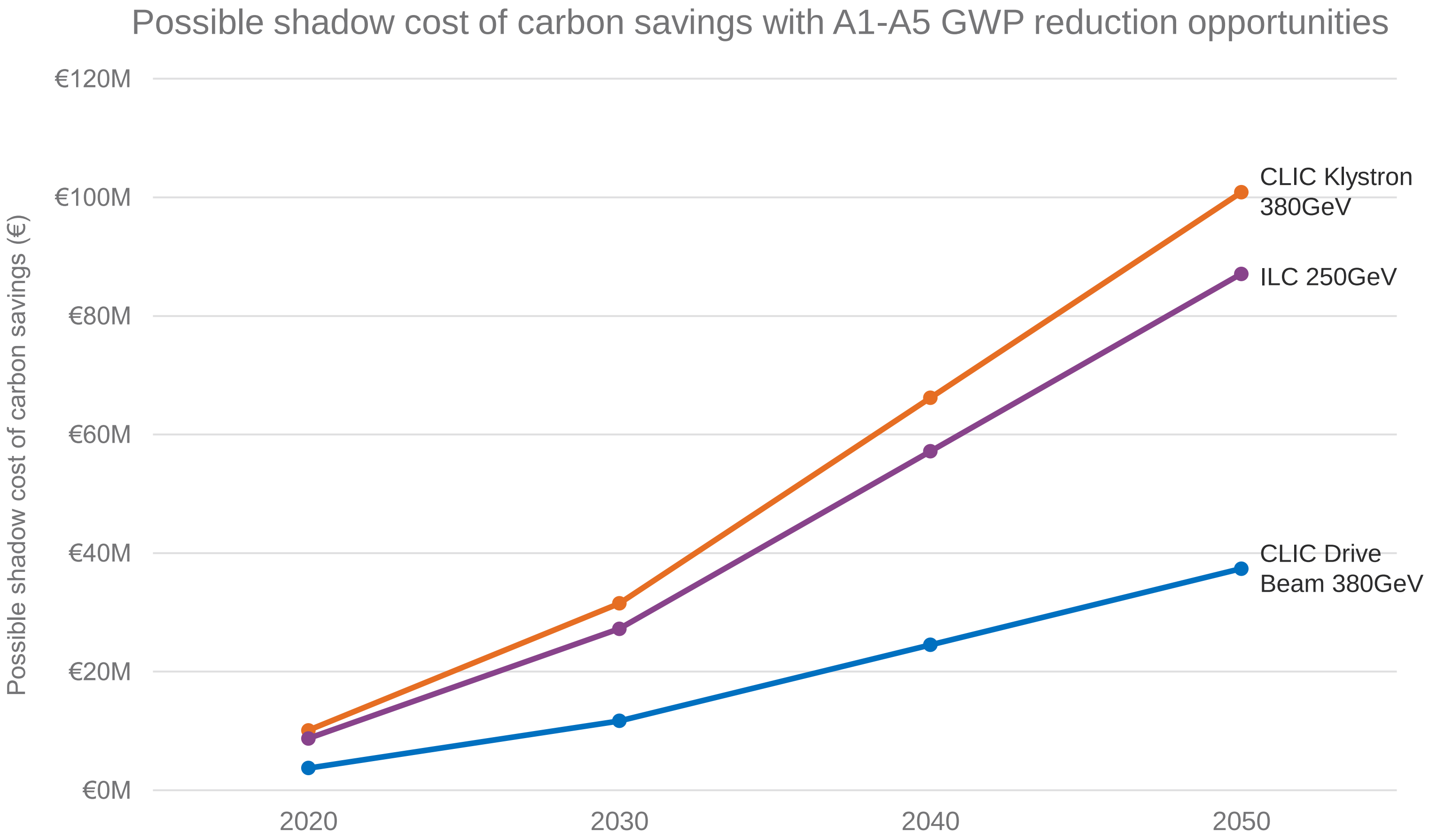
Reduction opportunities conclusions

Possible shadow cost of carbon savings

If the reduction opportunities quantified in this LCA were, the possible shadow cost of carbon saving could be significant, see the chart to the right. Note that these quantified reduction opportunities are not exhaustive. More carbon reduction opportunities can be identified if a consistent carbon management process is integrated in the project development – see PAS2080:2023.

If CLIC and ILC are constructed in 2030, there is a possible €12M – €30M shadow cost of carbon saving.

As detailed on page 102, every decade the shadow cost of carbon per tCO_2e increases significantly, therefore there is monetary incentive, as well as sustainability, to reduce carbon emissions of the designs.



5

Conclusions, recommendations & next steps

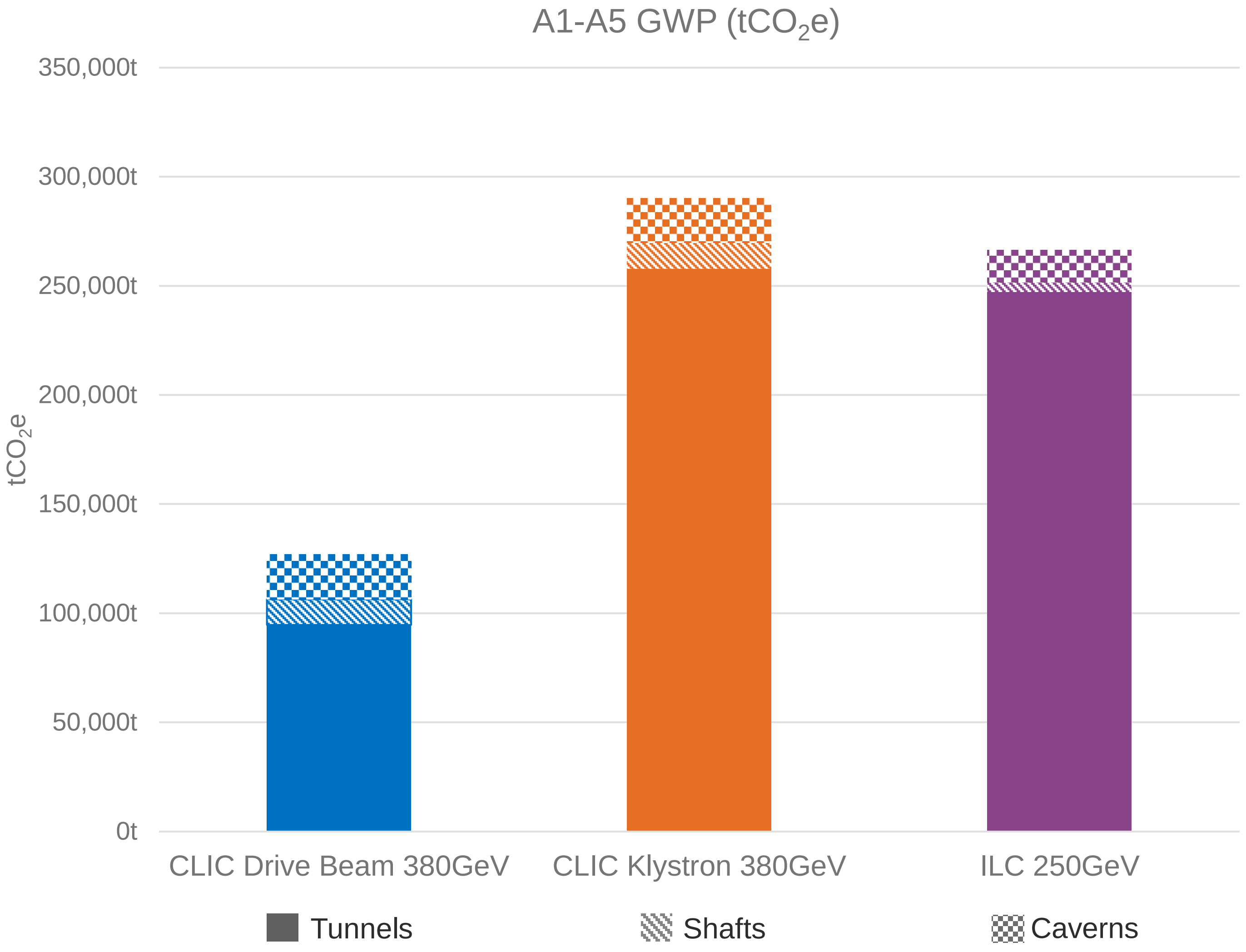
Conclusions

A life cycle assessment was completed for:

1. **CLIC Drive Beam**, 5.6m internal diameter, Geneva (380GeV, 1.5TeV and 3TeV)
2. **CLIC Klystron**, 10m internal diameter, Geneva (380GeV)
3. **ILC**, arched 9.5m span, Tohoku Region Japan (250GeV)

A1-A5 GWP was evaluated at system and sub-system level. A1-A3 GWP was evaluated at component and sub-component level. The GWP results highlight the elements of design that have the largest GWP contribution. This enabled GWP reduction opportunities to be identified for CLIC and ILC designs.

At sub-system level across all CLIC and ILC options the biggest GWP contributor was the material of the tunnels (A1-A3). This was further analysed at component and sub-component level which identified the permanent lining, invert/roadbed concrete and shielding wall being the largest contributors.



Recommendations and future considerations

Recommendations

The GWP results suggest that there is an opportunity for material and design optimisation of the current CLIC and ILC designs. This includes but is not limited to:

- Consideration of low carbon concrete technologies in replacement of Portland cement
- Replace the shielding wall in CLIC and ILC with concrete casing and earthworks fill, repurposed from tunnel excavation. This is to be confirmed with CERN and KEK upon shielding wall requirements.
- Reduce the precast concrete segmental lining thickness for CLIC Drive Beam and Klystron. This is a potential indication of achievable limits, based on design optimisation. Innovations in design could reduce this further.
- Consideration of projected 2030 electricity mix at the time of construction and how this transition can be influenced.
- Consideration of steel manufacturing processes (EAF or BF) and thus possible % of recycled steel content. Consideration of performance levels outlined in the Responsible Steel standard.
- Consideration of SFRC alternatives such as plant fibres and recycled tyre steel fibres.
- It is recommended that the LCA is updated at key design and development milestones going forward.

Carbon management

It is important to challenge all projects on their alignment with the net zero carbon transition at sector or region level. We encourage the projects to adopt a consistent approach to carbon management that is integrated into the decision-making throughout the project delivery, see PAS2080:2023.

The non-exhaustive list of recommendations within this report demonstrates that 40% less embodied carbon compared to current practice is possible. However, many more opportunities could be identified if the design and requirements were challenged on the grounds of carbon.

Innovation

Carbon reduction relies heavily on implementing innovative design, material and construction technologies to replace the existing high-carbon practices. Incentivising and building in allowance for additional time and resource to mature innovation will be key.

Governance

PAS2080 recognises the need for appropriate Governance in place that ensures integration of carbon reduction into decision-making. Our experience shows that many carbon reduction ideas are generated but not taken forward without executive ownership.

Procurement

Procurement for low carbon is necessary to drive low carbon outcomes. This would require different approach to risk sharing and mitigation when it comes to incentivising innovation. It is important to set appropriate baselines and targets to measure performance.

Alignment with net zero carbon transition

There is a much bigger carbon challenge than just embodied carbon: local, national and international commitments have agreed to rapidly diminishing available carbon budgets that must be shared fairly across all sectors of economy and society. Demand for renewable / low carbon electricity already exceeds capacity, with significant capital carbon needed for new infrastructure to address demand. This will challenge any additional demand coming online.

Operational aspects are outside this scope but should be part of future considerations as colliders have a significant impact on the grid.

EIB outlines the shadow cost of carbon price projections are set triple from 2030 to 2050, highlighting the need for decarbonisation of CLIC and ILC assets in construction and operation.