ARUP

Life Cycle Assessment

Comparative environmental footprint for future linear colliders CLIC and ILC

Interim Report (Draft)

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Contents

Executive summary

Approach

This interim report evaluates the A1-A3 results from a Life Cycle Assessment (LCA) completed for 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.

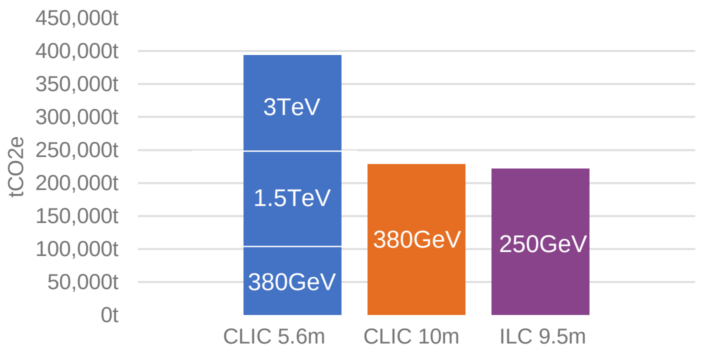
A1-A3 Global Warming Potential (GWP) hotspots have been evaluated and possible reduction opportunities have been identified.

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

A1-A3 Outcomes

A1-A3 considers material environmental impacts only (raw material extraction, transport to manufacturer and manufacture).

The absolute A1-A3 GWP (tCO2e) values are detailed below, and constitutes a baseline GWP for the current design for the CLIC and ILC. CLIC Klystron 380GeV and ILC 9.5m span 250GeV have similar A1-A3 GWP of approximately 0.2 MtCO2e. The CLIC Klystron 380GeV has approximately 2.5 times the A1-A3 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.



Recommendations & next steps

The A1-A3 GWP results indicate the current baseline and the areas where there may be opportunity for material and design optimisation of the current CLIC and ILC designs. This includes but is not limited to:

- Replacement of portland cement with SCMs, such as GGBS, FA or SF.
- Replacing the shielding wall in CLIC Klystron 10m dia. and ILC 9.5m span 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.
- Reducing the precast concrete segmental lining thickness for CLIC Drive Beam 5.6m dia. and CLIC Klystron 10m dia. The lower bound value in ITA segmental tunnel lining guidance, 2019. is a potential indication of achievable limits, based on design optimisation. Innovations in design could reduce this further.
- 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.

Further GWP recommendations will be provided on completion of A4-A5 Life Cycle Assessment. Further reduction opportunities will be investigated along with innovative material technologies.

Nomenclature

BF Blast Furnace

CLIC Compact Linear Collider

EAF Electric Arc Furnace

EOFP Photochemical oxidant formation: ecosystem quality

FA Fly Ash

FEP Freshwater eutrophication

FETP Freshwater ecotoxicity

FFP Fossil resource scarcity

GGBS Ground Granulated Blast-furnace Slag

GWP Global Warming Potential

HOFP Photochemical oxidant formation: human health

HTPc Human toxicity: cancer

HTPnc Human toxicity: non-cancer

ILC International Linear Collider

IRP Ionising Radiation Potential

LCA Life Cycle Assessment

LCI Life Cycle Inventory Analysis

LCIA Life Cycle Impact Assessment

LOP Land use

MEP Marine Eutrophication

METP Marine ecotoxicity

ODP Ozone Depletion Potential

PMFP Fine Particulate Matter Formation Potential

RICS Royal Institution of Chartered Surveyors

SF Silica Fume

SOP Mineral resource scarcity

TAP Terrestrial acidification

TETP Terrestrial ecotoxicity

WCP Water use

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Life Cycle Assessment approach

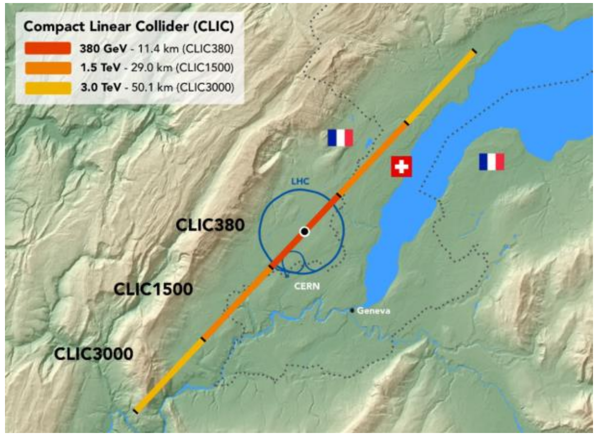
1.1 Background

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) head-on 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.

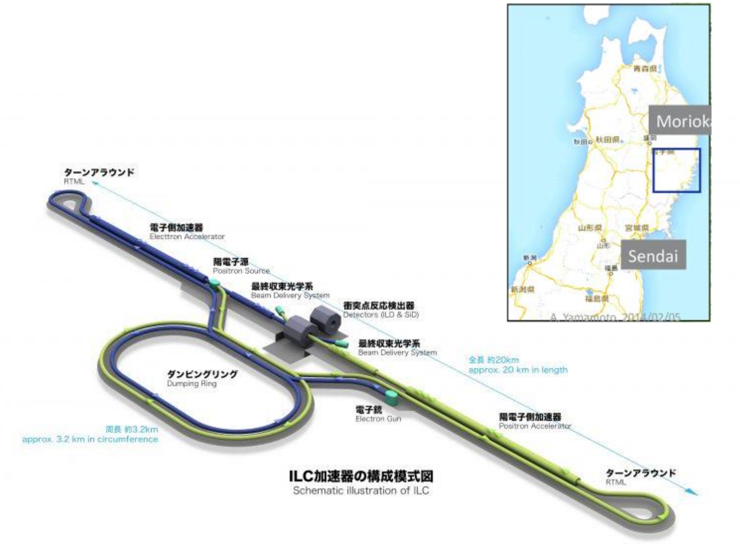
The site length ranges from 11 to 50 km stretching across the French-Swiss border near Geneva. The construction of the first CLIC energy stage is proposed to start by 2026. This would allow the first beams to be available by 2035 to start the CLIC physics programme spanning the following 25 to 30 years.



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, 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 (LCA).

Background

Context

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

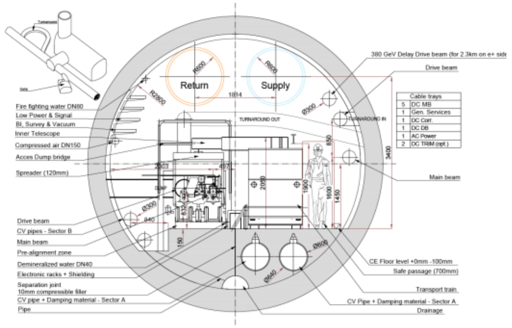
1. **CLIC Drive Beam**, 5.6m internal diameter, Geneva (380GeV, 1.5TeV and 3TeV)
2. **CLIC Klystron**, 10m internal diameter, Geneva (380GeV)
3. **ILC**, arched 9.5m span, Tohoku Region, Japan (250GeV)

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 energy only.

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

Data sources

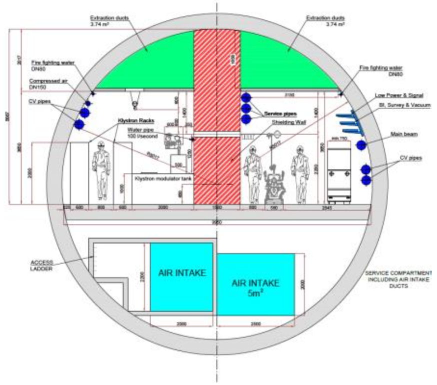
- CLIC Project Implementation Plan 2018 and CERN assumptions and clarifications.
- Tohoku ILC CE Plan 2020 and KEK clarifications in progress meetings.



CLIC Drive beam, 5.6m dia.

Geneva

Energies: 380GeV, 1.5TeV, 3TeV.



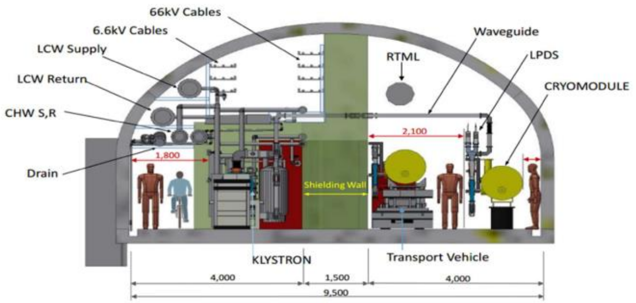
CLIC Klystron, 10m dia.

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 is 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.

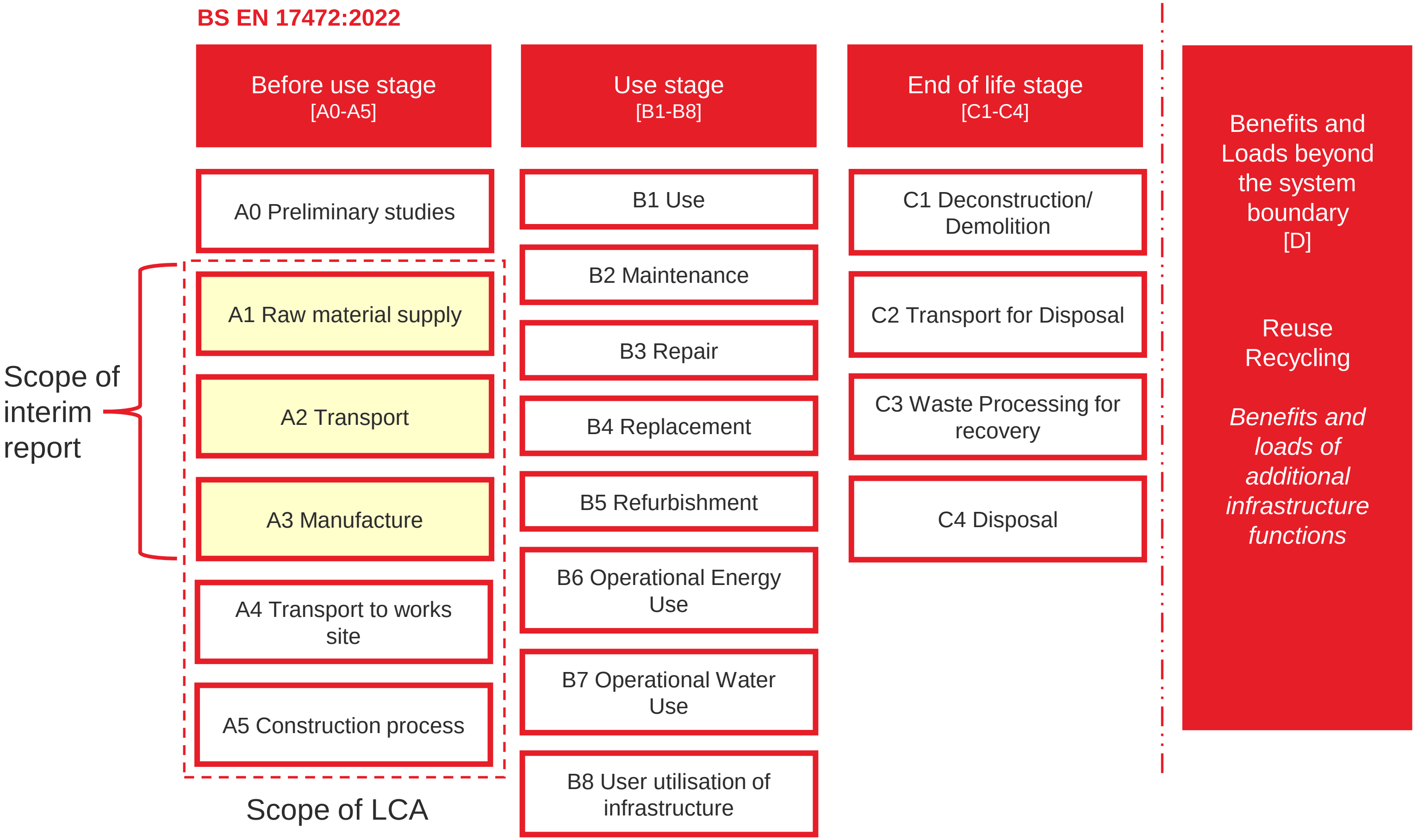
The life cycle is broken down into life cycle modules, as outlined in BS EN 17472:2022.

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.

This interim report evaluates A1-A3 for the three proposed linear colliders as highlighted in section 1.1.

The transport and construction activities (A4 and A5) will be evaluated in the final report.



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 ISO14040/44 and BS EN 17472:2022 and has chosen the most appropriate LCIA method for the LCA.

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 will be made and clearly stated. The scope of this report is A1-A3. A4-A5 will be evaluated at the next stage.

Arup will provide key conclusions and recommendations associated with reduction opportunities for CLIC and ILC. This will be compiled within the full in the final report.

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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, 79.6m2 cross section
- Location: Spain
- System boundaries: A1-A5 (incl. ventilation & lighting)
- Functional unit: kgCO2e/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)

CO2 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: kgCO2 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, 67m2 cross section
- Location: Norway
- System boundaries: A5 incl. ventilation and lighting
- Functional unit: tCO2e/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 CO2e/m tunnel length

Huang, L. (2014)

Environmental impact of drill and blast tunnelling: life cycle assessment

- 3km road tunnel, 67m2 cross section
- Location: Norway
- System boundaries: A5 (D&B, loading and hauling, scaling)
- Functional unit: tCO2e/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: 0.9tCO2e/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 and ISO 14044 standards – however not specified.
- Impact categories: EP, CC, PA, PE, ADP, AA, FOP presented.
- Construction activities: D&B and TBM
- Results: In case of 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 project LCAs that there is no consistent approach of completing a LCA for tunnels. This is expected, as the field of LCA for tunnels is a field 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 additional 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 A1A3 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 additional 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. 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. A4-A5 modules will be reported in the final report.

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 5.6m dia. (380GeV, 1.5TeV, 3TeV), CLIC Klystron 10m dia. (380GeV), and ILC 9.5m span (250GeV).

The A1-A3 results are evaluated to identify hotspots and reduction opportunities across the 3 linear collider options.

System Boundary

The system boundary of this interim report is A1-A3, raw material extraction to manufacture – see section 1.2. The transport and construction activities (A4 and A5) will be evaluated in the final report. 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

Impact Categories	Abbr.	Unit
Global warming	GWP	kg CO2 eq
Stratospheric ozone depletion	ODP	kg CFC11 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 SO2 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	m2a crop eq
Mineral resource scarcity	SOP	kg Cu eq
Fossil resource scarcity	FFP	kg oil eq
Water consumption	WCP	m3

Reference: ReCiPe Midpoint (H) 2016

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A1-A3 assessment

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2.1 Assumptions & exclusions

Assumptions

A1-A3

CLIC Drive Beam, 5.6m diameter

Materials:

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

Design:

- Rock bolt diameter 40mm
- Rock bolting caverns assumed ¾ of the wall heights, excludes floor, includes roof
- Rock bolting shafts, full wall area

LCIA factors:

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

CLIC Klystron, 10m diameter

Materials:

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

Design:

- Shafts and caverns are the same as CLIC Drive Beam, 5.6m diameter
- Rock bolt diameter 40mm
- Rock bolting caverns assumed ¾ of the wall heights, excludes floor, includes roof
- Rock bolting shafts, full wall area

LCIA factors:

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

ILC, 9.5m span

Materials:

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

Design:

- Shaft steel ribs spaced 1.5m
- Rock bolt diameter 25mm
- Rebar density of insitu permanent lining 50kg/m3
- 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)

LCIA factors:

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

Exclusions

A1-A3

CLIC Drive Beam, 5.6m diameter

- Water and electrical supplies
- Heating and ventilation
- Lighting
- Injector complex
- Embodied impact of MEP
- Embodied impact of plant
- Embodied impact of waterproofing system
- Embodied impact of invert drainage and survey pipes
- Embodied impact of temporary face support

CLIC Klystron, 10m diameter

- Water and electrical supplies
- Heating and ventilation
- Lighting
- Injector complex
- Embodied impact of MEP
- Embodied impact of plant
- Embodied impact of waterproofing system
- Embodied impact of invert drainage and survey pipes
- Embodied impact of temporary face support

ILC, 9.5m span

- Water and electrical supplies
- Heating and ventilation
- Lighting
- Drainage tunnel
- BDS service tunnel
- Embodied impact of MEP
- Embodied impact of plant
- Embodied impact of waterproofing system
- Embodied impact of invert drainage and survey pipes
- Embodied impact of temporary face support

2.2 Design parameters

Data Hierarchy

Asset hierarchy

An asset hierarchy was developed for CLIC and ILC to allow the data to be analysed at different levels enabling insights to be drawn as a system, or in more granular detail.

The hierarchy is defined as follows:

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

The hierarchy for CLIC Drive Beam and ILC 9.5m span is displayed in the table on the right.

System	Sub-system	Components	Sub-components
CLIC 5.6m and 10m dia.			
	Tunnels		
		Main accelerator tunnel and turnarounds	
			Primary Lining Permanent Lining Invert
	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 9.5m span 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, 5.6m diameter

Parameters

Design parameters

CLIC Drive Beam 5.6m diameter 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.

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/m3 SFRC 35kg/m3	Invert insitu concrete 30MPa Rebar 60kg/m3
		Turnarounds	Shotcrete, 200mm thk, 30MPa Rebar 60kg/m3 Rock bolt 2.5m (3x3m) 40mm dia.	Insitu concrete, 200mm thk, 40MPa Rebar 100kg/m3	-
	Shafts	9m – 18m dia.	Shotcrete, 300-500mm thk, 30MPa Rebar 20-50kg/m3 Rock bolts 7m (3x3m) 40mm dia.	Insitu concrete, 300-600mm thk, 40MPa Rebar 60-130kg/m3	-
	Caverns	BDS, UTRC, UTRA, BC2, service, IR, detector and service hall	Shotcrete, 400mm thk, 30MPa Rebar 55kg/m3 Rock bolts 10m (3x3m) 40mm dia.	Insitu concrete, 110mm thk, 40MPa Rebar 120kg/m3	-
		Drive beam dump	Shotcrete, 200mm thk, 30MPa Rebar 55kg/m3 Rock bolts 10m (3x3m) 40mm dia.	Insitu concrete, 45mm thk, 40MPa Rebar 120kg/m3	

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, 10m diameter

Parameters

Design parameters

CLIC Klystron 10m diameter 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.

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/m3 SFRC 35kg/m3	Shielding wall insitu concrete 30MPa, Rebar 40kg/m3 Invert insitu concrete 30MPa, Rebar 60kg/m3
		Turnarounds	Shotcrete, 200mm thk, 30MPa Rebar 60kg/m3 Rock bolt 2.5m (3x3m) 40mm dia.	Insitu concrete, 200mm thk, 40MPa Rebar 100kg/m3	-
	Shafts	9m – 18m dia.	Shotcrete, 300-500mm thk, 30MPa Rebar 20-50kg/m3 Rock bolts 7m (3x3m) 40mm dia.	Insitu concrete, 300-600mm thk, 40MPa Rebar 60-130kg/m3	-
	Caverns	BDS, UTRC, UTRA, BC2, service, IR, detector and service hall	Shotcrete, 200mm thk, 30MPa Rebar 55kg/m3 Rock bolts 10m (3x3m) 40mm dia.	Insitu concrete, 110mm thk, 40MPa Rebar 120kg/m3	-
		Drive beam dump	Shotcrete, 200mm thk, 30MPa Rebar 55kg/m3 Rock bolts 10m (3x3m) 40mm dia.	Insitu concrete, 45mm thk, 40MPa Rebar 120kg/m3	

ILC 9.5m span

Tunnel parameters

Design parameters

ILC 9.5m span 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

Material parameters

System	Sub-system	Components	Sub-components		
			Primary lining	Permanent lining	Shielding wall
ILC 9.5m span 250GeV	Tunnels	Main accelerator tunnel	Shotcrete 30MPa Rock bolts, L=3m, 25mm dia.	Insitu concrete 40MPa, Rebar density 50kg/m3 Roadbed concrete 40MPa	Shielding wall 30MPa, Rebar 40kg/m3
		BDS Beam tunnels (Section A, B, C, D)	Shotcrete 30MPa Rock bolts, L=4m, 25mm dia. Rock bolt no. for sections A= 15no, B = 20no, C=25no, D=38no.	Insitu concrete 40MPa, Rebar density 50kg/m3 Roadbed concrete 40MPa	-
		Damping ring, loop at ends, widening, reversal pits, RTML, AT-DH and AT-DR	Shotcrete 30MPa Rock bolts, L=3m, 25mm dia.	Insitu concrete 40MPa, Rebar density 50kg/m3 Roadbed concrete 40MPa	Shielding wall for widening 30MPa, Rebar 40kg/m3
		Peripheral tunnels	Shotcrete 30MPa Rock bolts, L=3m, 25mm dia.	Shotcrete 30MPa Roadbed concrete 40MPa	-
		Access tunnel (CI)	Shotcrete 30MPa Rock bolts, L=3m, 25mm dia.	Shotcrete 30MPa Roadbed concrete 40MPa	-
		Access tunnel (CII)	Shotcrete 30MPa Rock bolts, L=3m, 25mm dia. Steel support H125 per 1.2m	Shotcrete 30MPa Roadbed concrete 40MPa	-
		Access tunnel (DI)	Shotcrete 30MPa Rock bolts, L=4m, 25mm dia. Steel support H125 per 1.0m	Shotcrete 30MPa Roadbed concrete 40MPa	-
		Access tunnel (DIII)	Shotcrete 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 40MPa, Rebar density 50kg/m3 Roadbed concrete 40MPa	-

ILC 9.5m span

Shafts & caverns parameters

Design parameters

ILC 9.5m span 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

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/m3	-
		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-A3 GWP results

Summary of A1-A3 GWP Results

Purpose

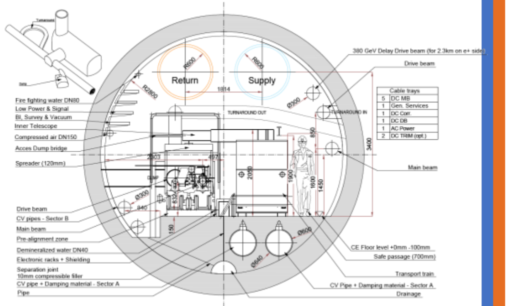
Global Warming Potential (GWP) was analysed as one of the 18 impact categories in the ReCiPe Midpoint (H) 2016 method. The GWP impacts contribute directly to increased greenhouse gas emissions in the atmosphere.

A1-A3 GWP results are reported and analysed for potential reduction opportunities. The additional 17 impact categories are reported and contrasted in section 2.5.

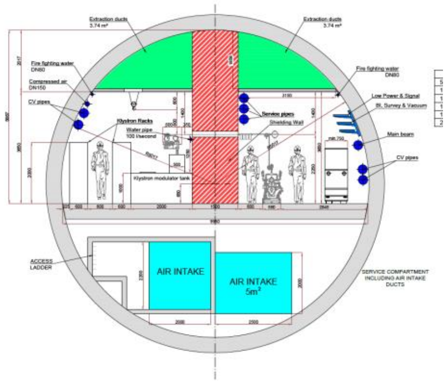
A summary of the A1-A3 GWP is evaluated for:

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)

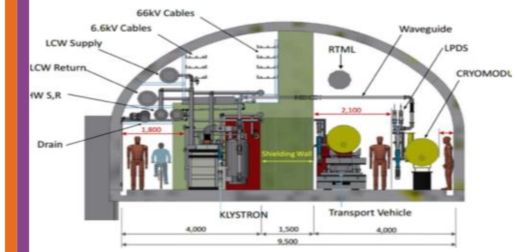
The results are colour coded blue, orange and purple respectively for ease of comparison between the 3 proposed linear collider options.



CLIC Drive beam, 5.6m dia.



CLIC Klystron, 10m dia.



ILC, 9.5m span

Summary of A1-A3 GWP Results

System Level

A1-A3 Absolute GWP

The absolute A1-A3 GWP results are listed below and are reported to 3 significant figures:

CLIC Drive Beam 5.6m dia. (built in 3 stages):

380GeV 98,500 tCO_2e
1.5TeV 133,000 tCO_2e
3TeV 161,000 tCO_2e

Total CLIC Drive Beam 3TeV: 393,000 tCO_2e

CLIC Klystron 10m dia.:

380GeV 229,000 tCO_2e

ILC 9.5m span:

250GeV 222,000 tCO_2e

Summary A1-A3 GWP Results

Sub-system Level

A1-A3 tCO2e/km of main accelerator tunnel

The tCO2e/km of main accelerator tunnel results are listed below:

CLIC 5.6m:

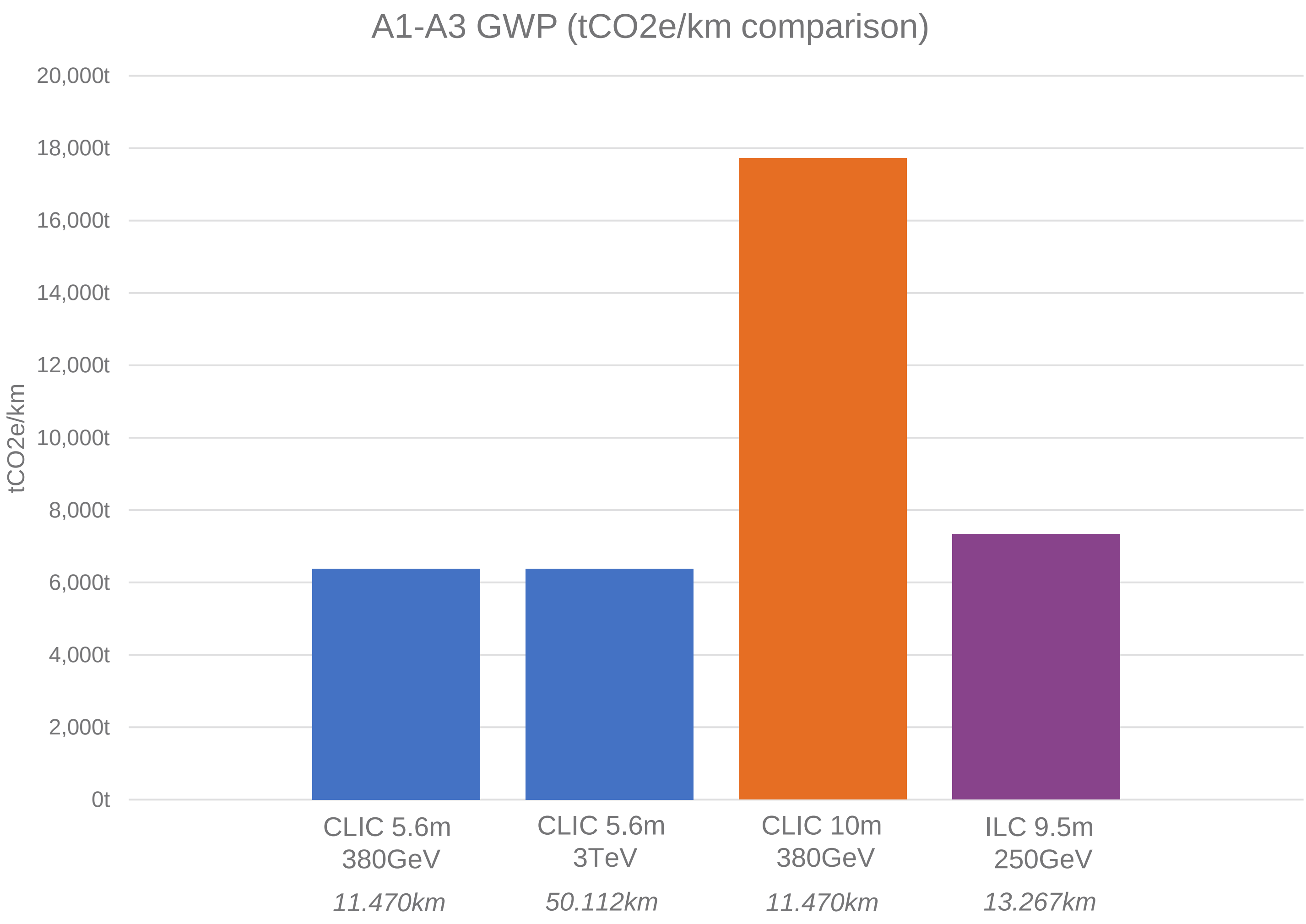
380GeV 6380 tCO2e/km
3TeV 6380 tCO2e/km

CLIC 10m:

380GeV 17700 tCO2e/km

ILC 9.5m:

250GeV 7340 tCO2e/km



CLIC Drive Beam 5.6m dia. A1-A3 GWP results

CLIC Drive Beam 5.6m diameter, 380GeV

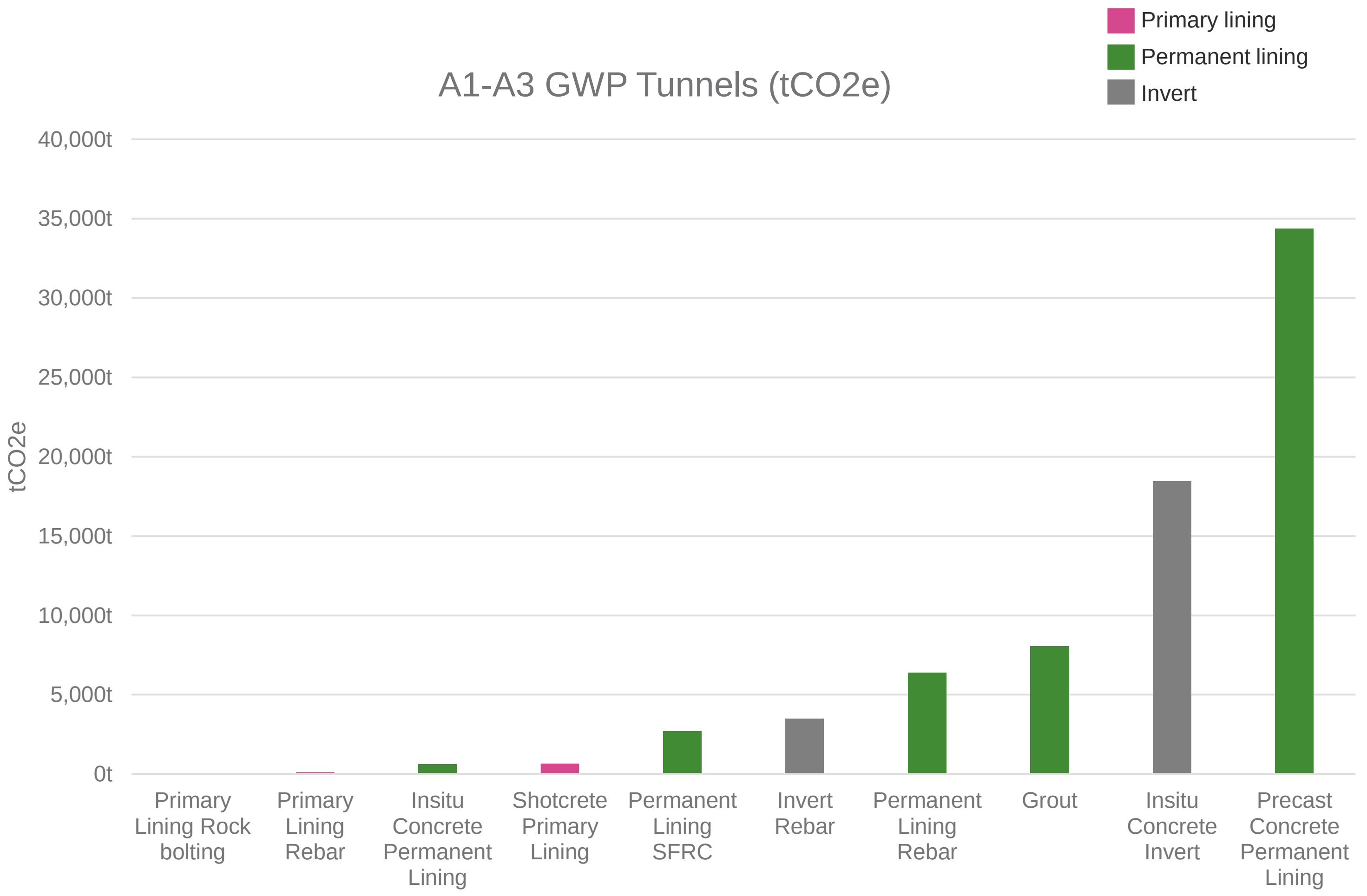
Sub-component Level

Tunnels

Tunnels are inclusive of:

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

Precast concrete permanent lining is the largest A1-A3 GWP contributor for the tunnels sub-component level for CLIC Drive Beam 5.6m 380GeV, with a lining thickness of 300mm at 50MPa. This is followed by insitu concrete invert (30MPa with 60kg/m3 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 tunnel.

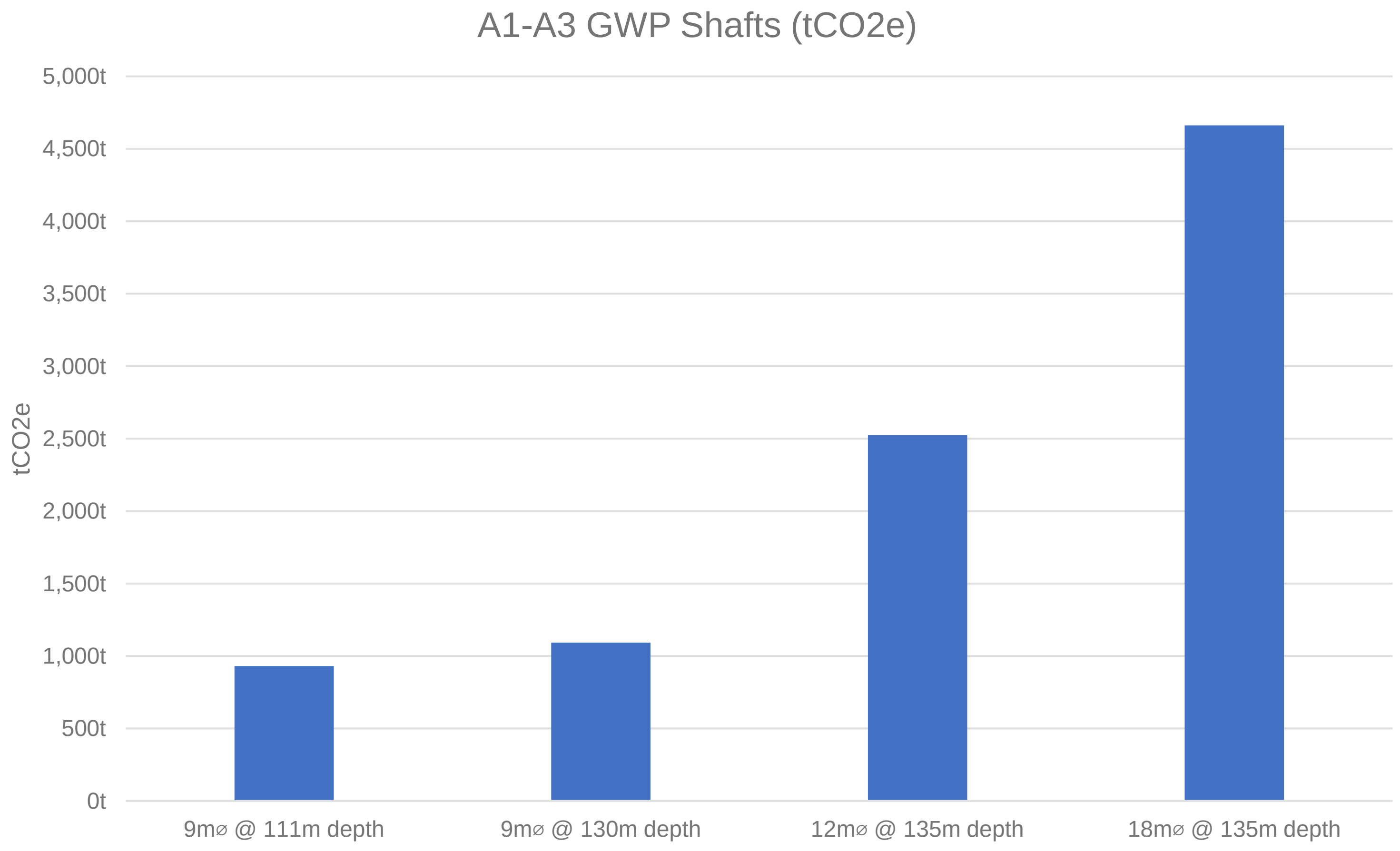
CLIC Drive Beam 5.6m diameter, 380GeV

Component Level

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

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 5.6m diameter, 380GeV

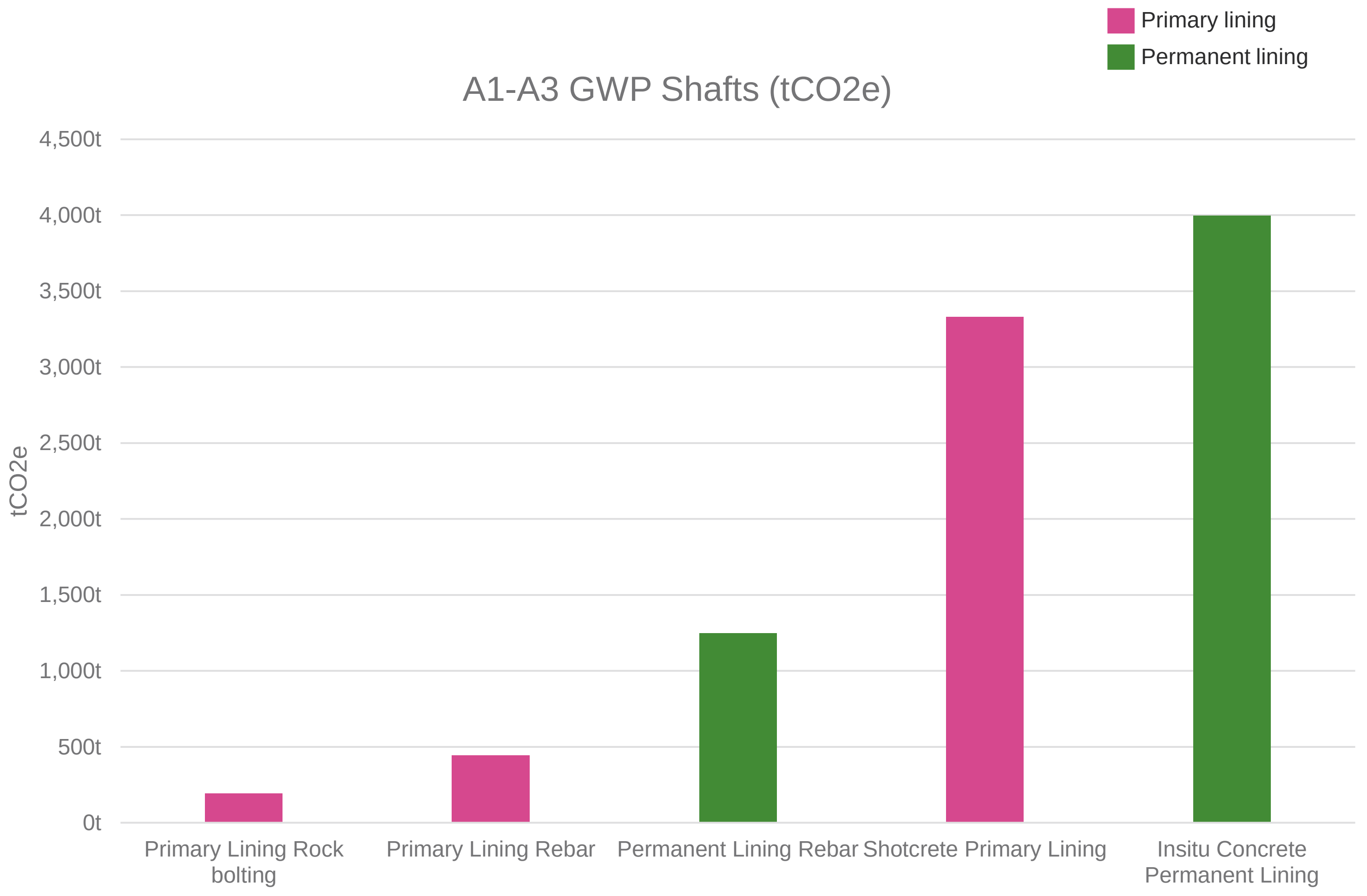
Sub-component Level

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.



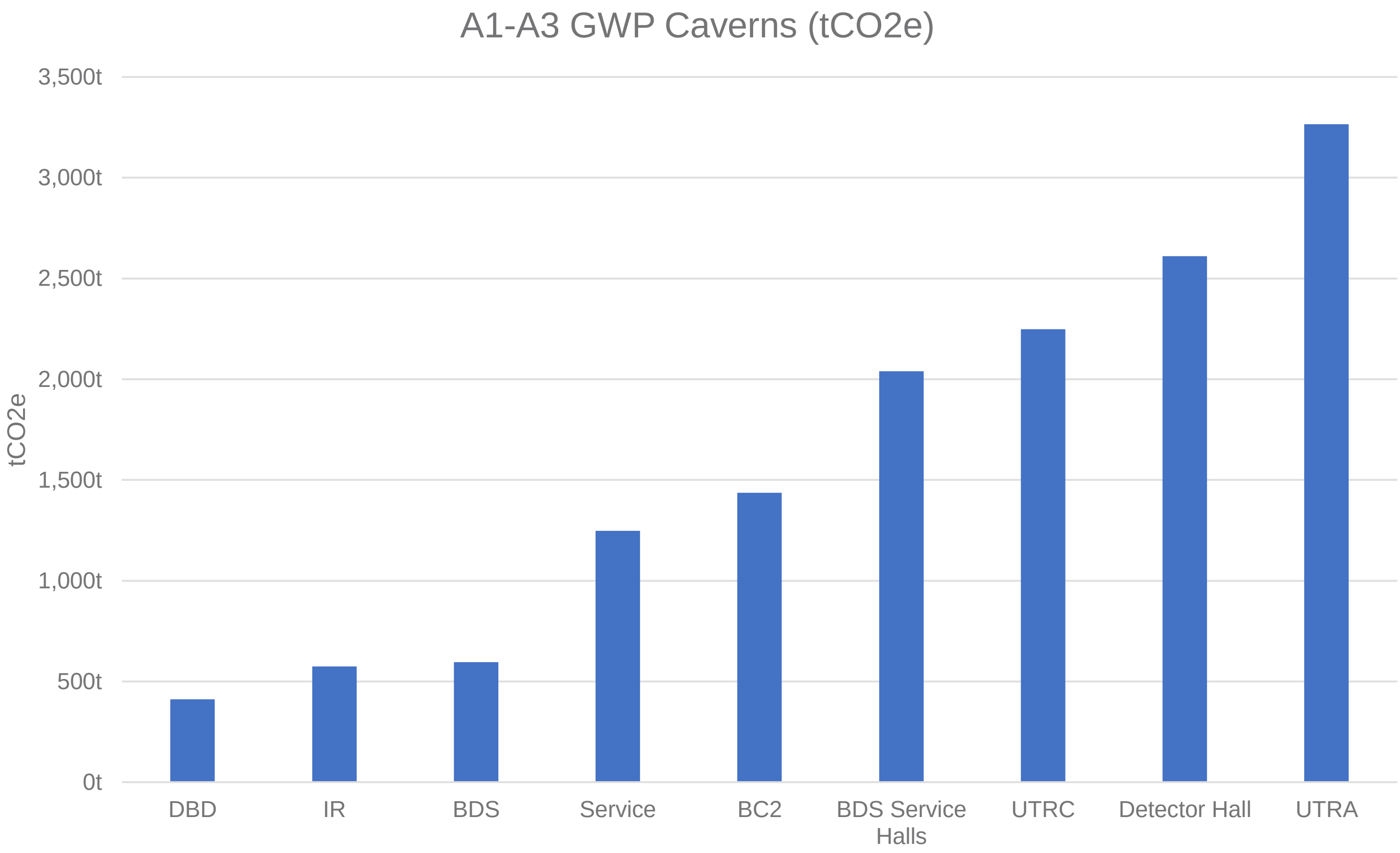
CLIC Drive Beam 5.6m diameter, 380GeV

Component Level

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 5.6m diameter, 380GeV

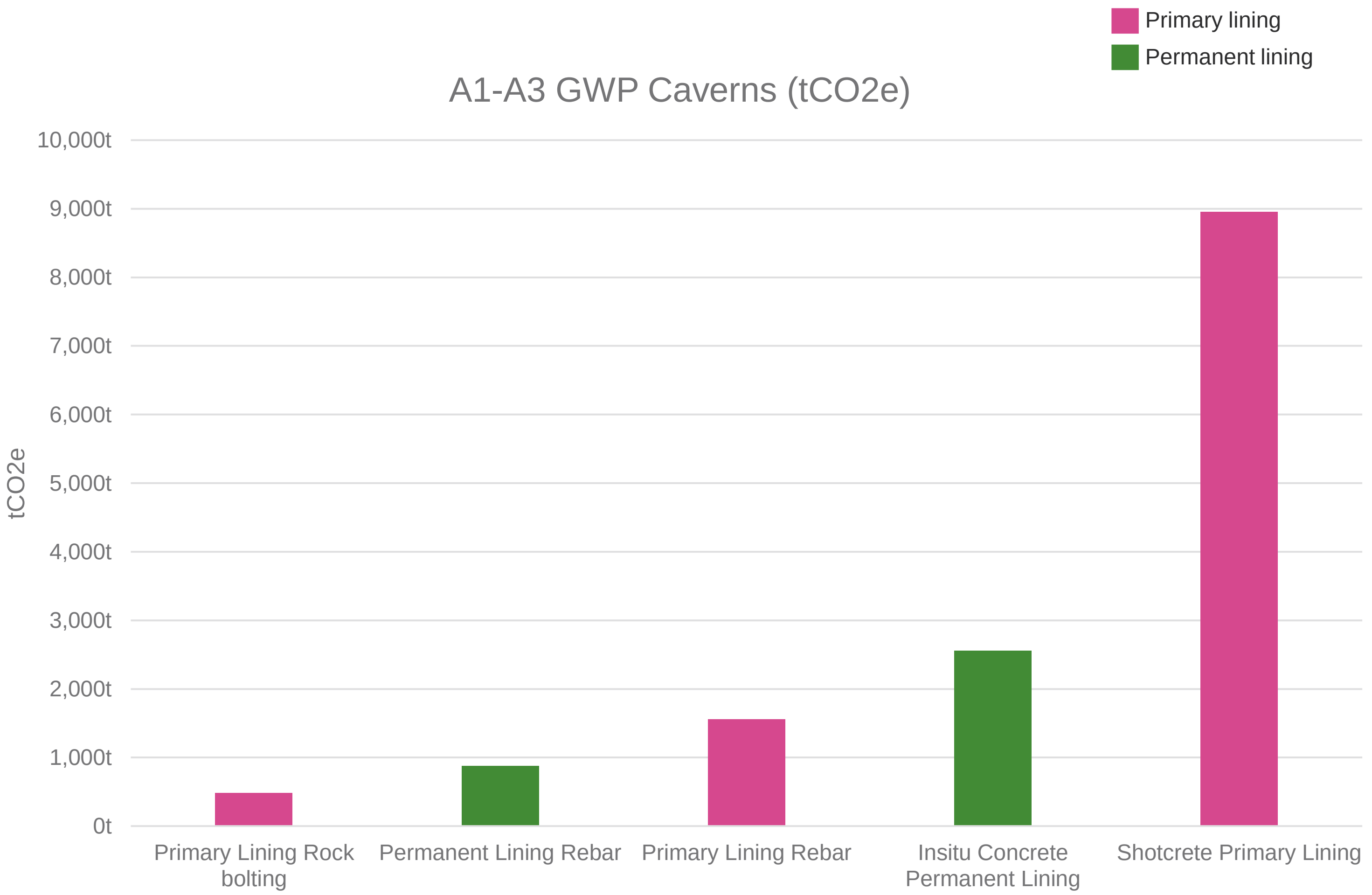
Sub-component Level

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 5.6m diameter, 1.5TeV

Sub-component Level

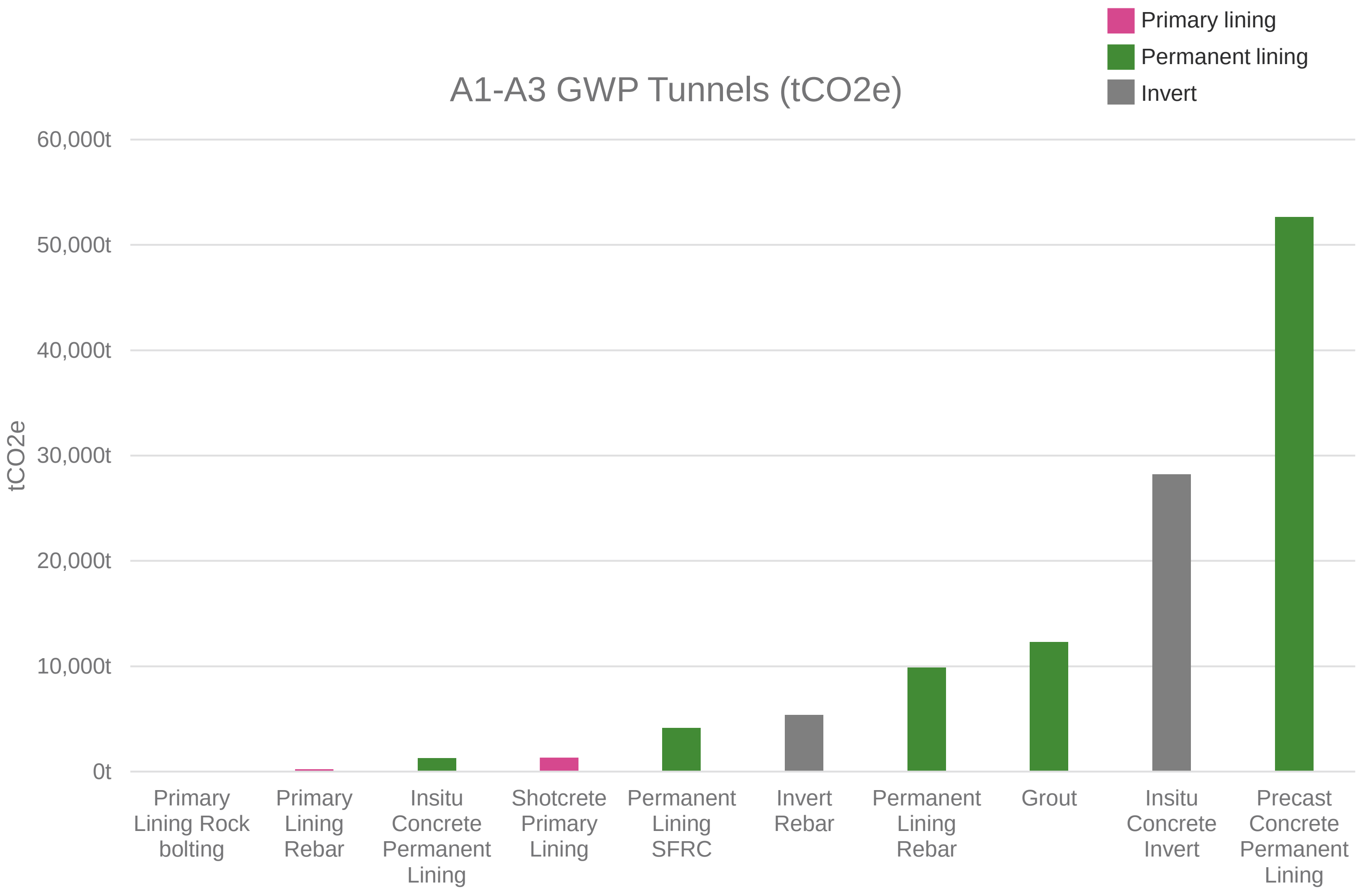
Tunnels

Tunnels are inclusive of:

- 17564m 5.6m dia. accelerator tunnel
- 20no. 3m 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/m3 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 tunnel.

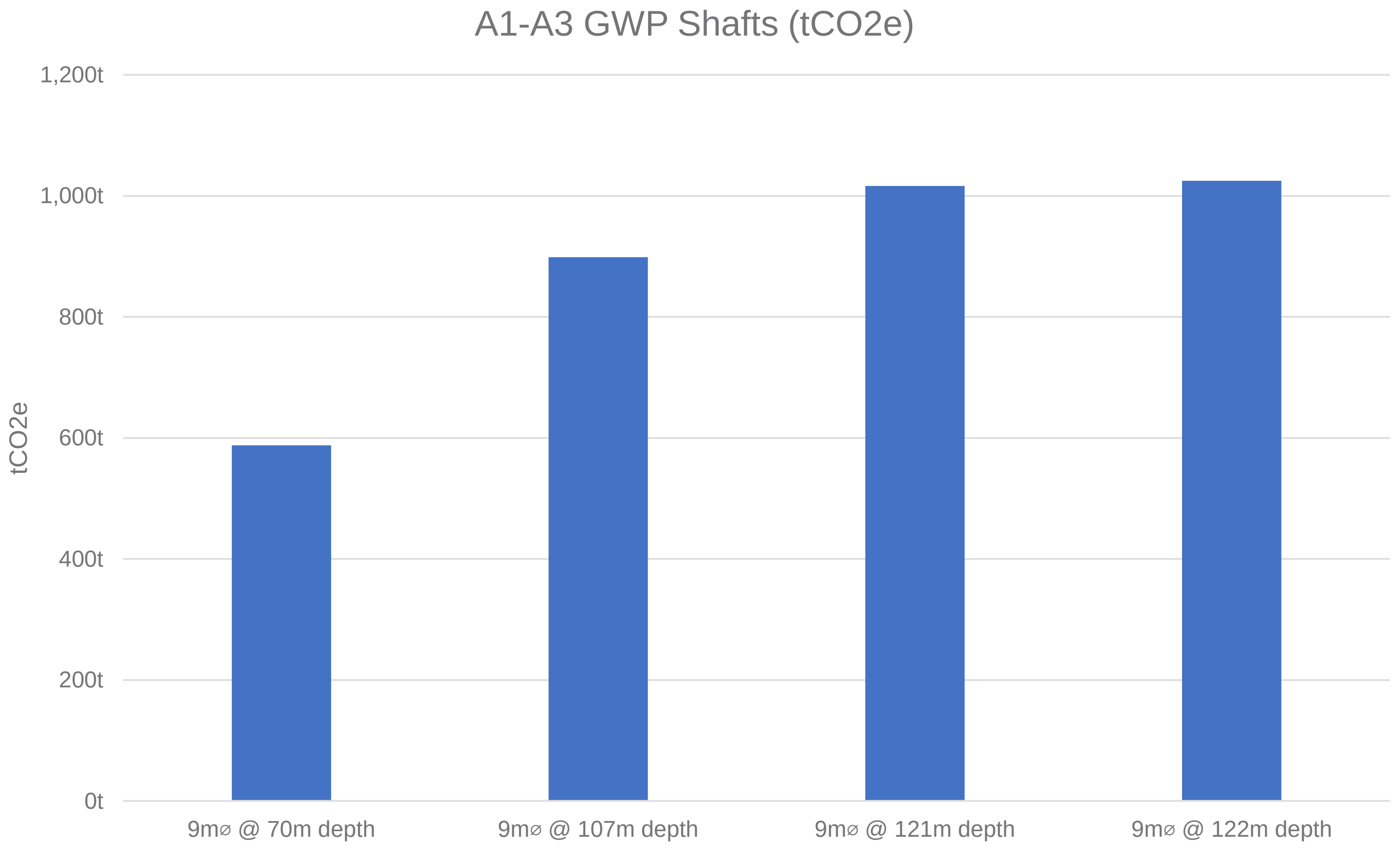
CLIC Drive Beam 5.6m diameter, 1.5TeV

Component Level

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

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



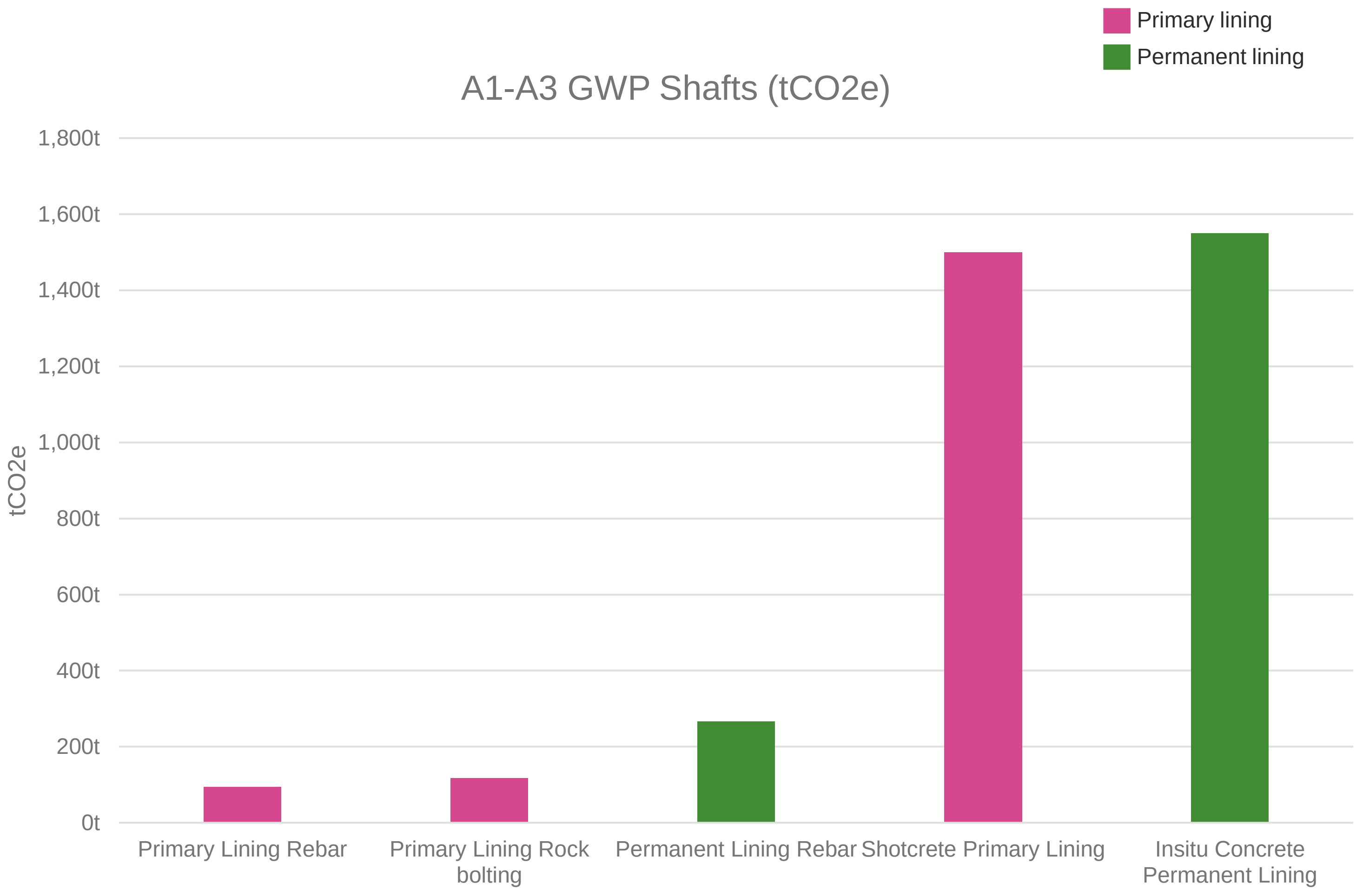
CLIC Drive Beam 5.6m diameter, 1.5TeV

Sub-component Level

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.



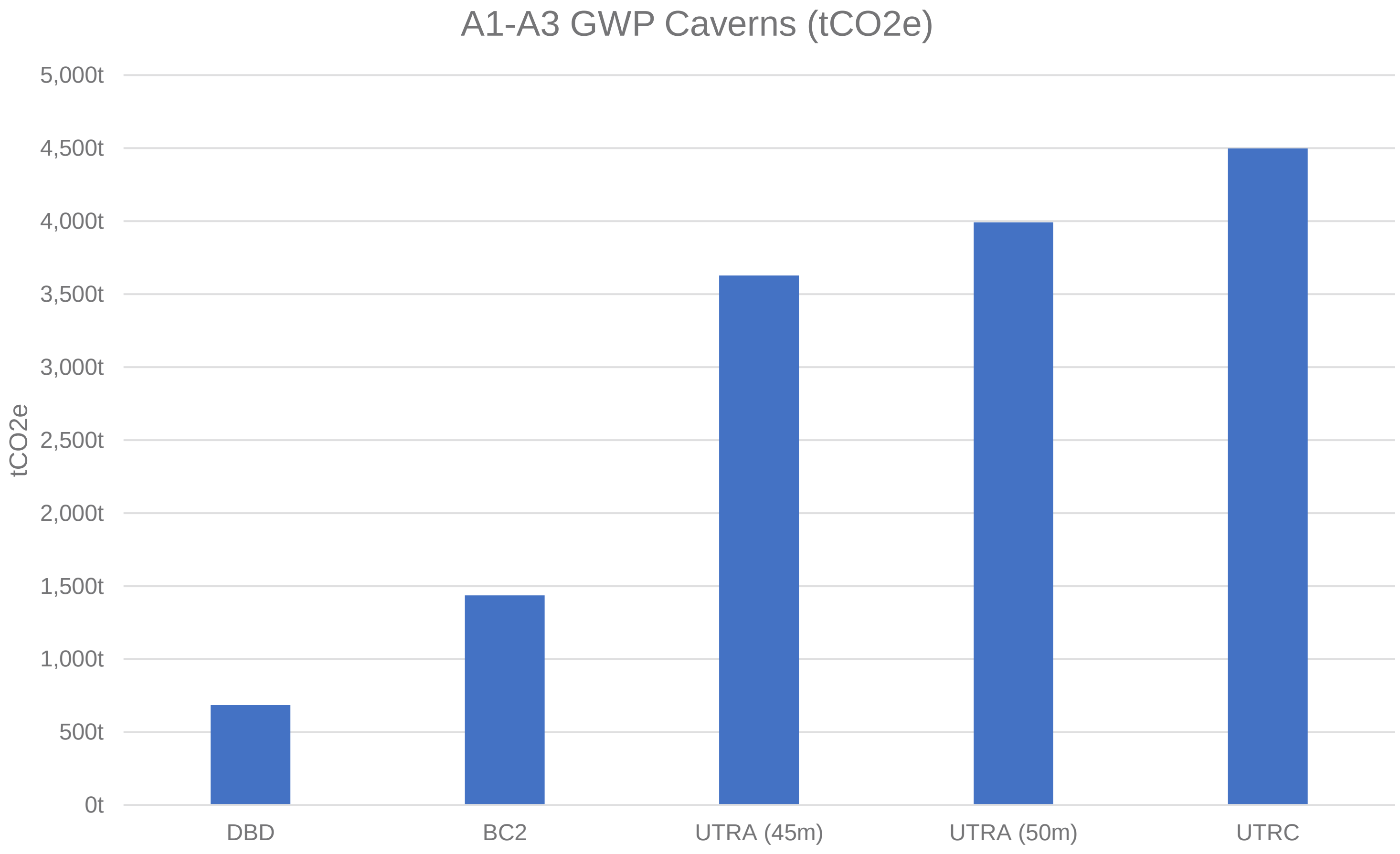
CLIC Drive Beam 5.6m diameter, 1.5TeV

Component Level

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 5.6m diameter, 1.5TeV

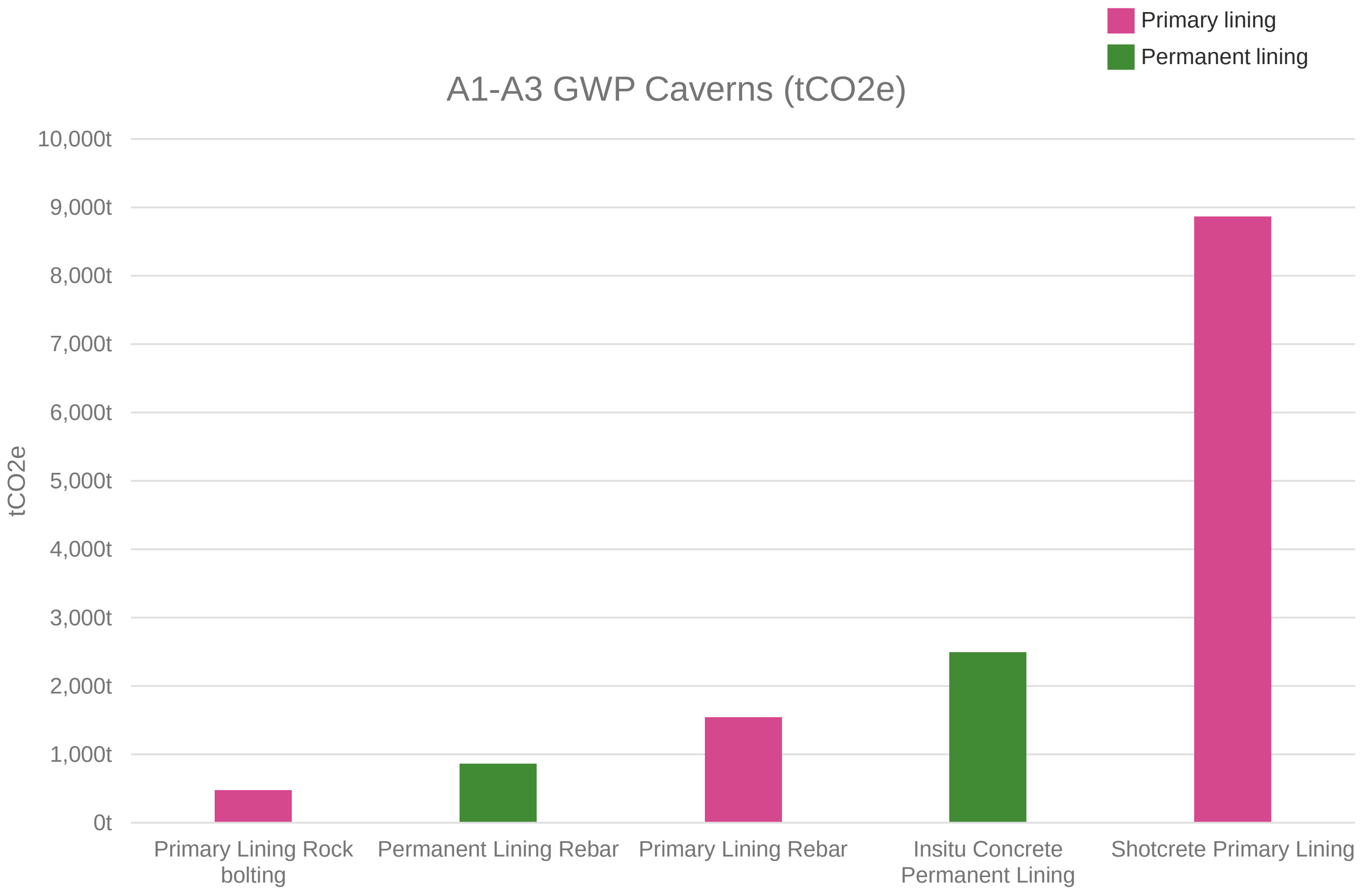
Sub-component Level

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 5.6m diameter, 3TeV

Sub-component Level

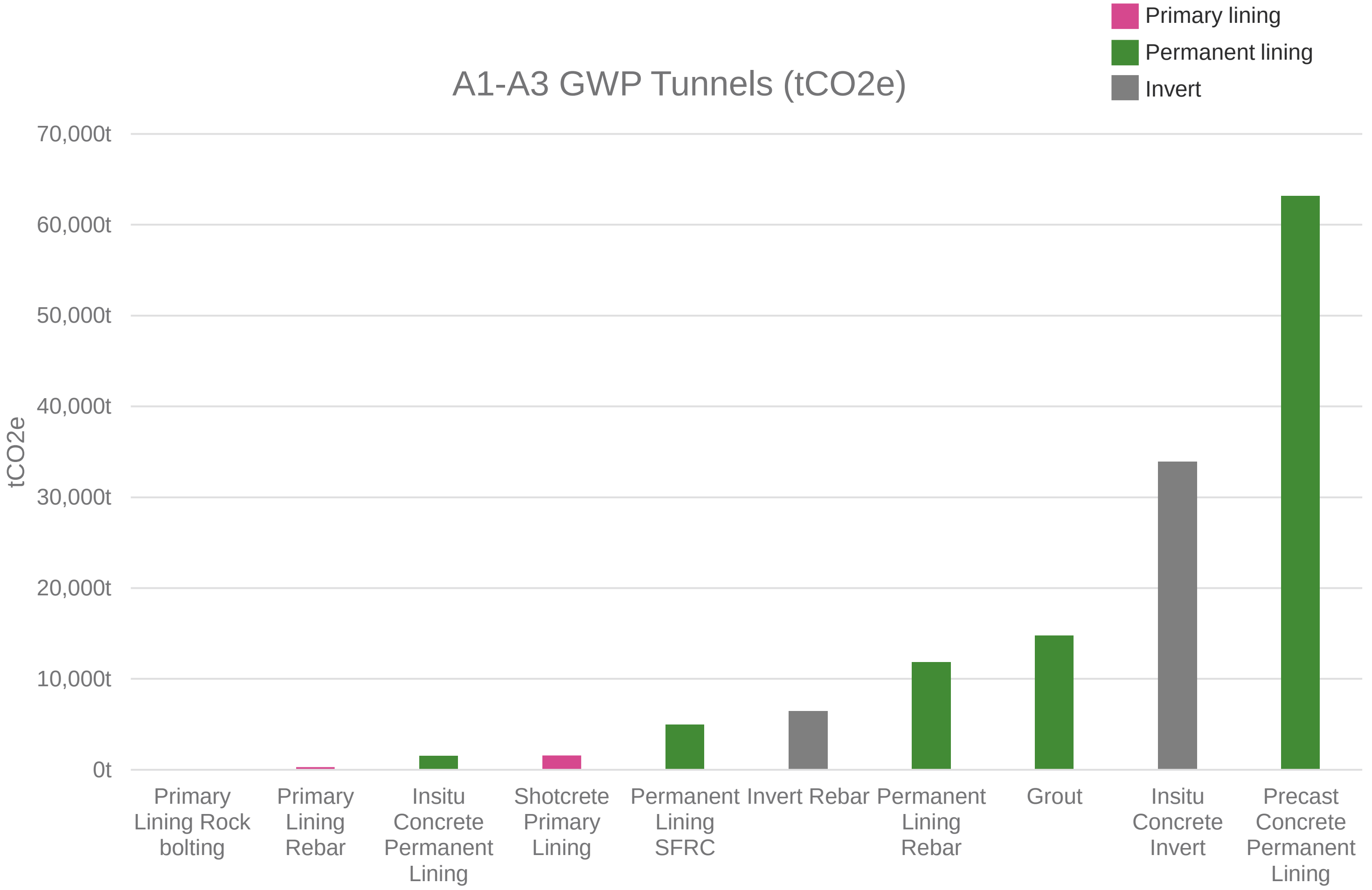
Tunnels

Tunnels are inclusive of:

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

This is the last extension stage for CLIC Drive Beam 5.6m.

Precast concrete permanent lining is the largest A1-A3 GWP contributor for the tunnels sub-component level for CLIC 5.6m 380GeV, with a lining thickness of 300mm at 50MPa. This is followed by insitu concrete invert (30MPa with 60kg/m3 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 tunnel.

CLIC Drive Beam 5.6m diameter, 3TeV

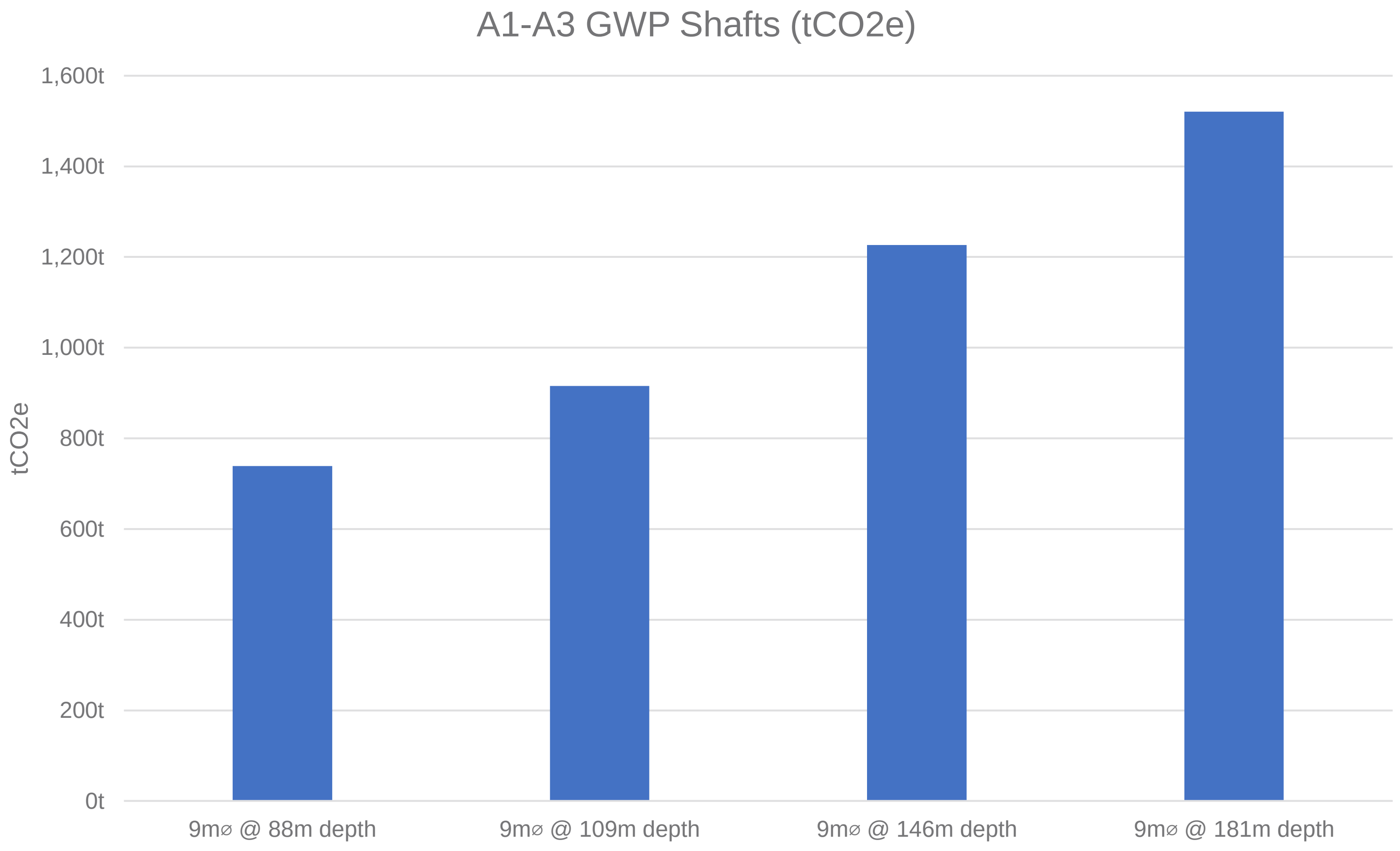
Component Level

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

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 5.6m diameter, 3TeV

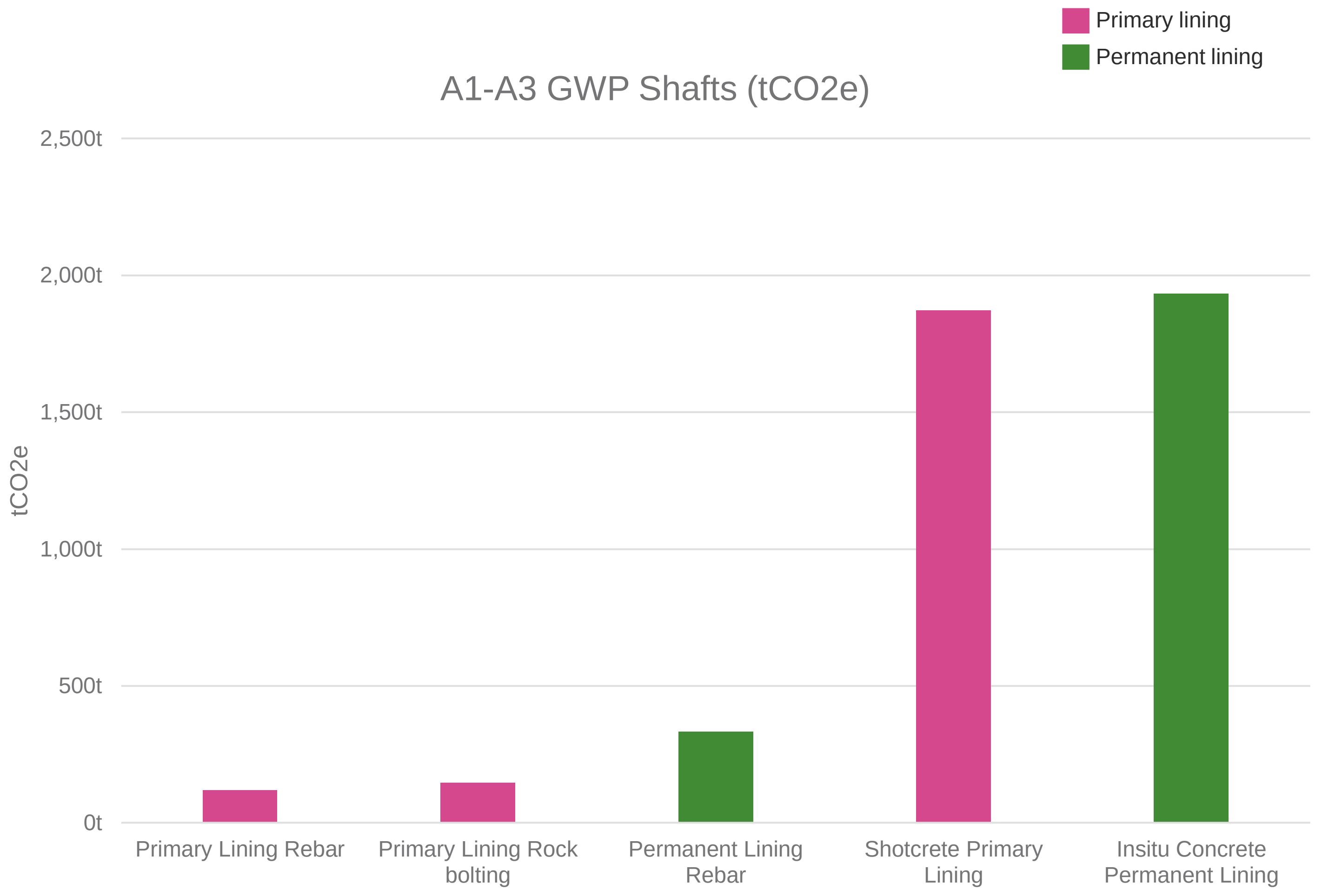
Sub-component Level

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.



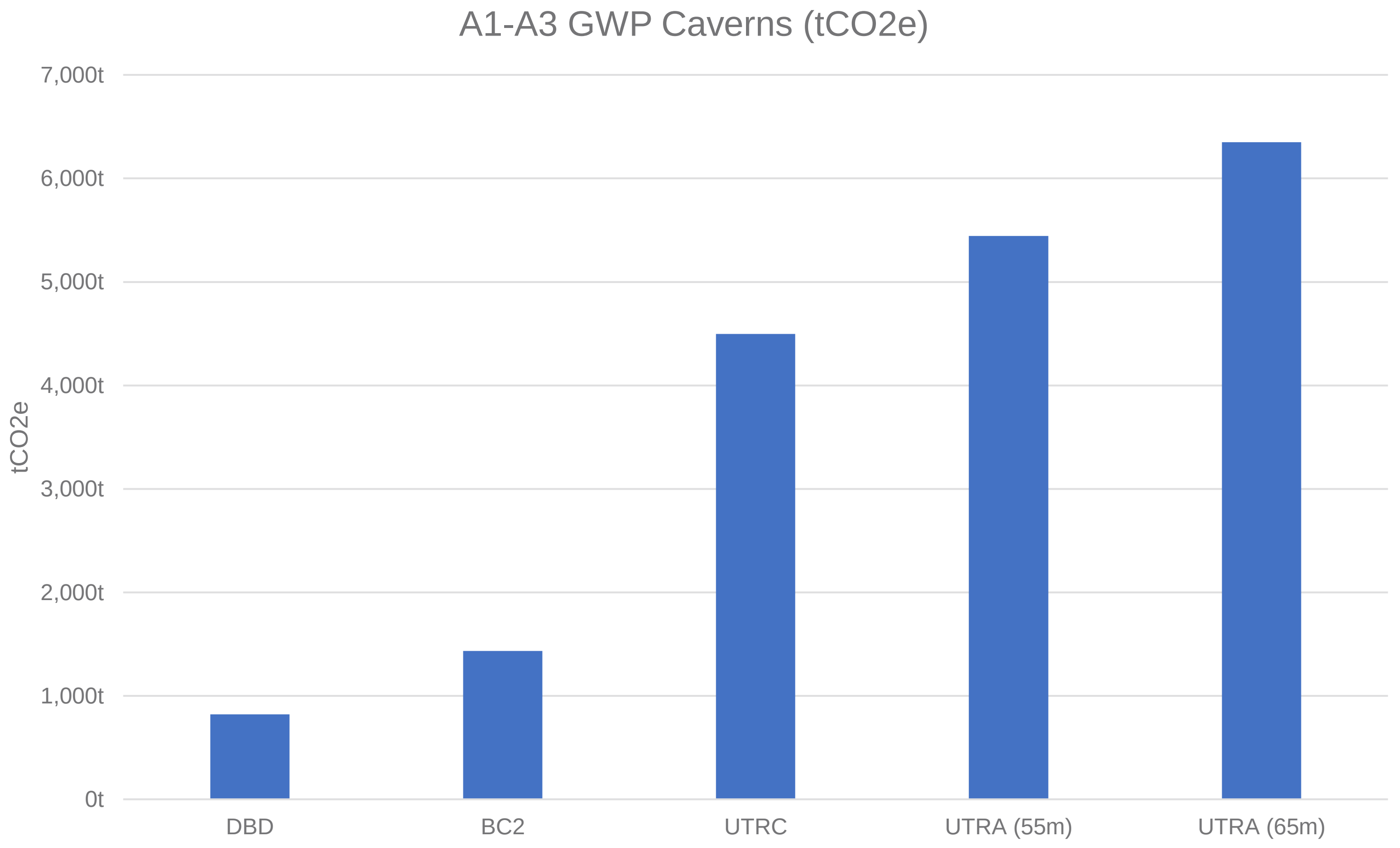
CLIC Drive Beam 5.6m diameter, 3TeV

Component Level

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 5.6m diameter, 3TeV

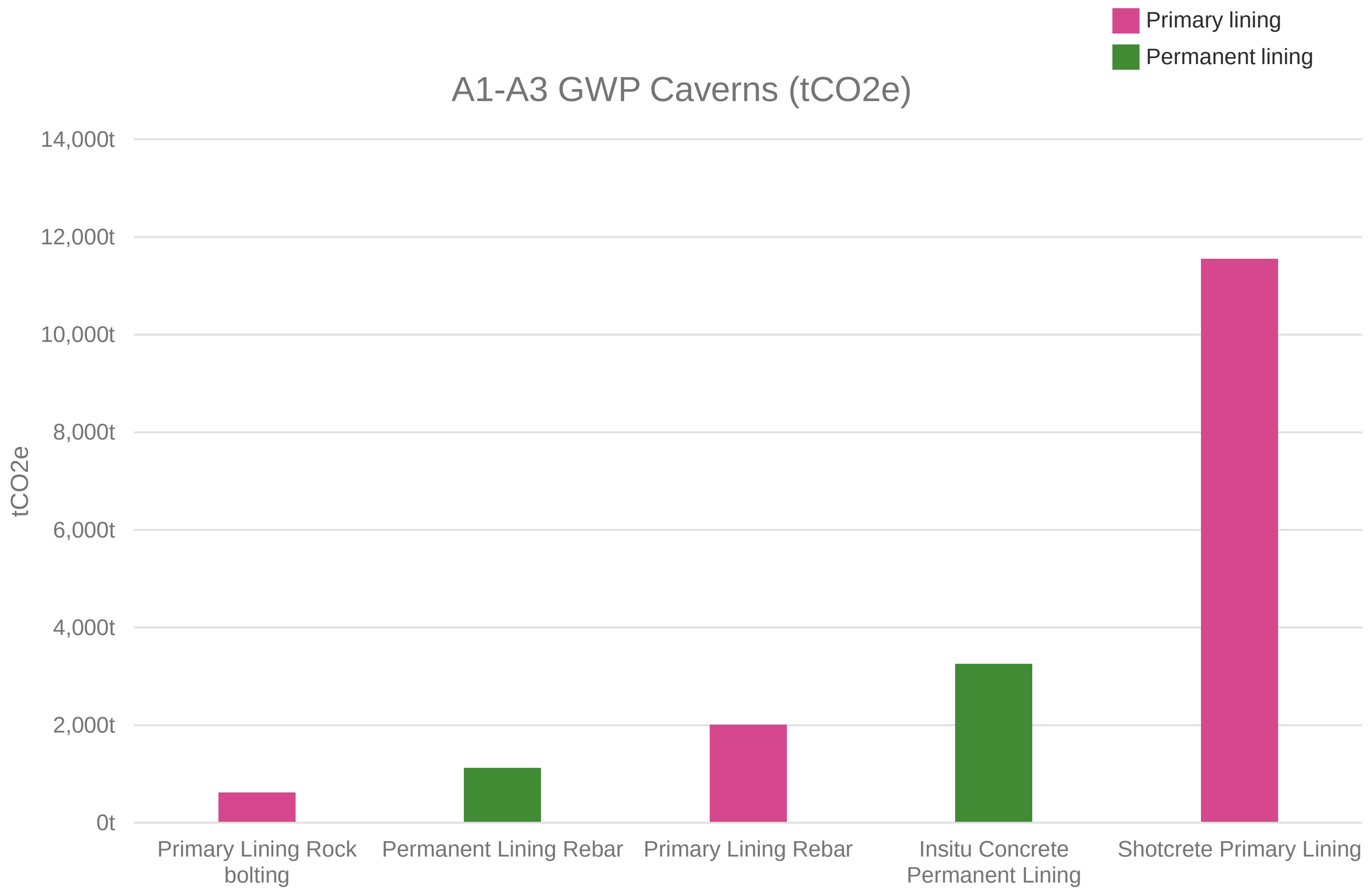
Sub-component Level

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 5.6m dia. A1-A3 GWP Results

Conclusions

CLIC Drive Beam 5.6m diameter is proposed to be built in 3 stages to enable experiments to run at the three energies 380GeV, 1.5TeV and 3TeV.

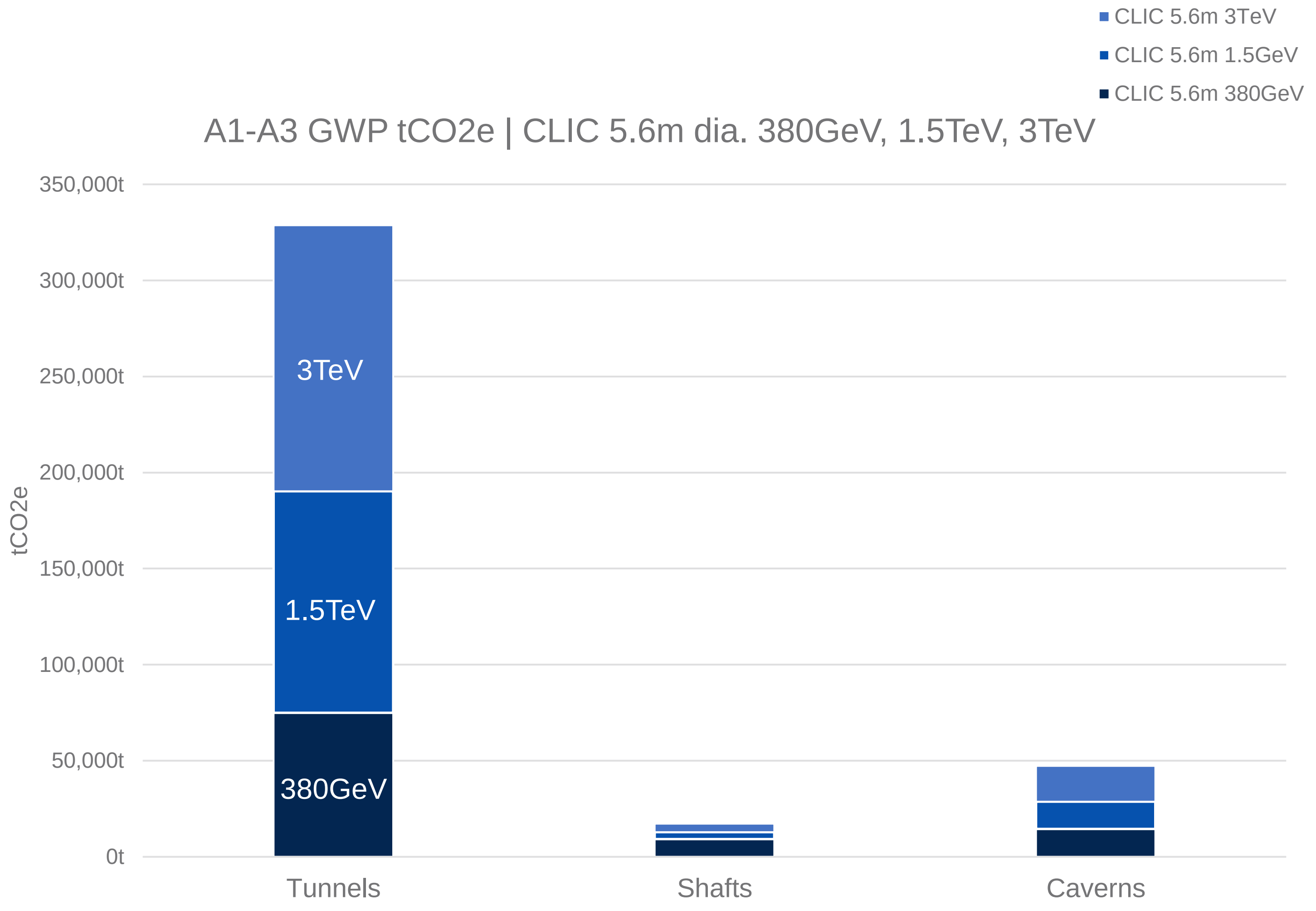
1.5TeV and 3TeV are calculated as an extension to 380GeV to reflect the 3 build stages.

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 2.4.



ARUP

CLIC Klystron 10m dia. A1-A3 GWP results

CLIC Klystron 10m diameter, 380GeV

Sub-component Level

Tunnels

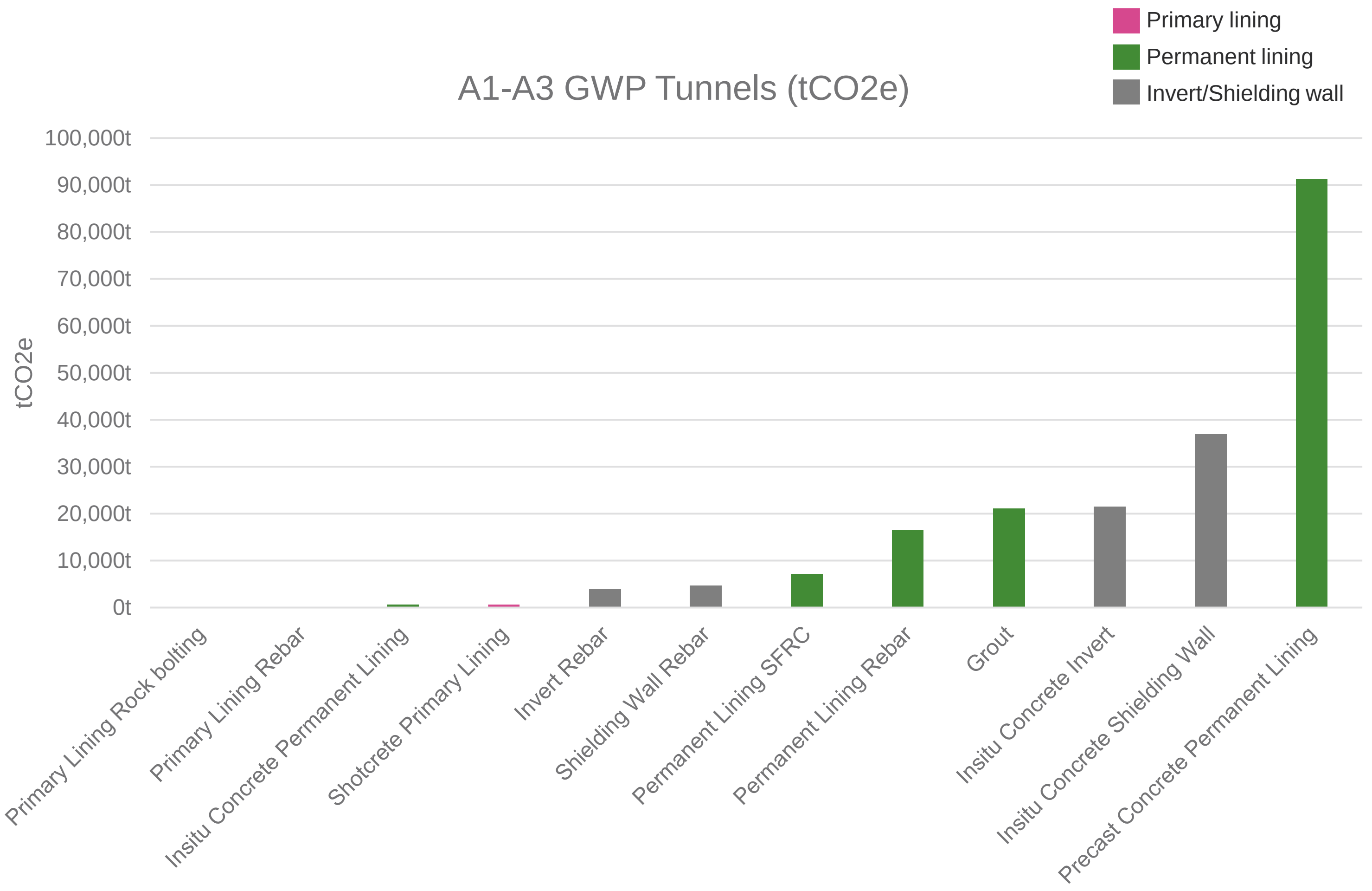
Tunnels are inclusive of:

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

CLIC Klystron 10m dia. A1-A3 GWP Results

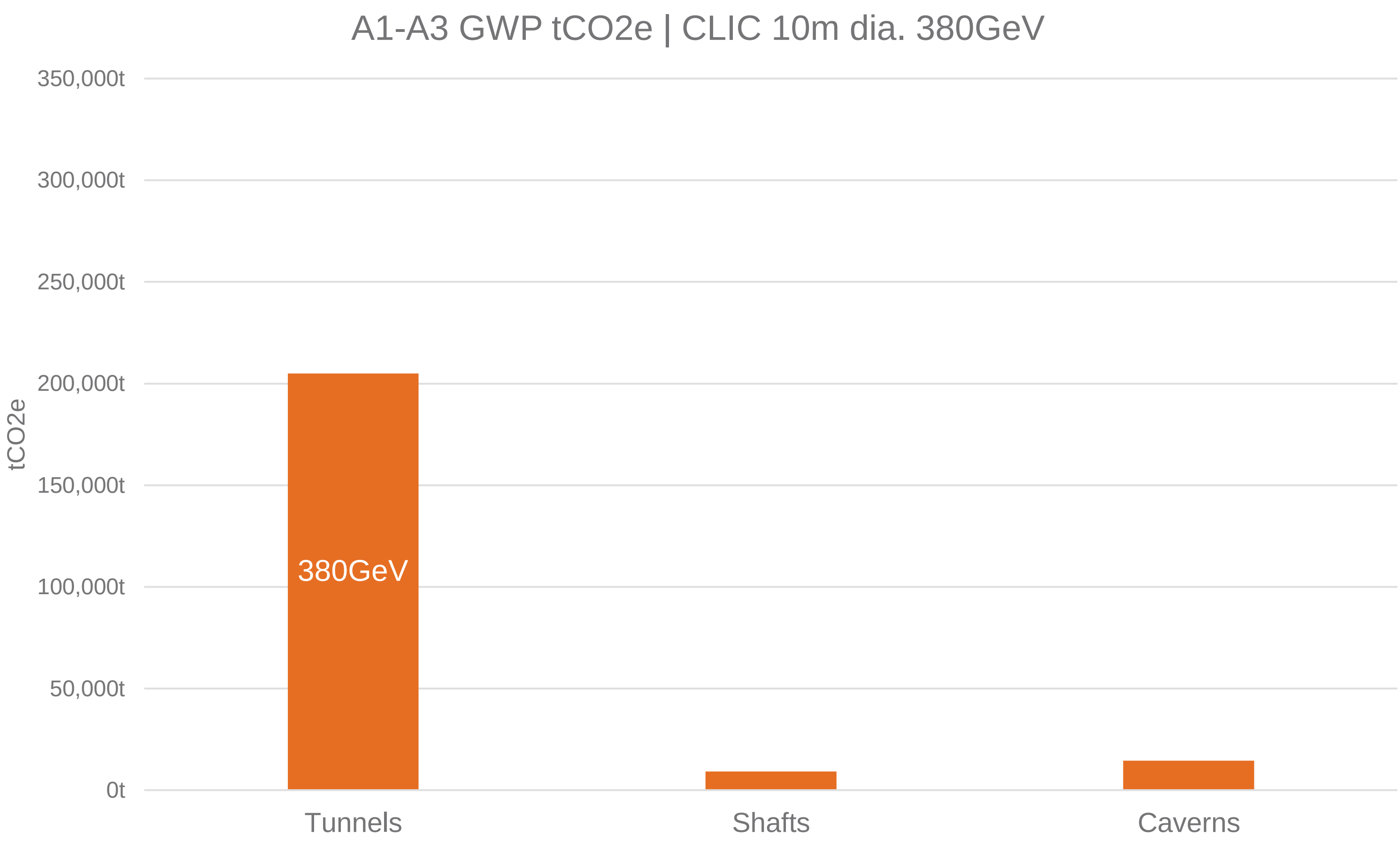
Conclusions

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 2.4.



ARUP

ILC 9.5m span A1-A3 GWP results

ILC 9.5m span, 250GeV

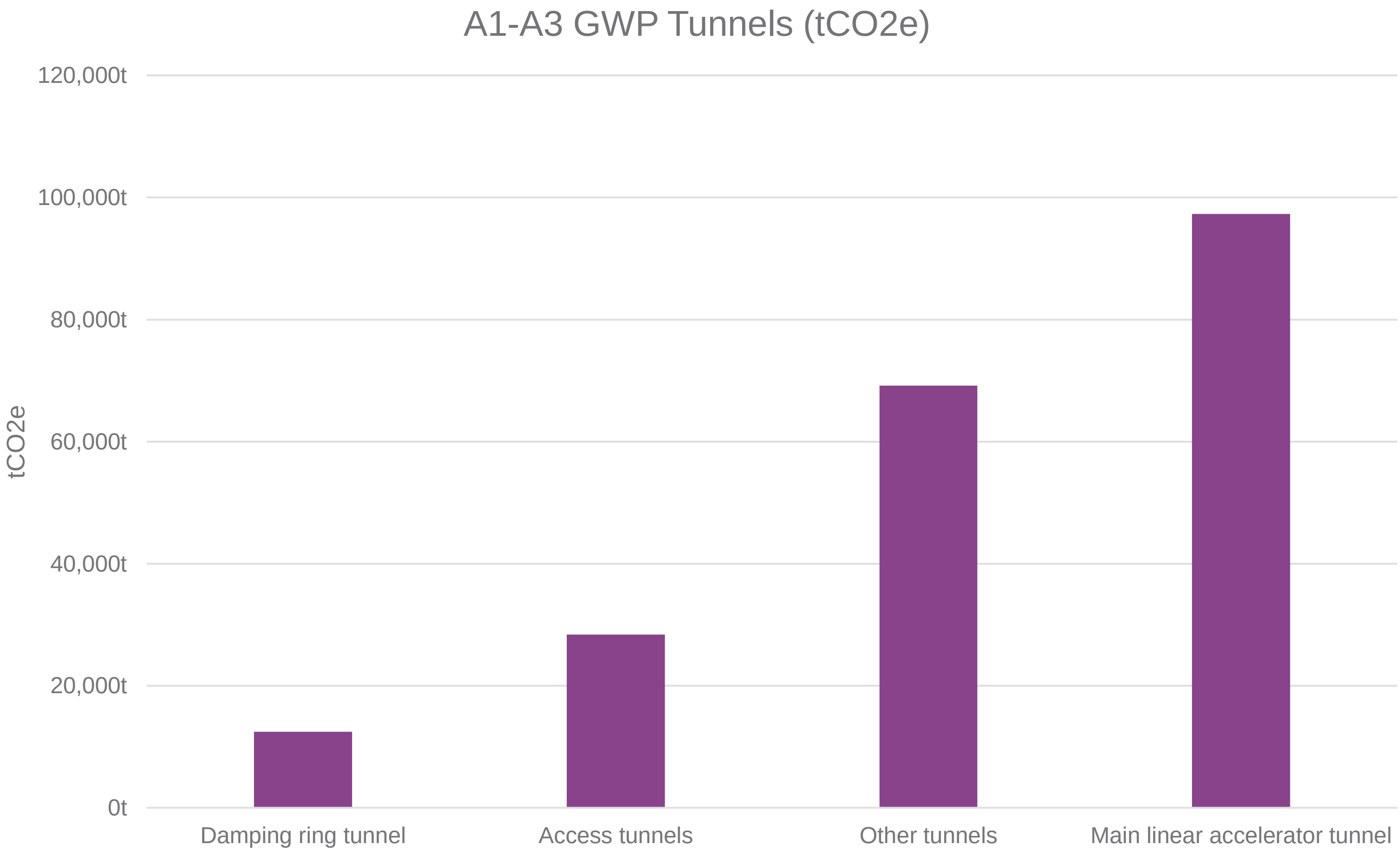
Component Level

Tunnels

<u>Tunnels are inclusive of (total length: 33,042m)</u>
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
- Damping ring tunnel
- 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

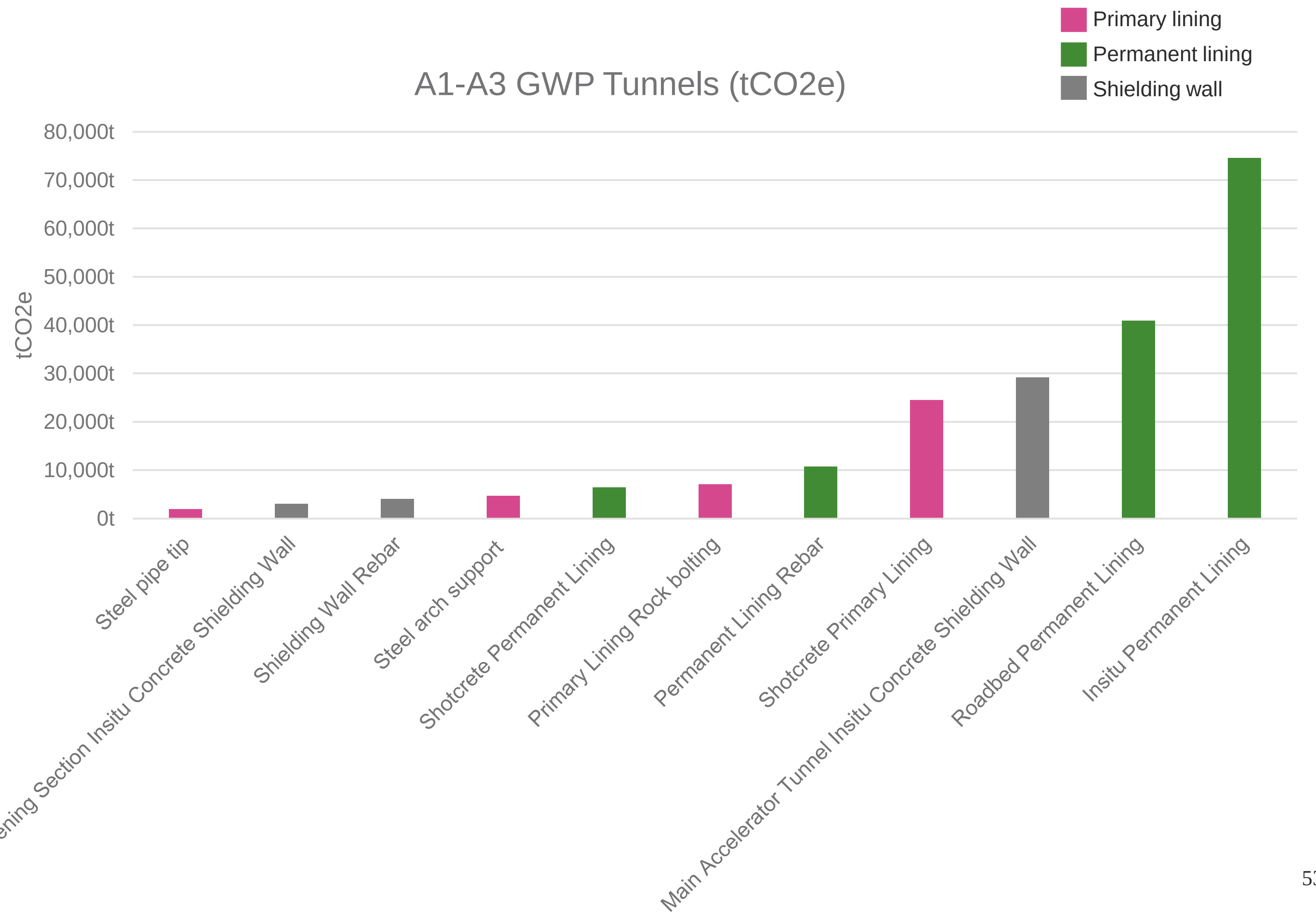


ILC 9.5m span, 250GeV

Sub-component Level

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 9.5m span, 250GeV

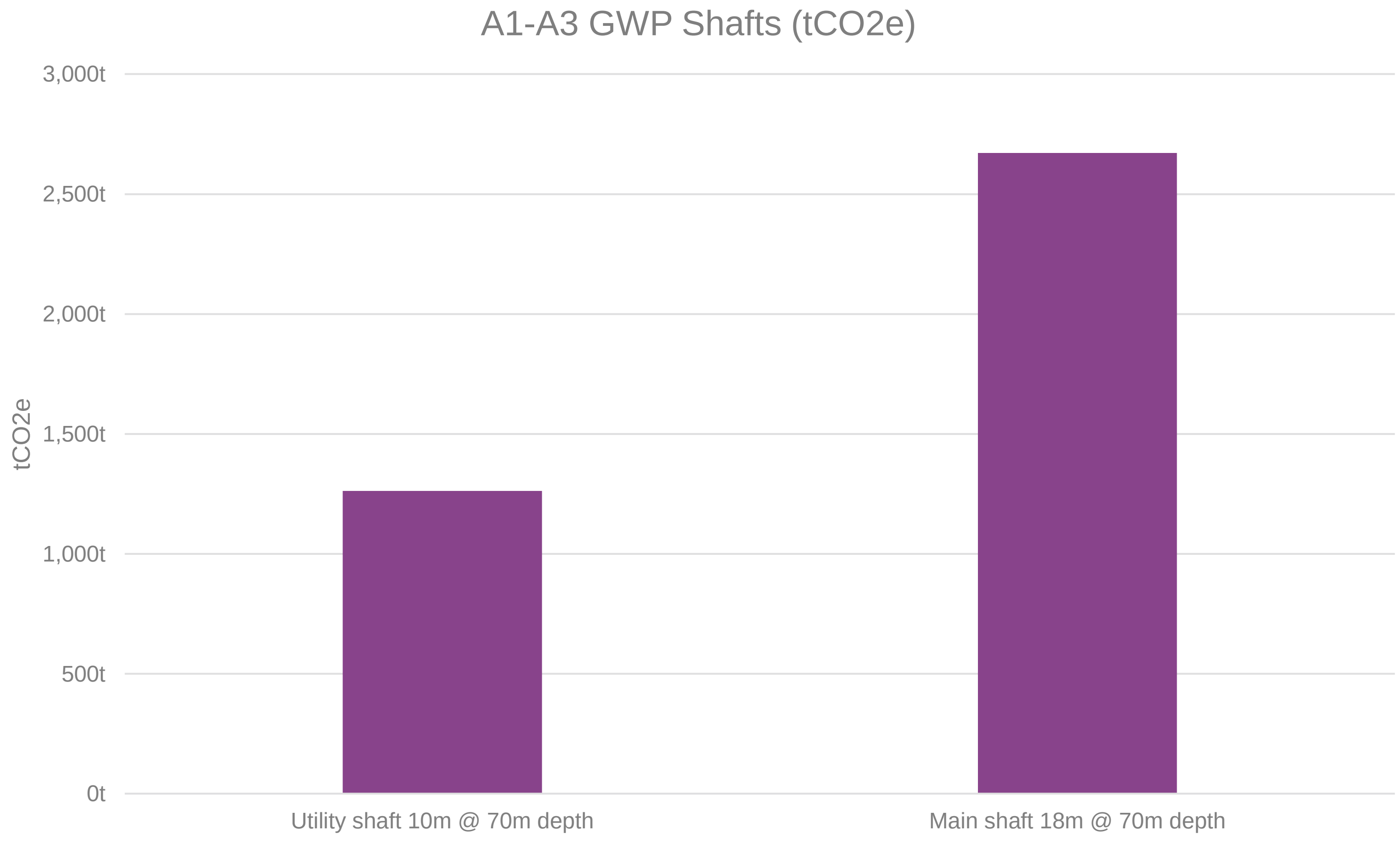
Component Level

Shafts

Shafts are inclusive of:

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

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



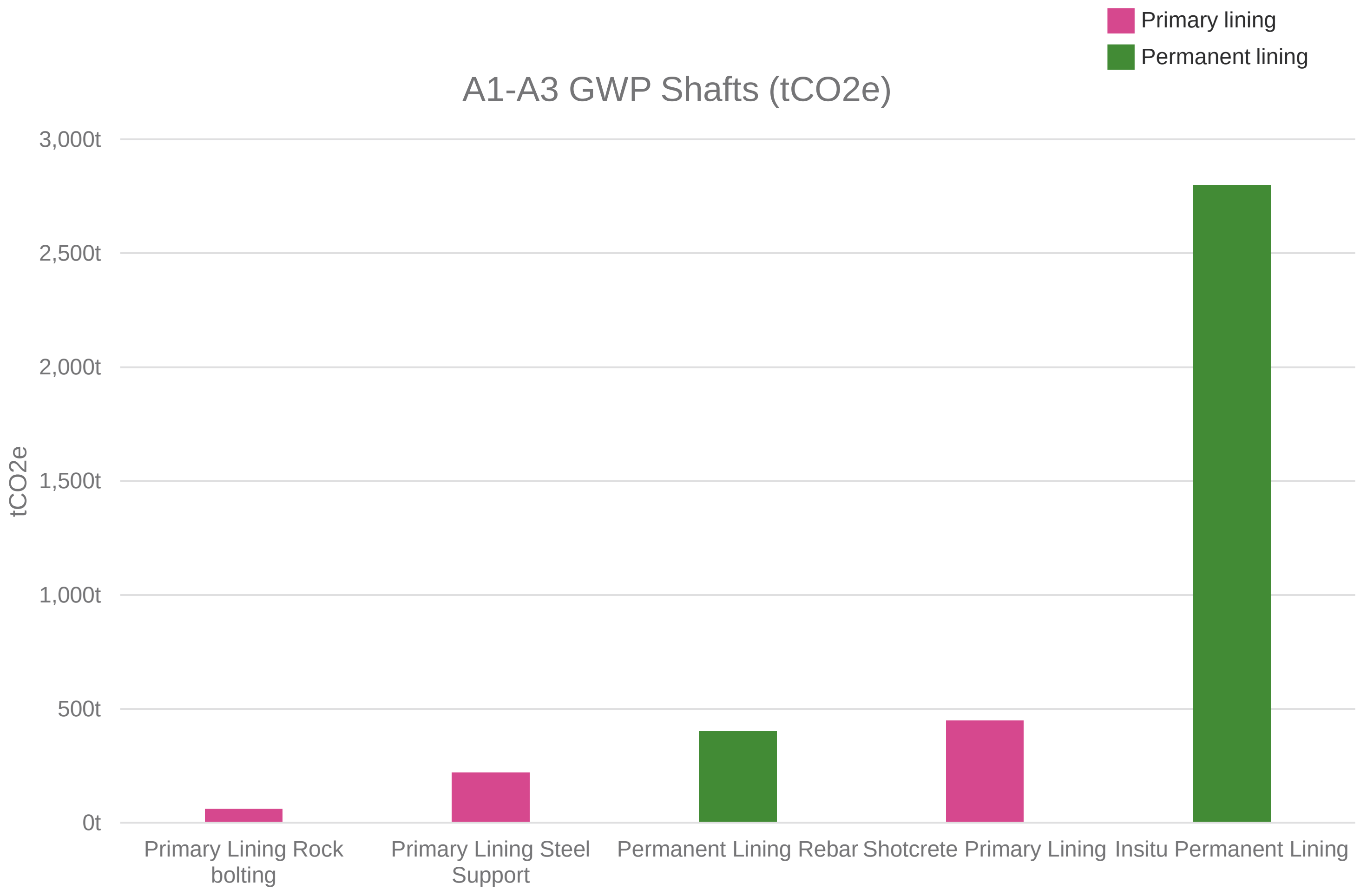
ILC 9.5m span, 250GeV

Sub-component Level

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.



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ILC 9.5m span, 250GeV

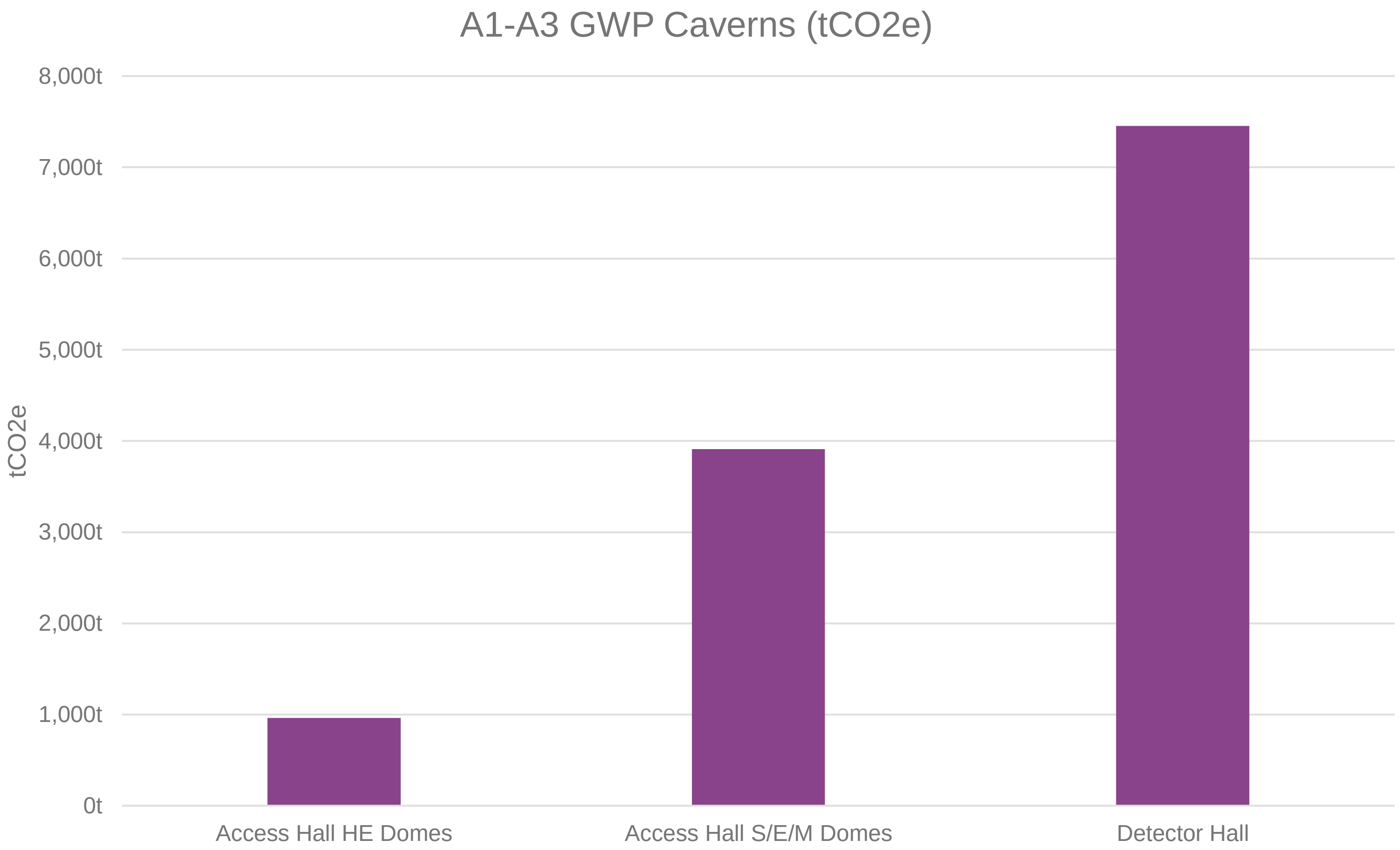
Component Level

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 9.5m span, 250GeV

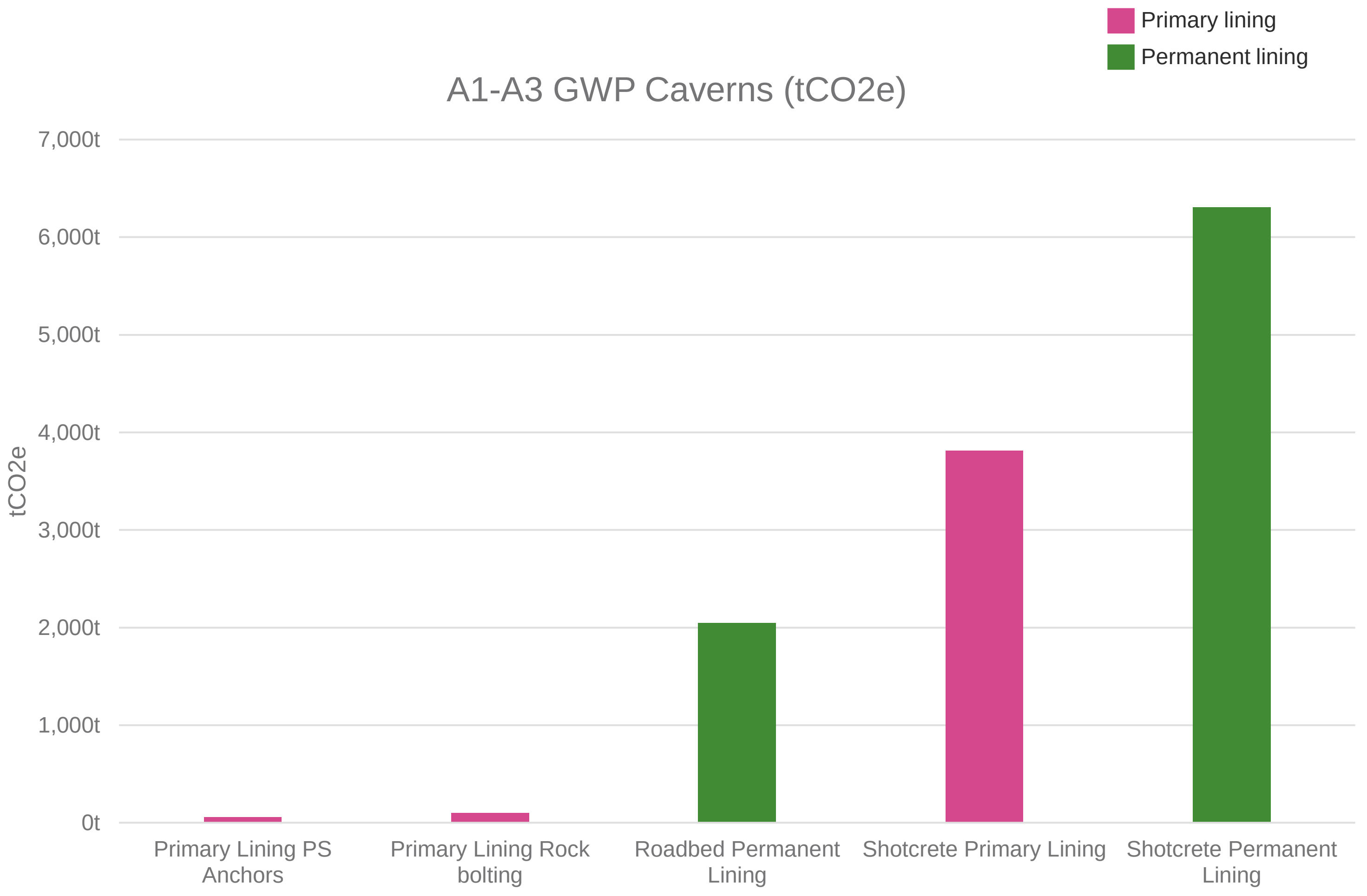
Sub-component Level

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 9.5m span, 250GeV A1-A3 GWP Results

Conclusions

ILC 9.5m span 250GeV energy was evaluated.

The tunnel is the shafts and caverns have the smallest A1-A3 GWP contribution.

Reduction opportunities are highlighted in section 2.4.

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2.4 Sensitivity analysis & reduction opportunities

Sensitivity Analysis

A sensitivity analysis was completed for material and design optimisation opportunities. This will be expanded upon at the next stage, incorporating A4-A5 impacts.

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. This can be refined at the next stage.

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 (to 3 significant figures):

- Concrete, 194000 tCO2e (79%)
- Steel, 50500 tCO2e (21%)

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. This will be expanded on further in the next stage.

Steel

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 graph on the right details the kgCO2e/kg of steel reinforcement bars and rolled open sections with varying % recycled content. The majority of this data is from Simapro 9.4.0.2 (Ecoinvent 3.8 database).

The BAU manufacturing process for steel in Europe is 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.

The benefits of steel recycling for future resource availability will be evaluated at the next stage (in Module D – see section 1.2). It's important to consider all aspects of steel production including its recyclability.

Steel risks

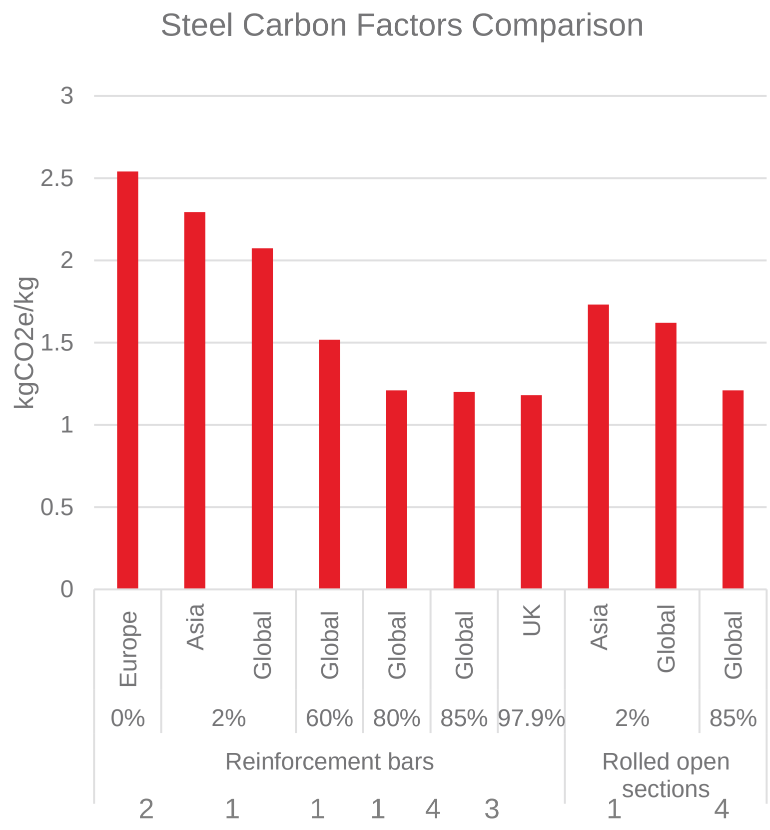
There are some risks associated with the production of low carbon steel:

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 BAU, 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

Concrete

Concrete opportunities

The embodied carbon impact of concrete is mostly due to the amount of portland cement that it contains.

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. This data has been extracted from Simapro 9.4.0.2.

The graph details the A1-A3 concrete carbon factors for CEMI global and various SCM replacement quantities. With an increased quantity of SCM the embodied carbon kgCO2e/kg of concrete is reduced.

Note Further concrete technologies and opportunities will be explored at the next stage.

Concrete risks

There are some risks associated with SCMs, highlighted below.

Availability of SCMs

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

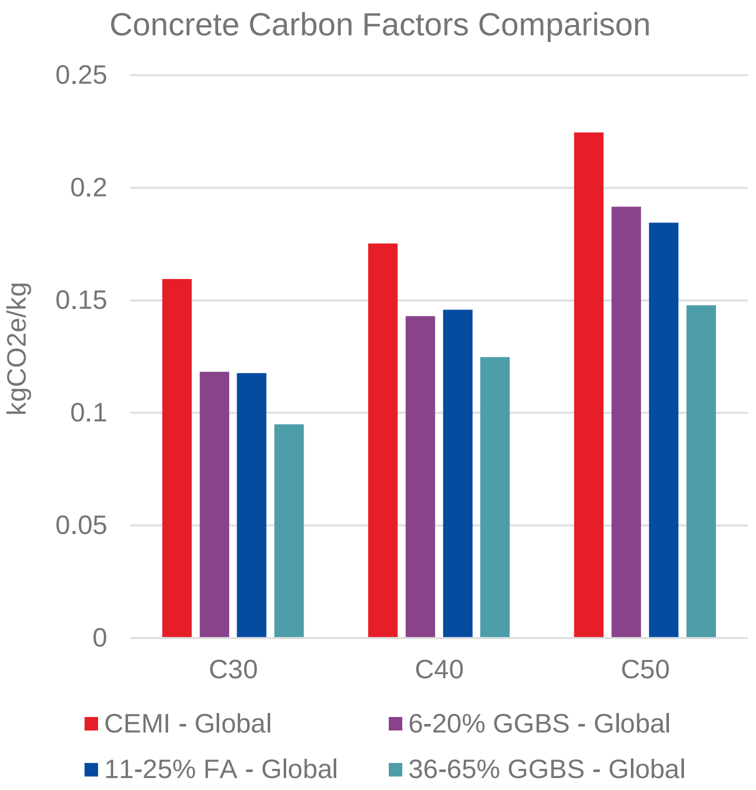
Cost impact

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.



Reference: Simapro (Ecoinvent 3.8 database 2021)

CLIC Drive Beam 5.6m dia. 380GeV A1-A3 GWP

Reduction opportunities

The following reduction opportunities have been identified at sub-system level.

Tunnels *(41% possible A1-A3 GWP reduction)*

- Replacement of CEMI with CEMIII/A (36-65% 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.

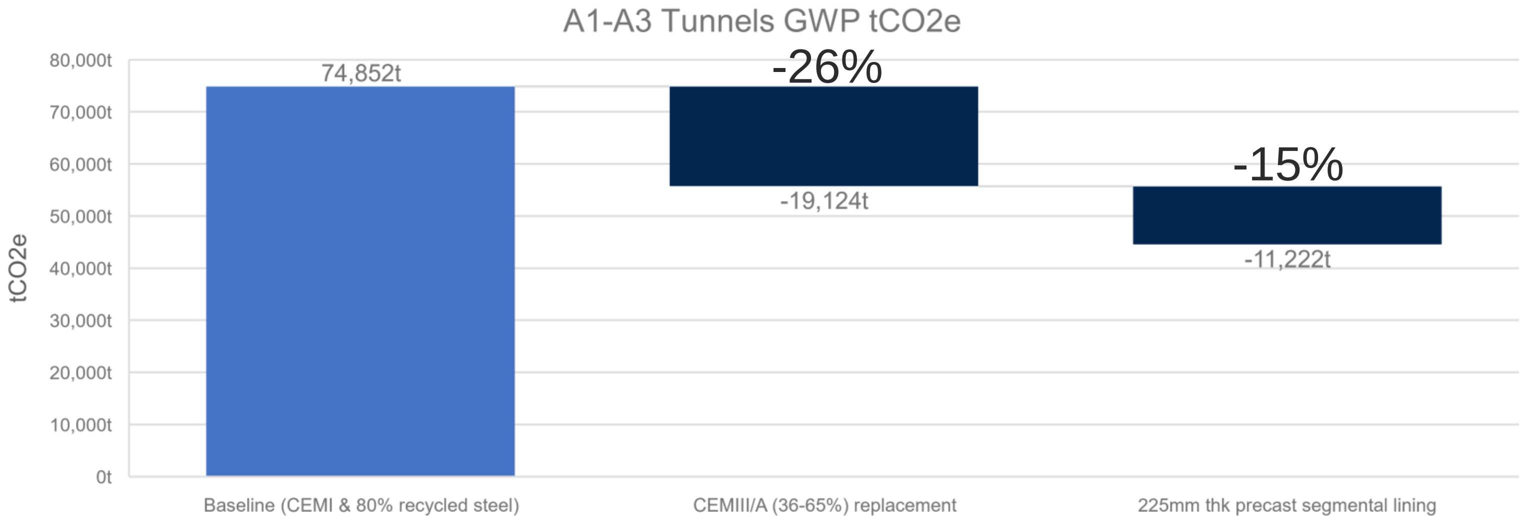
Shafts *(27% possible A1-A3 GWP reduction)*

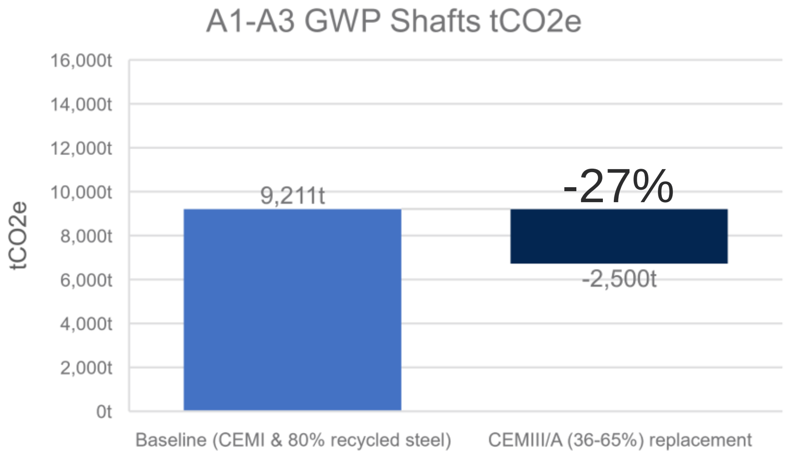
- Replacement of CEMI with CEMIII/A (36-65% GGBS).

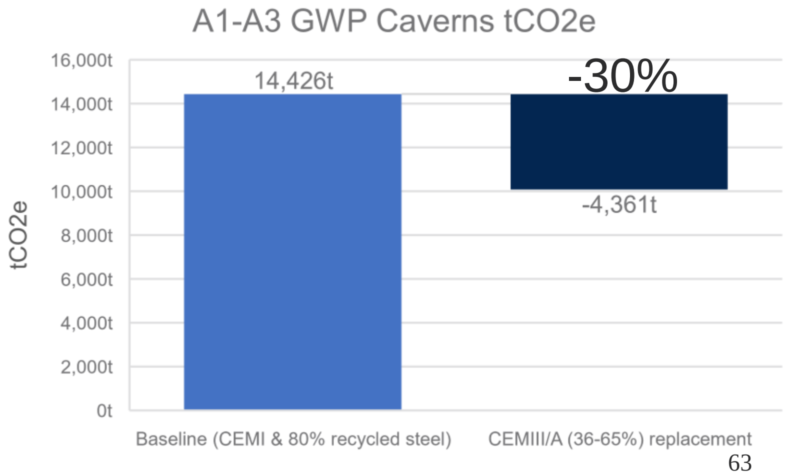
Caverns *(30% possible A1-A3 GWP reduction)*

- Replacement of CEMI with CEMIII/A (36-65% GGBS).

Further reduction opportunities will be investigated at the next stage.







CLIC Drive Beam 5.6m dia. 1.5TeV A1-A3 GWP

Reduction opportunities

The following reduction opportunities have been identified at sub-system level.

Tunnels *(41% possible A1-A3 GWP reduction)*

- Replacement of CEMI with CEMIII/A (36-65% 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.

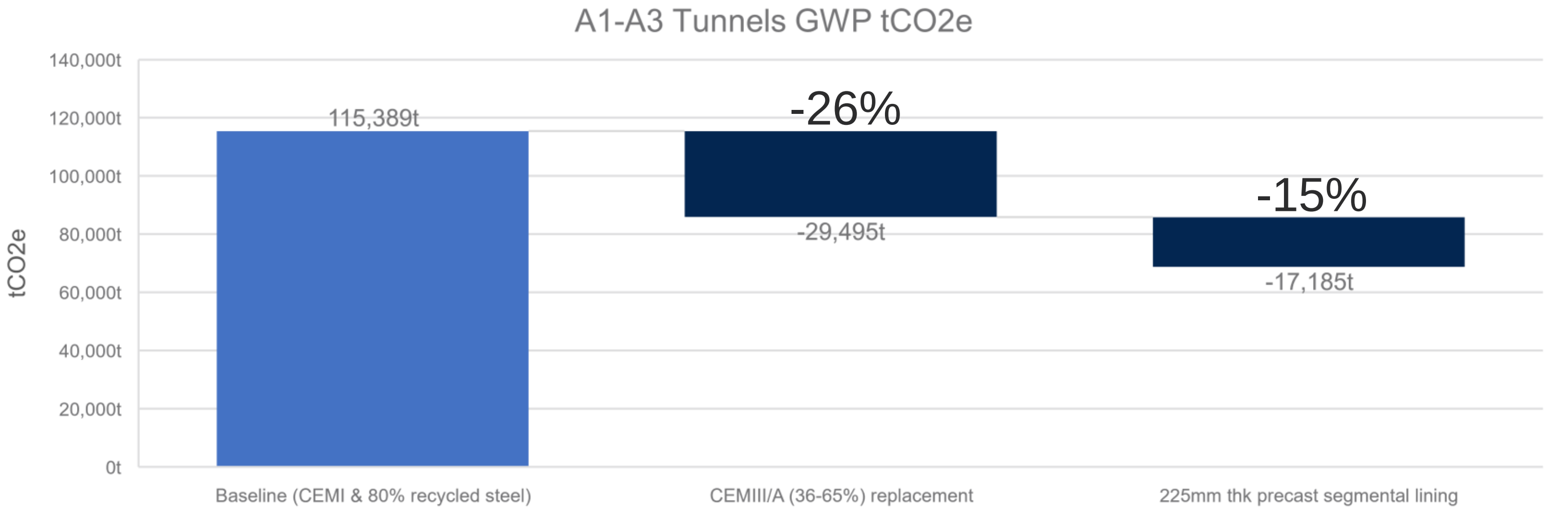
Shafts *(30% possible A1-A3 GWP reduction)*

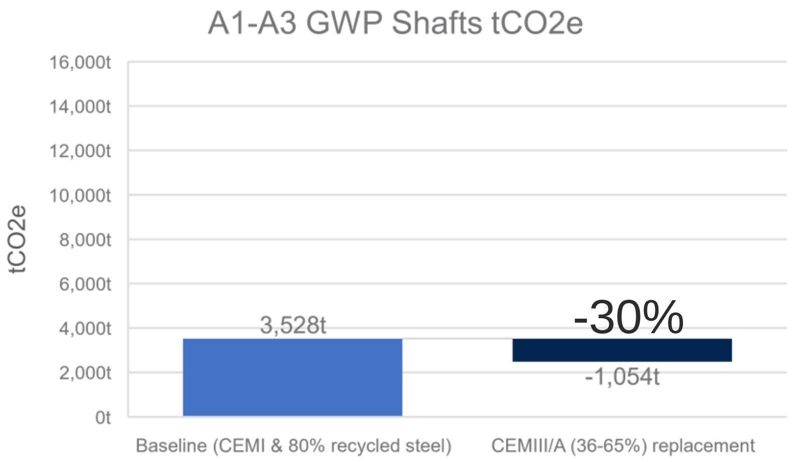
- Replacement of CEMI with CEMIII/A (36-65% GGBS).

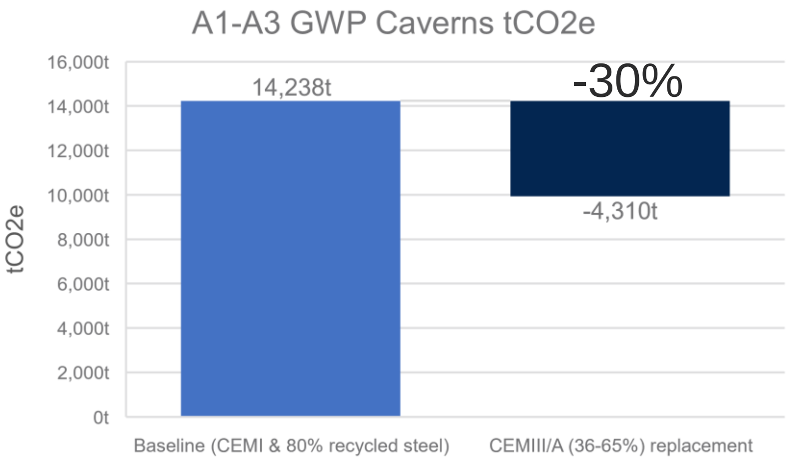
Caverns *(30% possible A1-A3 GWP reduction)*

- Replacement of CEMI with CEMIII/A (36-65% GGBS).

Further reduction opportunities will be investigated at the next stage.







CLIC Drive Beam 5.6m dia. 3TeV A1-A3 GWP

Reduction opportunities

The following reduction opportunities have been identified at sub-system level.

Tunnels *(41% possible A1-A3 GWP reduction)*

- Replacement of CEMI with CEMIII/A (36-65% 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.

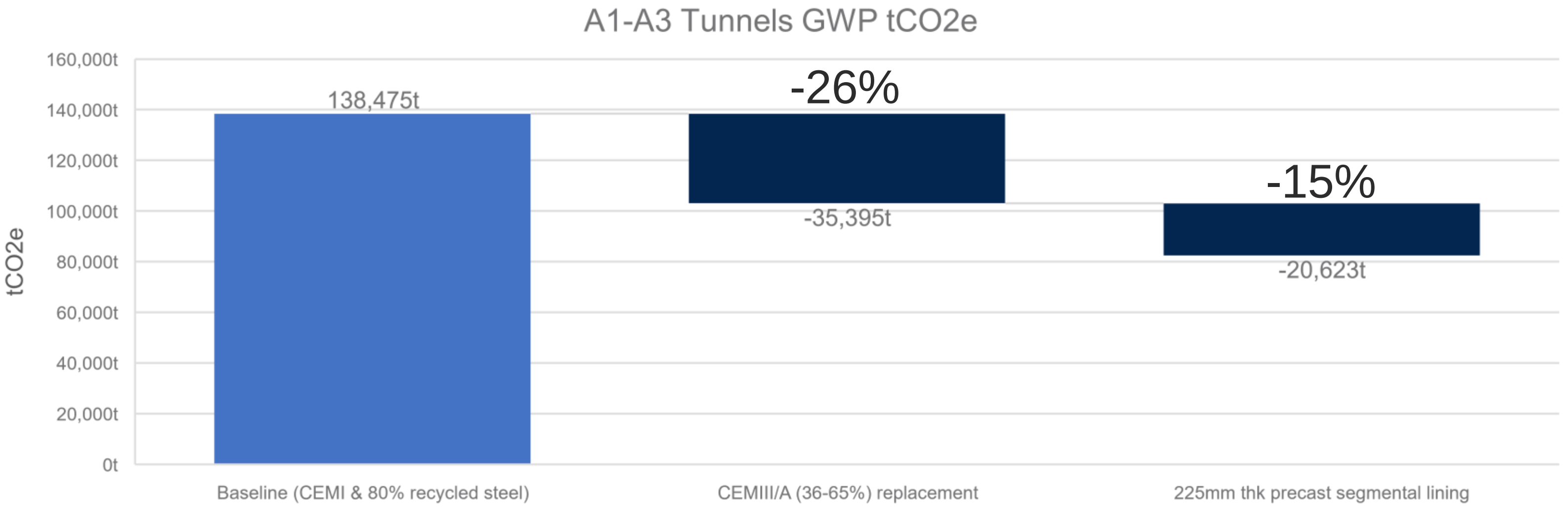
Shafts *(30% possible A1-A3 GWP reduction)*

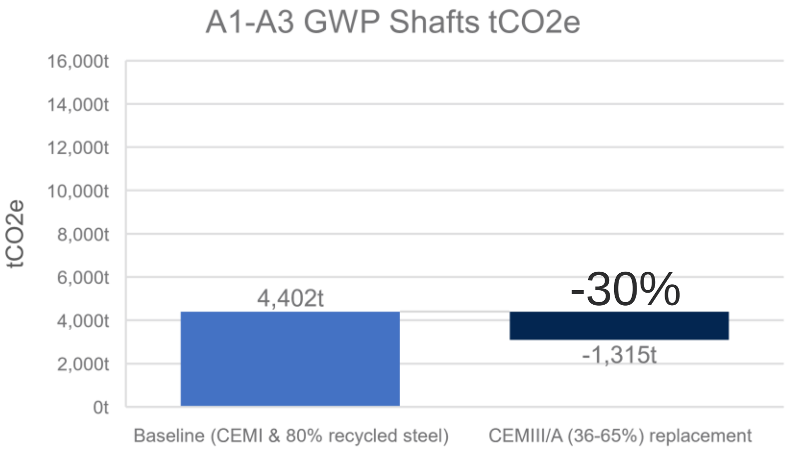
- Replacement of CEMI with CEMIII/A (36-65% GGBS).

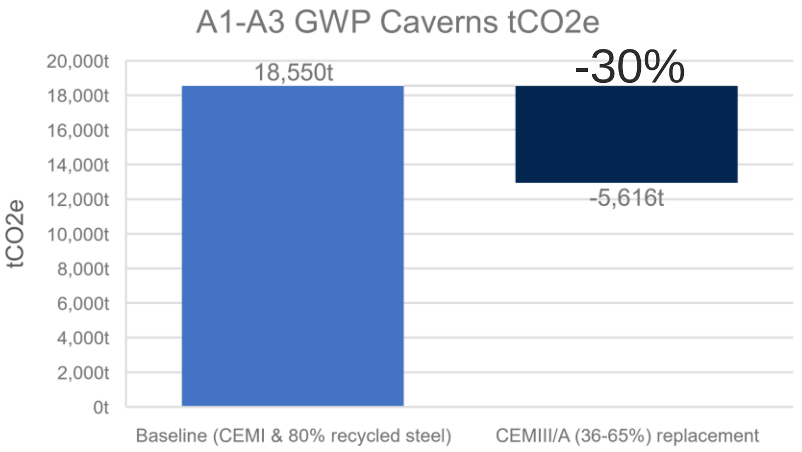
Caverns *(30% possible A1-A3 GWP reduction)*

- Replacement of CEMI with CEMIII/A (36-65% GGBS).

Further reduction opportunities will be investigated at the next stage.







CLIC Klystron 10m dia. 380GeV A1-A3 GWP

Reduction opportunities

The following reduction opportunities have been identified at sub-system level.

Tunnels *(47% possible A1-A3 GWP reduction)*

- Replacement of CEMI with CEMIII/A (36-65% 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.

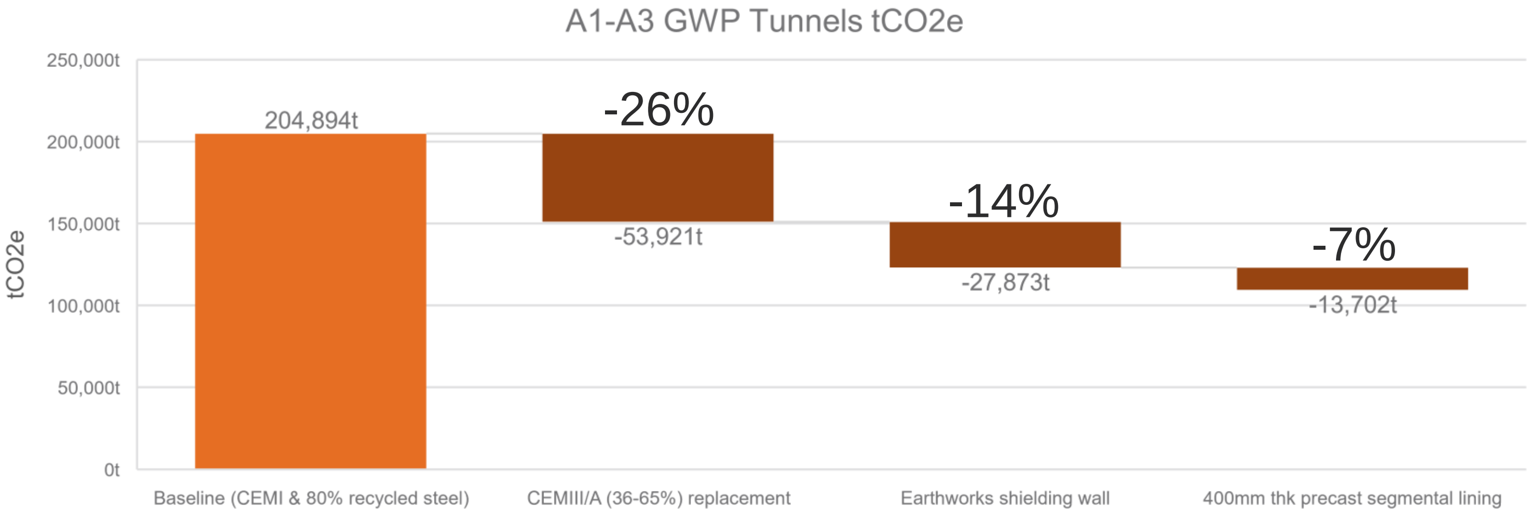
Shafts *(27% possible A1-A3 GWP reduction)*

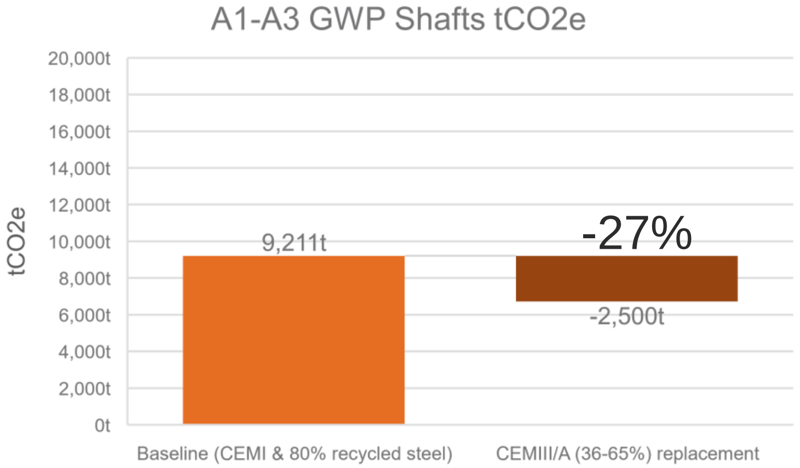
- Replacement of CEMI with CEMIII/A (36-65% GGBS).

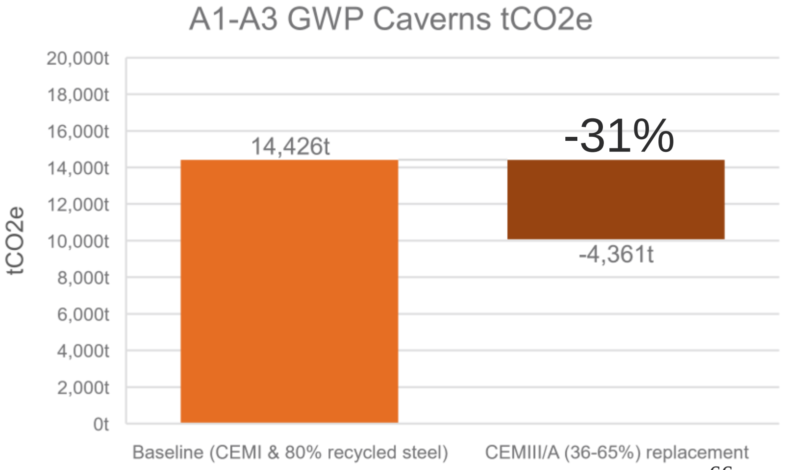
Caverns *(31% possible A1-A3 GWP reduction)*

- Replacement of CEMI with CEMIII/A (36-65% GGBS).

Further reduction opportunities will be investigated at the next stage.







ILC 9.5m span, 250GeV A1-A3 GWP

Reduction opportunities

The following reduction opportunities have been identified at sub-system level.

Tunnels *(38% possible A1-A3 GWP reduction)*

- Replacement of CEMI with CEMIII/A (36-65% GGBS).
- Replace concrete shielding wall for main accelerator tunnel and widening sections with 250mm concrete casing, 0.2% rebar, filled with compact earthworks from excavation.

Note The design has been completed in accordance with the Tohoku ILC Civil Engineering Plan 2020. The lining thickness of the tunnel has not been changed for the purposes of this report.

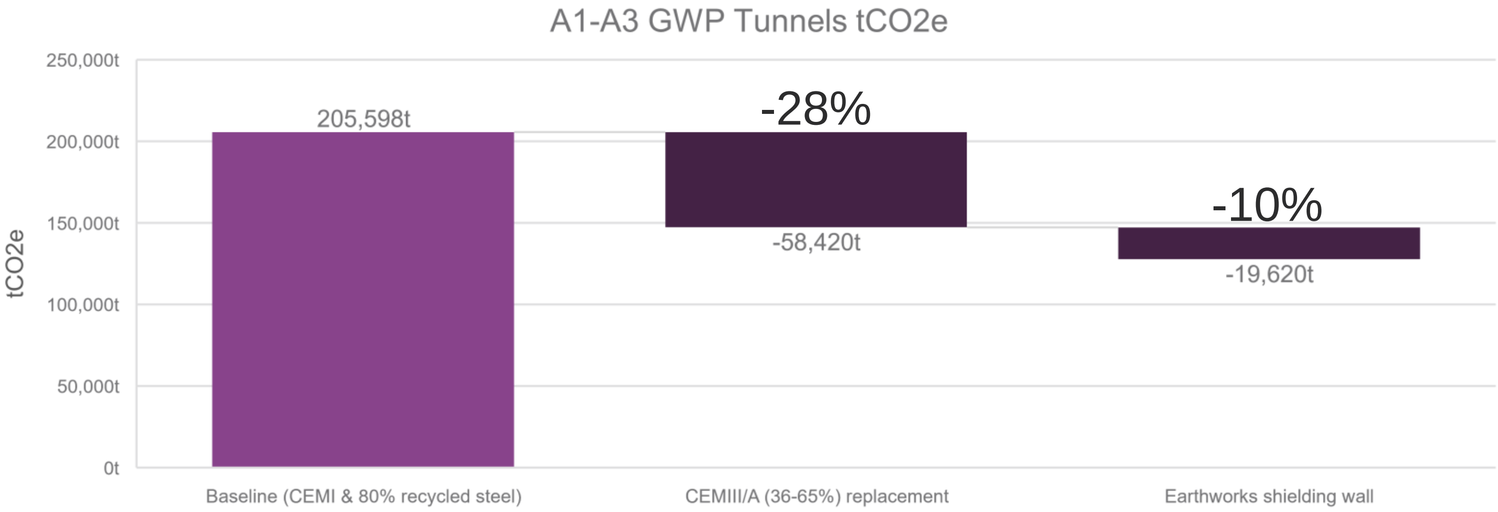
Shafts *(24% possible A1-A3 GWP reduction)*

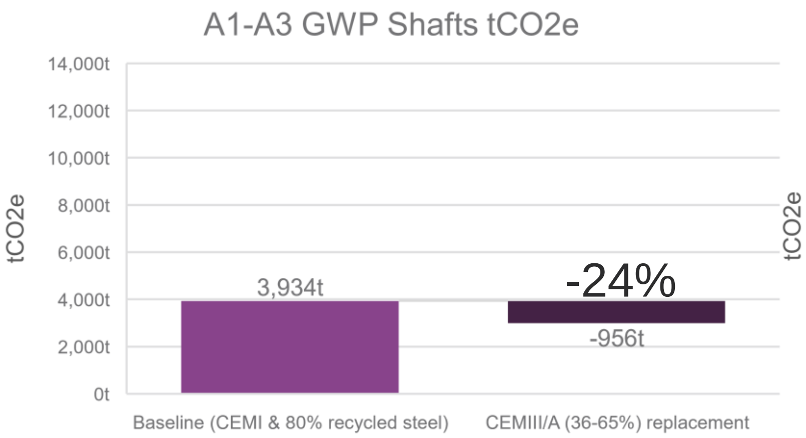
- Replacement of CEMI with CEMIII/A (36-65% GGBS).

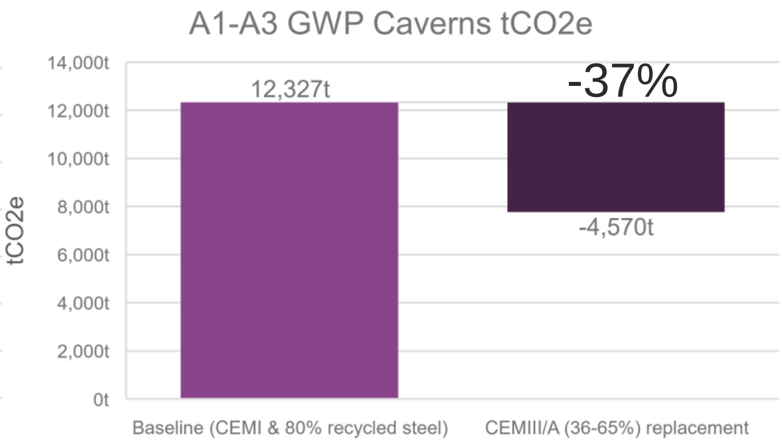
Caverns *(37% possible A1-A3 GWP reduction)*

- Replacement of CEMI with CEMIII/A (36-65% GGBS).

Further reduction opportunities will be investigated at the next stage.







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2.5 A1-A3 Additional Impact Categories results

A1-A3 Additional Impact Categories

Impact Categories

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

The additional 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-A3 impacts on these environmental areas of concern.

All 18 impact categories are reported as relative contribution of each sub-system to total environmental impact, where the sub-systems are tunnels, shafts and caverns, as highlighted in section 2.2.

Note Relative contribution of each stage A1-A3, A4 and A5 will be evaluated at the next stage and included in the final report.

Impact Categories	Abbr.	Unit	Environmental issue measured
Global warming	GWP	kg CO2 eq	Increased greenhouse gas emissions increases global mean temperature
Stratospheric ozone depletion	ODP	kg CFC11 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 NOx 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 NOx 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 SO2 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	m2a 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	m3	Mains, surface and groundwater consumption leading to reduction in freshwater availability, thus water shortage for irrigation, reduction in plant diversity and changed river discharge.

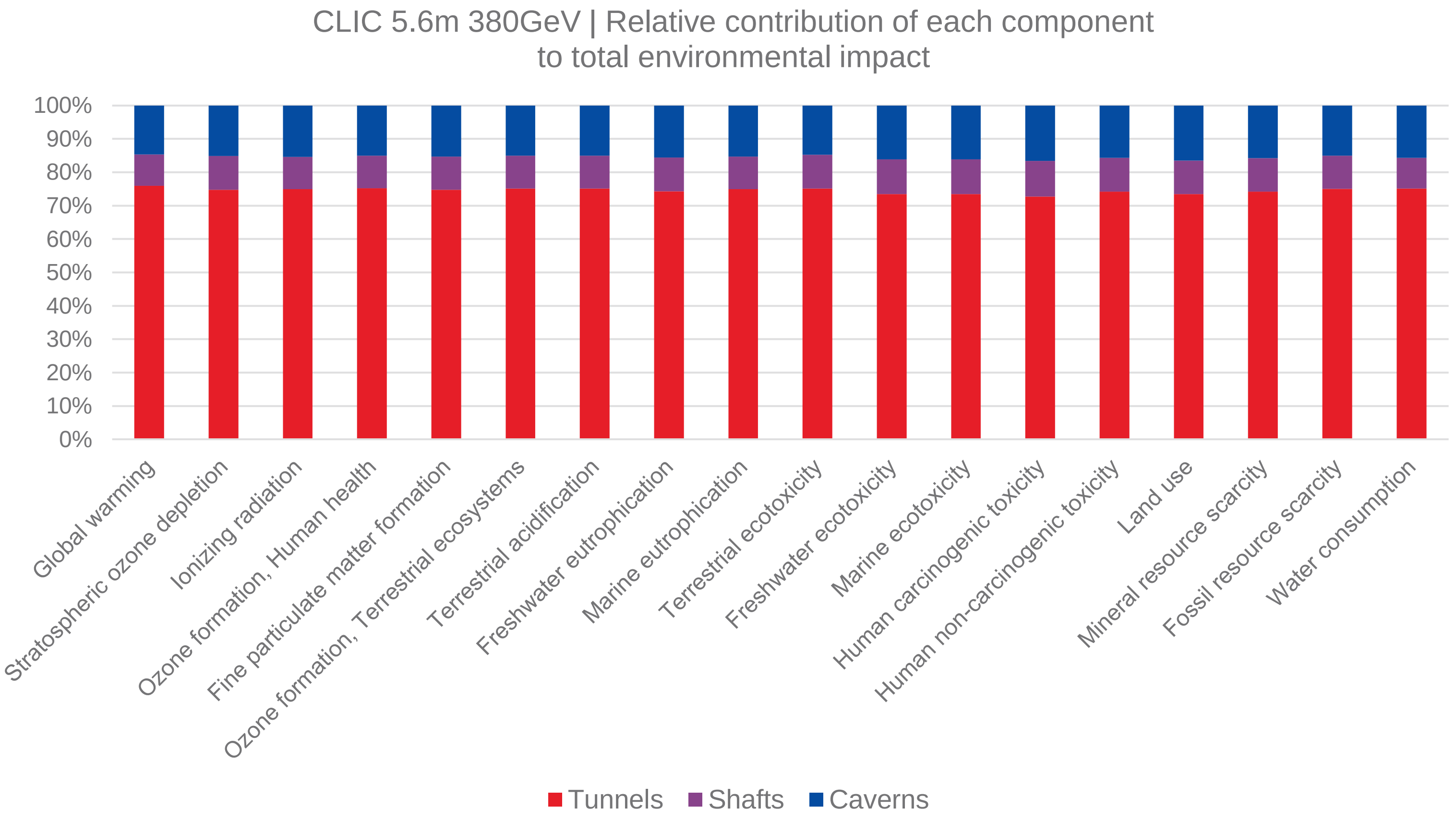
Reference: ReCiPe Midpoint (H) 2016

CLIC Drive Beam 5.6m diameter, 380GeV

A1-A3 LCA Results

The absolute values are reported below:

Impact Categories	Absolute value	Unit
Global warming	98489241	kg CO2 eq
Stratospheric ozone depletion	17.5	kg CFC11 eq
Ionizing radiation	4073300	kBq Co-60 eq
Fine particulate matter formation	223688	kg PM2.5 eq
Ozone formation, Human health	85735	kg NOx eq
Ozone formation, Terrestrial ecosystems	228836	kg NOx eq
Terrestrial acidification	201062	kg SO2 eq
Freshwater eutrophication	23054	kg P eq
Marine eutrophication	1582	kg N eq
Terrestrial ecotoxicity	309925230	kg 1,4-DCB
Freshwater ecotoxicity	3579857	kg 1,4-DCB
Marine ecotoxicity	4932619	kg 1,4-DCB
Human carcinogenic toxicity	30502387	kg 1,4-DCB
Human non-carcinogenic toxicity	51923760	kg 1,4-DCB
Land use	3732900	m2a crop eq
Mineral resource scarcity	1082419	kg Cu eq
Fossil resource scarcity	13392913	kg oil eq
Water consumption	776965	m3



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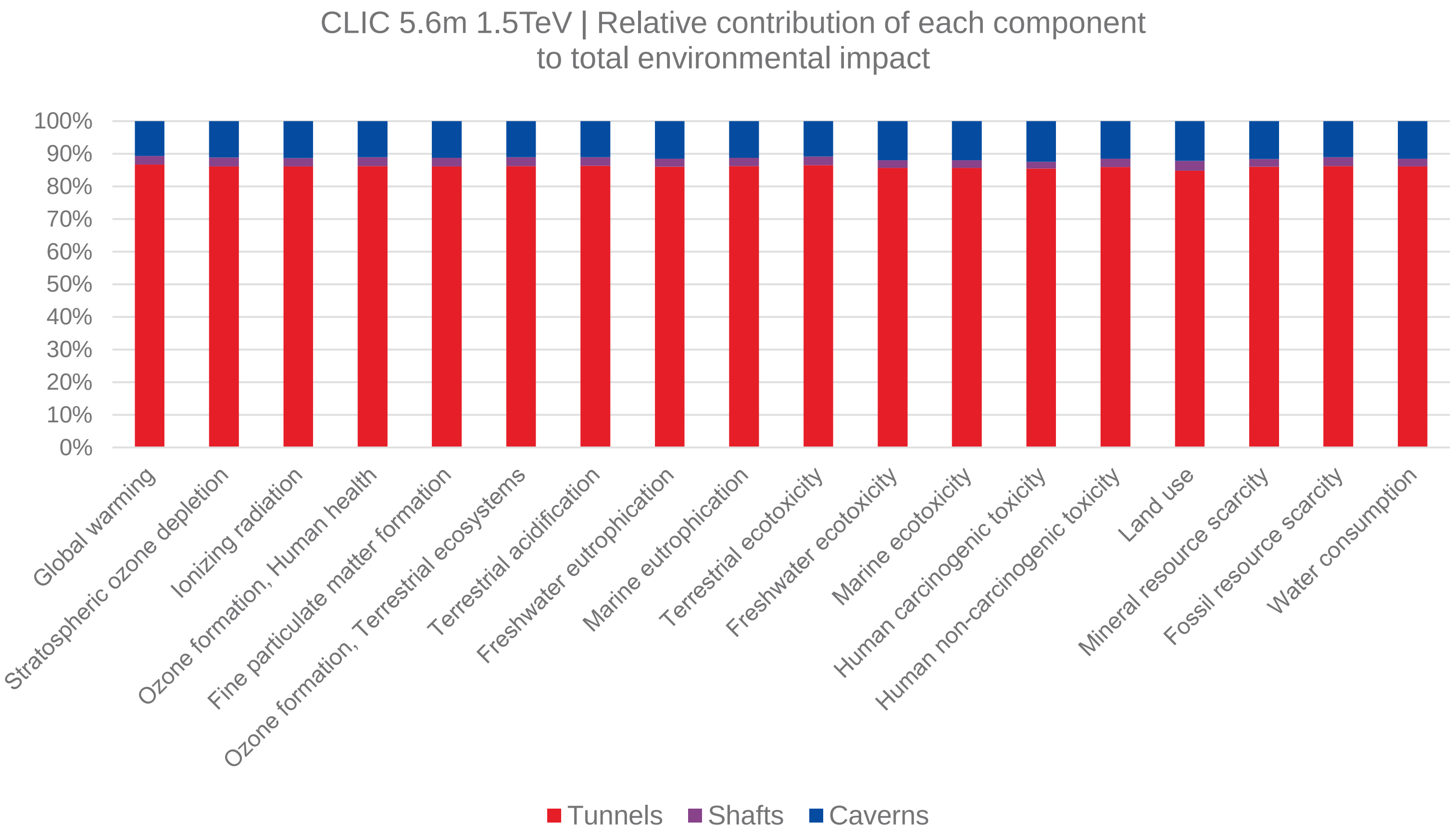
CLIC Drive Beam 5.6m diameter, 1.5TeV

A1-A3 LCA Results

The absolute values are reported below:

Impact Categories	Absolute value	Unit
Global warming	133155404	kg CO2 eq
Stratospheric ozone depletion	23.5	kg CFC11 eq
Ionizing radiation	5466646	kBq Co-60 eq
Fine particulate matter formation	300823	kg PM2.5 eq
Ozone formation, Human health	114812	kg NOx eq
Ozone formation, Terrestrial ecosystems	307674	kg NOx eq
Terrestrial acidification	270203	kg SO2 eq
Freshwater eutrophication	30748	kg P eq
Marine eutrophication	2123	kg N eq
Terrestrial ecotoxicity	415346519	kg 1,4-DCB
Freshwater ecotoxicity	4740040	kg 1,4-DCB
Marine ecotoxicity	6532154	kg 1,4-DCB
Human carcinogenic toxicity	40085518	kg 1,4-DCB
Human non-carcinogenic toxicity	69195694	kg 1,4-DCB
Land use	4985139	m2a crop eq
Mineral resource scarcity	1441406	kg Cu eq
Fossil resource scarcity	17971434	kg oil eq
Water consumption	1045699	m3

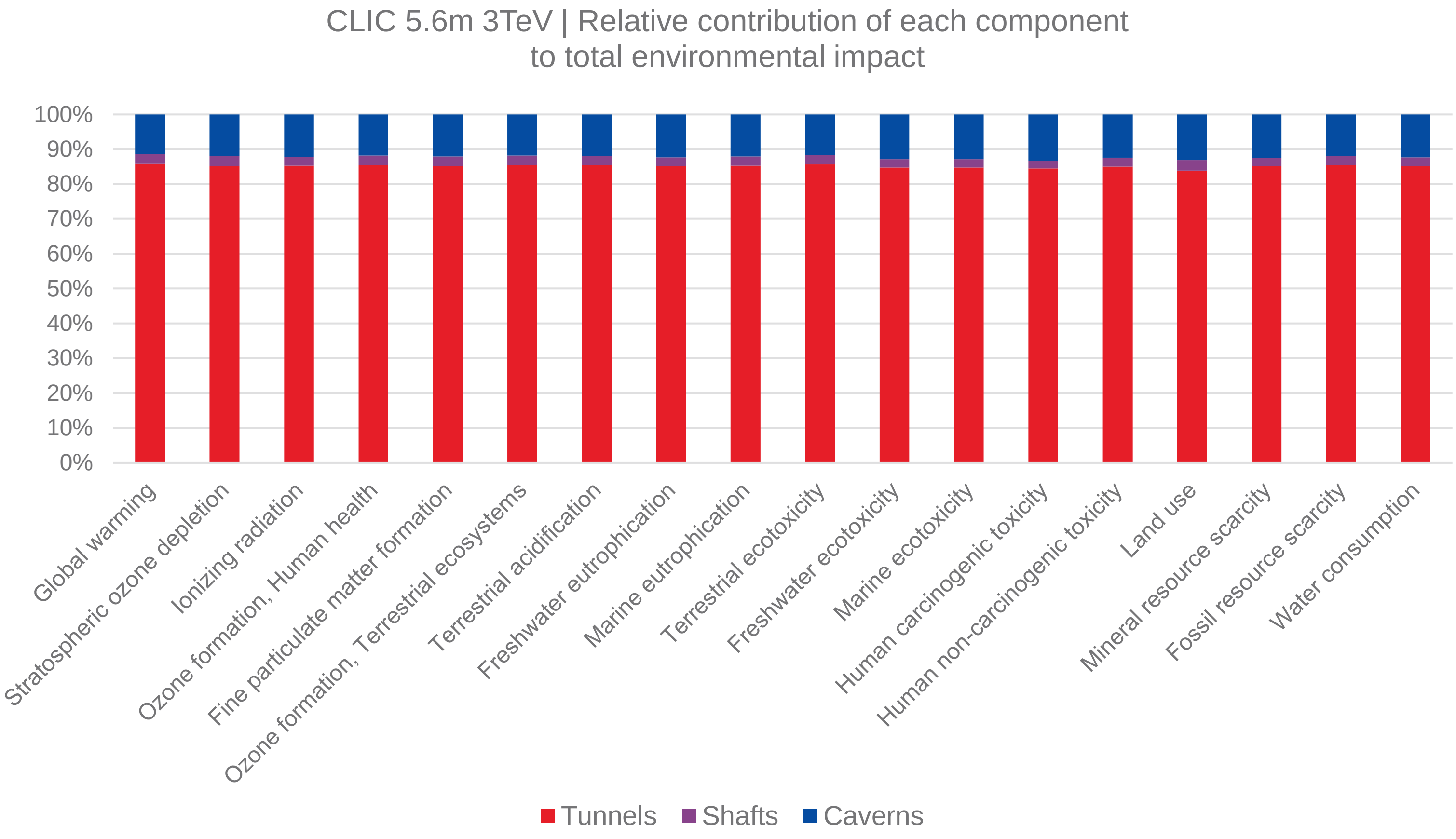


CLIC Drive Beam 5.6m diameter, 3TeV

A1-A3 LCA Results

The absolute values are reported below:

Impact Categories	Absolute value	Unit
Global warming	161425817	kg CO2 eq
Stratospheric ozone depletion	28.5	kg CFC11 eq
Ionizing radiation	6630262	kBq Co-60 eq
Fine particulate matter formation	364806	kg PM2.5 eq
Ozone formation, Human health	139251	kg NOx eq
Ozone formation, Terrestrial ecosystems	373117	kg NOx eq
Terrestrial acidification	327670	kg SO2 eq
Freshwater eutrophication	37299	kg P eq
Marine eutrophication	2575	kg N eq
Terrestrial ecotoxicity	503583078	kg 1,4-DCB
Freshwater ecotoxicity	5751604	kg 1,4-DCB
Marine ecotoxicity	7926015	kg 1,4-DCB
Human carcinogenic toxicity	48652154	kg 1,4-DCB
Human non-carcinogenic toxicity	83940565	kg 1,4-DCB
Land use	6052102	m2a crop eq
Mineral resource scarcity	1748518	kg Cu eq
Fossil resource scarcity	21793882	kg oil eq
Water consumption	1268428	m3



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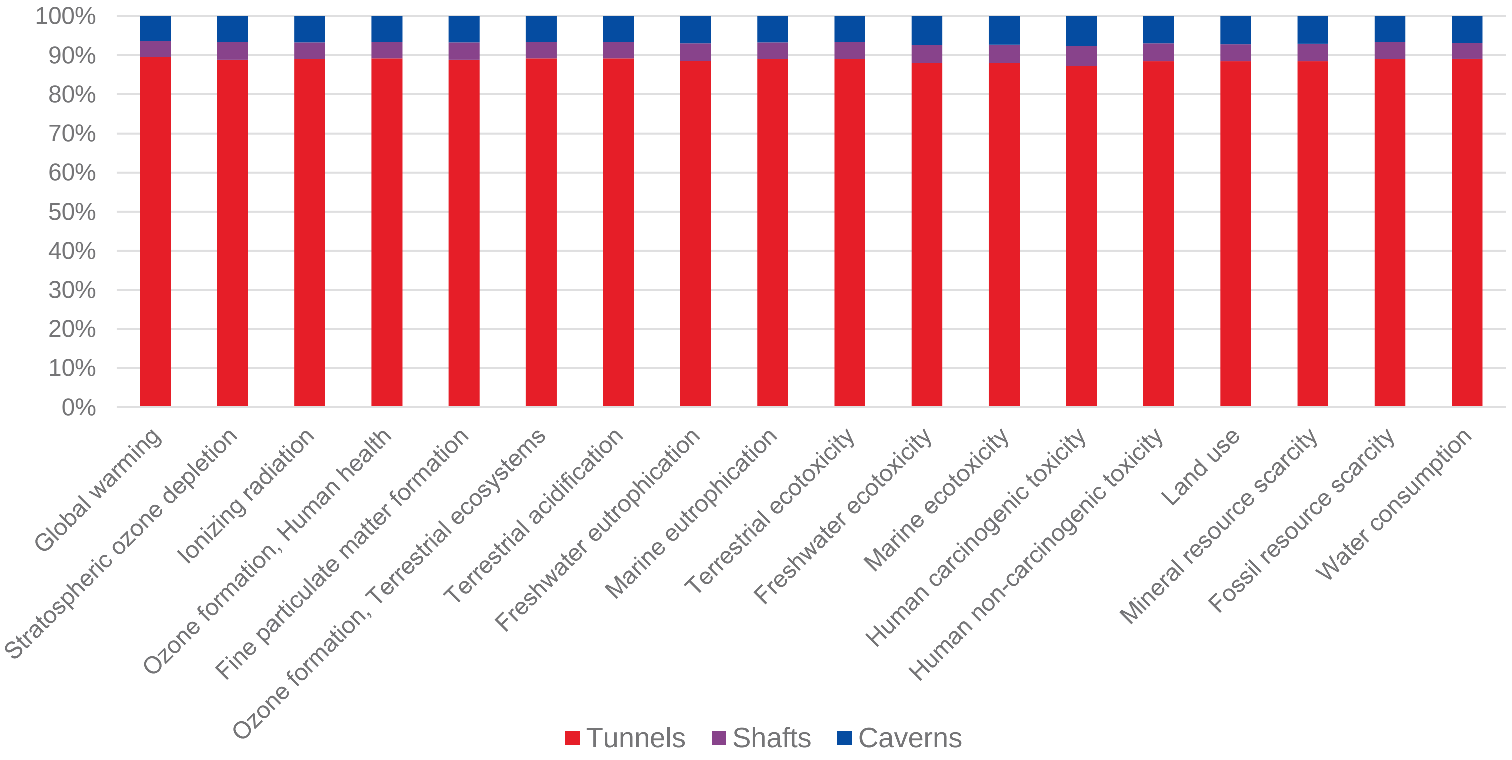
CLIC Klystron 10m diameter, 380GeV

A1-A3 LCA Results

The absolute values are reported below:

Impact Categories	Absolute value	Unit
Global warming	228531515	kg CO2 eq
Stratospheric ozone depletion	39.9	kg CFC11 eq
Ionizing radiation	9295519	kBq Co-60 eq
Fine particulate matter formation	514896	kg PM2.5 eq
Ozone formation, Human health	194930	kg NOx eq
Ozone formation, Terrestrial ecosystems	526417	kg NOx eq
Terrestrial acidification	461158	kg SO2 eq
Freshwater eutrophication	51750	kg P eq
Marine eutrophication	3611	kg N eq
Terrestrial ecotoxicity	703053720	kg 1,4-DCB
Freshwater ecotoxicity	7877850	kg 1,4-DCB
Marine ecotoxicity	10857279	kg 1,4-DCB
Human carcinogenic toxicity	65594677	kg 1,4-DCB
Human non-carcinogenic toxicity	116447928	kg 1,4-DCB
Land use	8583172	m2a crop eq
Mineral resource scarcity	2411678	kg Cu eq
Fossil resource scarcity	30605830	kg oil eq
Water consumption	1781064	m3

CLIC 10m 380GeV| Relative contribution of each component to total environmental impact

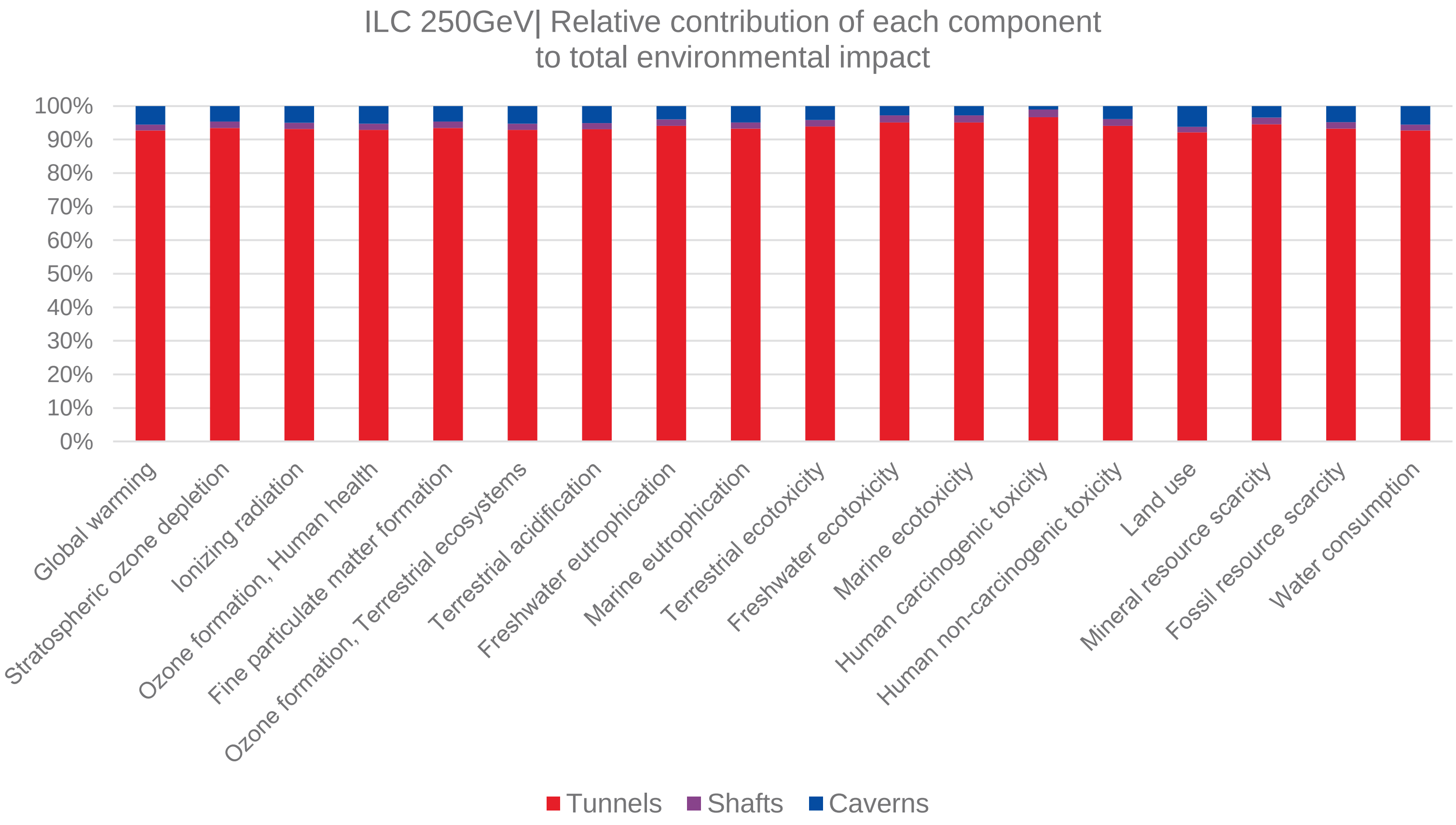


ILC 9.5m span, 250GeV

A1-A3 LCA Results

The absolute values are reported below:

Impact Categories	Absolute value	Unit
Global warming	221859509	kg CO2 eq
Stratospheric ozone depletion	41.1	kg CFC11 eq
Ionizing radiation	8682415	kBq Co-60 eq
Fine particulate matter formation	523710	kg PM2.5 eq
Ozone formation, Human health	191316	kg NOx eq
Ozone formation, Terrestrial ecosystems	534814	kg NOx eq
Terrestrial acidification	458167	kg SO2 eq
Freshwater eutrophication	48047	kg P eq
Marine eutrophication	3443	kg N eq
Terrestrial ecotoxicity	705650266	kg 1,4-DCB
Freshwater ecotoxicity	6915406	kg 1,4-DCB
Marine ecotoxicity	9553680	kg 1,4-DCB
Human carcinogenic toxicity	52721447	kg 1,4-DCB
Human non-carcinogenic toxicity	109960323	kg 1,4-DCB
Land use	9080569	m2a crop eq
Mineral resource scarcity	2106905	kg Cu eq
Fossil resource scarcity	30739364	kg oil eq
Water consumption	1491387	m3



A1-A3 Additional Impact Categories

Conclusions

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

Across all impact categories the tunnels have the largest contribution to each environmental impact. This is due to the larger quantity of steel and concrete in the tunnels compared to the shafts and caverns.

The relative contribution of each stage A1-A3, A4 and A5 will be evaluated at the next stage and included in the final report. This will provide more useful insights as to how transport, construction activities and associated energy usage will change the relative contribution at each stage.

On completion of A4-A5, further insights will be drawn for the additional 17 impact categories.

Limitations

A number of limitations were found during the LCA of the additional 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 17 impact categories for tunnels. 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
- **Silvertown Tunnel** – concept stage
- **Californian high-speed rail system** – proposed scheme
- **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 to calculate carbon.

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 (CTRL HS1) 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

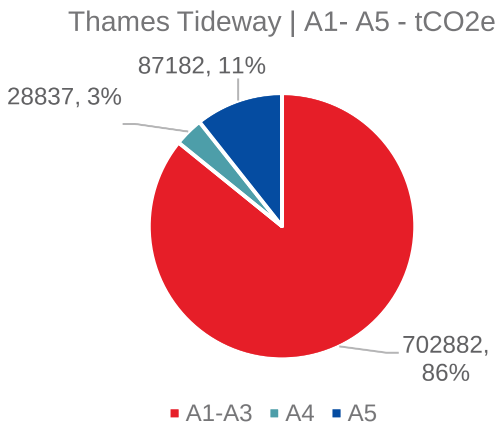
Thames Tideway – Super Sewer

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



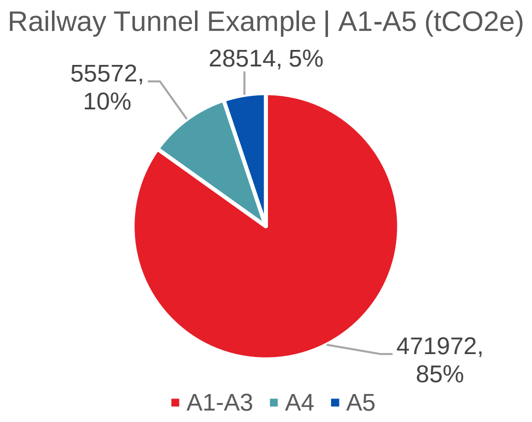
Reference: Thames Tideway Tunnel, Thames Water Utilities Limited, Application for Development Consent, Energy and Carbon Footprint Report, (2013).

Railway Tunnel (Arup Internal Example)

Concept stage

An internal A1-A5 carbon calculation was completed for a 9.75m diameter (OD), 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.



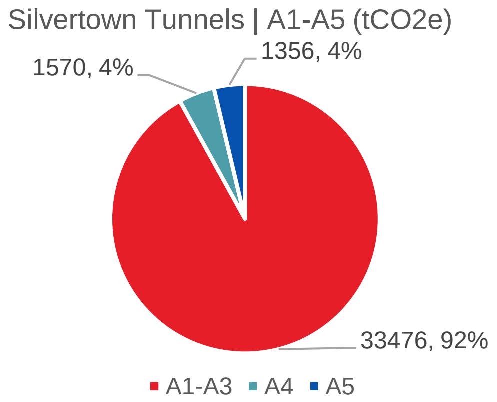
Reference: Arup Railway Tunnel Carbon Calculation internal study, (2022).

Silvertown Tunnel

Concept stage

A baseline carbon assessment of a 1.4km long, twin bore, 10.7m ID tunnel was undertaken. This assessment utilised the project concept design.

Note the A5 value was informed by the RICS guide (Whole Life Carbon Assessment for the built environment, 2017) relating to overall project costs.



As this project utilises a TBM this is likely to be an underestimation of A5 emissions.

Reference: Silvertown Tunnel, Baseline Carbon assessment Report (2020)

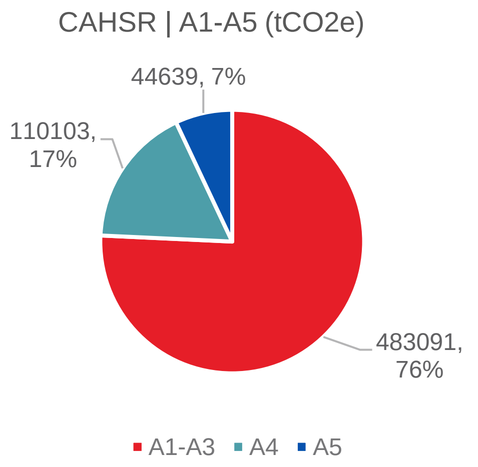
Benchmarking

Data from tunnel projects

Californian high-speed rail system (CAHSR)
Proposed scheme

49km of twin-bore 9m I.D NATM tunnel

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

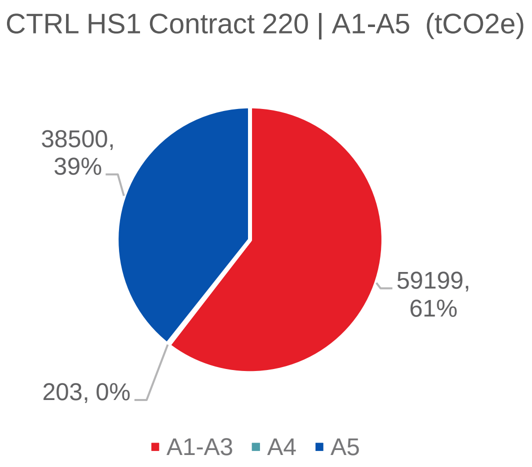


Reference:
Understanding the contribution of tunnels to the overall energy consumption of and carbon emissions from a railway J. A. Pritchard , J. Preston, Transportation Research Group, University of Southampton, (2018).

Contract 220 CTRL - HS1 – retrospective evaluation
As built

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

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



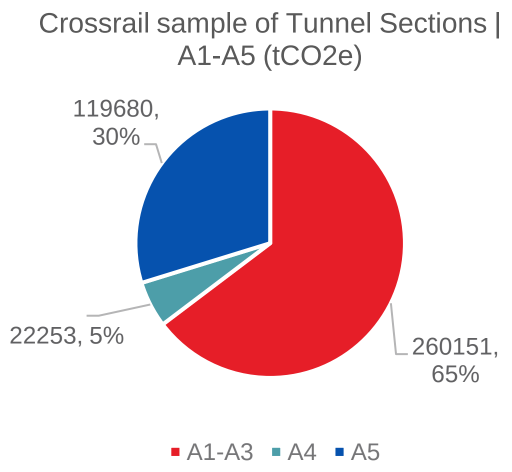
References:
Embodied energy evaluation for sections of the UK Channel Tunnel Rail link, Geotechnical Engineering, vol.165 Chau, Soga, O'Riordan and Nicholson (2011).

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
As built

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

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



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

Conclusions

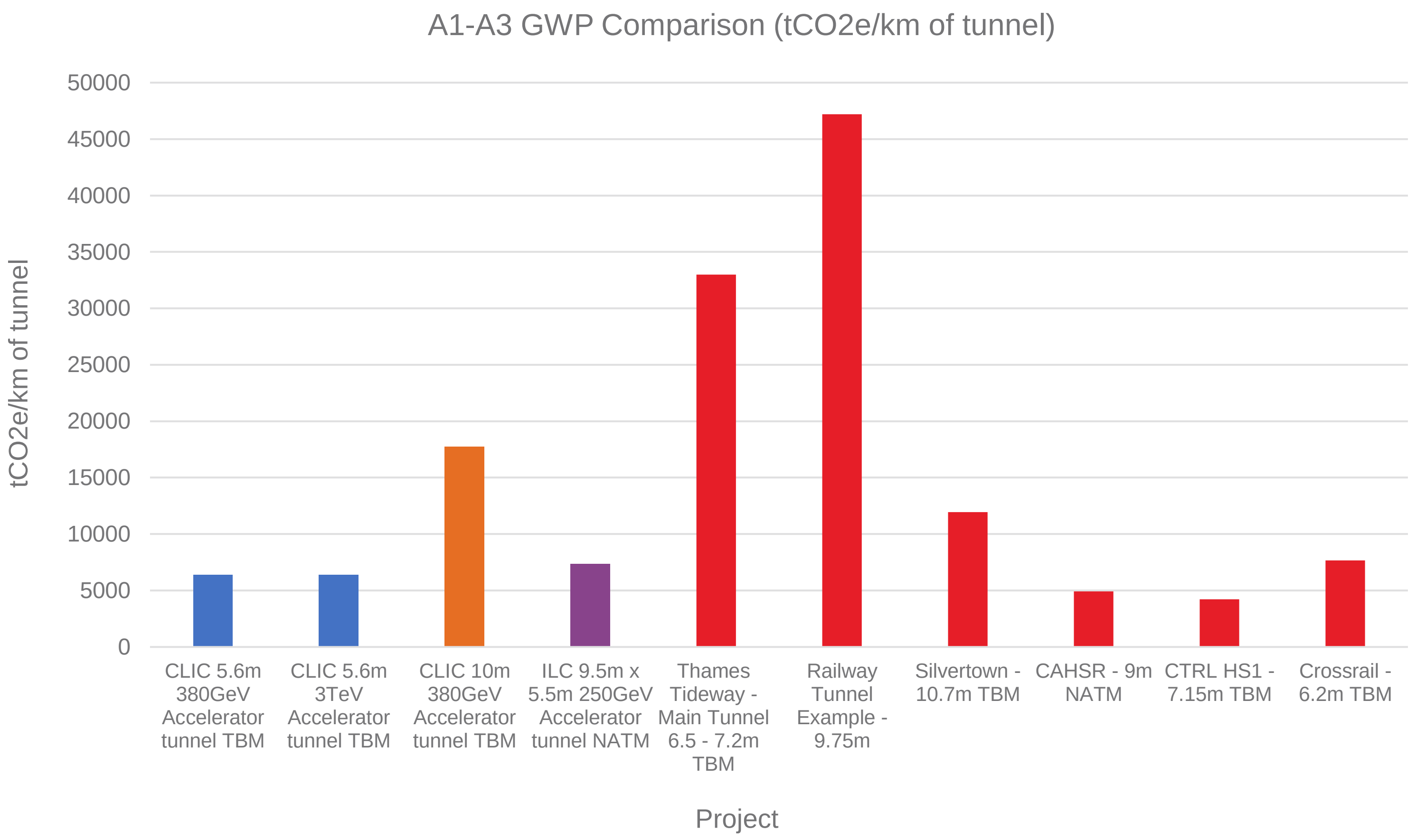
It can be concluded that A1–A3 tCO2e/km results for the CLIC Drive Beam (5.6m dia.) and ILC tunnels are in good agreement with the GWP estimates produced in the other studies on major tunnelling projects, see graph to the right.

CLIC Drive Beam 5.6m dia. tCO2e/km estimate is within 20-35% of as built estimates CTRL HS1 and Crossrail.

Furthermore, the CLIC Klystron 10m dia. tCO2e/km estimates are within 35% of a similar sized diameter tunnel, Silvertown tunnel (concept stage).

ILC 9.5m span tCO2e/km estimate is within 35% of similar sized NATM tunnelling project, Californian high-speed rail system (proposed scheme).

Note CLIC and ILC A4 and A5 GWP results will be compared with benchmarking data at the next stage.



4

Conclusions, recommendations & next steps

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)

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

Recommendations highlight key points of consideration for A1-A3 prior to the final report being completed.

Recommendations

A1-A3 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:

- Replacement of portland cement with SCMs, such as GGBS, FA or SF.
- Replacing the shielding wall in CLIC Klystron 10m dia. and ILC 9.5m span 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.
- Reducing the precast concrete segmental lining thickness for CLIC Drive Beam 5.6m dia. and CLIC Klystron 10m dia. The lower bound value in ITA segmental tunnel lining guidance, 2019. is a potential indication of achievable limits, based on design optimisation. Innovations in design could reduce this further.
- 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.

Next steps

GWP reduction opportunities should be discussed to understand if the design and material property changes could be implemented.

An A4-A5 assessment will be evaluated for CLIC and ILC options and included in the final report.

Further reduction opportunities will be investigated along with innovative material technologies.