Linear colliders

Sustainability studies for LCs
Life Cycle Assessments

Steinar Stapnes

CLIC mini workshop 11.12.23 – hence focus on CLIC

From costs and power to sustainability and life cycle assessments

1. **Reduce power/energy (hand in hand with cost optimisation)**
2. **Operation energy use means carbon –> use the minimum energy, of the right type and at the right time, compensate**
3. **Life Cycle Assessments**

Power optimization – examples

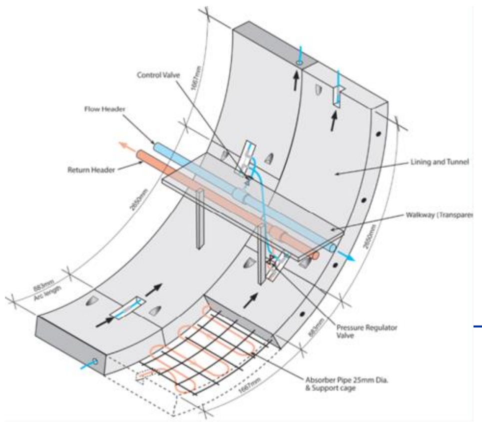
Design Optimisation:
All projects aim to optimize – most often energy reach, luminosities and cost. Power is becoming at least as important, maybe even compromising ultimate performance for power saving.

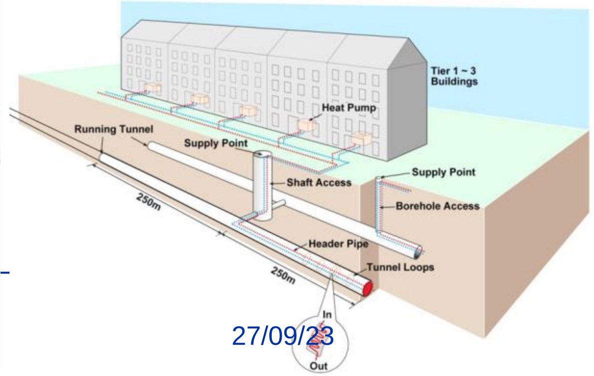
Technical Developments:
Technical developments targeting reduced power consumptions at system level high efficiency klystrons and RF systems generally, RF cavity design and optimisation, magnets (traditional SC and HTS including cryo, and also permanents magnets).

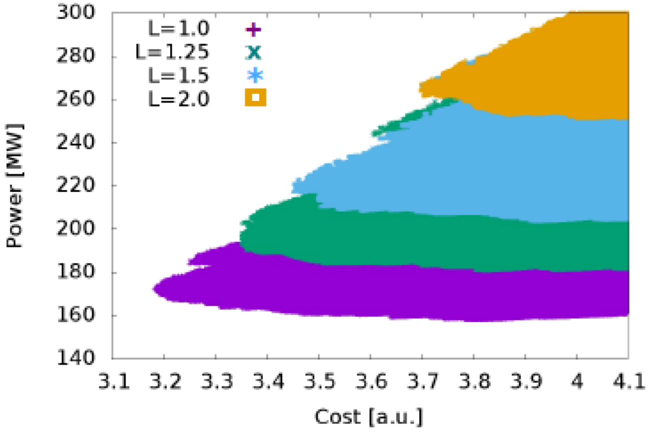
Heat recovery:

Already implemented in point 8 for LHC

Tunnel heat recovery study by ARUP in 2022, results interesting but …

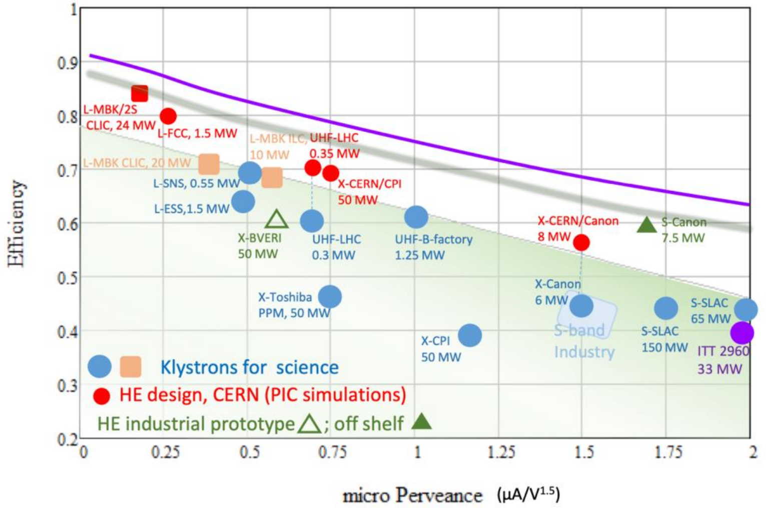






Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum

The designs of CLIC, including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost and power



Nanobeams

A very important part of increasing the energy efficiency of a collider is reducing the beamsizes at the collision point.

This involved optimisation of every part of the machine, from injectors to damping rings to main linacs/rings to beam-delivery/interaction point.

and covers in terms of design and technologies:

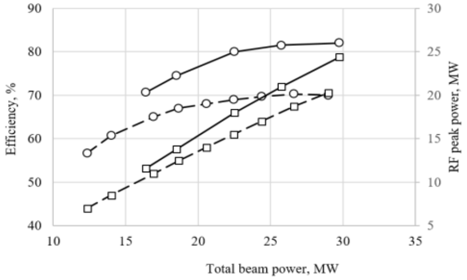
beam-dynamics, steering and feedback, precise instrumentation, alignment, stability (passive/active), injection, extraction, precise magnets, vacuum, studies of ground vibrations and stray-field, temperature control and more.

This has been extensively developed and prototyped in CLIC, ILC, FEL linacs.

Beyond studies and HW developments, test in beam facilities as ATF2, FACET, light sources and FEL linacs are essential.

High Eff. Klystrons

L-band, X-band (for applications/collaborators and test-stands

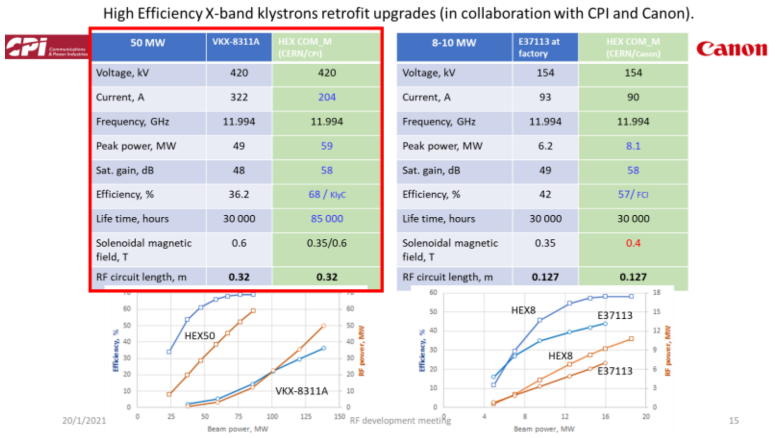


Location: CERN Bldg: 112

Drivebeam klystron: The klystron efficiency (circles) and the peak RF power (squares) simulated for the CLIC TS MBK (solid lines) and measured for the Canon MBK E37503 (dashed lines) vs total beam power. See more later.
Publication: https://ieeexplore.ieee.org/document/9115885

High Efficiency implementations:

- New small X-band klystron – recent successful prototype
- Large X-band with CPI
- L-band two stage, design done, prototype desirable

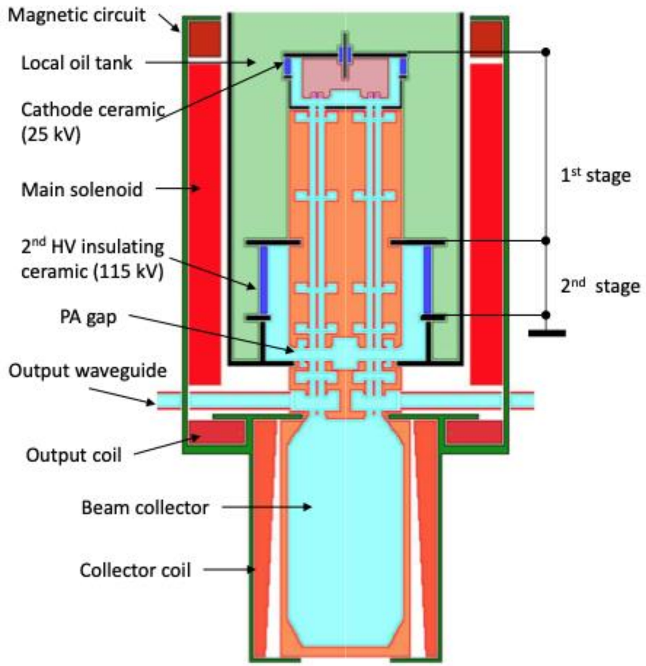


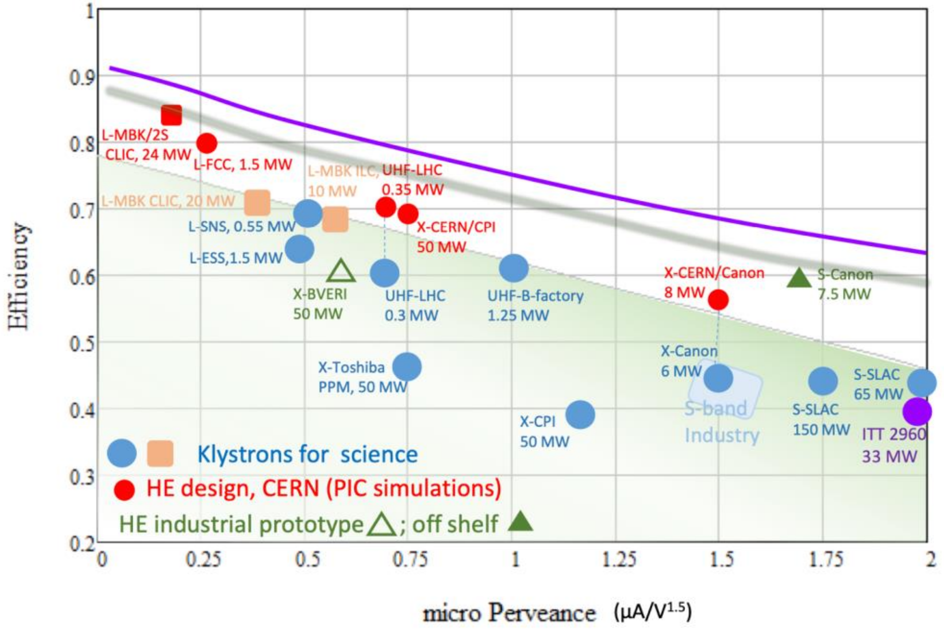
High Efficiency X-band klystrons retrofit upgrades (in collaboration with CPI and Canon).

50 MW	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	58
Efficiency, %	36.2	68 / KlyC
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.35/0.6
RF circuit length, m	**0.32**	**0.32**

8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	93	90
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	58
Efficiency, %	42	57/ FCI
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.4
RF circuit length, m	**0.127**	**0.127**

20/1/2021 RF development meeting 15





Magnets also important in Higgs factories

1.5 TeV CLIC power
Magnets second largest

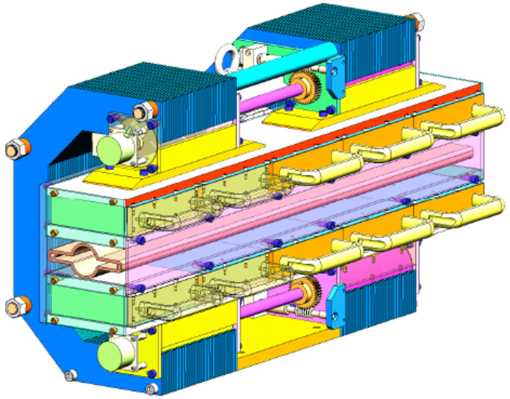
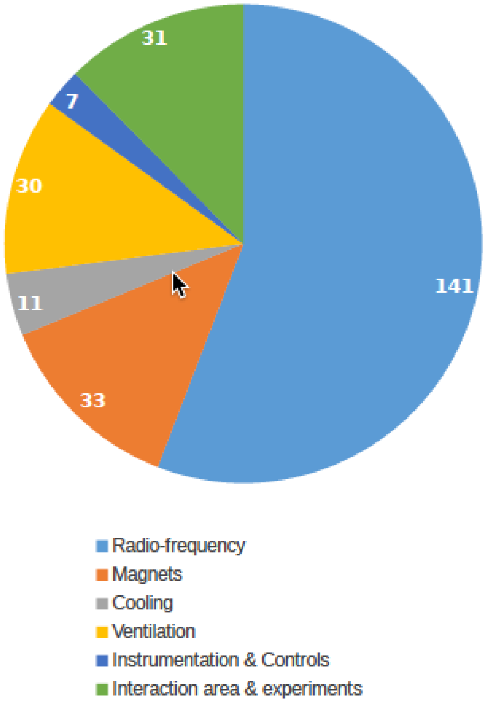
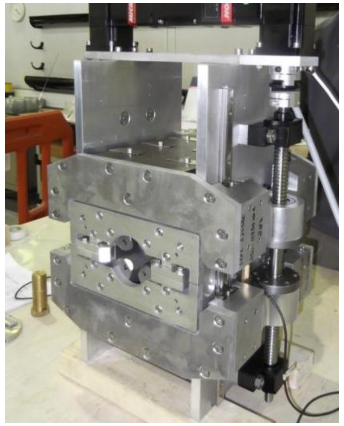


Figure 3: Overview of possible design of PM dipole for ILC damping ring.



ZEPTO (Zero Power Tuneable Optics) project is a collaboration between CERN and STFC Daresbury Laboratory to save power and costs by switching from resistive electromagnets to permanent magnets.

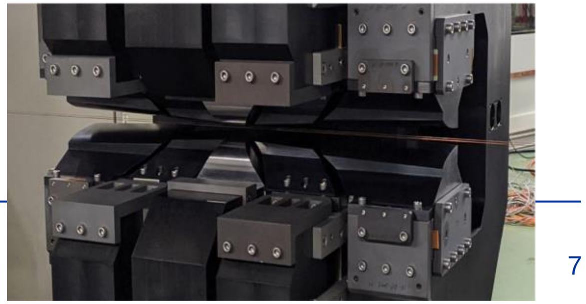
For CLIC the dominant power is in the drive-beam quadrupoles, successfully prototyped and tested as permanent (two different strengths) magnets, and also dipoles (in drivebeam turn arounds)



HTS magnets might be of interests in all circular and linear Higgs factories to reduce power.

Longitudinal gradient dipole magnet for the CLIC DR (CIEMAT)

doi:10.18429/JACoW-IPAC2018-MOPML048 CC-BY-3.0



From costs and power to sustainability and life cycle assessments

1. Reduce power/energy (hand in hand with cost optimisation)

2. **Operation energy use means carbon –> use the minimum energy, of the right type and at the right time, compensate**

3. Life Cycle Assessments

Running on renewables and when electricity is cheap

Two studies in 2017:

- Supply the annual electricity demand of the CLIC-380 by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators) at a cost of slightly more than 10% of the CLIC 380 GeV cost.
  - Study done for 200 MW, in reality only ~110 MW are needed
- Self-sufficiency during all times can not be reached but 54% of the time CLIC could run independently from public electricity supply with the portfolio simulated.

- Can one run an accelerator as CLIC in a mode where one turn “on” and “off” depending prices (fluctuating with weather, demand, availability etc) ?
- Specify transition times (relatively fast for a LC) and the annual luminosity goal
- Significant savings – but the largest saving is the obvious one, not running in the winter.
- Flexibility to adjust the power demand is expected to become increasingly important and in demand by energy companies.

More information (link)

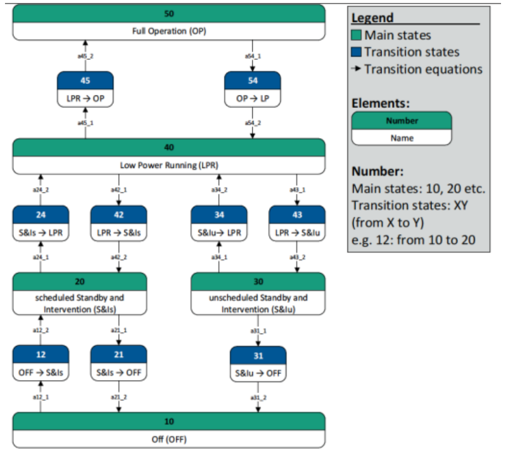
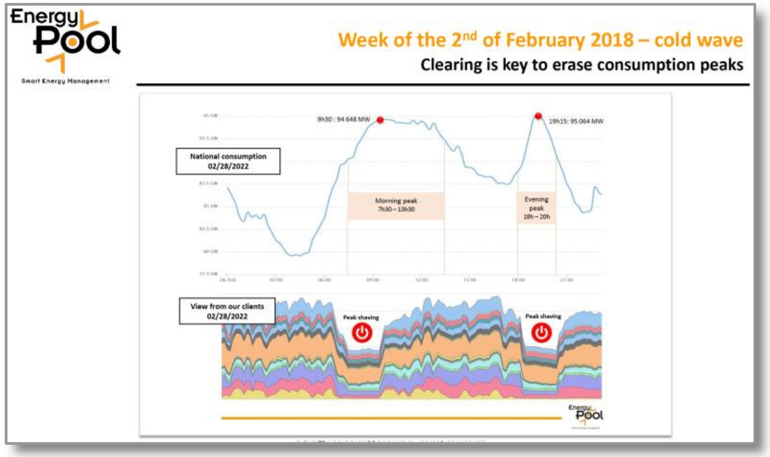


Figure 1-1: Schematic representation of the finite state machine

(Regenerative) Power availability varies
Linear accelerators have no stored beam -> ideal for flexible operation

Study by Fraunhofer institute considered running
on renewables and participating in **demand side flexibility**


Week of the 2nd of February 2018 – cold wave

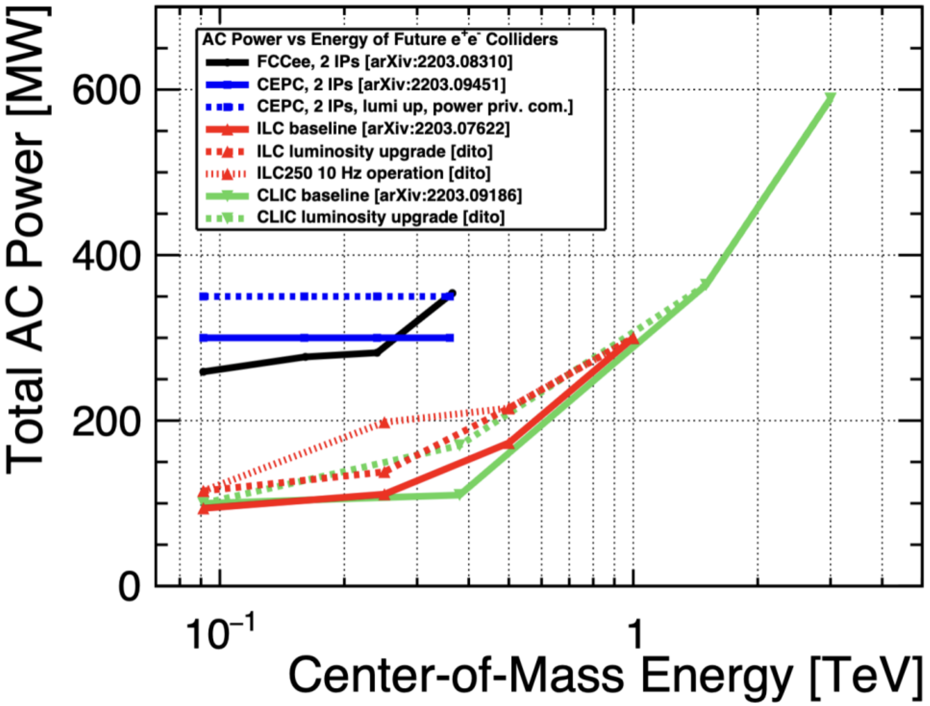
Clearing is key to erase consumption peaks

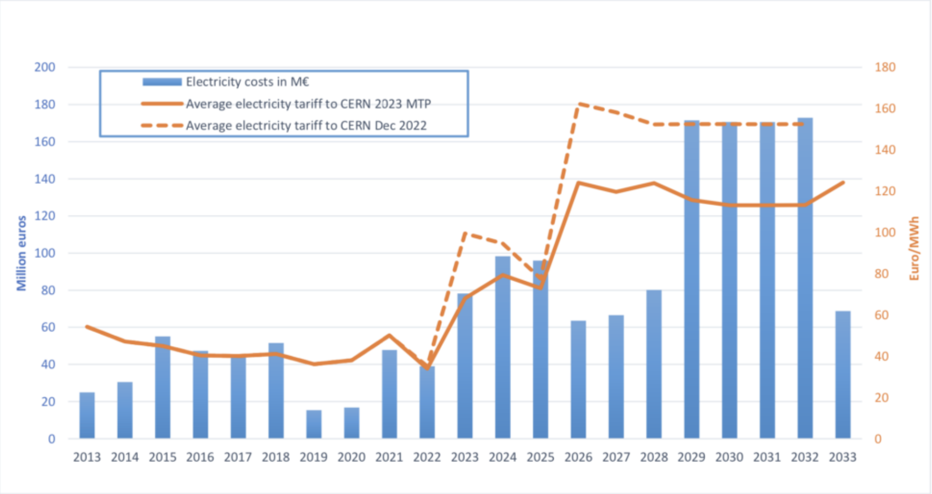
C. Gaunand, B. Remenyi: *Introduction to Demand Side Flexibility*
ESSRI Workshop 2022 https://indico.esrf.fr/event/2/contributions/94/

Power and energy

Typical power numbers for Higgs factories on the right – see also table on page above.

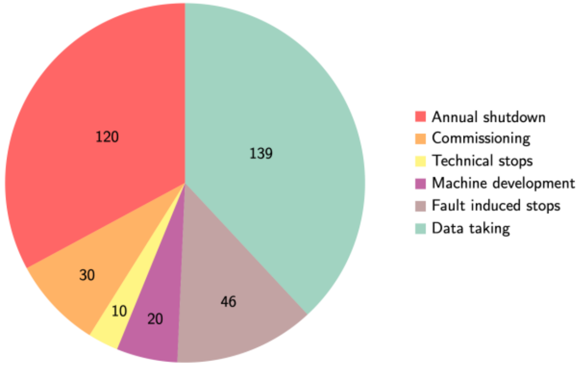
The CERN “standard” running scenario is shown below right, used to convert to annual energy needs.



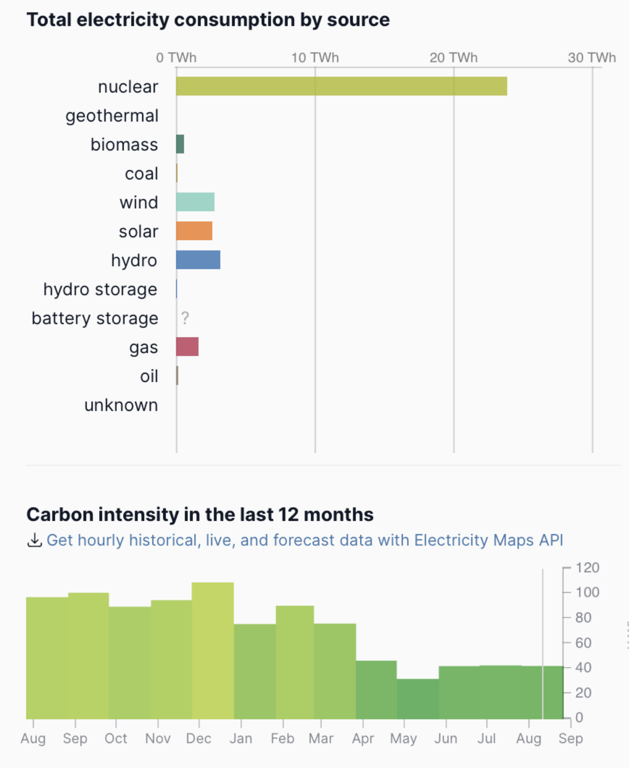


Very uncertain but MTP assumes 120 MCHF/TWh beyond 2026.

With “standard” running scenario (on the right) every 100 MW corresponds to ~0.6 TWh annually, corresponding to ~75 MCHF annually (European costing)



From energy to CO2 – in 2040-50

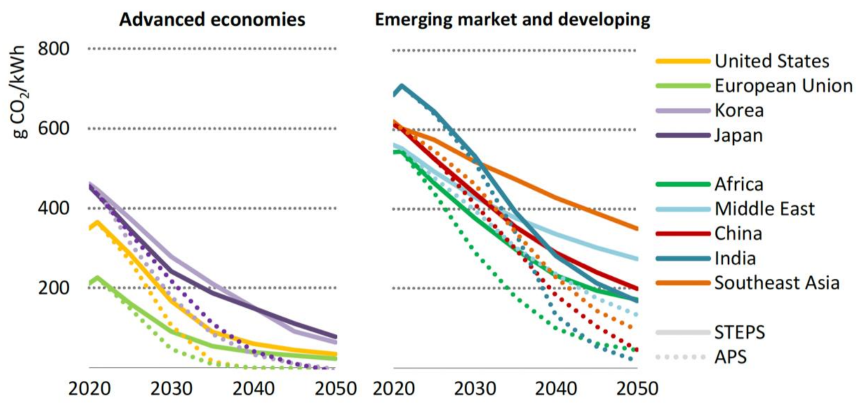


From: https://app.electricitymaps.com/zone/FR
Contains also g/kWh per source

What is the carbon intensity of energy in ~2050 (operation):

- 50% nuclear and 50% renewable give ~10-15g/kWh
- France summer-months are today ~40g/kWh
- ILC has a green implementation concept including compensation and contracting renewable energy
- Reductions predicted (LINK)

Figure 6.14 ▷ **Average CO_2 intensity of electricity generation for selected regions by scenario, 2020-2050**



IEA. CC BY 4.0.

CO_2 intensity of electricity generation varies widely today, but all regions see a decline in future years and many have declared net zero emissions ambitions by around 2050

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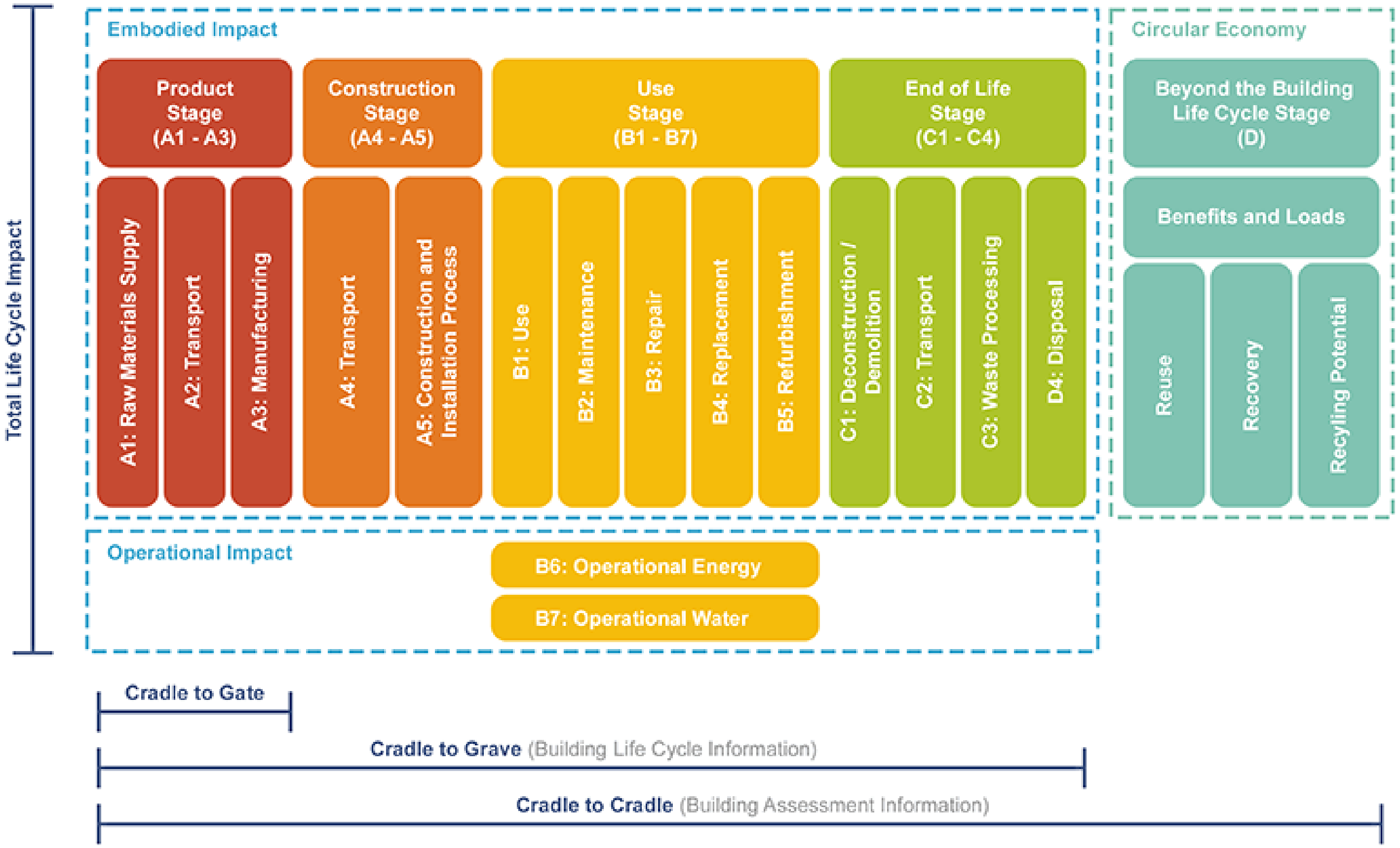
Sustainable Construction – Life Cycle Assessment

For carbon emission the construction impact will be much earlier and might be more significant (also rare earths and many other issues etc):

- Construction: CE, materials, processing and assembly – not easy to calculate
- Markets will push for reduced carbon, responsible purchasing crucial (see right) – construction costs likely to increase

Decommissioning – how do we estimate impacts ?



Responsible purchasing – and understanding the impact on our supply chain, costs and potential for changes – will be essentials for future projects (CERN implementation information from E.Cennini)

Life Cycle Assessment

Comparative environmental footprint for future linear colliders CLIC and ILC

The International Workshop on Sustainability in Future Accelerators 2023 | 26/09/2023

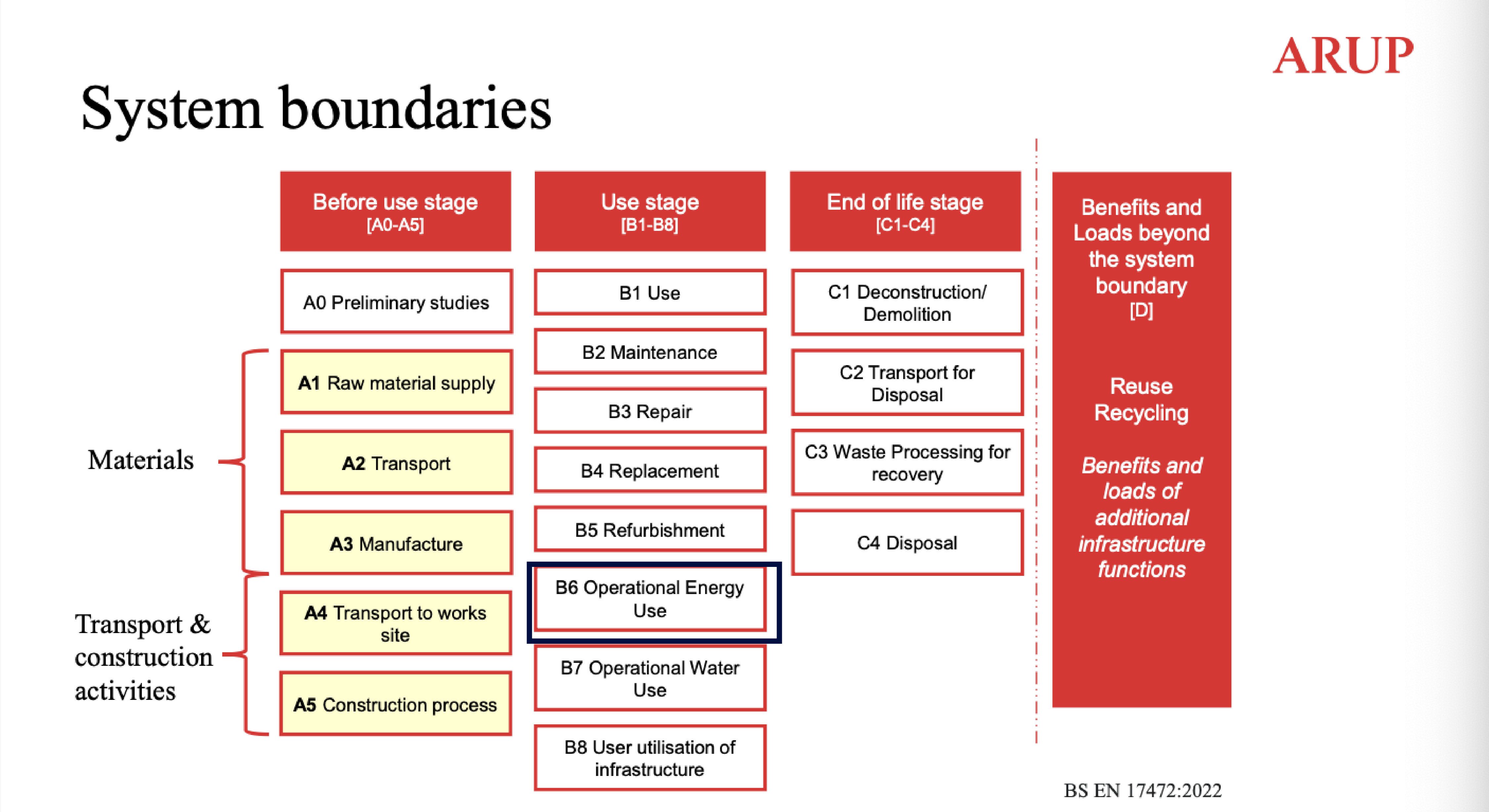
ARUP: *Suzanne Evans, *Jin Sasaki, Ben Castle, Yung Loo, Heleni Pantelidou, Marin Tanaka
CERN: John Osborne, Steinar Stapnes, Benno List, Liam Bromiley
KEK: Nobuhiro Terunuma, Akira Yamamoto, Tomoyuki Sanuki

(*presenters: suzanne.evans@arup.com, jin.sasaki@arup.com)

The report: https://edms.cern.ch/ui/#!master/navigator/document?D:101320218:101320218:subDocs

ARUP

System boundaries



Before use stage
[A0-A5]

- A0 Preliminary studies
- **A1** Raw material supply
- **A2** Transport
- **A3** Manufacture
- **A4** Transport to works site
- **A5** Construction process

Materials: A1–A3

Transport & construction activities: A4–A5

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

BS EN 17472:2022

Only B6 discussed in all the slides above, now discuss A1-A5 for the CE
Missing A1-A5 for accelerator, some surface installations, all maintenance and upgrades, all EoL activities

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).

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

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.

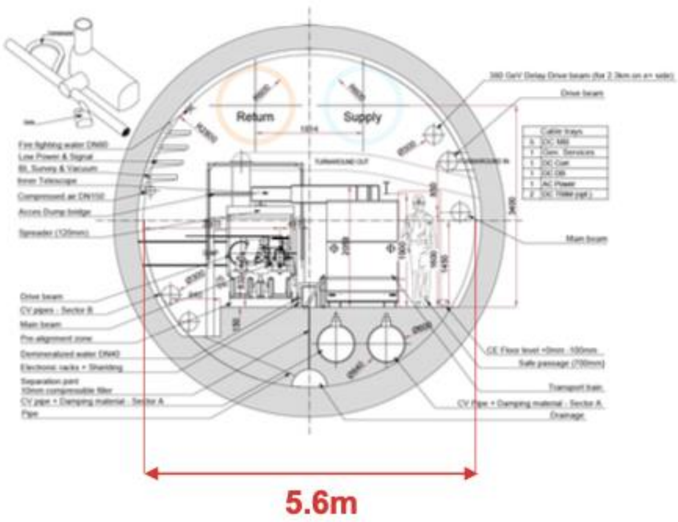
Reference: ReCiPe Midpoint (H) 2016

ARUP

Linear Collider Options

1. CLIC Drive Beam

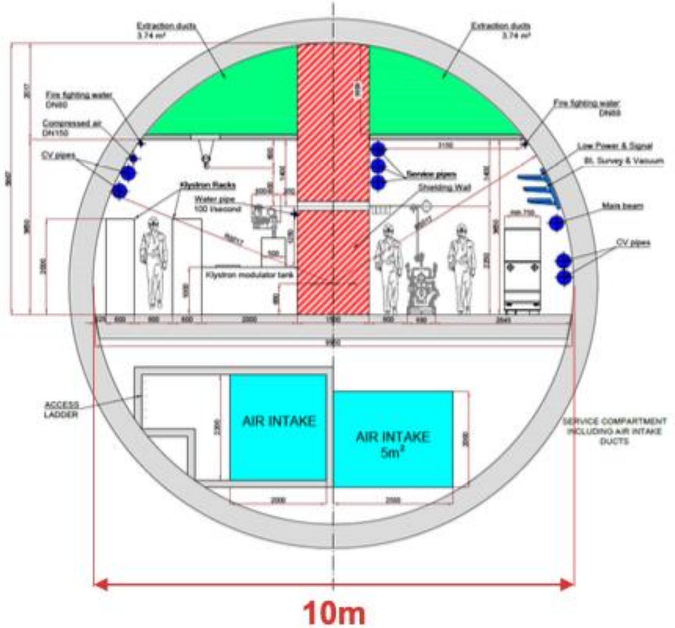
5.6m internal dia. Geneva.
(380GeV, 1.5TeV, 3TeV)



Reference: CLIC Drive Beam tunnel cross section, 2018

2. CLIC Klystron

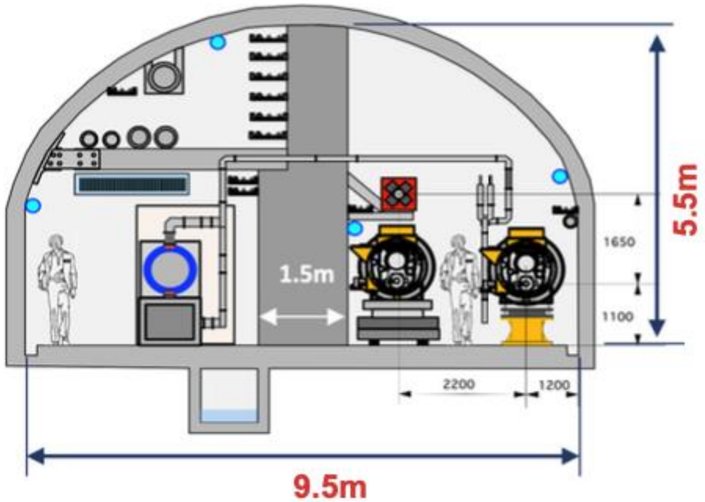
10m internal dia. Geneva.
(380GeV)



Reference: CLIC Klystron tunnel cross section, 2018

3. ILC

Arched 9.5m span. Japan.
(250GeV)

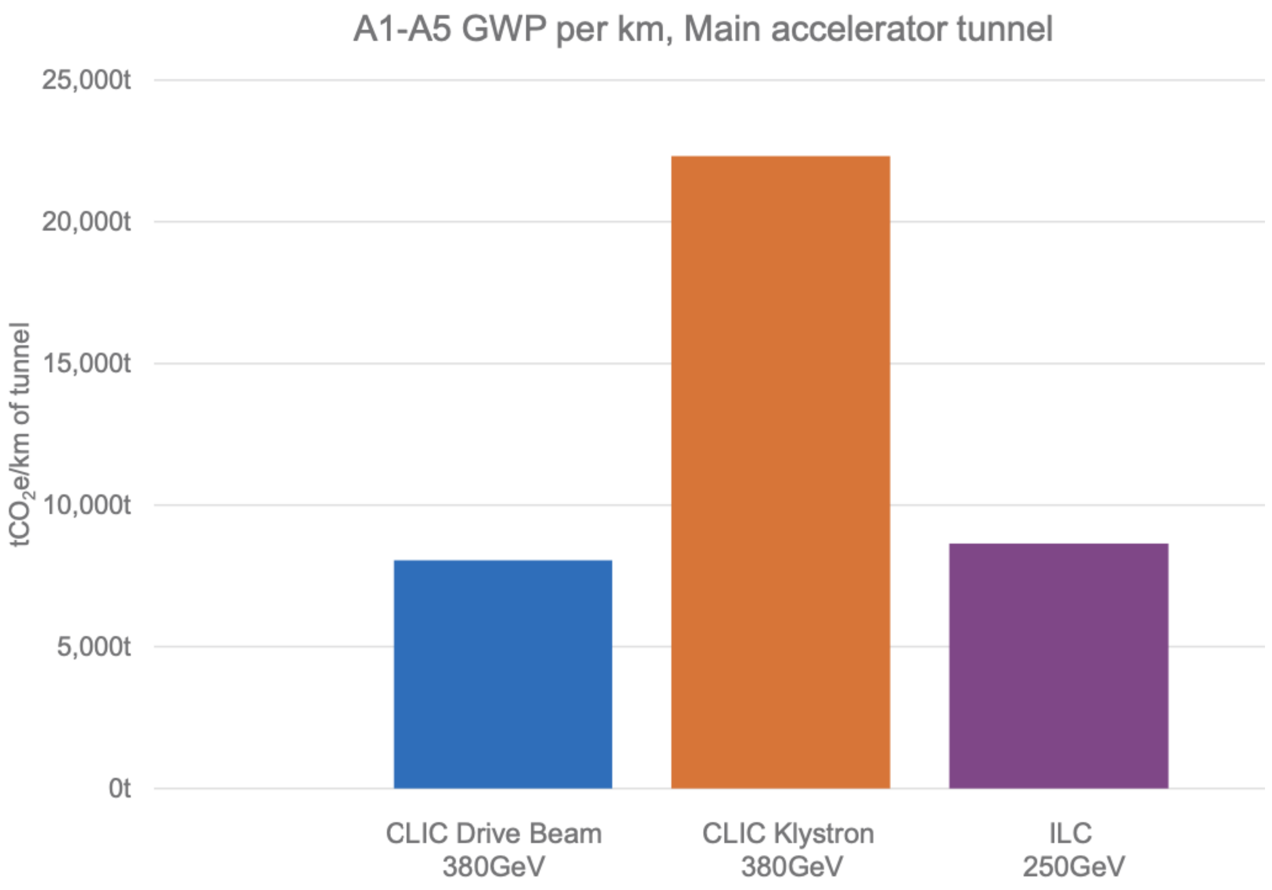


Reference: Tohoku ILC Civil Engineering Plan, 2020

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

2030 Baseline assumptions

<table>
<tr><th colspan="2">LCA Modules</th><th>CLIC Drive Beam</th><th>CLIC Klystron</th><th>ILC</th></tr>
<tr><td>A1-A3</td><td>Materials</td><td colspan="3">Concrete (CEMI) & Steel (80% recycled)</td></tr>
<tr><td>A4</td><td>Transport of materials to site</td><td colspan="2">Concrete: Local by road (50km)
Steel: European by road (1500km)</td><td>Concrete: Local by road (50km)
Steel: National by road (300km)</td></tr>
<tr><td>A5</td><td>Material wasted in construction</td><td colspan="3">Concrete insitu: 5%
Precast concrete: 1%
Steel reinforcement: 5%</td></tr>
<tr><td>A5</td><td>Transport of disposal materials off site</td><td colspan="3">Concrete and steel recycling: 30km by road
Concrete and steel landfill: 30km by road
Spoil: 20km by road
Assumed that 90% of EoL construction materials are recycled or repurposed and 10% is in landfill.</td></tr>
<tr><td>A5</td><td>Construction process</td><td colspan="2">Tunnel Boring Machine (TBM)</td><td>Drill & Blast</td></tr>
<tr><td>A5</td><td>Electricity mix 2021/2022</td><td colspan="2">Fossil: 12%
Non-fossil: 88%</td><td>Fossil: 71%
Non-fossil: 29%</td></tr>
</table>



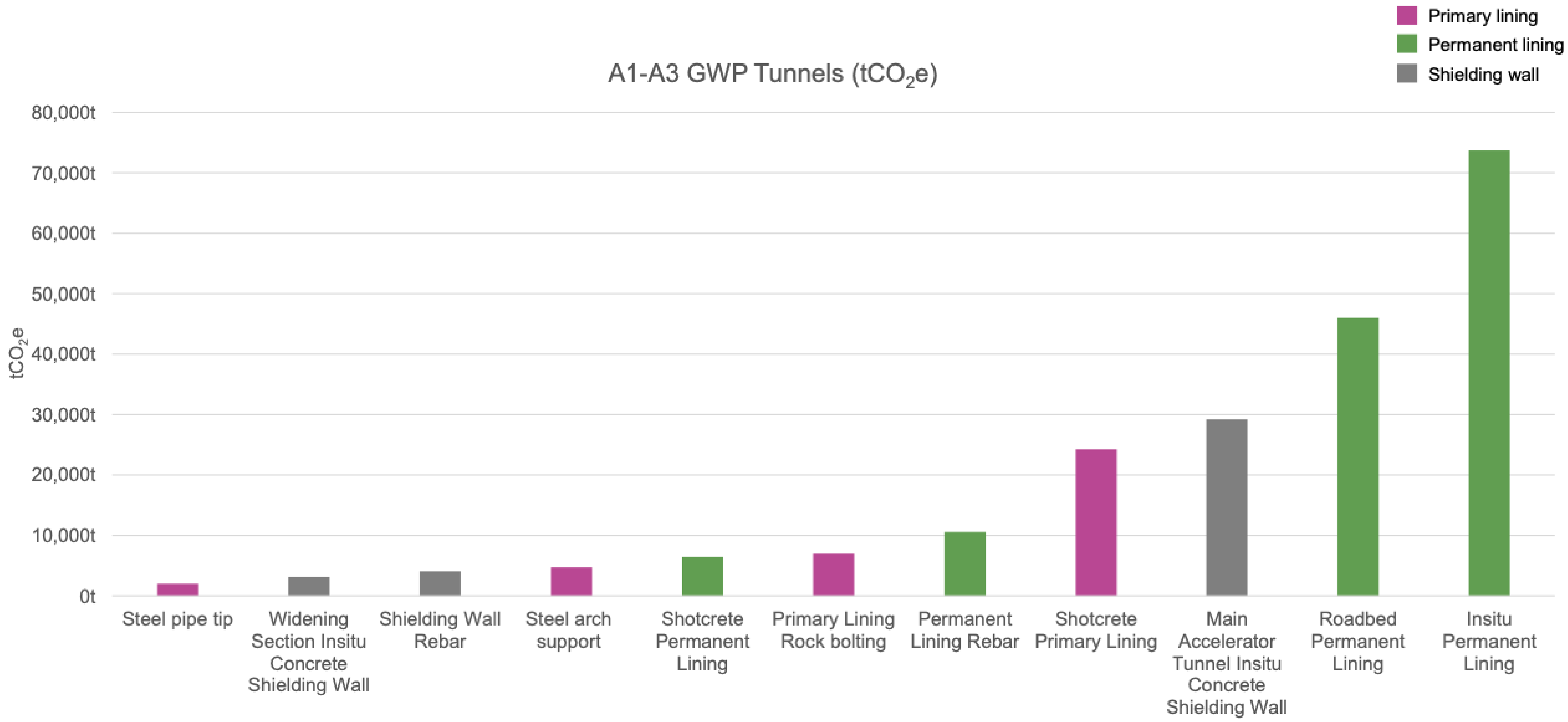
A1-A3 material only dominates
Around 6kton/km for CLIC DB and ILC

CLIC around 11km, ILC around 20 km

ILC 250GeV

ARUP

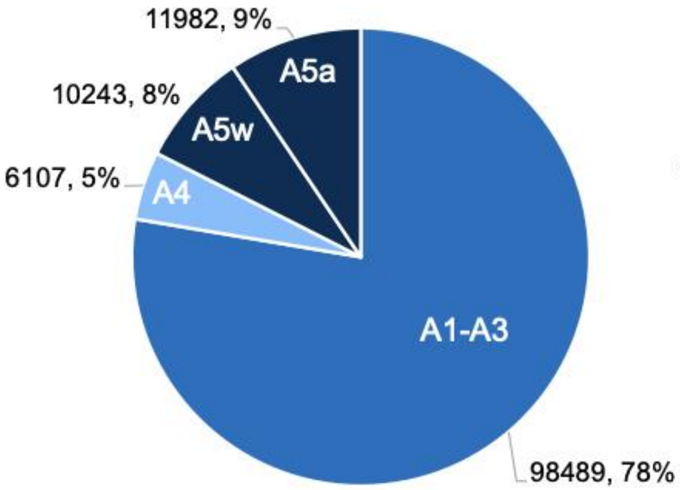
A1-A3 Global Warming Potential (tCO_2e)



ARUP

1. CLIC Drive Beam 380GeV

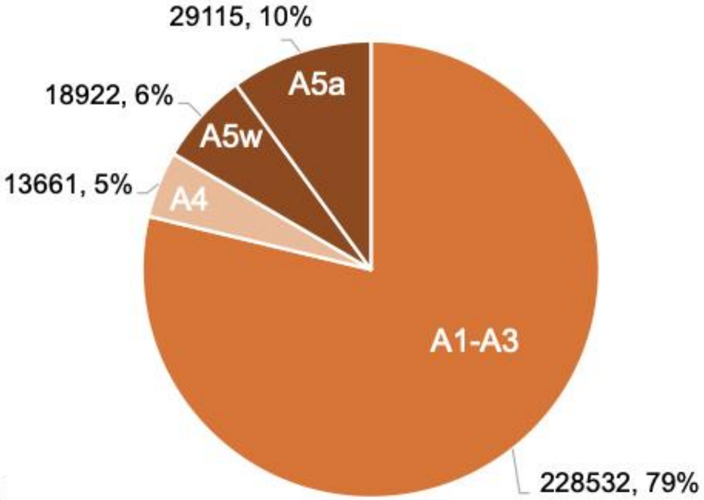
5.6m internal dia.
Geneva



Total A1-A5 GWP: 127000 tCO_2e

2. CLIC Klystron 380GeV

10m internal dia.
Geneva



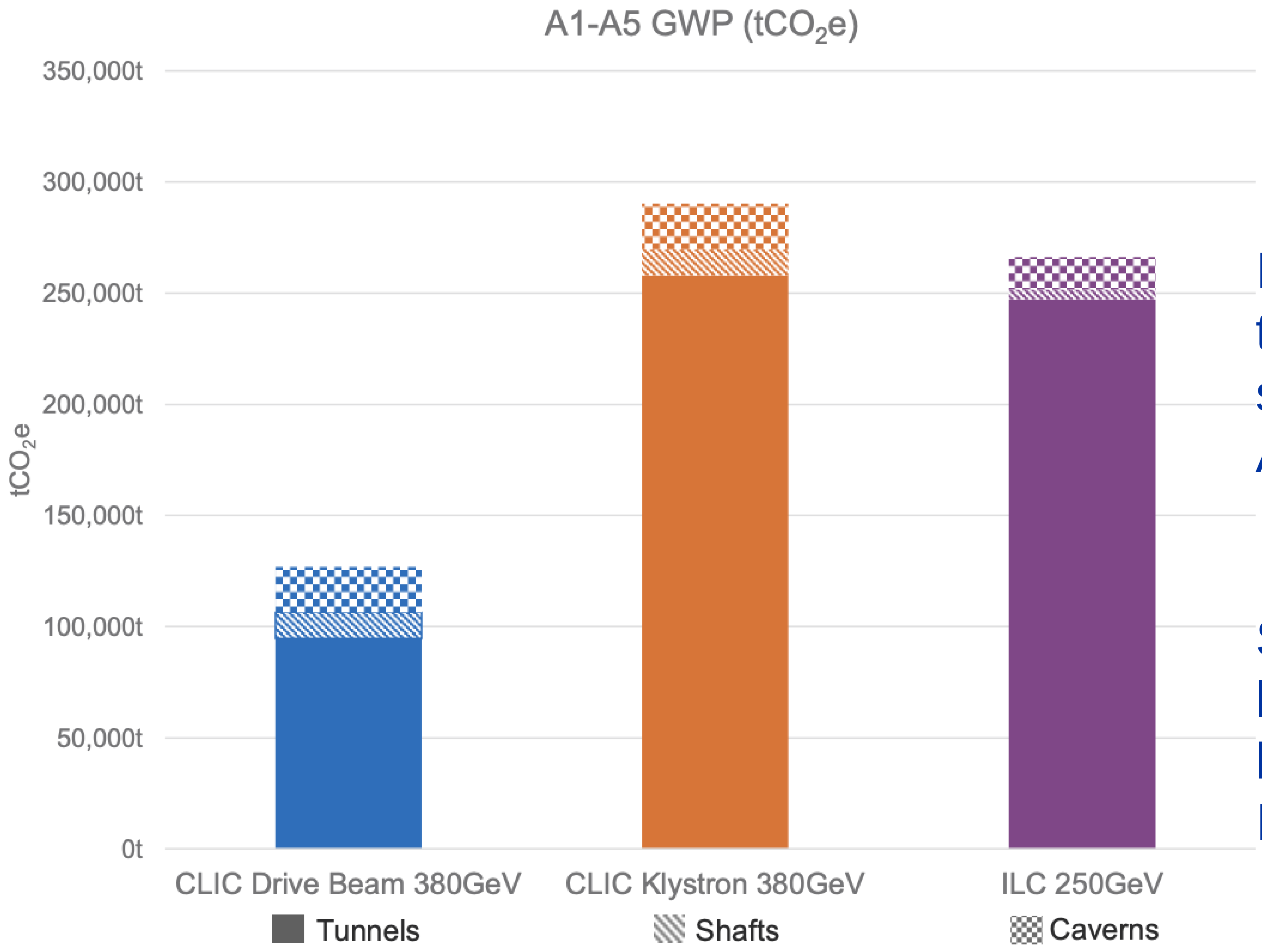
Total A1-A5 GWP: 290000 tCO_2e

3. ILC 250GeV

Arched 9.5m span
Japan

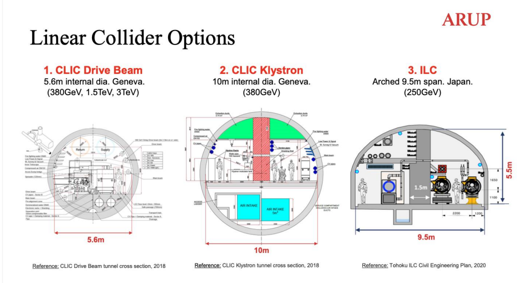
Total A1-A5 GWP: 266000 tCO_2e

Total GWP results reported to 3 significant figures



Include all tunnels (access, transfer, damping rings), shafts and caverns.
A1-A5

Scaling to main linac tunnel lengths we are now at 11-14 kton/km for the CLIC DB and ILC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Linear Collider Options

1. CLIC Drive Beam
5.6m internal dia. Geneva.
(380GeV, 1.5TeV, 3TeV)

2. CLIC Klystron
10m internal dia. Geneva.
(380GeV)

3. ILC
Arched 9.5m span. Japan.
(250GeV)

Reference: CLIC Drive Beam tunnel cross section, 2018

Reference: CLIC Klystron tunnel cross section, 2018

Reference: Tohoku ILC Civil Engineering Plan, 2020

CLIC Drive Beam 380GeV

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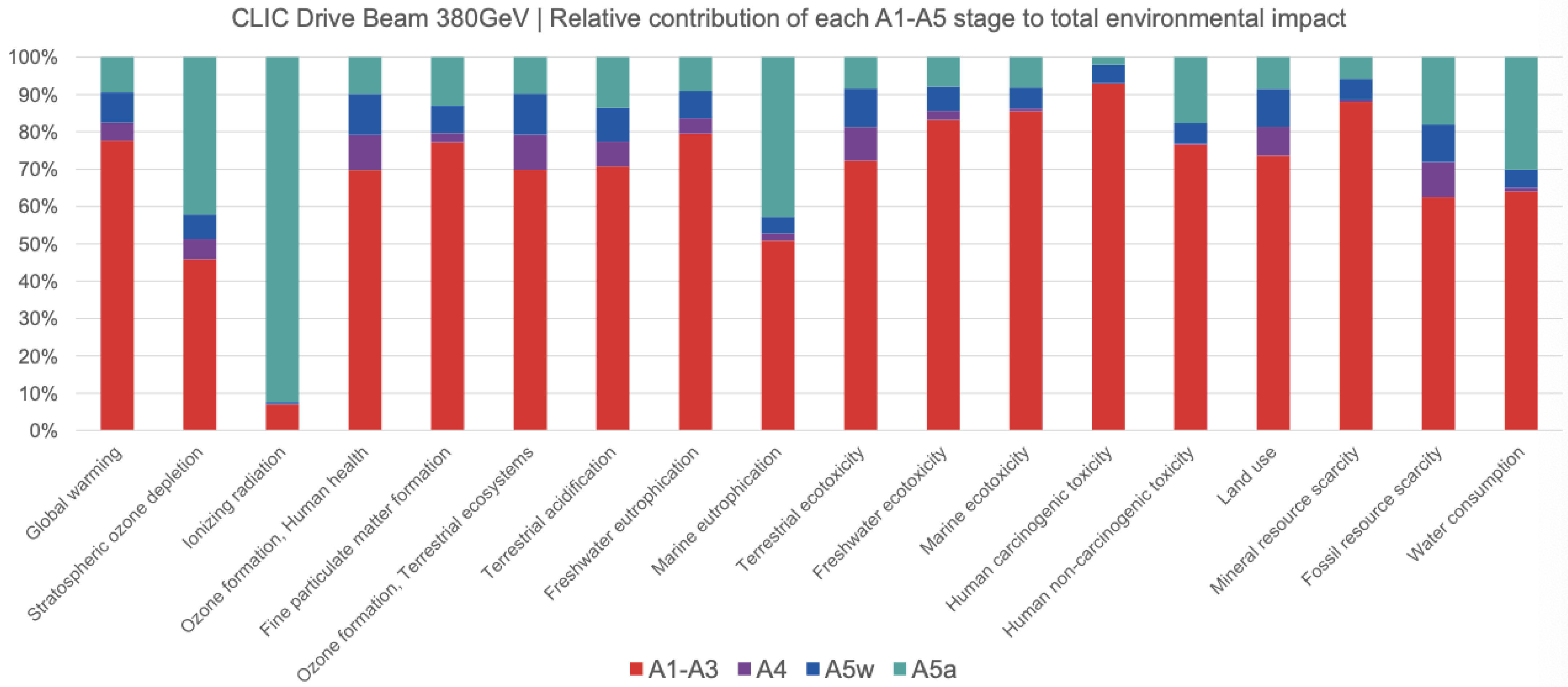
A1-A5 ReCiPe 2016 Midpoint (H) Impact Categories



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_2e/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_2e/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_2e/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_2e/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_2e/m tunnel length (D&B 29%, loading and hauling 36%, ventilation 31%).

Benchmarking

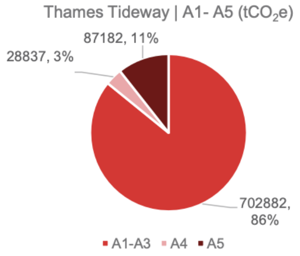
Data from tunnel projects

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



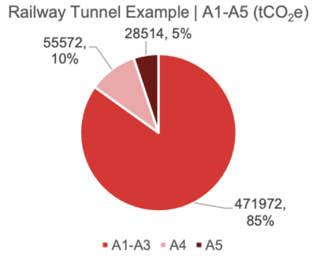
Total A1-A5 GWP: 819,000 tCO_2e

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_2e

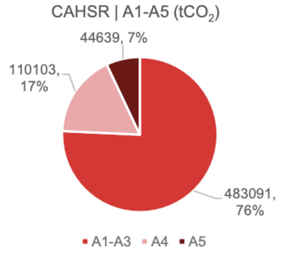
Californian High-speed Rail System (CAHSR), USA

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

CLIC Drive Beam 380GeV

Tunnels reduction opportunities

41% possible A1-A5 GWP reduction

- Materials
  - **A1** Raw material supply
  - **A2** Transport
  - **A3** Manufacture
- Transport & construction activities
  - **A4** Transport to works site
  - **A5** Construction process

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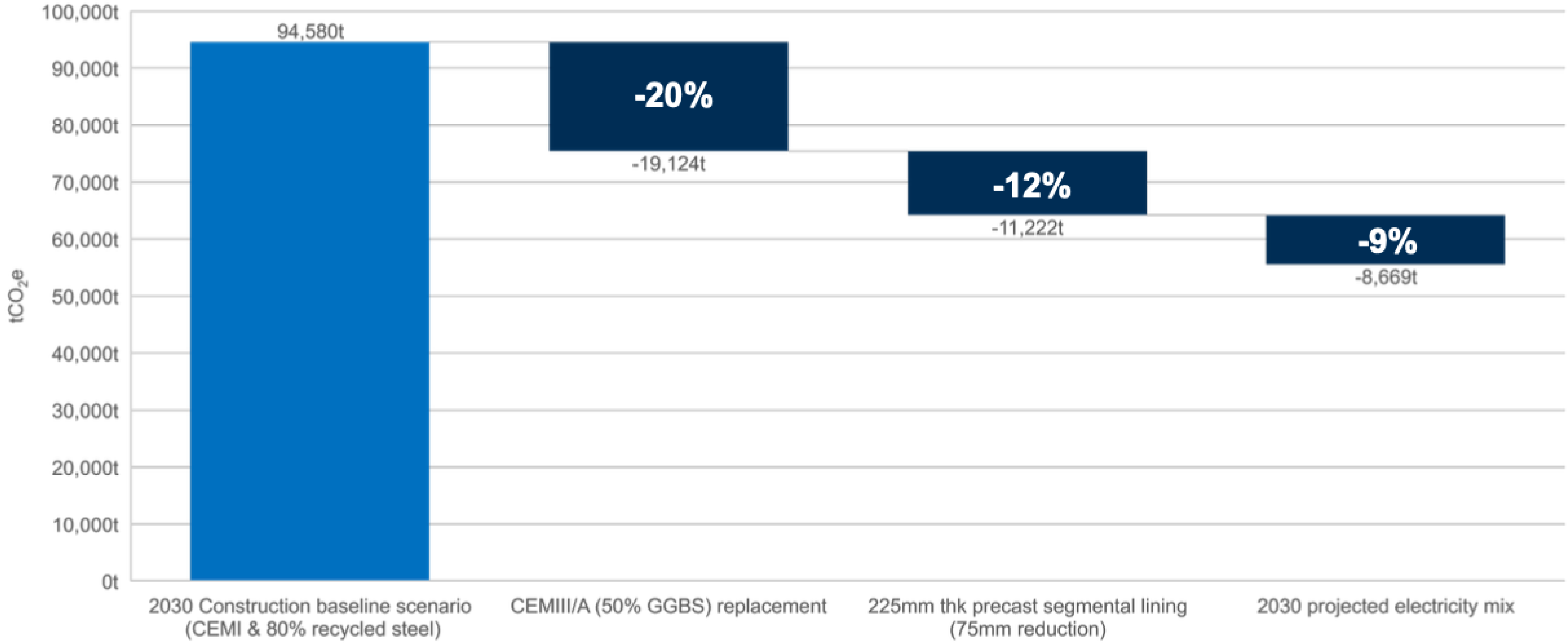
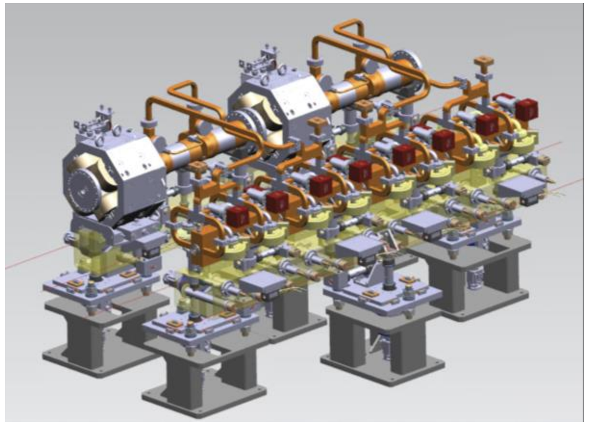
A1-A5 Tunnels GWP (tCO_2e)



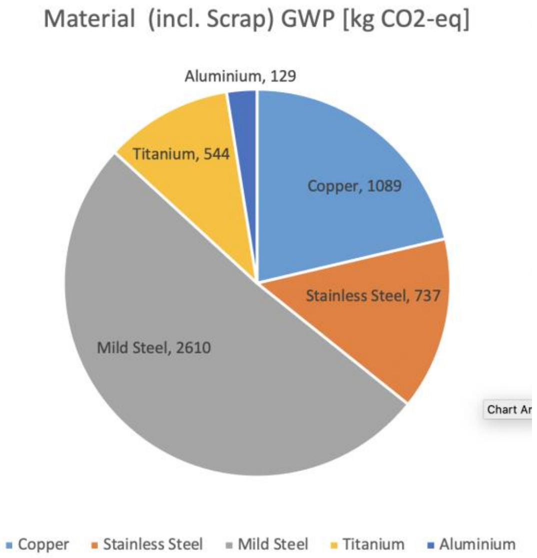
Looking at the impact of the accelerator components

- Study to estimate the Green House Gas emissions from raw materials in CLIC 2-beam module, including waveguides and supports
- ~2.5t CO2-eq / m:
  -> about half of CO2 for tunnel
- Half of CO2 impact is steel for supports
  -> optimization potential
- Services (power, cabling, cooling, ventilation) not included
- Situation in magnet-heavy sections (e.g. turn-arounds, bends, damping rings) may be different

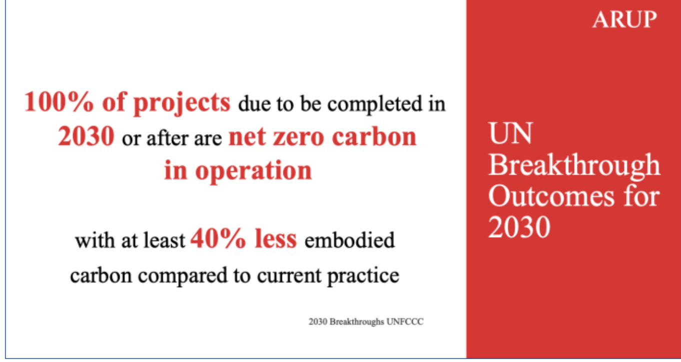


CO2 impact of accelerator components is comparable to CO2 of main tunnel – to be studies but easily 5 kton/km

Note: Careful with material processed away, recycled or not ?



Wrap-up



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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

2030 Breakthroughs UNFCCC

UN Breakthrough Outcomes for 2030

A1-A5: Tunnel construction (ILC and CLIC DB dimensions) is around 6kton/km

- Add shafts, caverns , access tunnels, DR, etc + from 30 to 60%
- Add transports, power used in construction, etc + 25%

= > ILC (20km) around 270 kton, CLIC (11 km) around 125 kton

Possible savings (but at a cost to be defined) of ~40%
Adding accelerator components and injectors more consistently (possibly 50% increase – very early days)

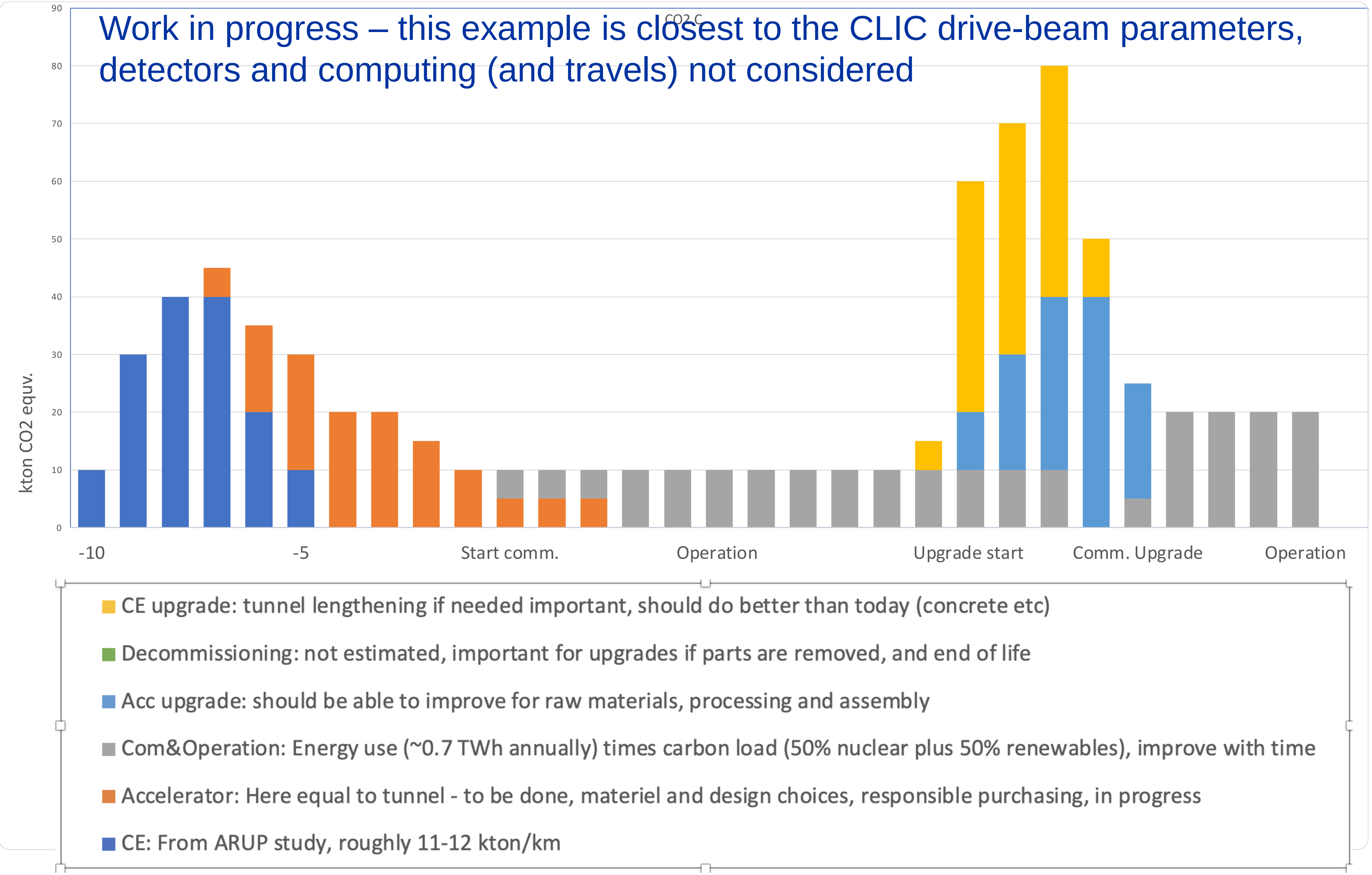
Operation (in ~2050)
Nuclear 5g/kWh and re-newables (sun/wind/hydro) 20g/kWh – suitable for Europe, what is suitable as goal for Japan ?
Can be higher with poor energy mix, can be lower with good contracting (good mix)
Assume 50/50 mix => Energy use estimated for LCs 0.6-0.8 TWh annually, i.e. around 10 kton CO2

France in summer months are at ~40 g/kWh, a factor three better towards 2050 within reach ?

In Japan this is much harder, contracting on low carbon energy an important tool
A green field site offers more flexibility for compensation (as in the green ILC approach)

Power nevertheless has huge cost impact, and secondary effects on CO2 (more material)

Towards Carbon Accounting with LCA



Work in progress – this example is closest to the CLIC drive-beam parameters, detectors and computing (and travels) not considered

- 🟨 CE upgrade: tunnel lengthening if needed important, should do better than today (concrete etc)
- 🟩 Decommissioning: not estimated, important for upgrades if parts are removed, and end of life
- 🟦 Acc upgrade: should be able to improve for raw materials, processing and assembly
- ⬜ Com&Operation: Energy use (~0.7 TWh annually) times carbon load (50% nuclear plus 50% renewables), improve with time
- 🟧 Accelerator: Here equal to tunnel - to be done, materiel and design choices, responsible purchasing, in progress
- 🟦 CE: From ARUP study, roughly 11-12 kton/km

Concluding:

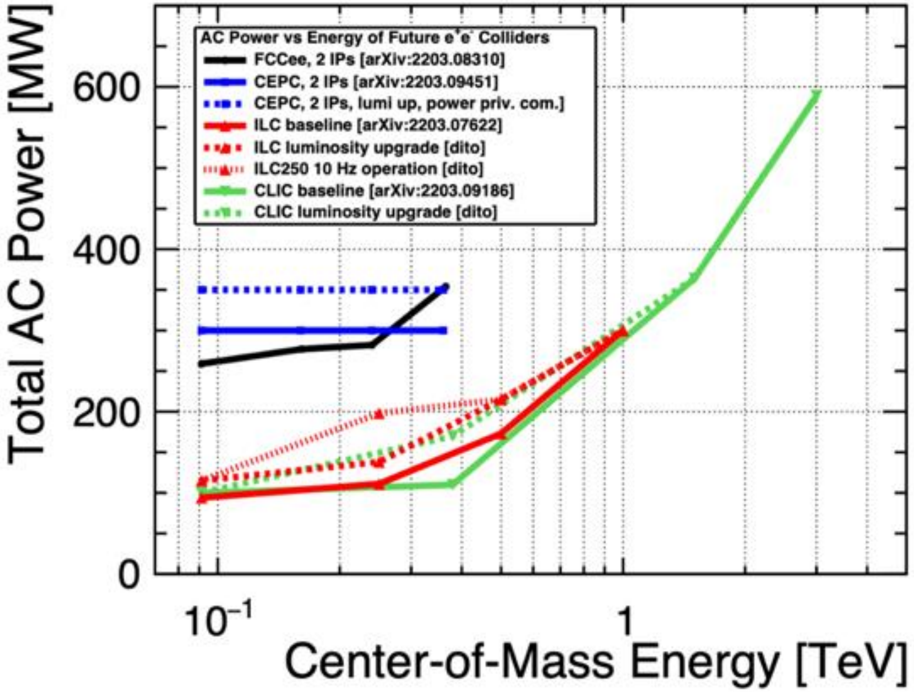
- Construction in the 2030'ies the most (time)critical carbon emission to address (A1-A5)

- LCA methodology is the way to go for sustainability studies, also for other parts (many missing) and other phases. Provides us with handles for optimisation.
  - Very good to see all the examples in this workshop of using or thinking about using this methodology

- Upgrades removing components and decommissioning likely other major CO2 sources
- All other factors to be considered, e.g. radiation, acidity, etc

Thanks:
CLIC and ILC teams
Benno List, Maxim Titov, Shin Michizono, Tomoyuki Sanuki, Nobuhiro Terunuma, Takayuki Saeki
John Osborne, Liam Bromiley and the entire ARUP team
Among them slides from Suzanne Evans ARUP talks at LCWS 2023 and yesterday
… many more

Power and energy

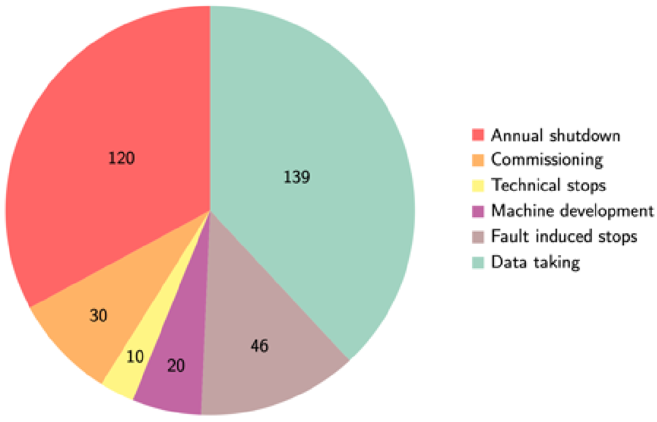


Power at 250-380 GeV in the 100-150 MW range for the projects above, reaching ~500 MW at 3 TeV for CLIC

With a running scenario on the right this corresponds to 0.6-0.8 TWh annually

CERN is currently consuming 1.2 – 1.3 TWh annually

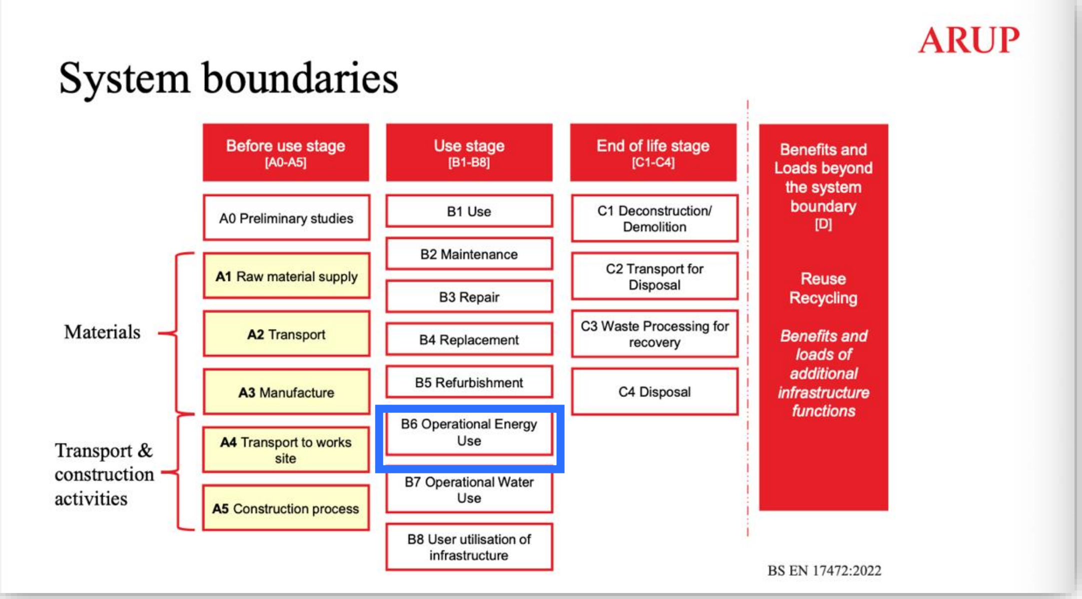
CERN “standard” running scenario used to convert to annual energy use



Includes studies of overall designs optimisation to reduce power, SRF cavities (grad,Q), cryo efficiency, RF power system (klystrons, modulators, components), RF to beam efficiencies, permanent magnets, operation when power is abundant, heat recovery, nanobeam and more.
Recent overview (LINK)

Sustainability: towards a Life Cycle Assessment (LCA) for LCs

LCA report for Civil Engineering: LINK



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System boundaries

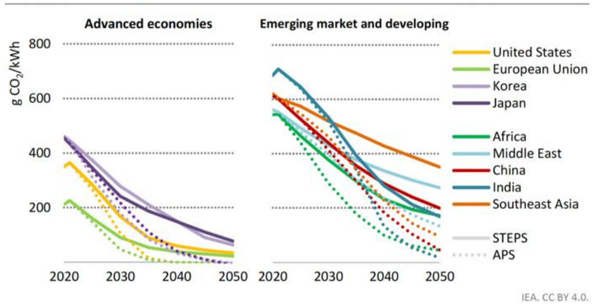
	Before use stage [A0-A5]	Use stage [B1-B8]	End of life stage [C1-C4]	Benefits and Loads beyond the system boundary [D]
	A0 Preliminary studies	B1 Use	C1 Deconstruction/ Demolition	Reuse Recycling
Materials	**A1** Raw material supply	B2 Maintenance	C2 Transport for Disposal	*Benefits and loads of additional infrastructure functions*
	A2 Transport	B3 Repair	C3 Waste Processing for recovery	
	A3 Manufacture	B4 Replacement	C4 Disposal	
		B5 Refurbishment		
Transport & construction activities	**A4** Transport to works site	B6 Operational Energy Use		
	A5 Construction process	B7 Operational Water Use		
		B8 User utilisation of infrastructure		

BS EN 17472:2022

What is the carbon intensity of energy in ~2050 (operation):

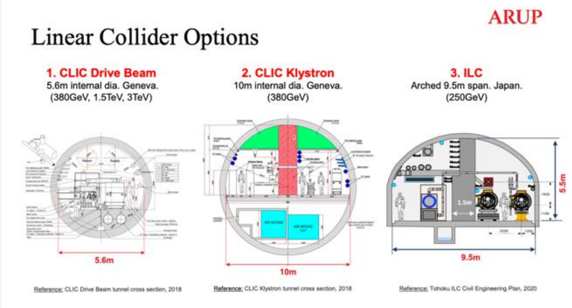
- 50% nuclear and 50% renewable give ~10-15g/kWh
- France summer-months are today ~40g/kWh
- ILC has a green implementation concept including compensation and contracting renewable energy
- Reductions predicted (LINK)

Figure 6.14 ▷ Average CO_2 intensity of electricity generation for selected regions by scenario, 2020-2050



IEA. CC BY 4.0.

CO_2 intensity of electricity generation varies widely today, but all regions see a decline in future years and many have declared net zero emissions ambitions by around 2050



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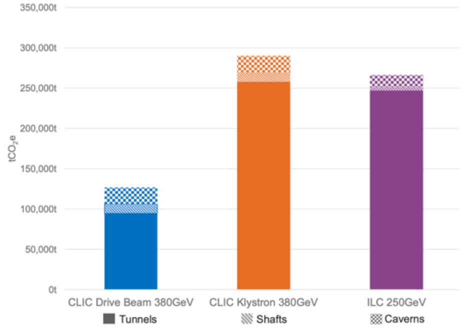
Linear Collider Options

Reference: CLIC Drive Beam tunnel cross section, 2018

Reference: CLIC Klystron tunnel cross section, 2018

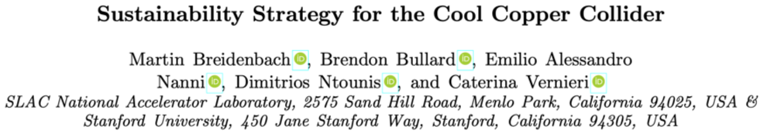
Reference: Tohoku ILC Civil Engineering Plan, 2020

A1-A5 GWP (tCO_2e)



Around 11-12 kton/km main linac (CLIC DB and ILC)

Recent C^3 paper using the LCA "methodology", also including considerations for other projects, is also well worth studying: LINK



Sustainability Strategy for the Cool Copper Collider

Martin Breidenbach, Brendon Bullard, Emilio Alessandro Nanni, Dimitrios Ntounis, and Caterina Vernieri

SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA & Stanford University, 450 Jane Stanford Way, Stanford, California 94305, USA