Sustainability Studies for ILC and CLIC

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Sustainability: What It Is…

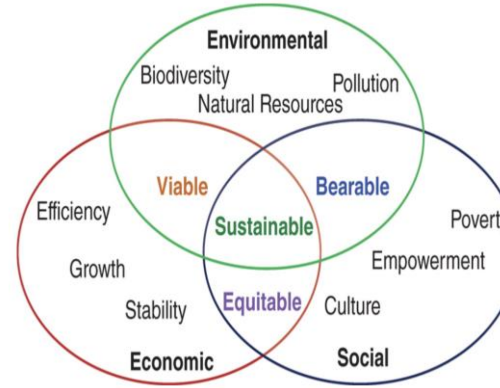
Cover of the "Brundtland Report" 1987

Gro Harlem Brundlandt at WEF 1989

*Development that meets the **needs of current generations without compromising the ability of future generations** to meet their needs and aspirations*. (WCED, 1987)

WCED (World Commission for Environment and Development) (1987) *Our Common Future*, Oxford University Press, Oxford.

https://sdgs.un.org



R.Y. Surampalli et al. (eds), Sustainability. Wiley 2020.

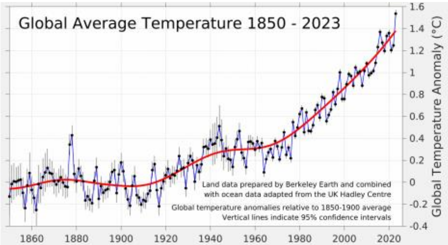
Three aspects:

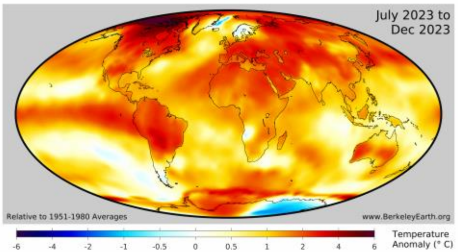
- environmental
- economical
- social

… and Why It Matters

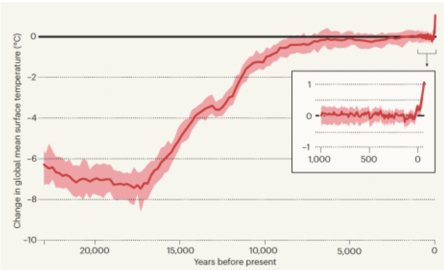
Climate is Warming

Faster than ever, leading to the highest temperatures in the last 125000 years





https://berkeleyearth.org/global-temperature-report-for-2023/



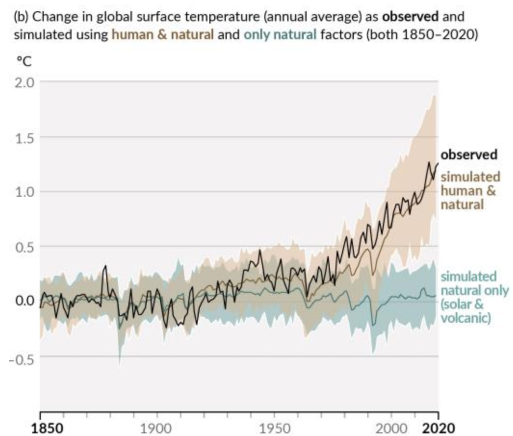
Nature **599**(2021)208.

Due to Anthropogenic Greenhouse Gas Emissions

In particular CO_2 and methane

*It is **unequivocal** that **human influence** has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.*

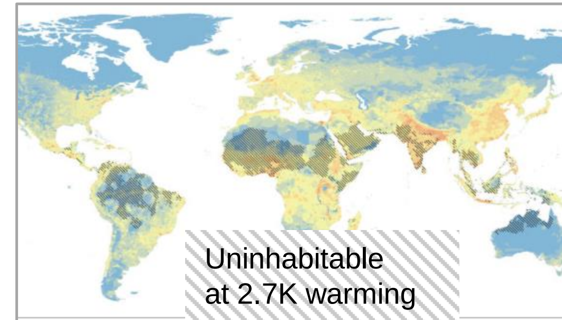
IPCC AR6

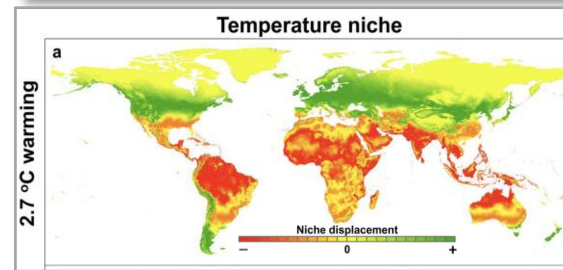


IPCC AR6 WG1 SPM, Fig SPM 1
https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM.pdf

With Negative Consequences

Making habitable regions uninhabitable, leading to famine, heat deaths and causing mass migration





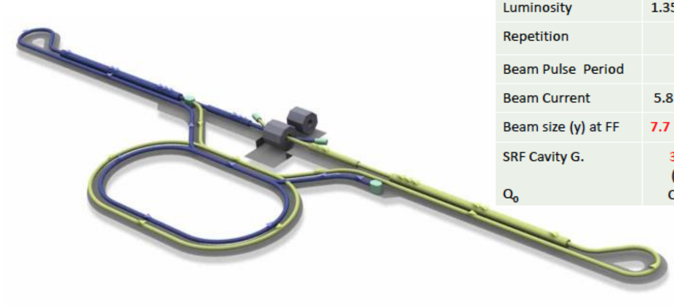
Nat. Sust. **6** (2023) 1237.

Extreme heat killing more than 100 people in Mexico hotter and much more likely due to climate change

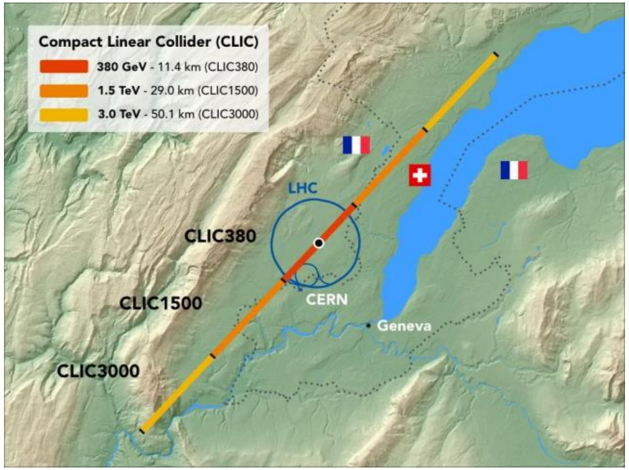
worldweatherattribution.org/

ILC and CLIC

Two e+e- linear collider designs, starting as a Higgs factory



Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} cm^{-2}s^{-1}
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10^{10}



International Linear Collider ILC

- Superconducting Cavities, 1.3GHz, 31.5MV/m
- 250GeV CME, upgradeable to 500, 1000 GeV
- L = 1.35E34 cm^{-2}s^{-1}
- 20km length, in Tohoku / Japan

Compact Linear Collider CLIC

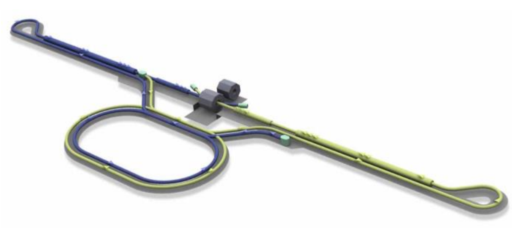
- NC Copper Cavities, 11.4GHz, 72MV/m
- Two-beam acceleration (or klystron driven initially)
- 380GeV CME, upgradeable to 1500, 3000 GeV
- L = 2.3E34 cm^{-2}s^{-1}
- 11.4km long, at CERN / France & Switzerland

Approaches to Improve Sustainability

- Accelerators for High Energy Physics are at the leading edge of technology: beam energy, intensity, luminosity…
- Ressource conservation is paramount:
- Sustainability adds new cost measures: e.g. CO_2, rare earth usage -> Lifecycle Assessment!

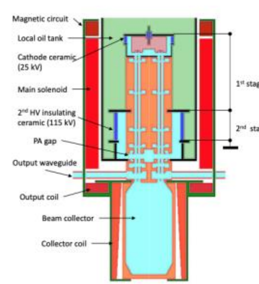
Overall System Design

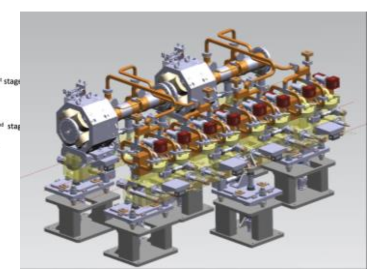
- Compact (short) accelerator -> high gradient
- Energy efficient -> low losses
- Effective -> small beam sizes



Subsystem and Component Optimisation

- High-efficiency cavities and klystrons
- Permanent magnets
- Heat-recovery in tunnel linings



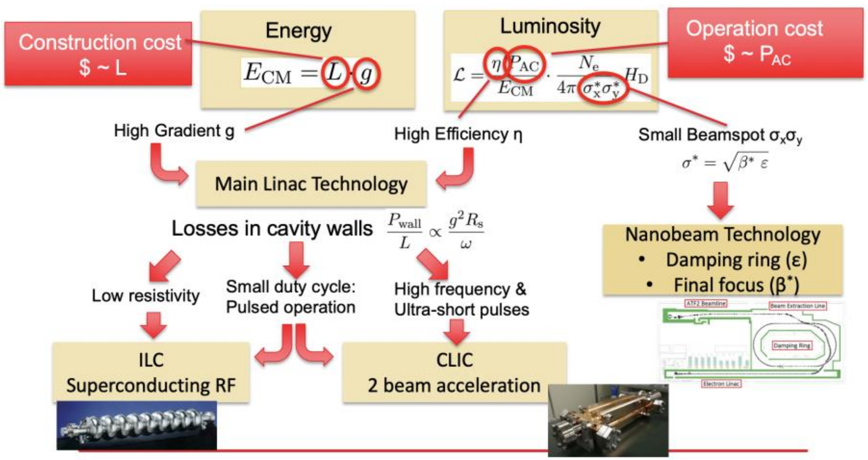


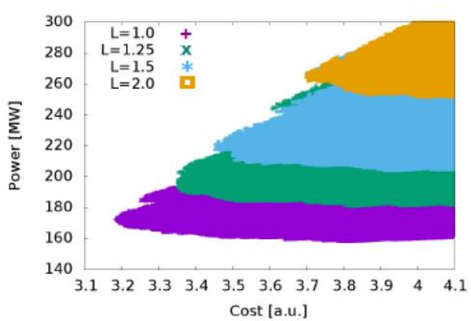
Operation

- Recycle energy (heat recovery)
- Adapt to regenerative power availability
- Exploit energy buffering potential

Overall System Design

BL: https://indico.cern.ch/event/981823/contributions/4328846/





Optimisation at CLIC: Parameter scan

- Challenge: Achieve target **energy** and **luminosity** with least possible amount of **resources**
- Conserve resources for construction:
  - compact -> high acceleration gradient
- Conserve ressources in operation:
  - Energy-efficiency (limit losses in cavity walls): superconducting RF – ILC
    high frequency & ultra-short pulses: CLIC
  - Effectiveness: maximum luminosity per charge -> nanobeam technology
- ILC and CLIC:
  - different solutions to the efficiency problem
  - Final power consumption similar

Inherent tension between invest and operation requires a quantitative approach:

Lifecycle Assessment

Optimisation of Components and Subsystems

Win-Win:

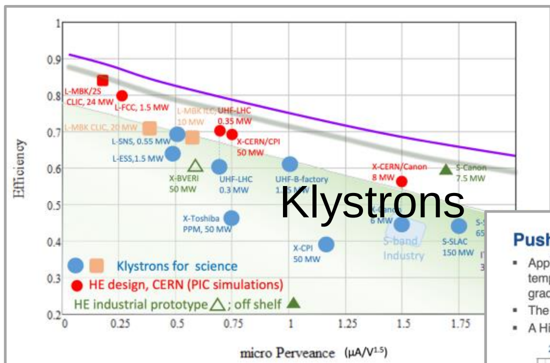
Better performance through better technology at same or lower cost

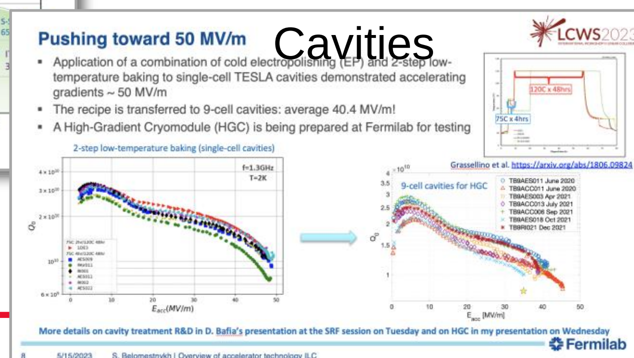
- High efficiency klystrons through better electron optics
  → pushing to 85% efficiency
- Cavities with higher gradient and lower losses
  → pushing for >45MV/m (ILC baseline: 35MV/m)

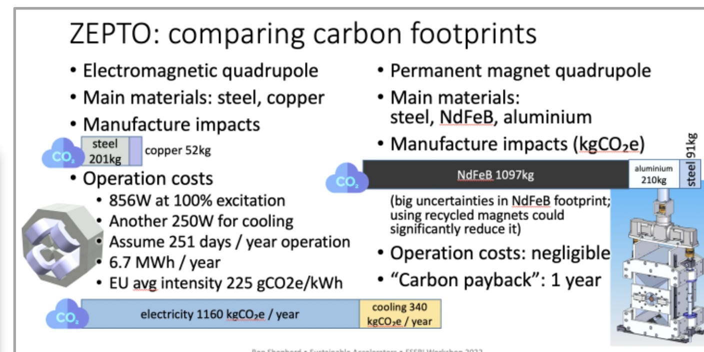
Trade-off:

Difficult: lower operating cost through higher invest / higher initial impact:
needs trade off studies → LCA

- Example permanent magnets:
  - Save CO2 from electricity during operation
  - Materials used in production, esp. rare earths, have high impact
  - ZEPTO (Zero Power Tuneable Optics) project is a collaboration between CERN and STFC Daresbury Laboratory, made an analysis:
    in case considered, production CO2 is amortized in 1 year





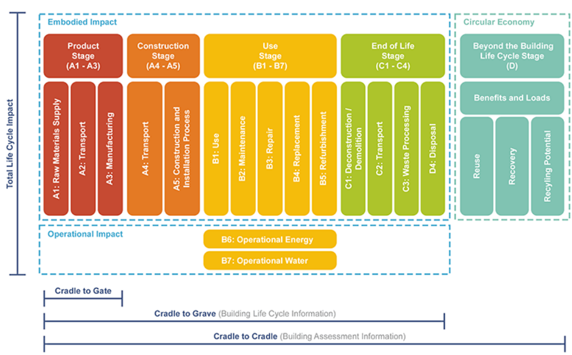


B. Shepherd, LCWS 2023

Lifecycle Thinking and Lifecycle Assessment (LCA)

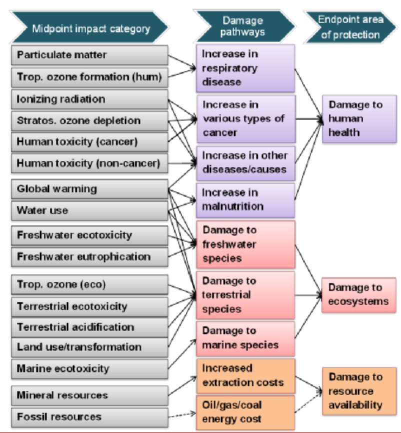
- Consider the **whole lifecycle** and its impact
- Avoid **burden shifting**, i.e. moving problems elsewhere: consider diverse impact categories
- Lifecycle Assessment (LCA)
  - Standardized approach to evaluate impact
  - Quantifying total damage by **endpoint** indicators difficult
  - ”**Midpoint** indicators” asses impact on environment in a quantitative way
- **Measure** in order to **improve:**
  - **Identify hot spots**
  - **Evaluate and choose alternatives**

https://www.nist.gov/el/systems-integration-division-73400/lifecycle-graphic

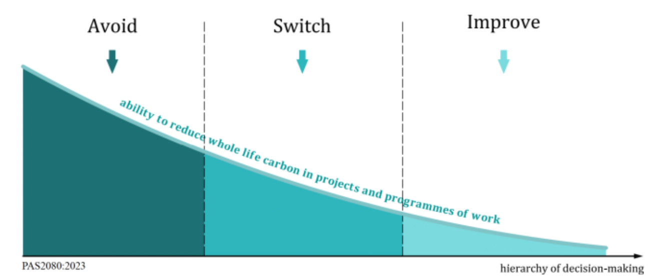


Lifecycle stages according to EN 15978

https://browningday.com/news/lca-stages-matter-when-tracking-embodied-carbon/
https://www.buildingenclosureonline.com/blogs/14-the-be-blog/post/89547-lca-stages-matter-when-tracking-embodied-carbon

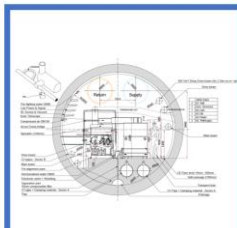


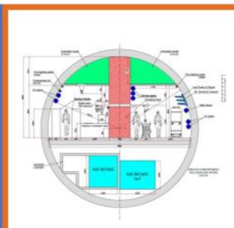
M.A.J. Huijbregts et al., Int. J. Life CycleAss. **22** (2017) 138, DOI:10.1007/s11367-016-1246-y

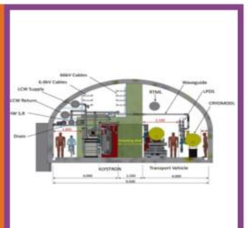


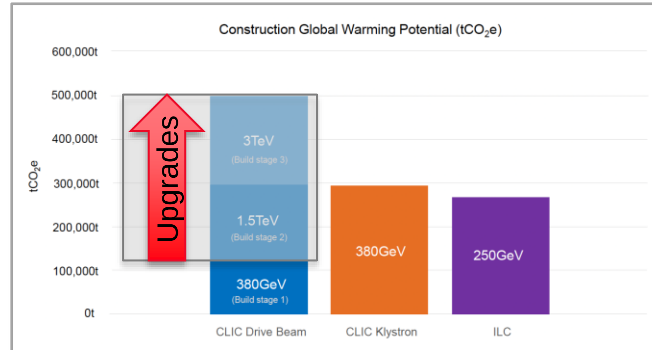
LCA of Civil Engineering Infrastructure

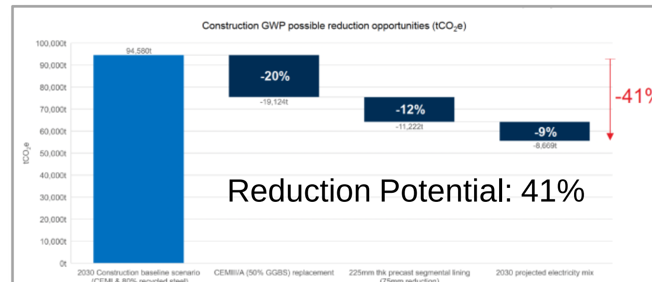
- LCA study of tunnels, shafts and caverns:
  - Common study for ILC and CLIC (link)
  - Professional consultant company: ARUP
  - Include two design alternatives for CLIC: Two-beam acceleration or klystron driven
- Results:
  - CLIC 2-beam design: 127 kton CO2-e
  - CLIC klystron: 290 kton CO2-e
  - ILC (250GeV CoM): 266 kton CO2-e
- LCA helps to compare design alternatives
- LCA identifies reduction potential:
  - 20% from using low carbon cement (CEM III/A)
  - 12% from thinner lining
  - (9% from future electricity mix -> not a project decision)

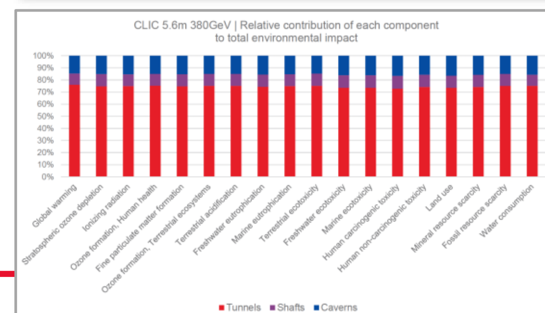

CLIC Drive beam, 5.6m dia.


CLIC Klystron, 10m dia.


ILC, 9.5m span





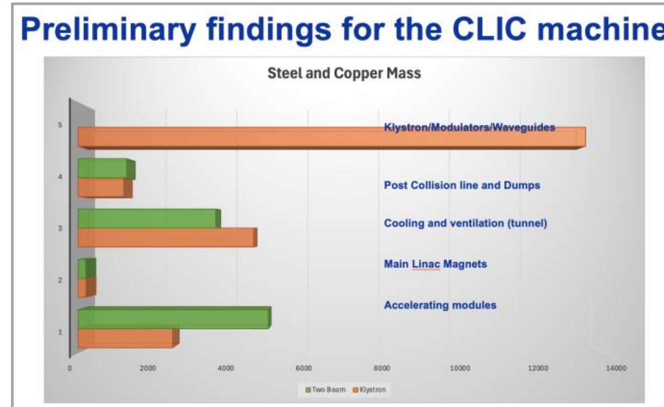


Further Impact categories

Full study: https://edms.cern.ch/document/2917948/1

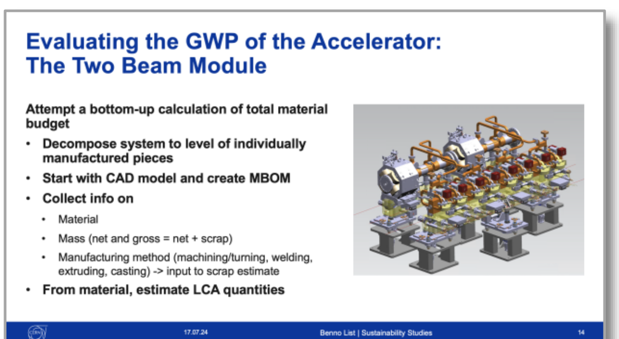
LCA of Accelerator

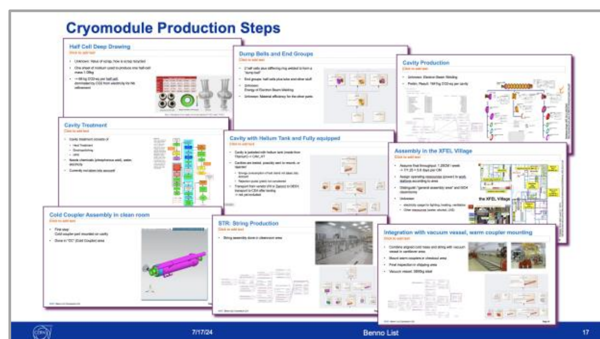
- LCA of accelerator and detectors much more demanding than civil infrastructure:
  - Many different components
  - Many materials, also unusual materials
- ILC and CLIC started LCA effort with ARUP
- Study still ongoing,
  looking on detail on Main Linac building blocks:
  - ILC Cryomodule
  - CLIC two beam module
- Main Linac components add several tons of CO_2 per meter compared to Main Linac tunnels at 6-7 tons/m



Comparison of CLIC Main Linac
for 2-beam and klystron options

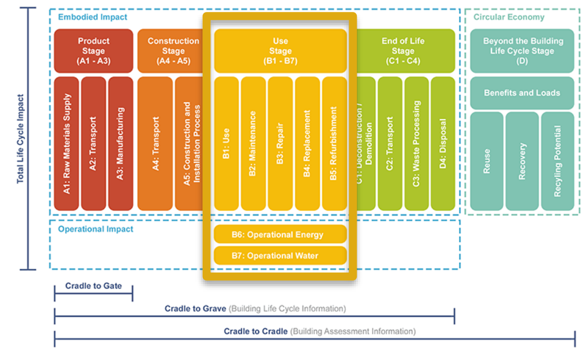
S. Doebert, LCWS 2024

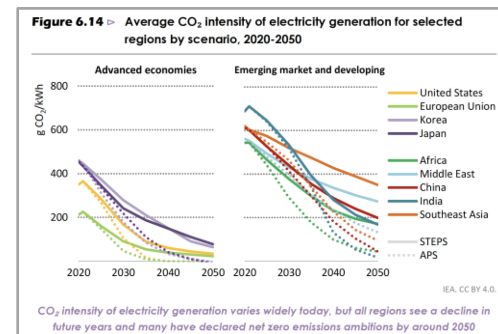




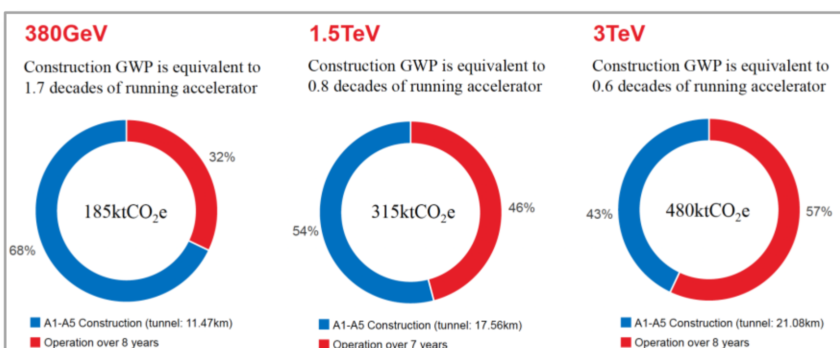
Operation

- Operation stage very important:
  Large CO2 emissions from electricity production
- Impact assessment depends on assumptions of future (reduction of) carbon intensity of electricity
  → common numbers would be helpful
- CLIC study indicates that 6 – 17 year of electricity cause as much CO2 as all tunnels/shafts/caverns
  - even at very low carbon intensity in France
- CLIC study in 2020 about running only on renewables (link):
  Energy can be provided, fluctuations require grid as buffer
  → **modulate operation (demand side flexibility)**
  → rapidly falling battery prices change the field,
  GWh size storage will be possible in 2030

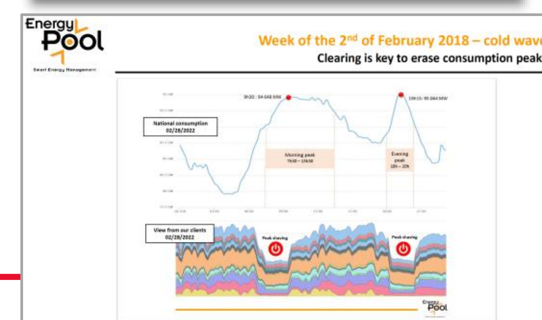




IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, CC BY NC SA 4.0



Evans, LCWS 2024

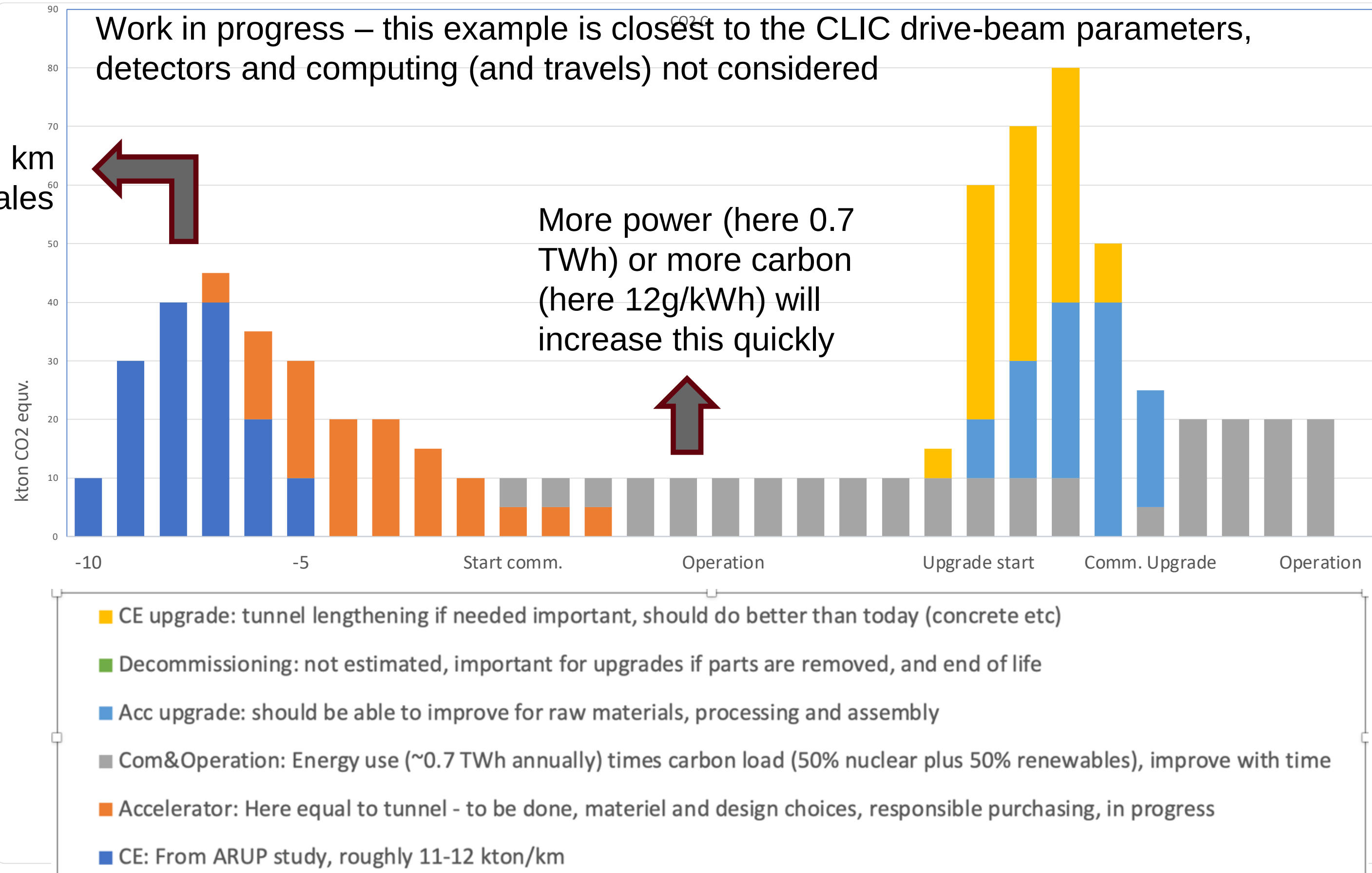


C. Gaunand, B. Remenyi: ESSRI 2022

Greenhouse Gas Emissions over the Full Lifecycle

Towards Carbon Accounting with LCA

This is for 11 km of tunnel, scales with length



Some brief conclusions

Accelerators are generally optimised for physics performance, costs, schedule and power consumption

Sustainability goals suggest the lifecycle approach, addressing for example carbon footprint and material use from construction to decommission, and integration in the local communities (water, landscaping, traffic, waste, etc)

- Changes the optimisation and also provides new opportunities

A recipe for a sustainable facility:

- Reduce size
- Reduce power consumption, understand/selects all materials being used carefully
- Integrate within local communities
- Use low carbon and renewable power, CO2 compensate
- Use the facility for a long time and understand its life cycle

Thank you

Many thanks to
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