The CERN LDG Sustainability Panel

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Sustainable HEP – 5th edition

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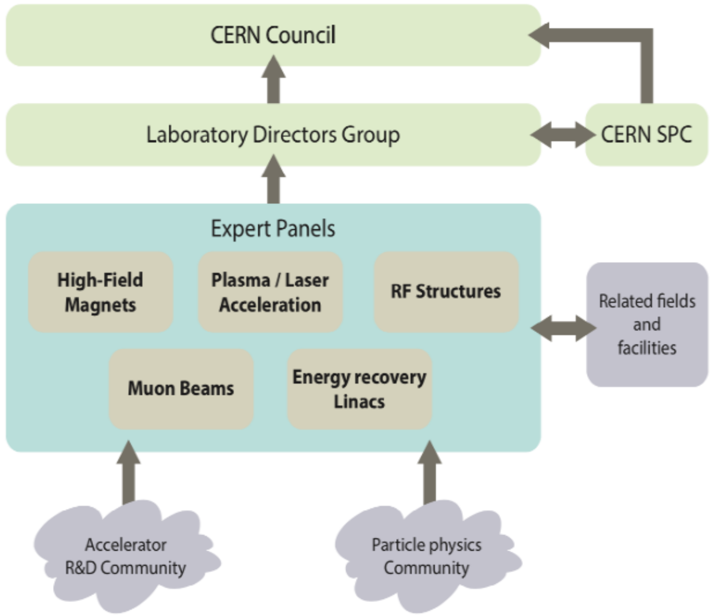
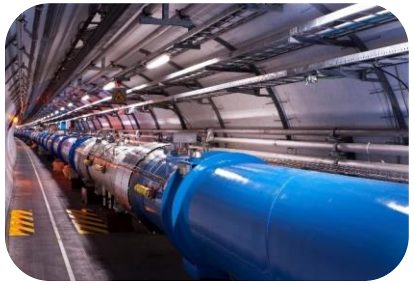
Overview

- Role of CERN’s Lab Directors’ Group: LDG
- LDG Sustainability Panel: building a green strategy
- Sustainability considerations for accelerators
  - Maximising positive benefits
  - Lifecycle Assessment: LCA
  - Impacts of future big facilities
- Next steps

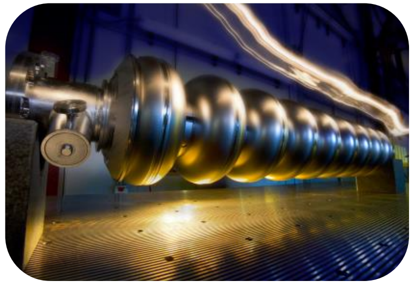
Introduction



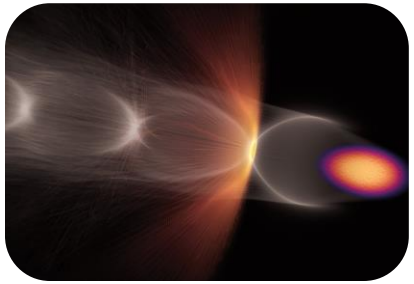
- CERN Lab Directors Group (LDG)
- Formed in 2021
- Reporting to CERN Council
- Originally five working groups



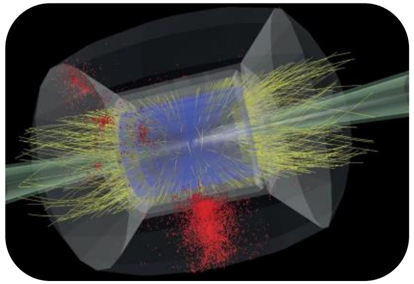
High-field magnets



RF structures



Novel acceleration



Muon colliders

Energy recovery linacs

- Sustainability WG added in January 2024

Motivation

- Accelerator-based research infrastructures
  - Big and getting bigger
  - Act as discovery and precision engines
  - Many other societal benefits
  - Significant environmental impacts
- Governments have adopted net zero targets
- Public demand for clean infrastructure
- Critical to assess and reduce our environmental impacts
- European Strategy on Particle Physics 2024:
  - Recommendation to implement a sustainability strategy

LDG Sustainability Working Group

- Mandate:
  to develop ***guidelines*** *and a minimum set of* ***key indicators*** *for the* ***sustainability assessment*** *of* ***future accelerators***
- Representatives from multiple accelerator labs:
  - CERN, DESY, STFC, NIKHEF, URFU
- Experts from future collider projects:
  - FCC, CEPC, ILC, CLIC, Muon Collider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Co-chairs

Input to Strategy Update

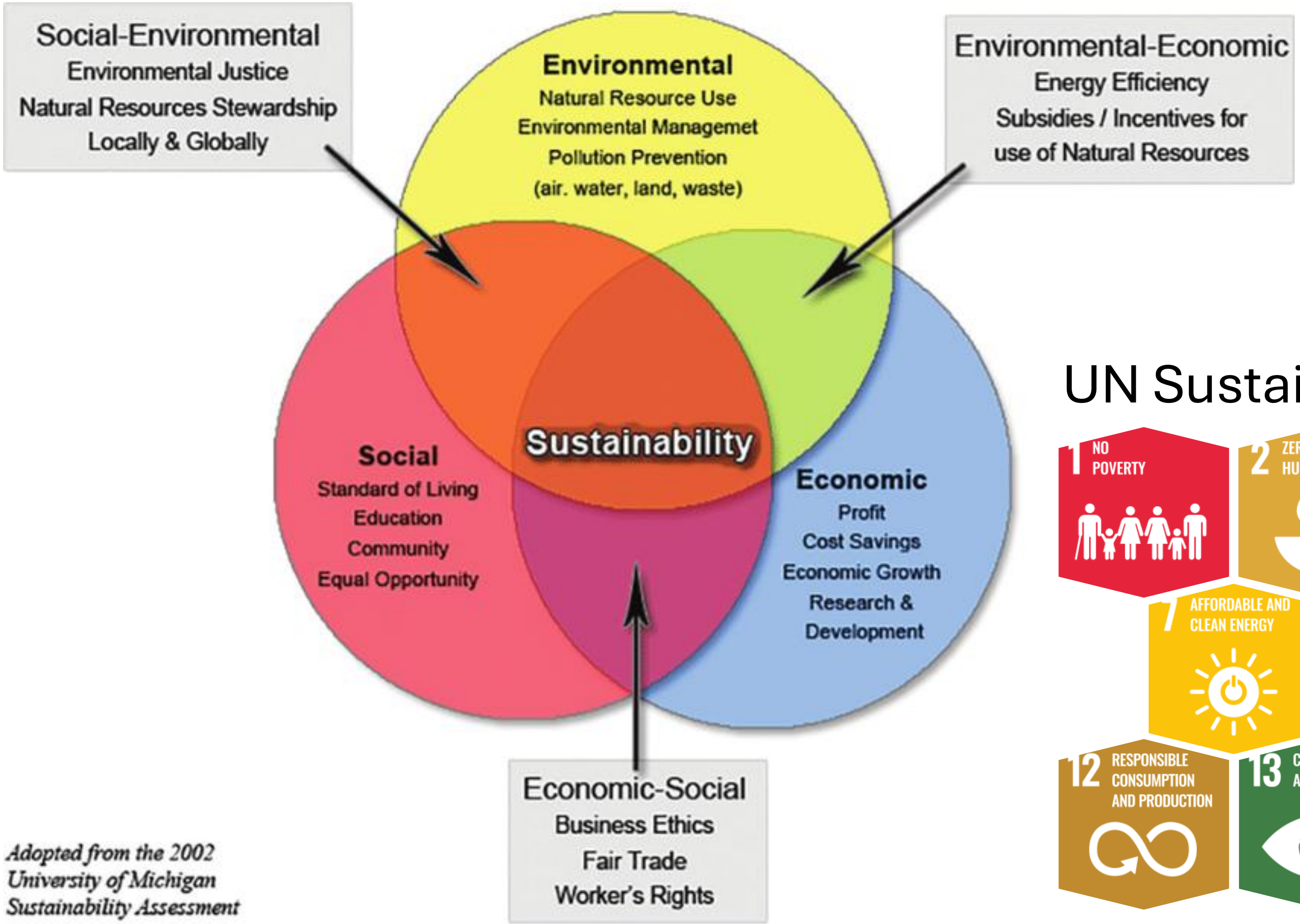
- European Strategy for Particle Physics 2025 Update (ESPPU)
- Sustainability considerations included for first time
- Significant contributions from LDG Sustainability WG

> *For new proposed projects, a detailed life cycle assessment should be carried out at each stage, from concept to design and implementation, in order to quantify and minimise environmental impact.*
>
> *The particle physics community should continue and intensify its efforts to develop and adopt sustainable solutions.*
>
> *An effective balance between in-person and online meetings should be considered in order to mitigate the environmental impact of carbon-intensive travel.*

Sustainability Assessment of Future Accelerators

- Report published September 2025, revised March 2026
- Access via arXiV: https://arxiv.org/abs/2509.11705v2

Three Pillars of Sustainability



Adopted from the 2002 University of Michigan Sustainability Assessment

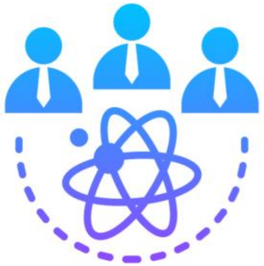
UN Sustainable Development Goals (SDGs)

Positive Externalities

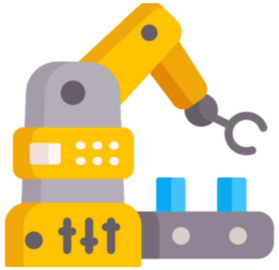
- Accelerator facilities have positive benefits

Fundamental physics knowledge

Education and training

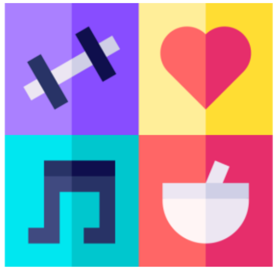


Engagement of international science communities



Industrial spillover

Open information and computing technologies



Cultural goods

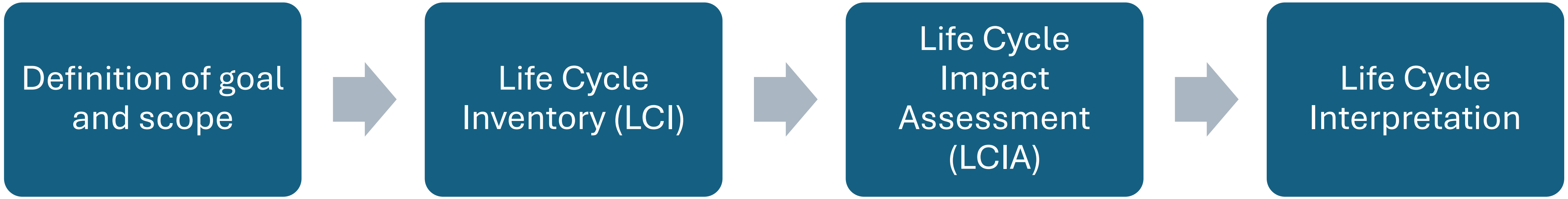
Environmental benefits

Innovation and R&D

International collaboration

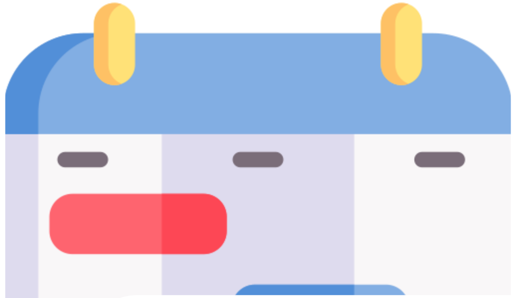
Lifecycle Analysis (LCA)

- Tool for identifying and quantifying **greenhouse gas emissions** (and other environmental impacts)
- Four stages



LCA Goals

- Motivation and goals are phase-dependent

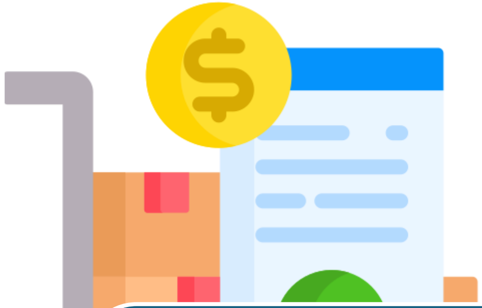


Planning

- Comparison of alternatives
- Biggest impact

Engineering

- Detailed decision-making
- Compliance

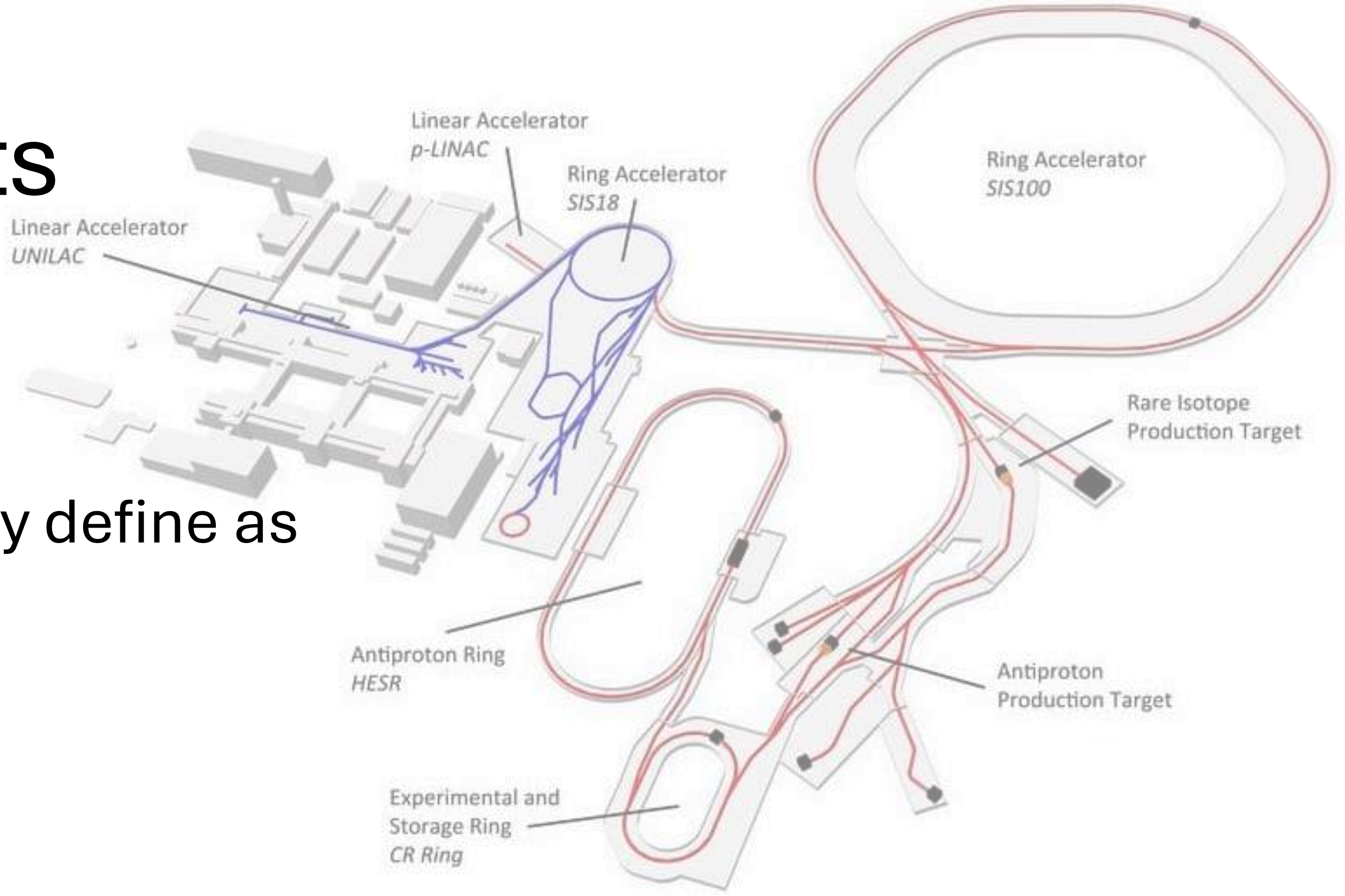


Procurement

- Supplier selection
- Demonstrate value for money

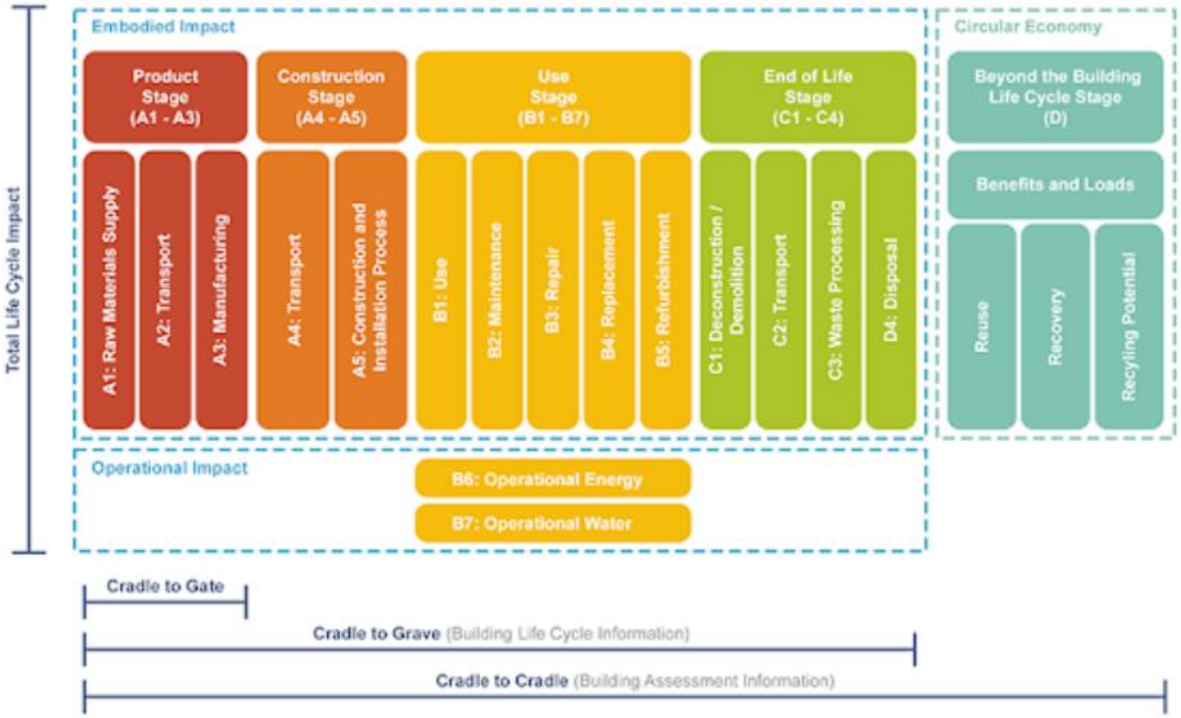
LCA Functional Units

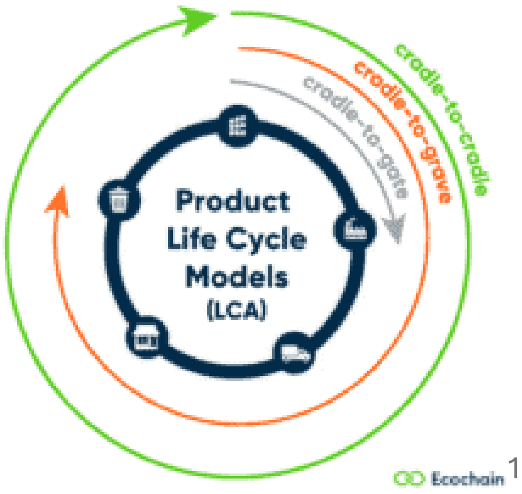
- For commercial LCAs, **functional unit** is usually the ‘thing’ being manufactured: car, fridge, pair of jeans, …
- For an accelerator project, usually define as
  - Beam delivery system
  - Detectors
  - All supporting infrastructure
- Need consistent definition to compare project proposals
- Specify
  - Which systems – and how to treat existing systems
  - Which programme phases – first run, upgrades, decommissioning?
  - Breadth of supporting infrastructure: buildings, cryoplants, data centres, roads



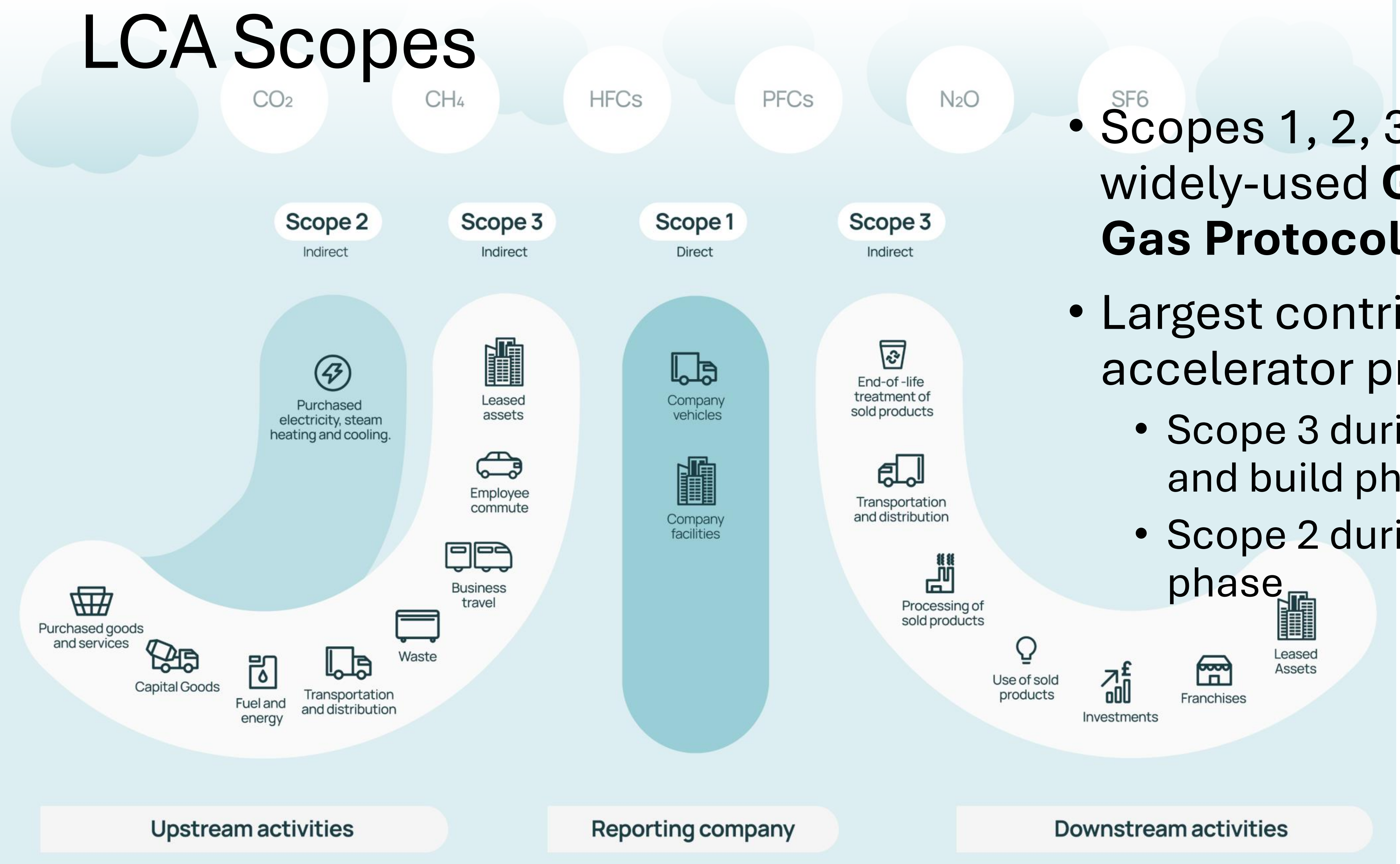
LCA System Boundaries

- Define system boundaries in relation to **lifecycle model**
- EN 15978 (for example) defines LCM of building projects
  - Product stage: raw materials production
  - Construction stage: transport and installation
  - Usage stage
  - End of life
- Options for analysis boundaries:
  - **Cradle-to-grave**: full life including operation and demolition
  - **Cradle-to-gate**: raw material and component production
  - **Cradle-to-cradle**: recycling materials into the same use
- The final stage often poses issues:
  - Infrastructure is often reused for subsequent projects (see PS, LEP etc)





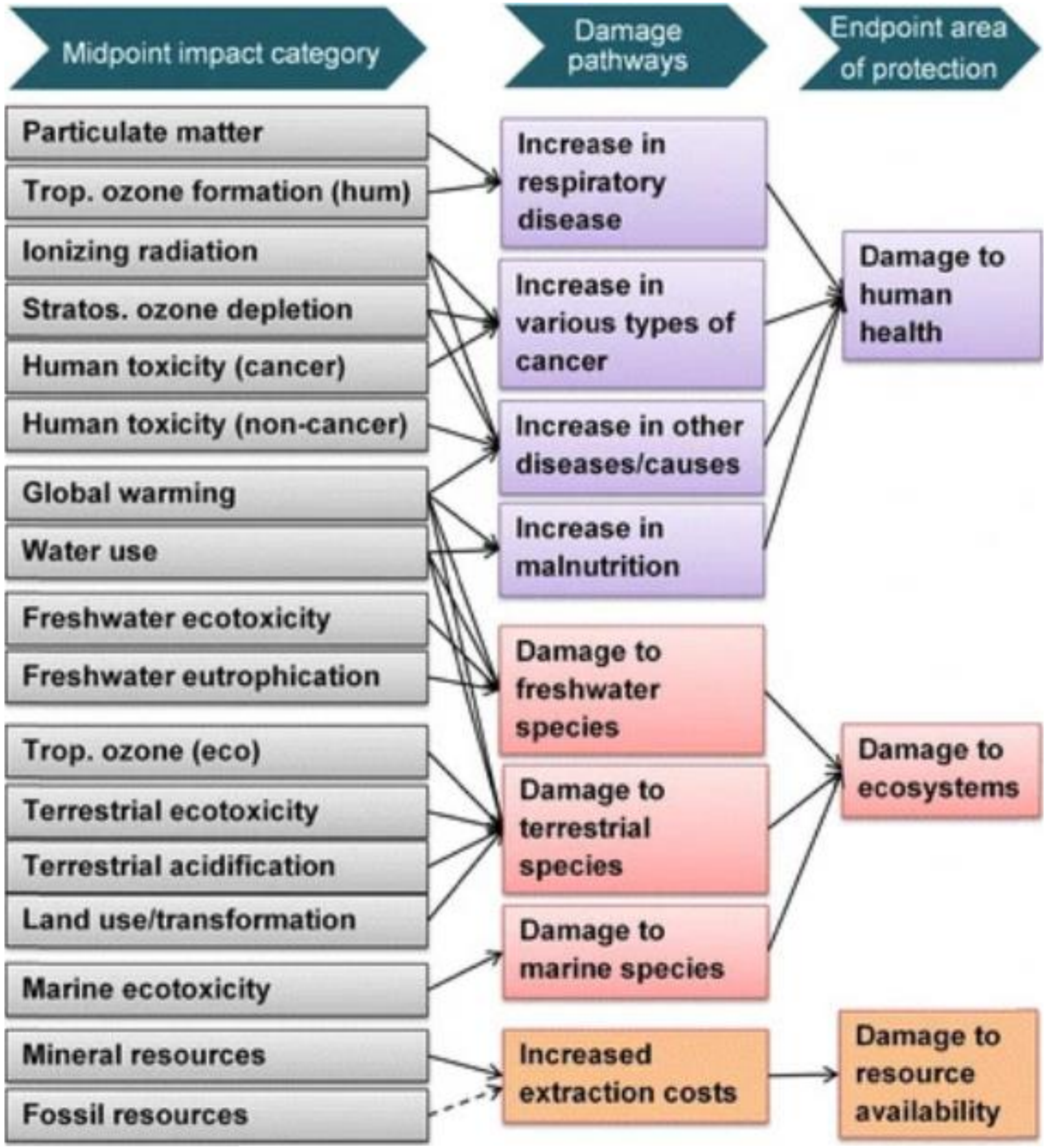
LCA Scopes



- Scopes 1, 2, 3 defined in widely-used **Greenhouse Gas Protocol**
- Largest contributors for accelerator projects:
  - Scope 3 during manufacture and build phase
  - Scope 2 during operation phase

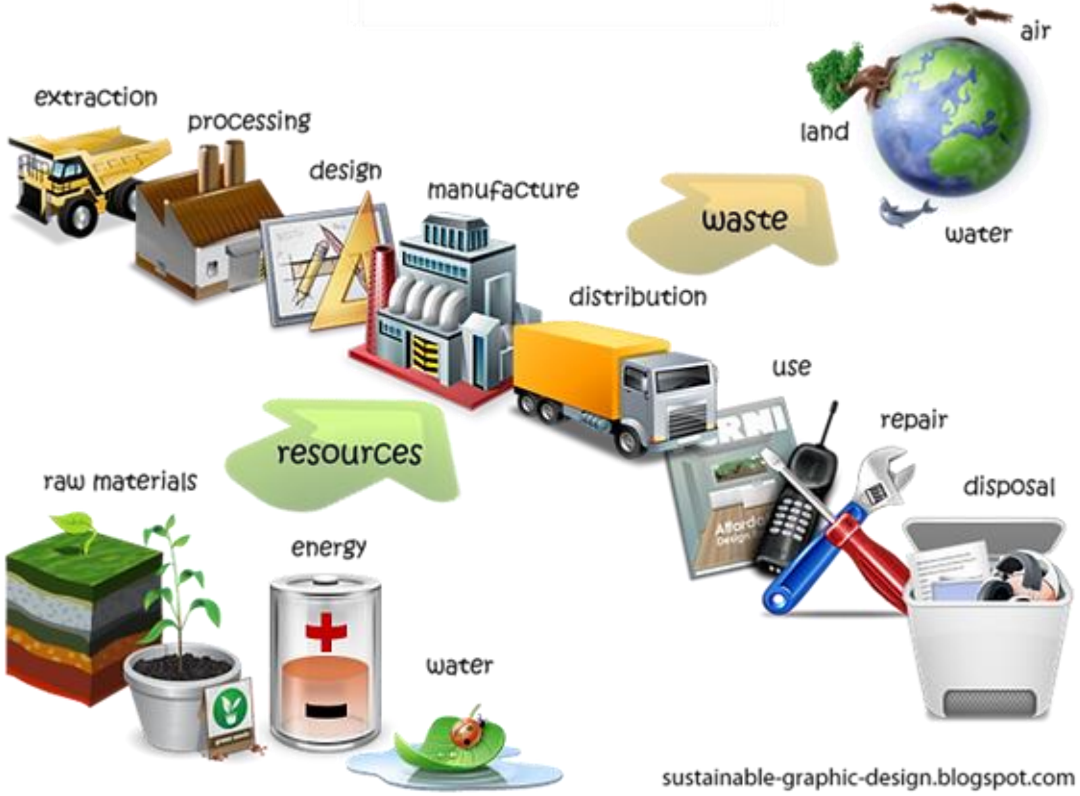
LCA Impact Categories

- Quantifying impact
- Many different pathways of environmental impact
- Midpoint categories: direct effects
  - **Global warming potential** (GWP) most frequently-cited
  - Ozone layer depletion
  - Eutrophication (nutrient over-enrichment)
  - Land use change
  - …
- Endpoint categories
  - Calculated by weighting midpoint impacts
  - Broader grouping: impact on human health, ecosystems, resources



***ReCiPe 2016**: most common LCA metric*

LCA Inventory and Assessment



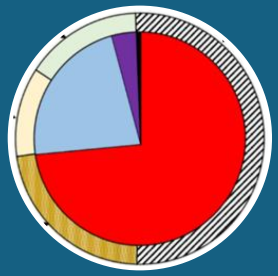
- Life Cycle Inventory: model flow of **materials** and **products** contributing to the **functional unit** during its lifecycle
- Published LCA databases contain impact data for these materials
  - e.g. ecoinvent (PSI) and GLAD
- Life Cycle Assessment: use data to calculate overall impact
- Commercial and open-source software tools are available
  - e.g. SimaPro, OpenLCA, One Click LCA
- Key issue for accelerators: we use 'unusual' materials without a large amount of available data
  - e.g. niobium for accelerator cavities, NdFeB for magnets

LCA Interpretation

- Performed throughout LCA process (not just at end) with the aim of guiding focus and improving accuracy of results

Sensitivity analysis

- Impact of choices



Hotspot analysis

- Dominant materials or processes

Contribution analysis

- Phasing of impact categories

Benchmarking

- Compare to other analyses

Uncertainty evaluation

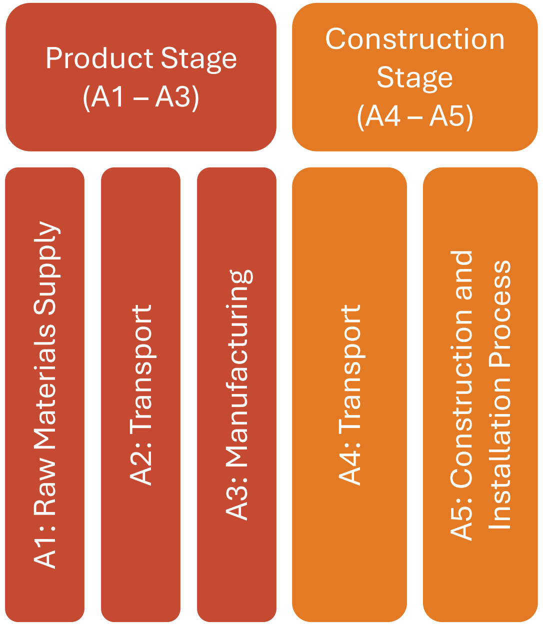
- Result accuracy

Accelerator Lifecycle Assessment: our recommendations

- Perform LCAs throughout design stages
- Use LCAs to reduce impact
- Use common methods
- Investigate widely-used components
- Publish reference data on materials

Impact assessment of accelerators

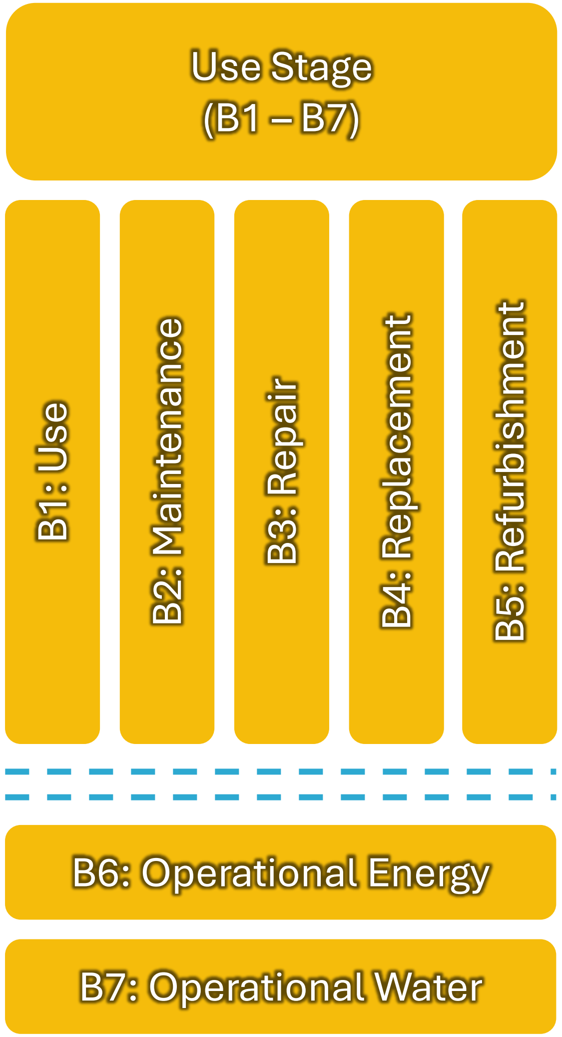
Construction phase



- Define consistent Product Breakdown Structure (PBS)
  - Civil engineering infrastructure
  - Raw material supply
  - Transport to and from factories
  - Manufacturing processes
  - Amounts of scrap produced
  - Assembly of components on site
  - Construction and installation
- Carry out LCA process **early** in the design phase
  - Results will be less accurate
  - More opportunity for improvements
  - Embed sustainability concerns into design mindset

Project phase	LCA detail level	Scope for mitigation
Definition	Low	High
Conceptual design	Medium	High
Technical design	Medium	Medium
Authorisation process	High	Low

Machine operation phase

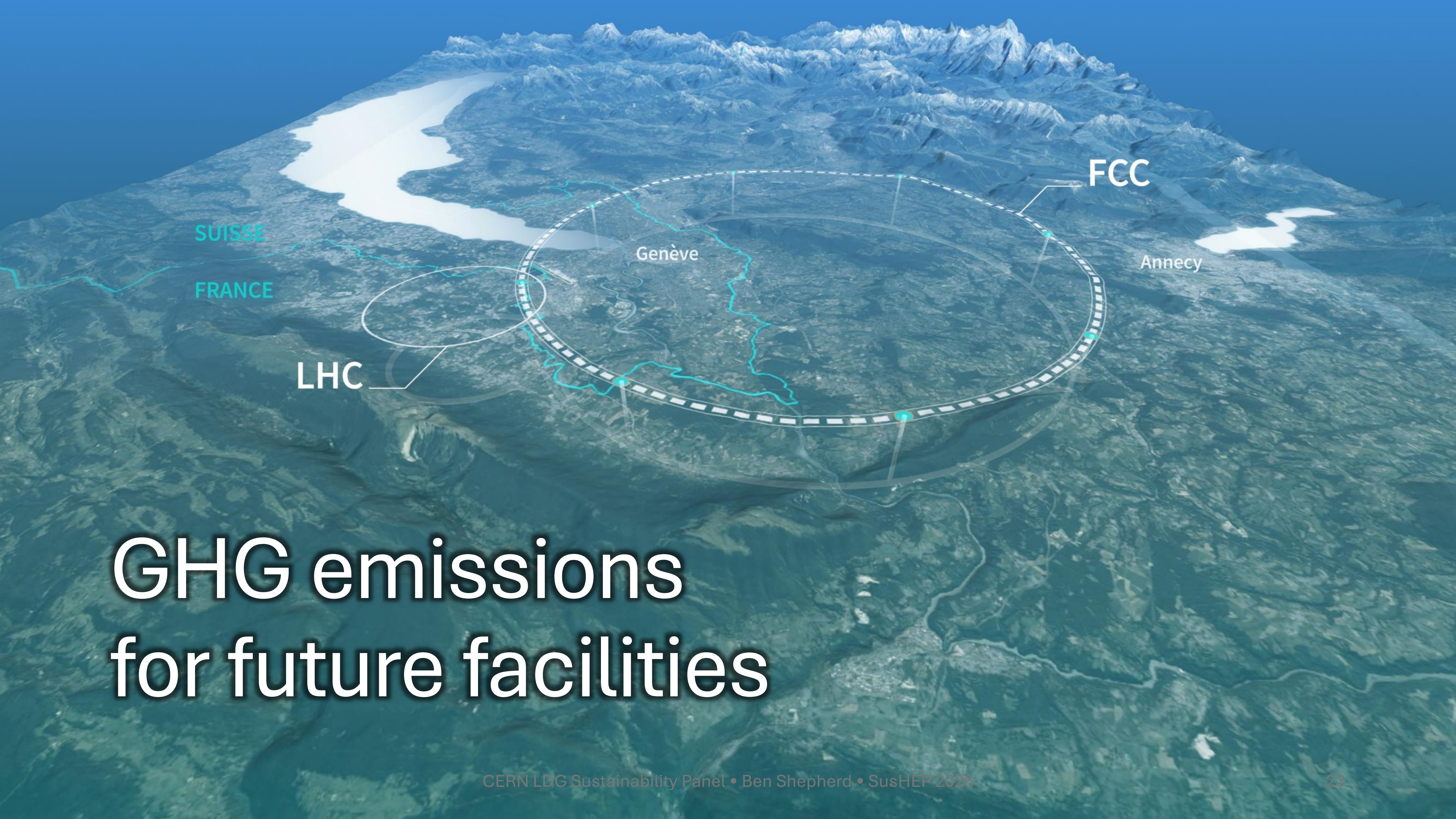


- Beamlines
  - Energy use is likely biggest contributor
- Particle detectors
  - Direct emissions of gases
- Data centres
  - Energy and water use

- Representative annual figures:
  - 3 MW running power, 0.3 MW standby
  - 250 operating days
  - 19 GWh per year
  - 1-11 ktCO_2e, location dependent
  - Likely equivalent to construction emissions after 1-2 years' operation
- Biggest subsystems:
  - AC, water cooling
  - RF
  - Magnets

Decommissioning phase

- Accelerators often outlive original planned lifespan
- Components often ‘recycled’ into successor facilities
  - PS @ CERN (1959) → still part of LHC
  - HERA @ DESY → ALPS-II uses original dipoles
- Disposal complicated by activated materials
  - Usually ‘very low level’
  - Beam dumps, targets can reach medium levels
  - Activation level depends on beam type, history, material
  - Legalities vary by jurisdiction

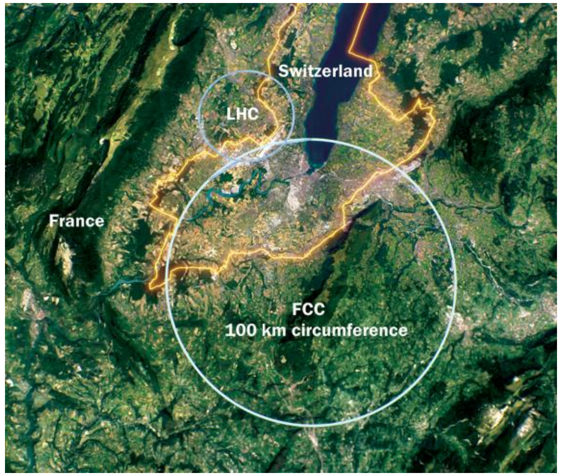


GHG emissions for future facilities

Future Circular Collider: FCC-ee

Most mature LCA

- Proposed 90km staged circular collider: 91 GeV for Z bosons up to 365 GeV for $t\bar{t}$ collisions
- LHC pre-accelerator complex as hadron injector

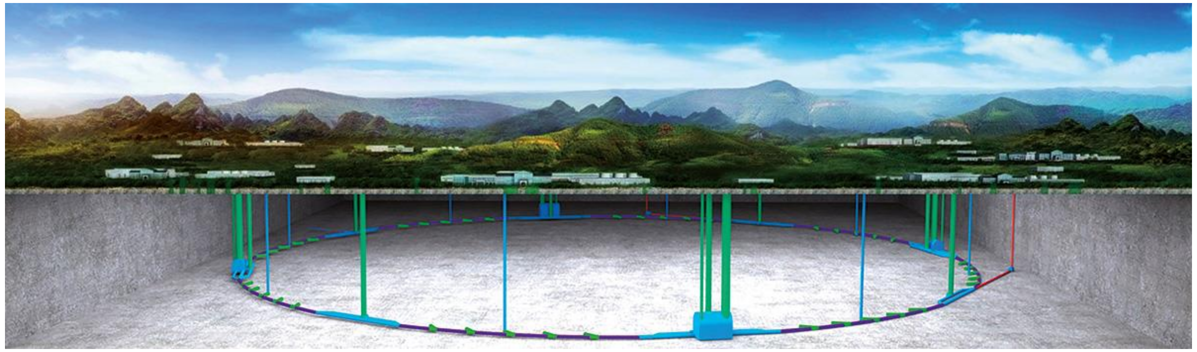


FCC Mode	Z	W	ZH	$t\bar{t}$
CoM energy [GeV]	91.2	160	240	365
Luminosity/IP [10^{34}cm^{-2}s^{-1}]	140	20	7.5	1.4
Number of IPs	4			
Operation time for physics/yr [10^7s/yr]	1.2[1]			
Integrated luminosity/ yr [1/fb/ yr]	68 000	9 600	3 600	670
Host countries	France and Switzerland			
GHG emissions from construction, stage A1-A5				
Subsurface tunnels, caverns, shafts [kt CO_2e]	480 (according to EN ISO 15804+A2) ~1000 (with generic LCA data)			
Surface sites and constructions [kt CO_2e]	50 (according to EN ISO 15804+A2) ~184 (with generic LCA data)			
All constructions [kt CO_2e]	530 (according to EN ISO 15804+A2) ~1184 (with generic LCA data)			
Accelerator (coll.) [kt CO_2e]	Not estimated: subject to equipment design & procurement			
Accelerator (inj.) [kt CO_2e]	Not estimated: subject to equipment design & procurement			
Detectors (A1 - A3, scaled from linear colliders) [kt CO_2e]	142 - 186			
Total [kt CO_2e]	Not estimated			
Collider tunnel length [km]	90.658			
Collider tunnel diameter [m]	5.5			
Concrete GWP used for LCA [kg CO_2e/ m^3]	220 (C12/15), 340 - 422 (C35/45), 400 - 540 (C40/50)			
Low-carbon concrete GWP (for comparison) [kg CO_2e/ m^3]	150 (C12/15), 170 (C35/45), 175 (C40/50)			
Accelerator GWP / m [t CO_2e/ m]	Not estimated: subject to equipment design & procurement			
GHG emissions from operation				
Maximum power in operation [MW]	222	247	273	357
Average power in operation [MW]	122	138	152	202
Electricity consumption / yr [TWh/ yr]	1.2	1.3	1.4	1.9
Years of operation	4	2	3	5
Carbon intensity of electricity [g CO_2e/ kWh]	14 - 18, conservative assumption based on actual data: 12.625[3] in France and 15.7[2] in Switzerland			
GHG emissions/year of physics operation [kt CO_2e/yr]	18 - 26	20 - 29	22 - 31	29 - 40

Chinese Electron-Positron Collider: CEPC

Site choice dominates emissions

- Higgs factory, 240 GeV with potential upgrade to 360 GeV
- 100km tunnel, 2 IPs
- No site fixed yet
  - Estimated grid intensity varies between 12.5 gCO_2e/kWh (Qinghai) to 673 gCO_2e/kWh (Neimenggu)

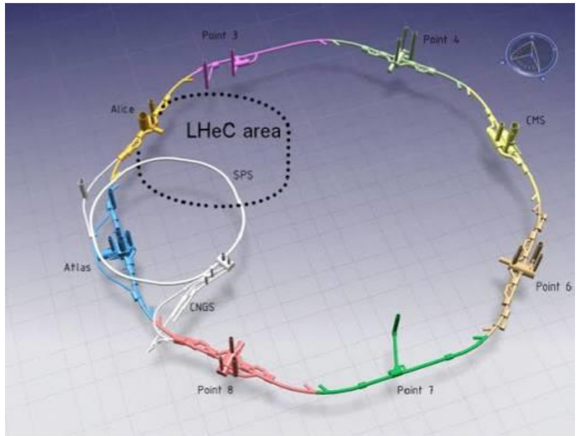


CEPC	ZH	$t\bar{t}$
CoM energy [GeV]	240	360
Luminosity/IP [$10^{34}cm^{-2}s^{-1}$]	5.0	0.8
Number of IPs	2	
Operation time for physics/yr [10^7s/yr]	1.3[1]	
Integrated luminosity/ yr [1/fb/ yr]	1300	217
Host countries	China	
GHG emissions from construction, stage A1-A5		
Subsurface tunnels, caverns, shafts [kt CO_2e]	1137[2]	
Surface sites and constructions [kt CO_2e]	Not estimated	
Accelerator (coll.) [kt CO_2e]	Not estimated	
Accelerator (inj.) [kt CO_2e]	Not estimated	
Detectors [kt CO_2e]	Not estimated	
Total [kt CO_2e]	**1137**	
Collider tunnel length [km]	100	
Collider tunnel diameter [m]	6.5	
Concrete GWP [kg CO_2e/ kg]	0.16 (C25/C30)	
Accelerator GWP / m [t CO_2e/ m]	Not estimated	
GHG emissions from operation		
Maximum power in operation [MW]	260	433
Average power in operation [MW]		
Electricity consumption[4] / yr [TWh/ yr]	1.3	2.2
Year of operation	2035	2035
Carbon intensity of electricity[5] [g CO_2e/ kWh]	12.5	12.5
Average Scope 2 GHG emissions / yr [kt CO_2e]	16.4	27.3

Large Hadron-Electron Collider: LHeC

Energy recovery technology

- Design based on energy recovery linac
- Reuse beam power rather than the beam itself
- 1.18 TeV collision energy, 1 IP
- Short: 8.9 km for collider tunnel



LHeC	
CoM energy [GeV]	1180
Luminosity/IP [10^{34}cm^{-2}s^{-1}]	2.4
Number of IPs	1
Operation time for physics/yr [10^{7}s/yr]	1.6
Integrated luminosity/ yr [1/fb/ yr]	180
Host countries	France and Switzerland
GHG emissions from construction, stage A1-A5	
Subsurface tunnels, caverns, shafts [kt CO_2e]	Not estimated
Surface sites and constructions [kt CO_2e]	Not estimated
Accelerator (coll.) [kt CO_2e]	Not estimated
Accelerator (inj.) [kt CO_2e]	Not estimated
Detectors [kt CO_2e]	Not estimated
Total [kt CO_2e]	
Collider tunnel length [km]	8.9
Collider tunnel diameter [m]	5.5
Collider tunnel GWP / m [t CO_2e/ m]	8.0
Concrete GWP [kg CO_2e/ kg]	0.16 (C30)
Accelerator GWP / m [t CO_2e/ m]	Not estimated
GHG emissions from operation	
Maximum power in operation [MW]	220
Electricity consumption / yr [TWh/ yr]	1.06
Years of operation	2041 -
Carbon intensity of electricity [g CO_2e/ kWh]	
Average Scope 2 GHG emissions / yr [kt CO_2e]	

Linear Colliders: ILC and CLIC

Most complete comparative studies

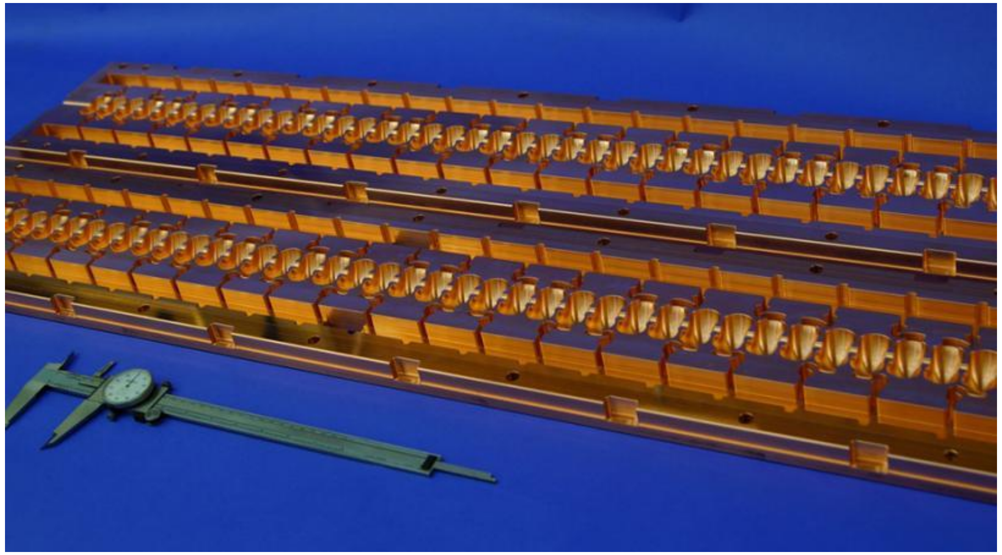
- ILC: 250/500 GeV
- CLIC: 380/1500 GeV
- Comprehensive comparative assessments carried out

	ILC 250	ILC 500	LCF 250 LP/FP	LCF 550 LP/FP	CLIC Stage 1	CLIC Stage 2
CoM energy [GeV]	250	500	250	550	380	1500
Luminosity/IP [$10^{34} cm^{-2} s^{-1}$]	1.35 / 2.7	3.6	1.35 / 2.7	1.9 / 3.85	2.3 (4.5)	3.7
Number of IPs	1		2		1(2)	1
Operation time for physics/yr [10^7s/yr]	1.6		1.2		1.2	
Integrated luminosity/ yr [1/fb/ yr]	215 / 430	580	325 / 650	460 / 920	276 (524)	434
Host countries	Japan		France and Switzerland		France and Switzerland	
GHG emissions from construction, stage A1-A5						
Subsurface tunnels, caverns, shafts [kt CO_2e]	266	372	380		268	337
Surface sites and constructions [kt CO_2e]	Not estimated		Not estimated		118	
Accelerator (coll.) [kt CO_2e]	150	270	165	310	38	N.E.
Accelerator (inj.) [kt CO_2e]	59 / 82	83	60 / 84		110	N.E.
Services [kt CO_2e]	32	46	46		19	N.E.
Detectors [kt CO_2e]	94		94		94	
Total [kt CO_2e]	601 / 624	865	745 / 769	890 / 914	609	
Collider tunnel length [km]	20.5	33.5	33.5		11.5	17.6
Collider tunnel diameter [m]	9.5		5.6		5.6	
Collider tunnel GHG / m [t CO_2e/ m]	8.6		8.5		8.1	
Concrete GHG [kg CO_2e/ kg] / [kg CO_2e/ m^3] (type)	0.16 / 400 (C25/30)		0.16 / 400 (C25/30)		0.16	
Main Linac accelerator GHG / m [t CO_2e/ m]	5.3		5.3		Not estimated	
GHG emissions from operation						
Maximum power in operation [MW]	111 / 138	164	143 / 182	250 / 322	107 (160)	287
Electricity consumption / yr [TWh/ yr]	0.7 / 0.9	1.1	0.8 / 1.0	1.4 / 1.8	0.6(..)	
Reference year of operation	2040		2050		2040	2040
Carbon intensity of electricity [g CO_2e/ kWh]	81		16		16	
Average Scope 2 GHG emissions / yr [kt CO_2e]	59 / 74	87	13 / 15	23 / 28		

Cool Copper Collider: C^3

Smallest construction footprint

- High-gradient normal-conducting cavities operating at cryogenic temperatures
- 250/550 GeV collision energies

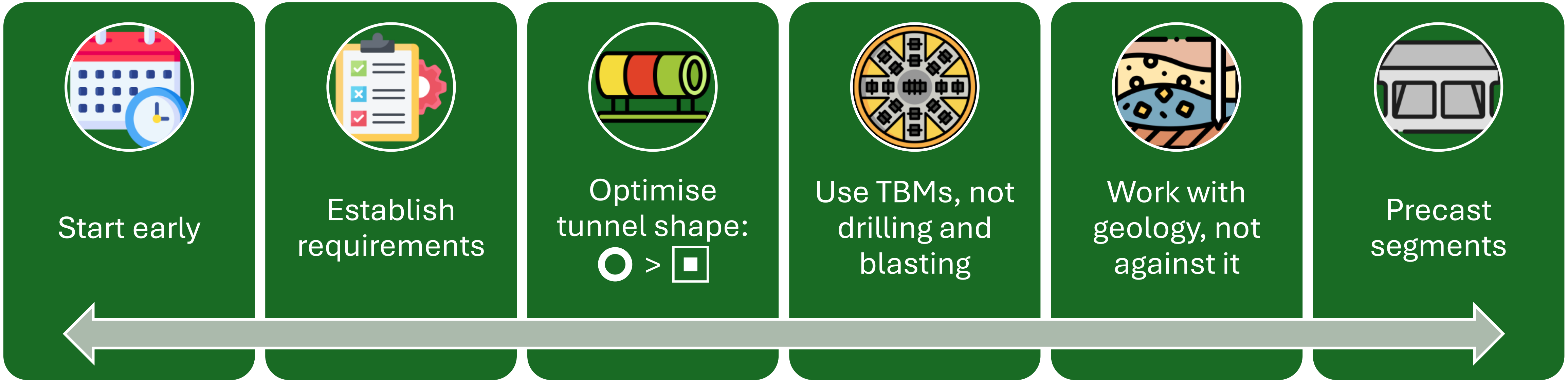


C^3	Stage 1	Stage 2
CoM energy [GeV]	250	550
Luminosity/IP [$10^{34}cm^{-2}s^{-1}$]	1.3	2.4
Number of IPs	1	1
Operation time for physics/yr [10^7s/yr]	1.6	
Integrated luminosity/ yr [1/fb/ yr]	200	400
Host countries	USA, EU	
GHG emissions from construction, stage A1-A5		
Subsurface tunnels, caverns, shafts [kt CO_2e]	146	+10
Surface sites and constructions [kt CO_2e]	Included Above	
Accelerator (coll.) [kt CO_2e]	Not estimated	
Accelerator (inj.) [kt CO_2e]	Not estimated	
Detectors [kt CO_2e]	Not estimated	
Total [kt CO_2e]		
Collider tunnel length [km]	8	
Collider tunnel diameter [m]	4-6.5	
Collider tunnel GWP / m [t CO_2e/ m]	17	
Concrete GWP [kg CO_2e/ kg]	0.18 (C40)	
Accelerator GWP / m [t CO_2e/ m]	Not estimated	
GHG emissions from operation		
Maximum power in operation [MW]	110	125
Electricity consumption / yr [TWh/ yr]	0.49	0.56
Years of operation	10	10
Carbon intensity of electricity [g CO_2e/ kWh]	20	
Average Scope 2 GHG emissions / yr [kt CO_2e]	9.8	11.2

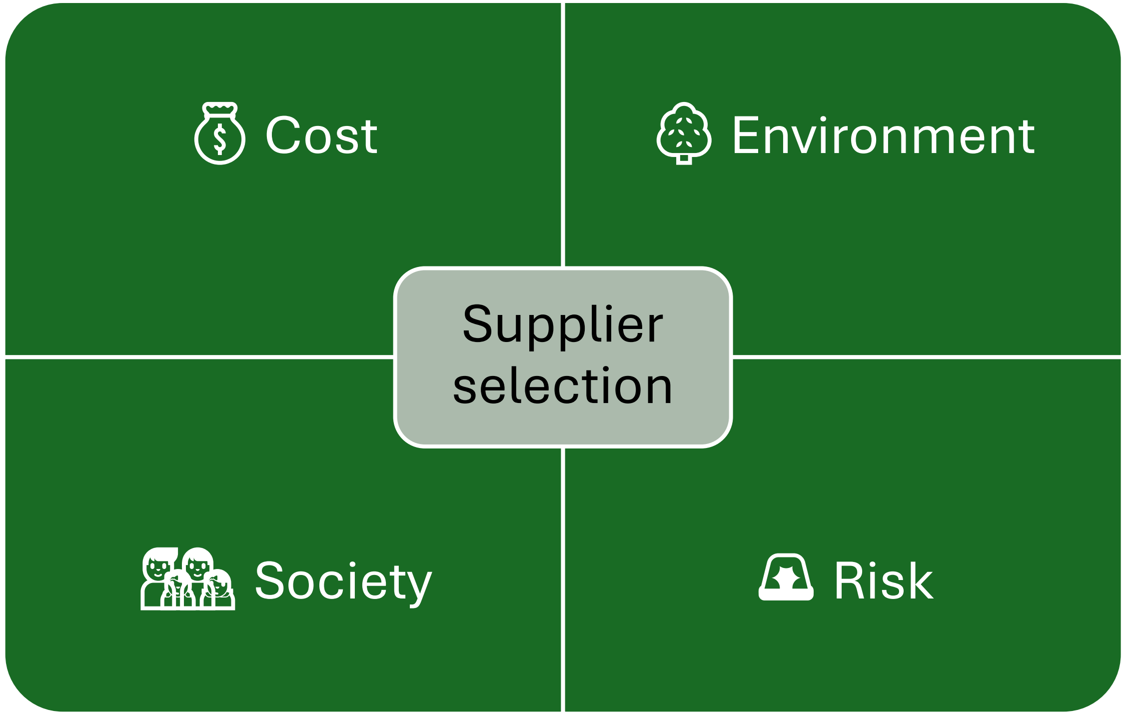
Greener Accelerators

Improved materials for civil engineering

- Sustainable construction needs standardisation, regulation, and partnership with industry and NGOs
- Strategies to reduce concrete use in tunnels

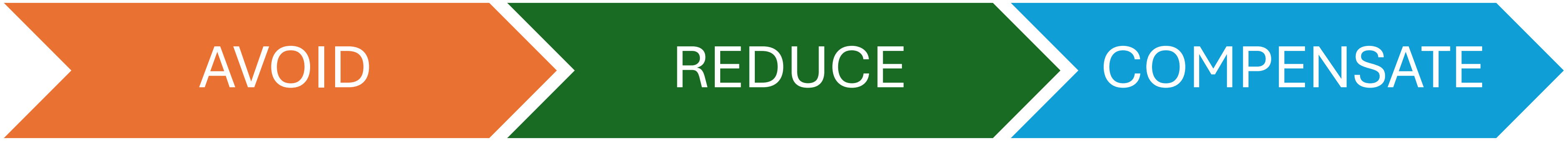


Responsible procurement



- Helps reduce overall cost
- Encourage public acceptance
- Improve risk management
- Establish an Environmental, Social and Governance (ESG) policy
- Use standard ISO 20400:2017

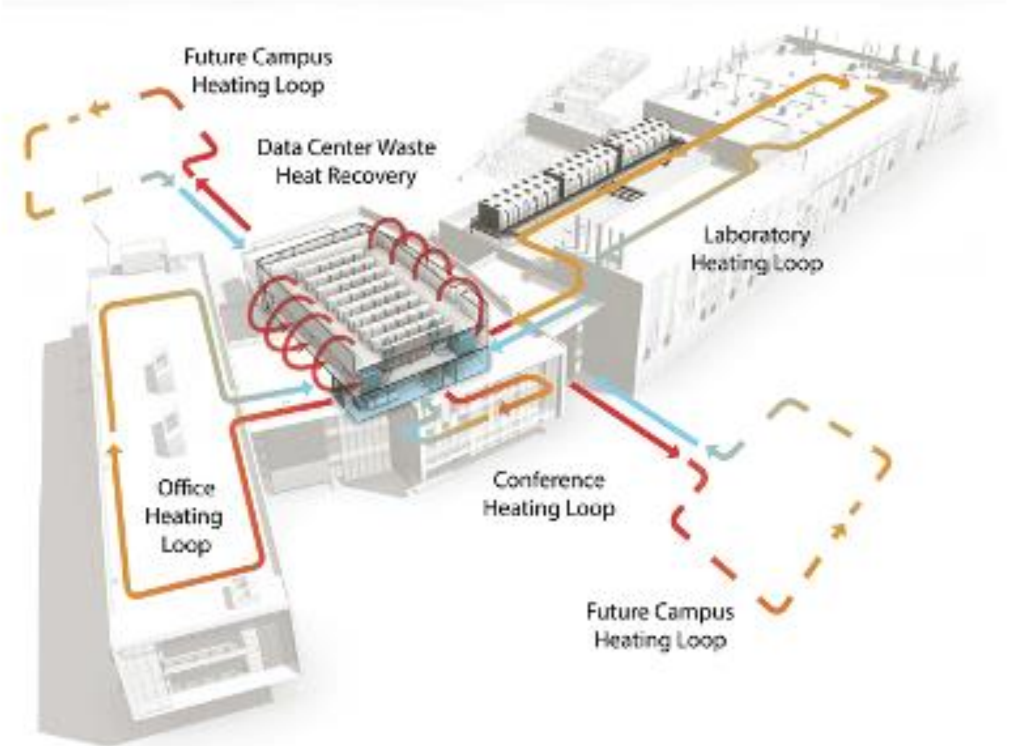
Energy optimisation



- Start with technical requirements
- Eco-design approach: reduce energy consumption
- Explore compensation measures, e.g. waste heat recovery
- This may trigger repeated design cycles

- Use official national value for grid intensity
- Calculate monetary value of fossil energy used – shadow pricing

Heat recovery



- All electricity used ends up as heat
- Typically low-grade heat, <45°C
- Usually dissipated to ambient air
- Could be used to heat office buildings or nearby homes

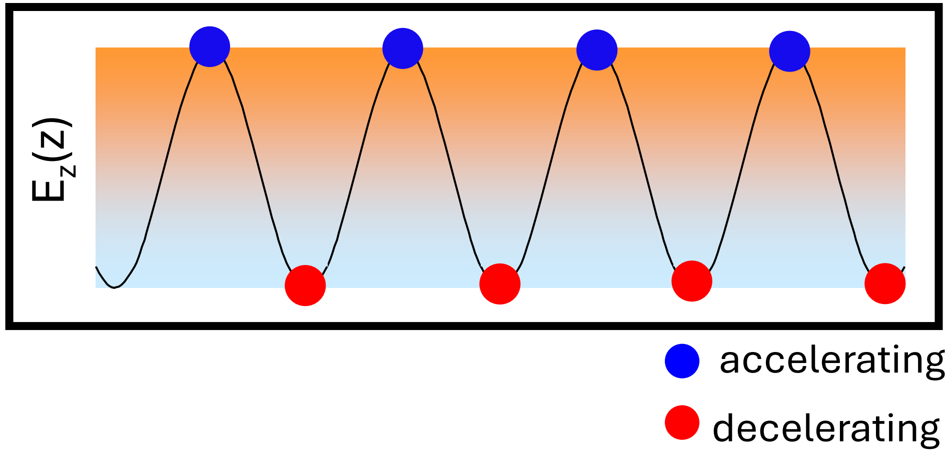
- Reduced energy, water usage
- Longer lifetime for cooling equipment
- Reduced heating-linked emissions
- Lower heating costs
- Potential for new activities locally

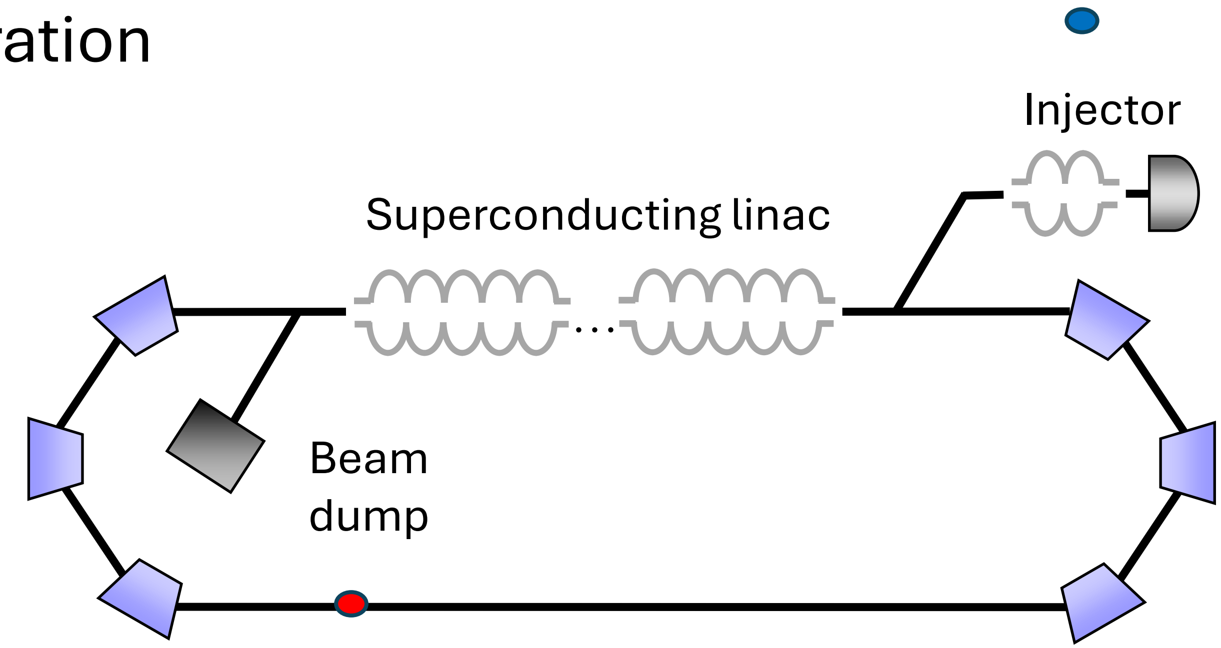
- Extra equipment (recovery, transport, heat increase, storage)
- Refurbishment of existing buildings
- Establishment of heat supplier

Energy recovery

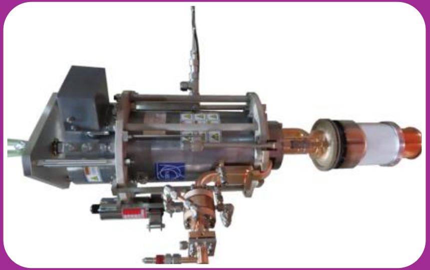
- Viable due to advances in SRF technology
- High cavity Q factors (10^{10}) enable long-lasting energy storage
- Multi-turn ERLs enable high-energy operation
  - CBETA @ Cornell: 150 MeV in 4 passes
- LHeC: ERL-based design keeps wall-plug power under 100 MW
  - PERLE: demonstrator facility under design now
- Electron-Ion Collider: ERLs to cool proton beams

Accelerate → Use → Decelerate:
A Game of Pass-the-Parcel
Slide: Peter Williams



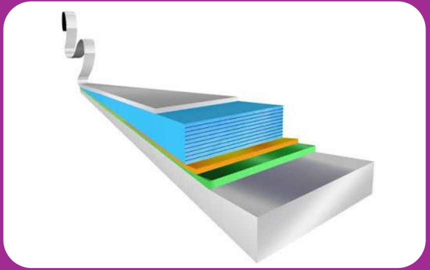


R&D investment in green technologies



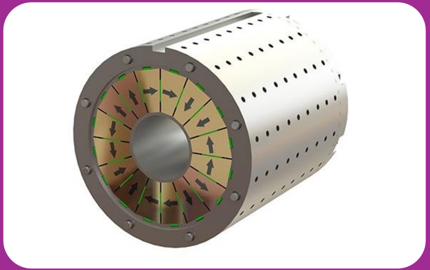
RF sources

- High-efficiency klystrons
- Fast Reactive Tuners



High-temperature superconductors

- Reduce cryogenic system load
- Increasing from 2K to 4K cuts cryogenic power by 66%



Permanent magnets

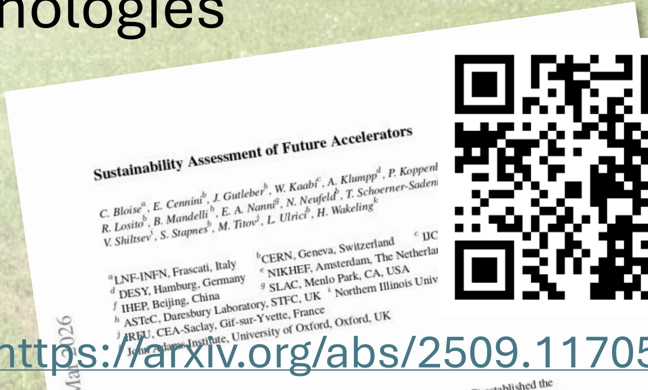
- Ideal for fixed-field devices
- ESRF upgrade: 54% energy reduction
- Ongoing R&D into tuneable PM systems

Conclusions

- Sustainability is now a **strategic requirement** for future accelerators
- Environmental impact must be assessed across the **full lifecycle**
- **Construction** and **operation** dominate greenhouse-gas emissions
- Major opportunities exist through **design choices**, **efficiency** and **innovation**
- Sustainability must be considered alongside **scientific** and **socio-economic value**

Next Steps

- Develop common sustainability assessment standards
- Expand **LCA databases** for accelerator materials and components
- Improve environmental reporting across **future projects**
- Strengthen **collaboration** between laboratories and projects
- Continue **R&D** on energy-efficient accelerator technologies



Sustainability Assessment of Future Accelerators

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https://arxiv.org/abs/2509.11705v2