

# Environmental Sustainability and Particle Accelerators

Dr. Hannah Wakeling

JAI Accelerator Course, Oxford

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# Overview

## Particle Accelerators

Intersection with The Climate Crisis

Reducing environmental impact

Evaluating environmental impact

# The Climate Crisis

- ▶ How does this actually relate to the field of accelerator physics?

## Definitions:

- ▶ **Sustainability** has many varied definitions: "a social goal for people to co-exist on Earth over a long time."
- ▶ **Greenhouse Gas (GHG)** – any gas that absorbs infrared radiation emitted from the Earth's surface
- ▶ **Global Warming Potential (GWP)** measures the heating effect of a GHGs compared to CO<sub>2</sub>
  - ▶ **CO<sub>2</sub>e** – Carbon Dioxide Equivalent
    - ▶ CO<sub>2</sub>, methane, nitrous oxide and fluorinated gases

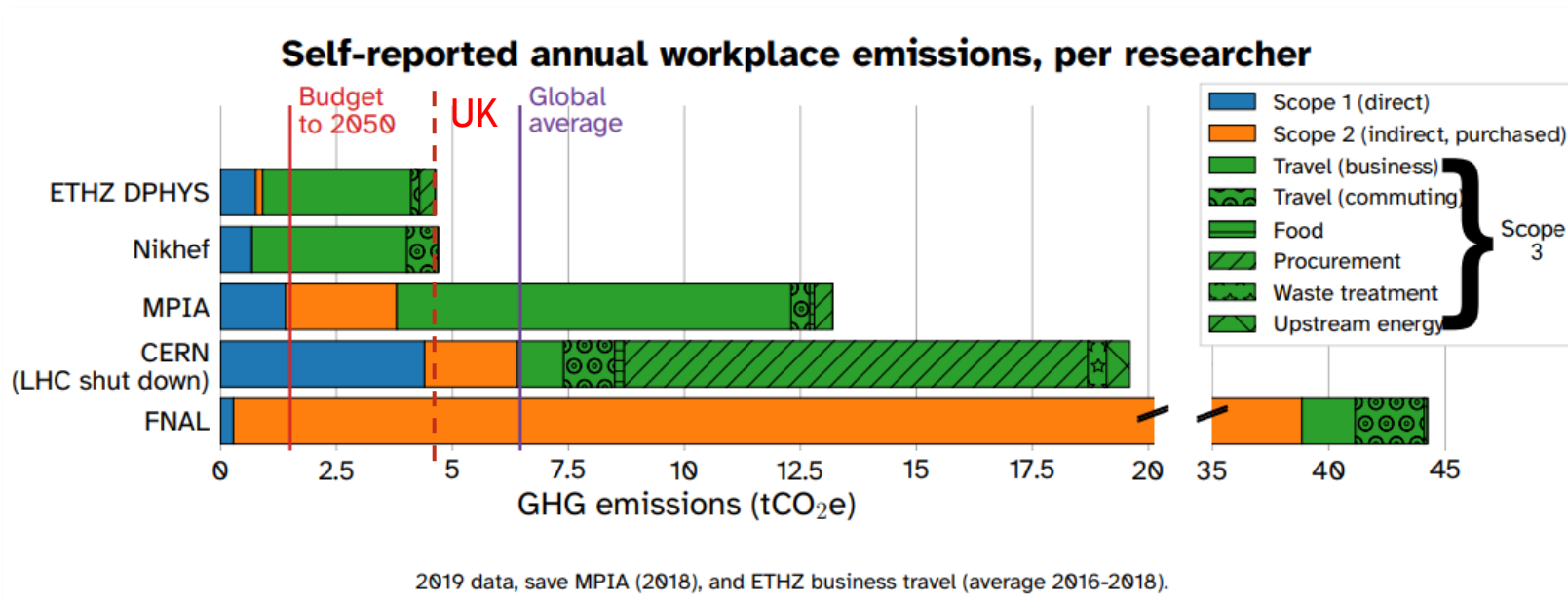
GWP of GHGs

The climate issue | Nature Astronomy

# Why particle accelerators?

Large accelerator facilities are generally unsustainable:

- ▶ resource consumptive, and
- ▶ next generations aim to grow in size and/or power, and therefore (generally) consumption.

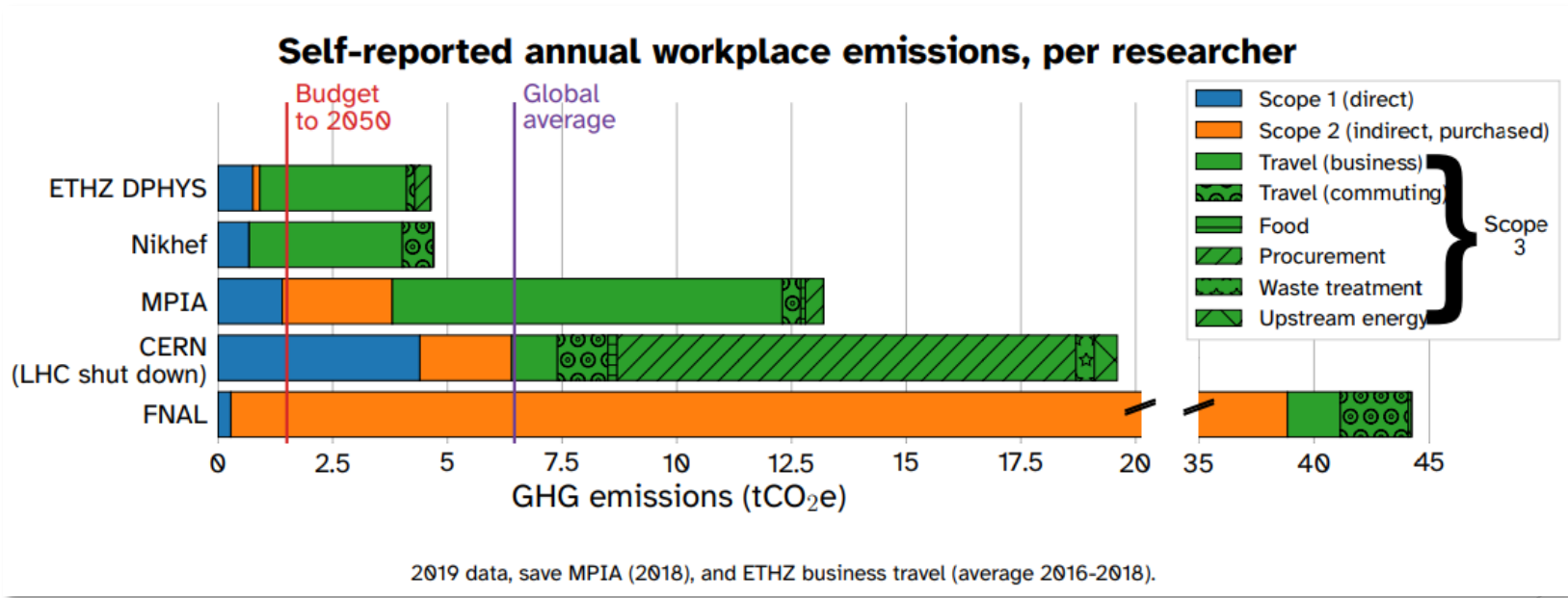


Reported workplace GHG emissions<sup>[1]</sup>.

For comparison, in the UK an average person emits 4.7 t CO<sub>2</sub>e a year

# Why particle accelerators?

Scope 1: direct GHG emissions  
i.e., on-site burning fossil fuels and chemical reactions.



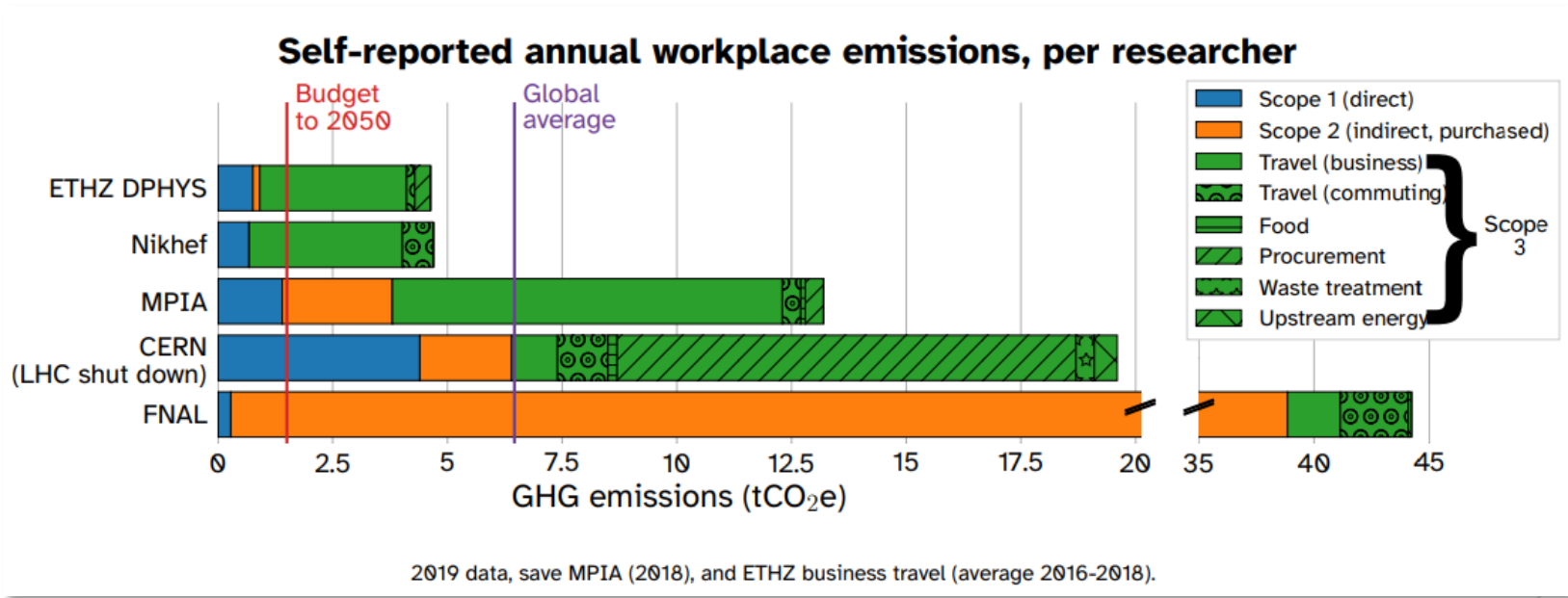
2019 data, save MPIA (2018), and ETHZ business travel (average 2016-2018).

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# Why particle accelerators?

Scope 2: indirect GHG emissions resulting from the generation of purchased electricity, heat, or steam.



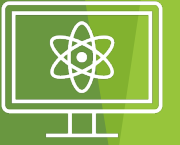
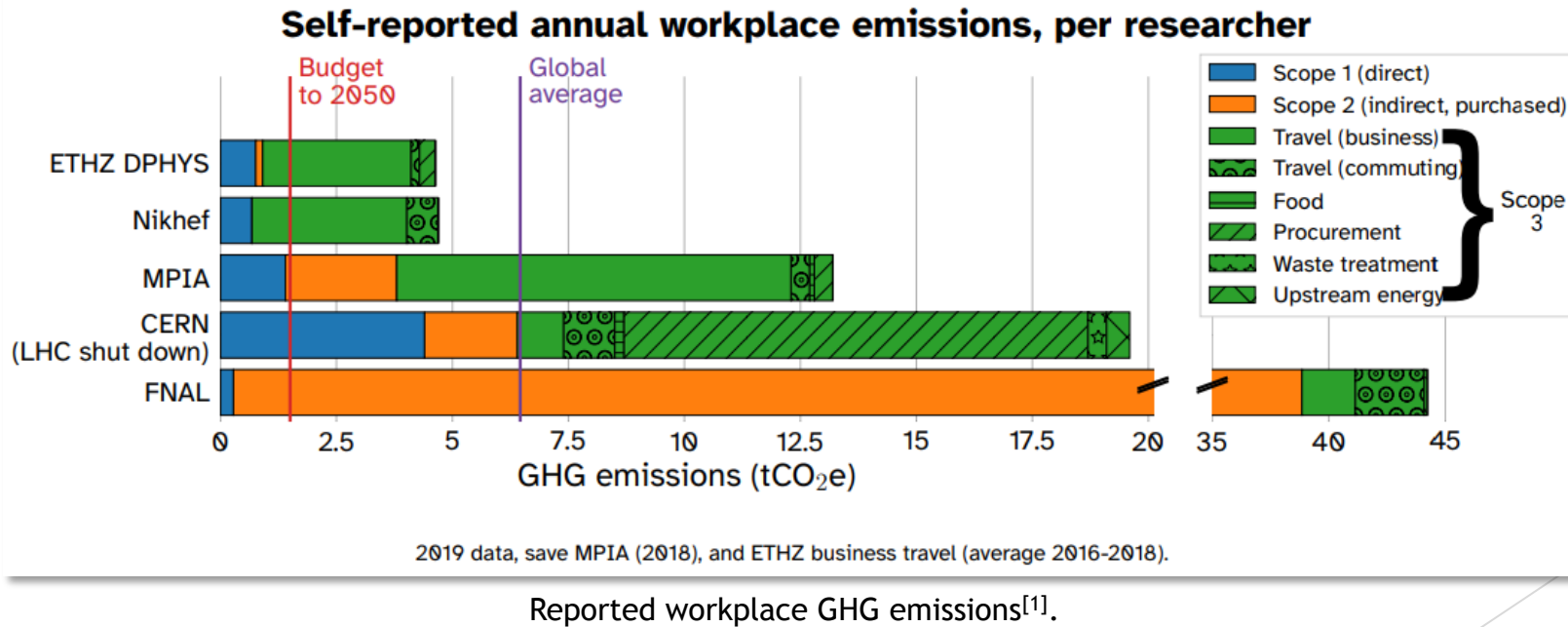
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# Why particle accelerators?

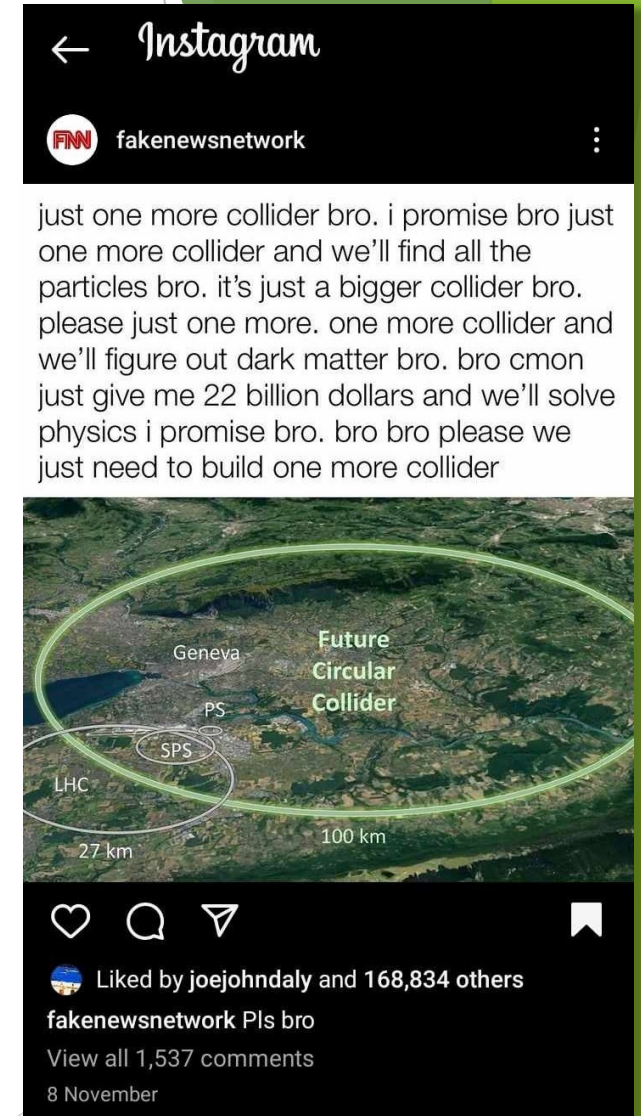
Scope 3: all other indirect GHG emissions in the value chain of the organisation associated with activities and sources including but not limited to: transportation of goods, extraction and production of purchased materials, employee commuting, investments, ...



# Why particle accelerators?

One *can* argue:

- ▶ There are so many other, larger and worse environmental impacts.
  - ▶ Accelerator physics has contributed so much knowledge and benefits to humanity, and will continue to do so; it's worth it.
1. The Climate Crisis is a compound problem, and an issue for everyone.
  2. Moral and social duty to lead by example.
  3. Policy affects us.
    - ▶ The environmental impact of construction of a large collider facility will have a carbon impact similar to that of a redevelopment of a neighbourhood in a major city. We **will** come under scrutiny.
  4. Often largely publicly funded. Governmental and taxpayer support is necessary.





# So, what can we do?

- ▶ We must adapt,
- ▶ reduce impact,
- ▶ & demonstrate our efforts

including considering and/or maintaining

- ▶ reliability,
  - ▶ lifetime,
  - ▶ efficiency,
  - ▶ & science output
- ▶ Many efforts ongoing around the world!



[Image Source](#)

The background features a series of overlapping, semi-transparent green geometric shapes, primarily triangles and polygons, that create a dynamic, layered effect. The colors range from light, pale greens to deep, forest greens. The shapes are positioned on the right side of the frame, extending towards the center, while the left side remains mostly white.

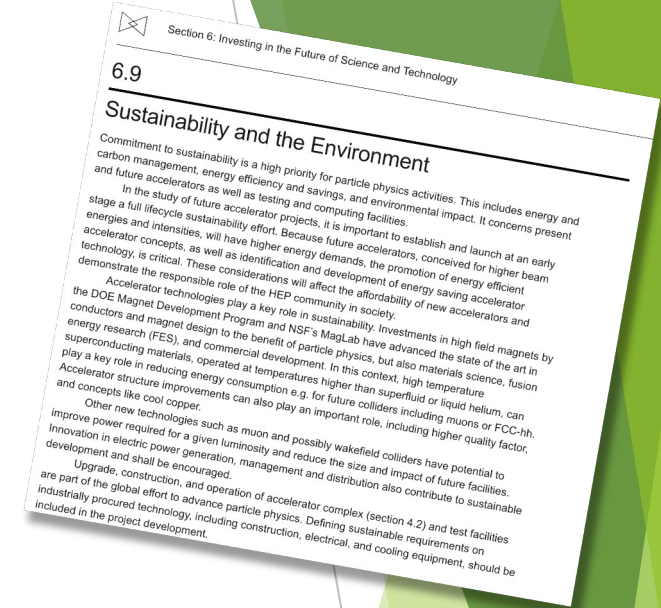
Reducing  
environmental  
impact

# Efforts that are ongoing

- ▶ Policy and culture change
- ▶ Carbon emissions and environmental impact reports
- ▶ Designing with the environment in mind
  - ▶ New(er) technologies and R&D
- ▶ Resource consumption and waste

# Recent policy changes

- ▶ Sustainability is getting a lot of first time mentions in physics
  - ▶ [U.S. Community Study on the Future of Particle Physics](#) Snowmass 2021
  - ▶ [Particle Physics Project Prioritization Panel \(P5\) report](#) 2023
- ▶ Naturally affected by other policy:
  - ▶ [Paris Agreement](#): Net Zero by 2050
  - ▶ [UN Breakthrough](#) (2030)
    - ▶ 100% of post-2030 projects must be net zero in operation and at least 40% less embodied carbon compared to current practice for 100% net zero for whole life cycle by 2050
  - ▶ UK Government: [biodiversity](#) net gain of 20%
- ▶ Self-imposed restrictions i.e. [air travel](#)



# Culture change

- ▶ We need it to make a real difference
- ▶ Embody sustainability within existing structures
- ▶ Design, manufacturing, operation etc. could carry on as normal without enforced policy/rules
- ▶ BUT with culture change
  - ▶ Not policy reliant
    - ▶ Can initiate change before policy is implemented
  - ▶ Creative, new solutions
  - ▶ Better attitudes and habits, i.e. air travel!

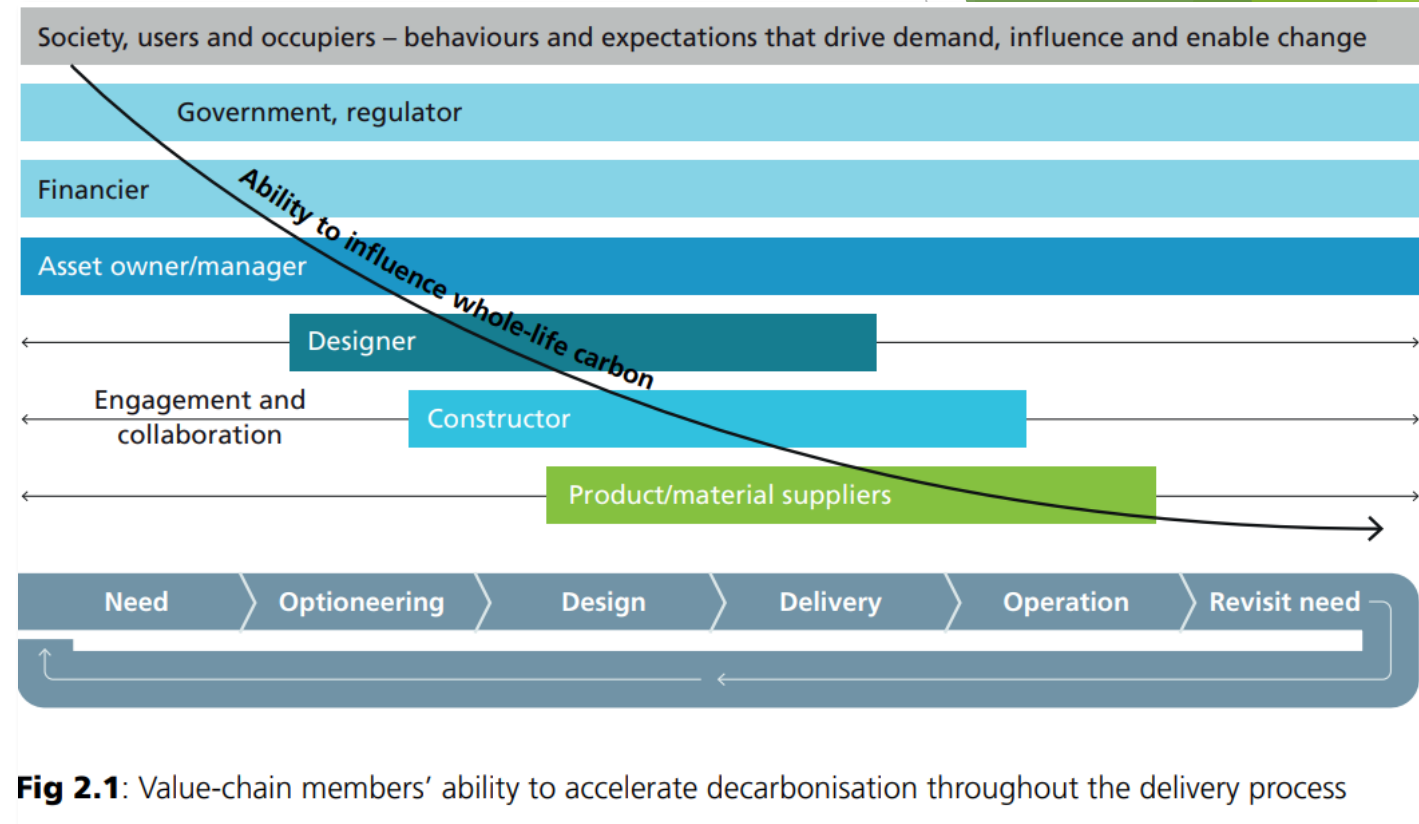
# Carbon emissions and impact reports

- ▶ Climate impacts of particle physics
- ▶ Publish environmental impact reports
  - ▶ i.e. CERN, DESY
  
- ▶ Use carbon impact reports to design with the environment in mind



# Designing with the environment in mind

- ▶ Climate impacts of particle physics
- ▶ Publish environmental impact reports
  - ▶ i.e. CERN, DESY
- ▶ Lots of ideas in the pipeline
  - ▶ ILC, FCC, CEPC, CLIC, C<sup>3</sup>

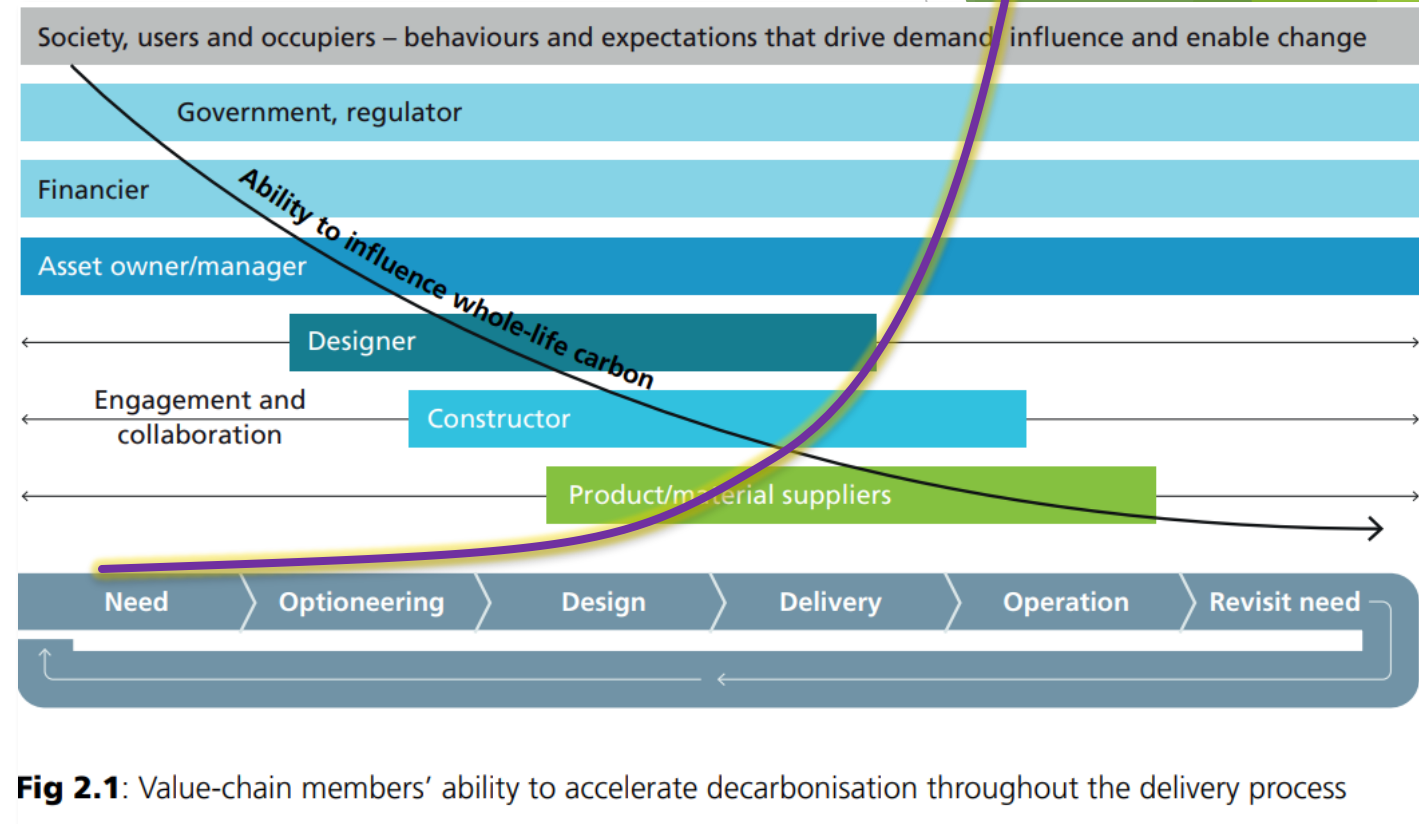


**Fig 2.1:** Value-chain members' ability to accelerate decarbonisation throughout the delivery process

PAS 2080 guidance document: Practical actions and examples to accelerate the decarbonisation of buildings and infrastructure

# Designing with the environment in mind

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**Fig 2.1:** Value-chain members' ability to accelerate decarbonisation throughout the delivery process

PAS 2080 guidance document: Practical actions and examples to accelerate the decarbonisation of buildings and infrastructure

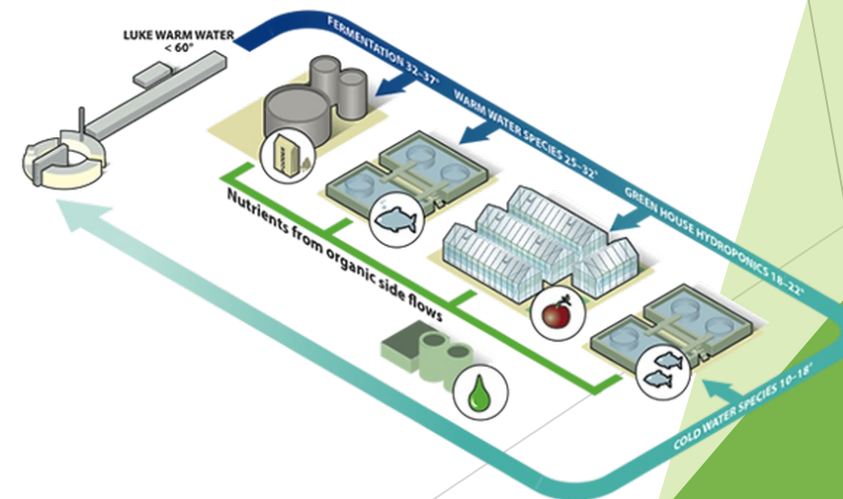
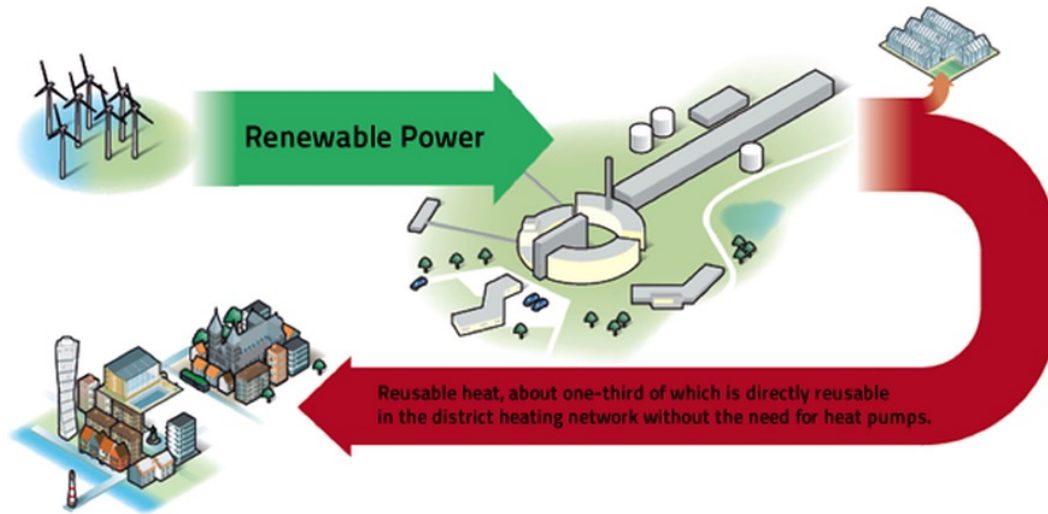


# European Spallation Source (ESS)

- ▶ <5 MW proton beam with a rotating target
- ▶ Committed to recycling the annual 254 GWh of waste heat energy via a district heating network
  - ▶ Built into the design of ESS
- ▶ Office (non-accelerator) buildings are **BREEAM** certified 'outstanding'



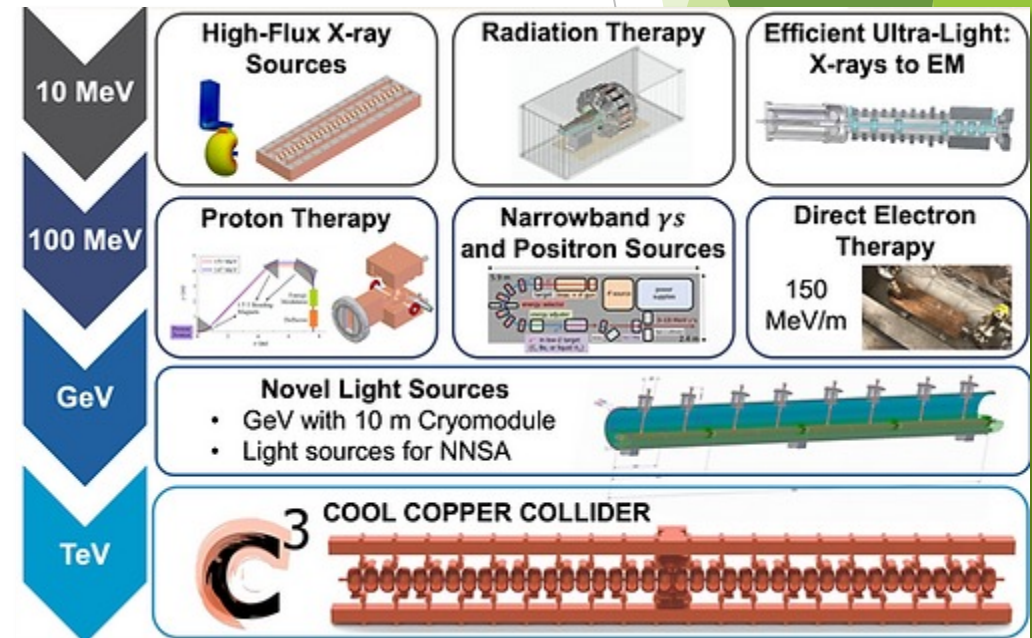
BREEAM®



# Cool Copper Collider (C<sup>3</sup>) at SLAC

- ▶ 250-550 GeV Linear Accelerator
- ▶ Compact 8km footprint, cut-and-cover construction evaluation
- ▶ Site power of 150 (175) MW for a beam power of 2.1 (2.45) MW
  - ▶ at an estimated 1.4% efficiency
- ▶ 185 MW solar farm could be built (\$150 million), double covering the average power requirement of C<sup>3</sup>
  - ▶ Where excess power could be stored for night usage.

<https://web.slac.stanford.edu/c3/about>



# Cool Copper Collider (C<sup>3</sup>) at SLAC

► Estimates of tunnelling impacts:

Global warming potential (GWP)

Project	Main tunnel length (km)	GWP (kton CO <sub>2</sub> e)		
		Main tunnel	+ other structures	+ A4-A5
FCC	90.6	578	751	939
CEPC	100	638	829	1040
ILC	13.3	97.6	227	266
CLIC	11.5	73.4	98	127
C <sup>3</sup>	8.0	133	133	146



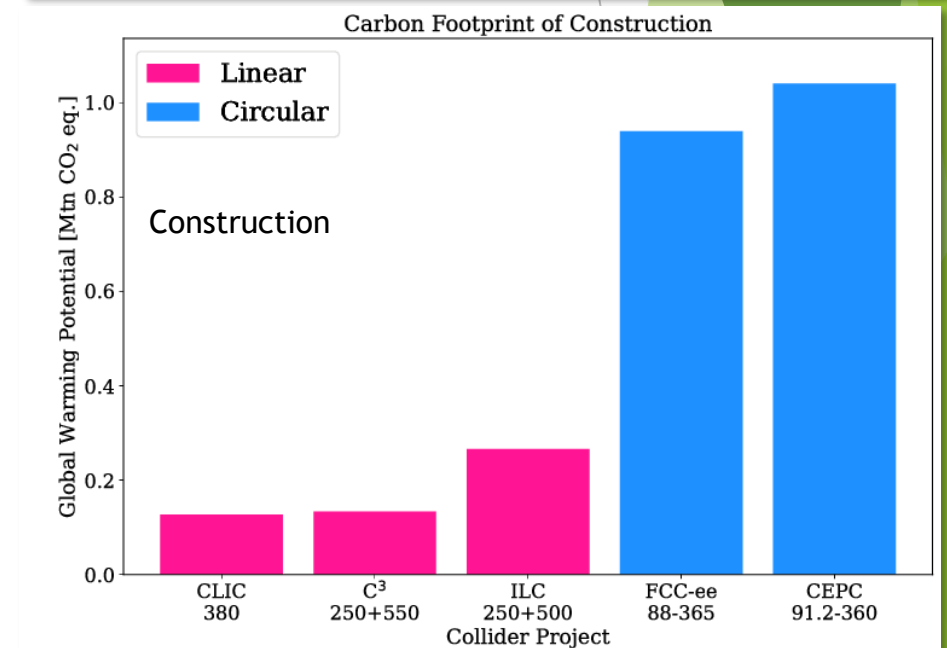
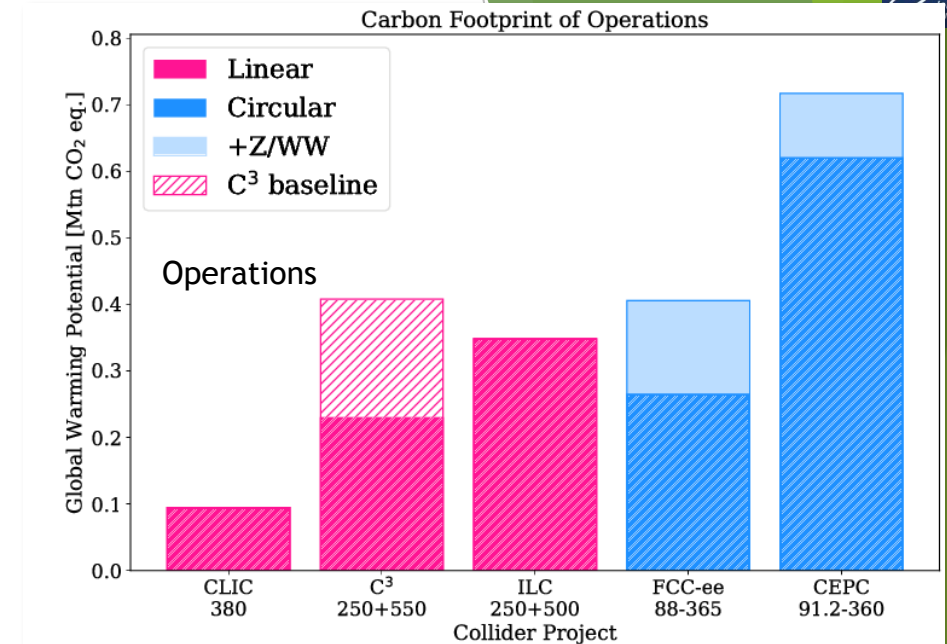
Science Photo Library



# Cool Copper Collider (C<sup>3</sup>) at SLAC

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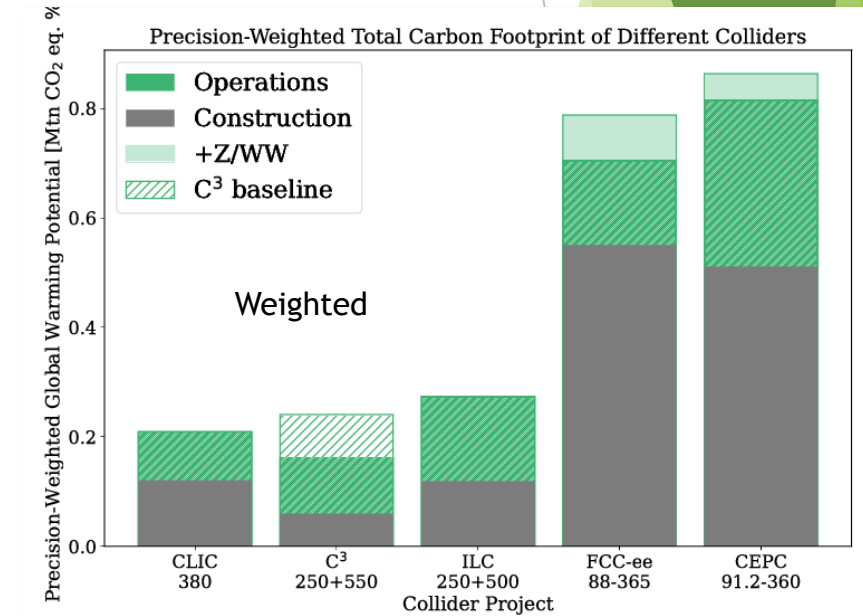
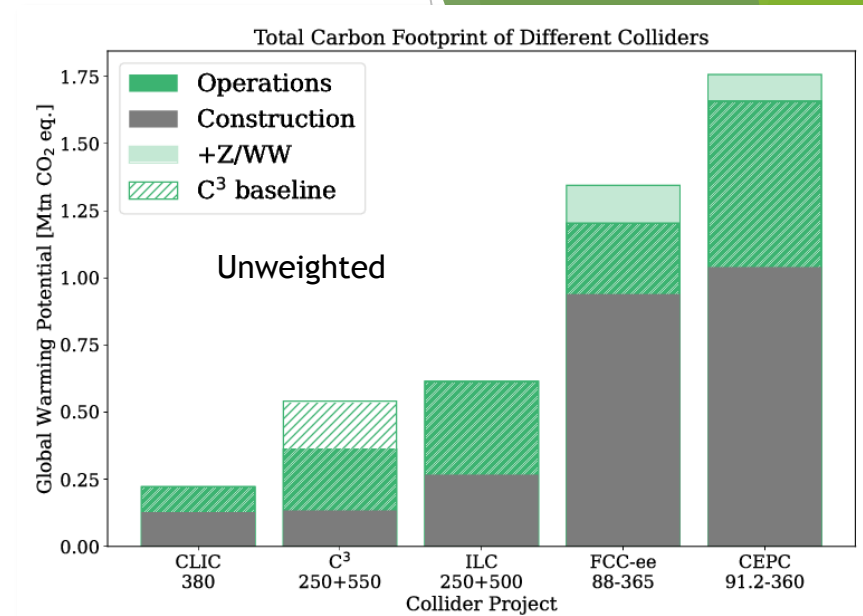
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- ▶ Comprehensive comparative evaluation of carbon footprint relative to their expected precision.

- ▶ Assumption: avg. of 20 tCO<sub>2</sub>/GWh.

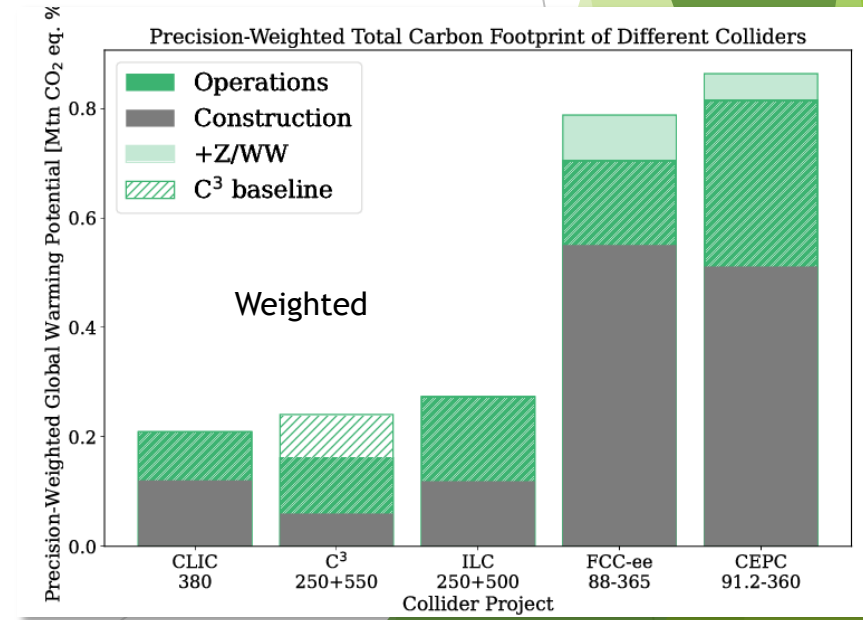
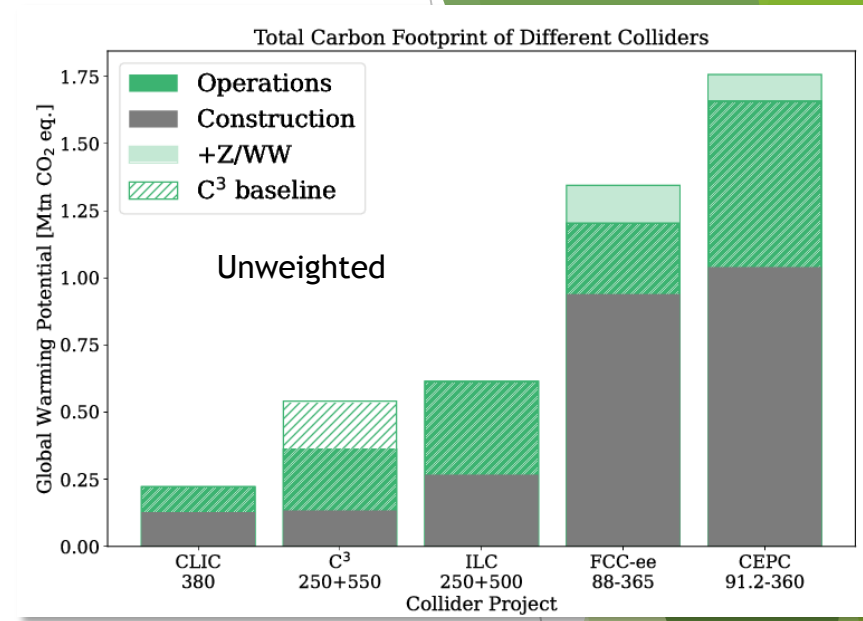


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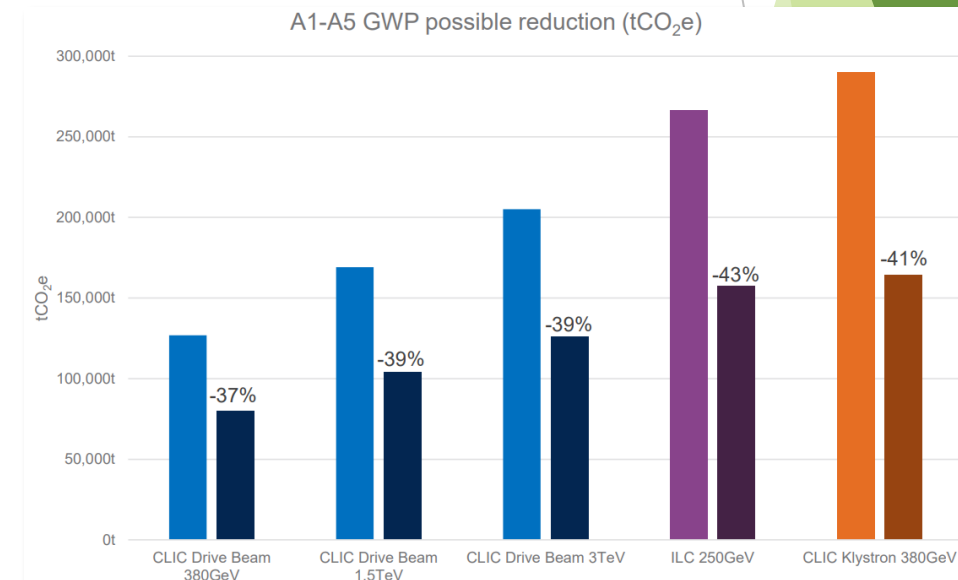
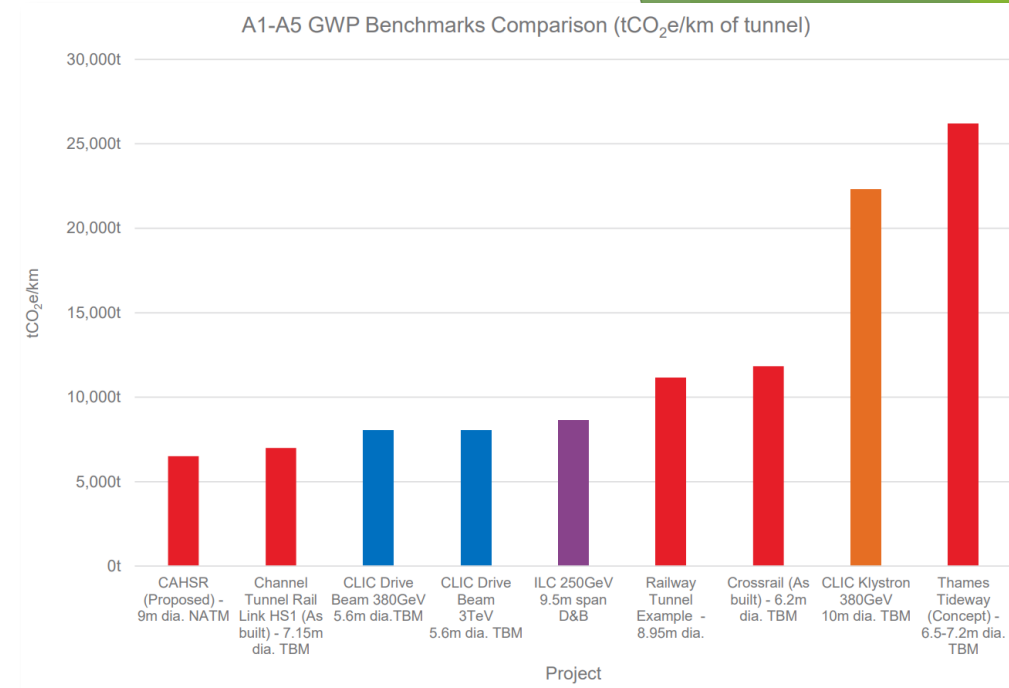
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- Comprehensive comparative evaluation of carbon footprint relative to their expected precision.
  - Assumption: avg. of 20 tCO<sub>2</sub>/GWh.
- Not occurring here, but be aware of potential for greenwashing or “science-washing”



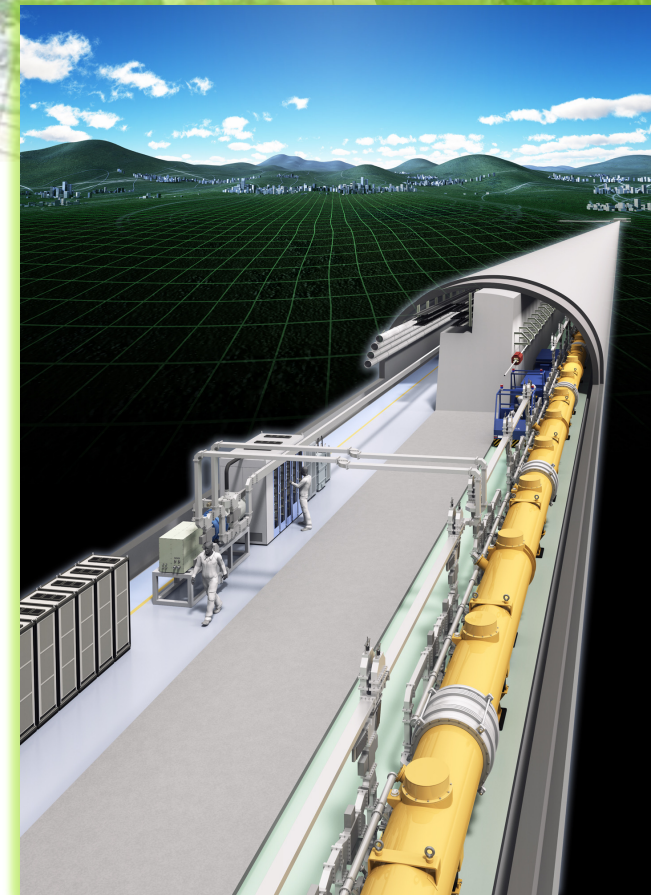
# CLIC and ILC tunneling Life Cycle Analysis (LCA)

- ▶ CLIC
  - ▶ Drive beam or Klystron
  - ▶ 380 GeV (1.5 TeV and 3 TeV) linear accelerator
  - ▶ 11 - 50 km
  
- ▶ ILC
  - ▶ 250 GeV (1 TeV) linear accelerator
  - ▶ 33 km



# Green ILC Project

- ▶ Evaluating options for a greener ILC
- ▶ Including:
  - ▶ Large wooden structures (from sustainable forestry)
  - ▶ Utilizing waste heat for greenhouses
  - ▶ Thermal storage (HASClay®)

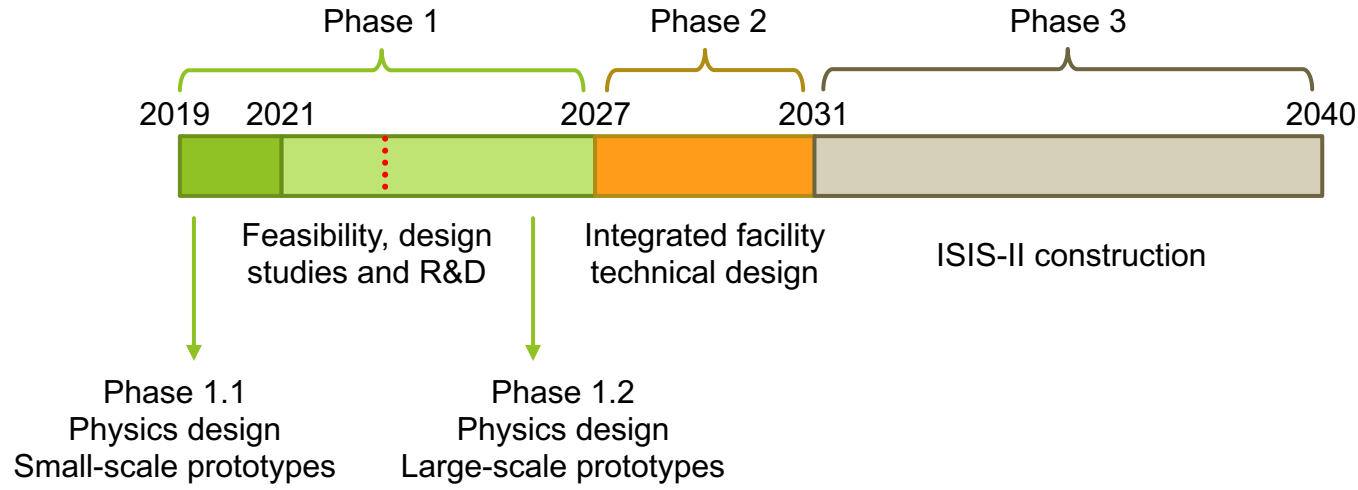




# Green ILC Project



# ISIS-II Neutron & Muon Source

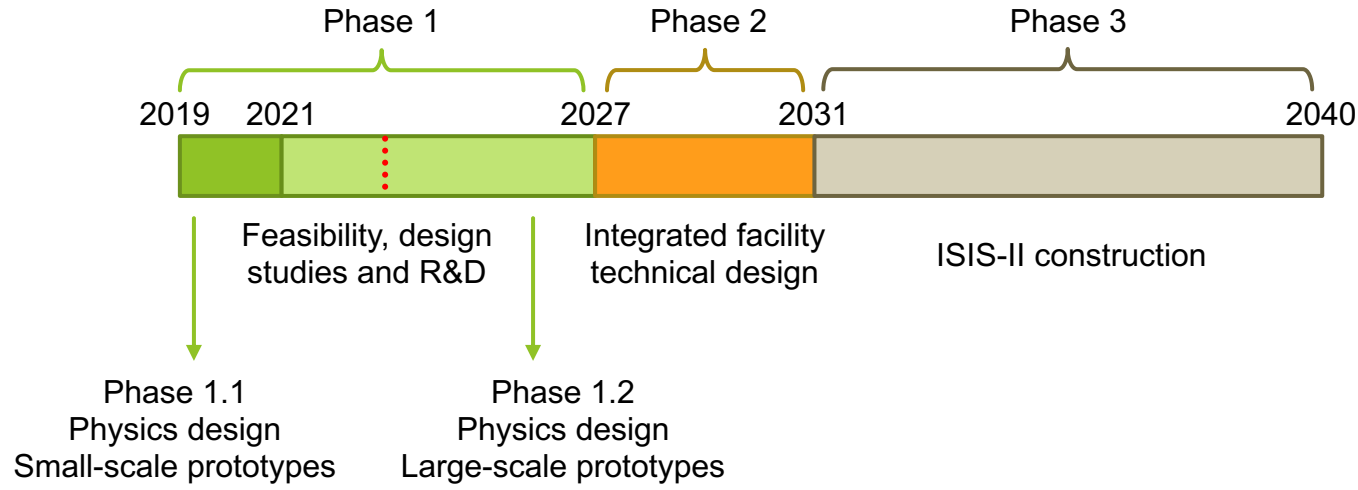


Proposed ISIS-II timeline.

- Environmental impact evaluation of the proposed facility is underway.

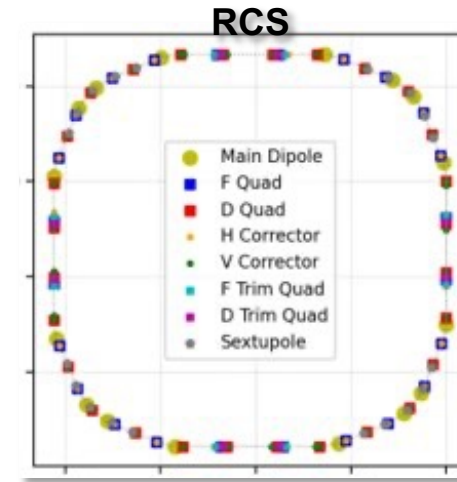


# ISIS-II Neutron & Muon Source

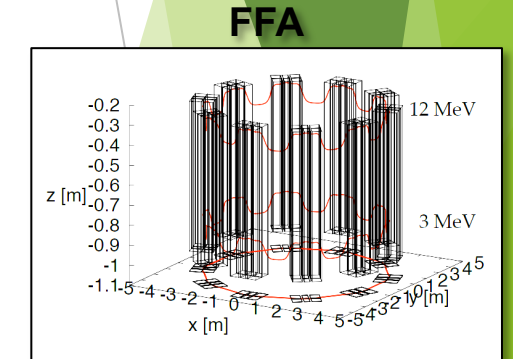
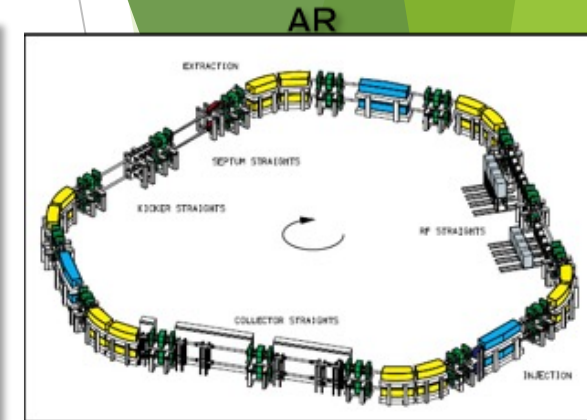


Proposed ISIS-II timeline.

- ▶ Environmental impact evaluation of the proposed facility is underway.
- ▶ (Simplified) Life Cycle Assessment underway to inform design options.



3 ring options for ISIS-II.

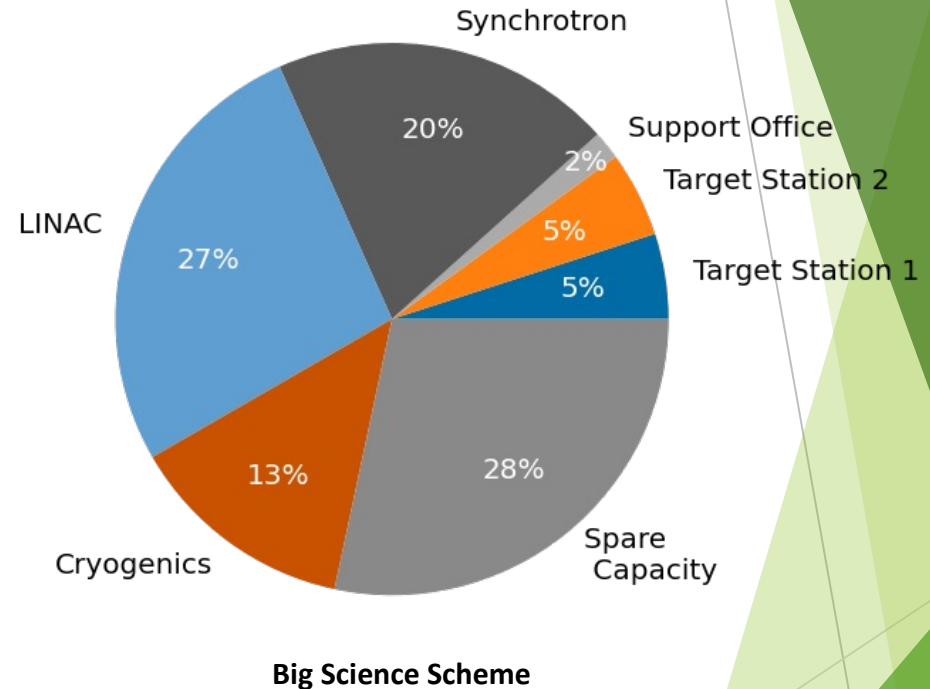


PRELIMINARY

# ISIS-II Power consumption

A first estimation of the emissions of CO<sub>2</sub>e due to the power consumption of ISIS-II over its lifetime.

Power	Big Science Scheme	
	[MVA]	Lifetime CO <sub>2</sub> e [tCO <sub>2</sub> e]
Target Station 1	1.5	30,156
Target Station 2	1.5	30,156
Support Office	0.5	10,052
Synchrotron	6	120,625
LINAC	8	160,834
Cryogenics	4	80,417
Spare Capacity	8.5	170,886
<b>TOTAL</b>	<b>30</b>	<b>603,126</b>



The power values are assumed to reflect the predicted beam on/off ratio of ISIS-II and present the 60-year operational lifetime CO<sub>2</sub>e impact of ISIS-II, including current predicted "decarbonization of the UK grid" estimates.

Year	CO <sub>2</sub> emissions [t CO <sub>2</sub> /kWh]
2020	1.415 × 10 <sup>-4</sup>
2030	8.51 × 10 <sup>-5</sup>
2040	6.36 × 10 <sup>-5</sup>
2050	3.32 × 10 <sup>-5</sup>

# Designing with the environment in mind but at a smaller scale

- ▶ Optimize individual components:
  - ▶ Power
  - ▶ Materials
  
- ▶ Important to consider whole lifecycle
- ▶ E.g., it's not just net weight, it's gross weight too
  - ▶ Case study: FETS RFQ at RAL
    - 16 blocks of oxygen-free copper totaling 4 tonnes
    - Machined to 16 vanes: 8 major (80kg each), 8 minor (20kg each)
    - 3.2 tonnes of copper, i.e. 80%, wasted.
      - Swarf and off cuts were recycled via commercial metal recycling.
  
- ✓ Machining of materials potentially optimizable



# More efficient technologies: RF Amplifiers

- ▶ Varying levels of power efficiency.
- ▶ Klystrons presently have ~50% efficiency (depending!)
- ▶ Multibeam RF sources can have RF source designs exceeding 80%
  - ▶ [Modeling and Design of a High-Efficiency Multibeam Klystron](#)
- ▶ This indicates a klystron amplifier efficiency of 70-80% is possible, leading to an overall RF source efficiency of 65%.
  - ▶ [High Efficiency 50MW X-band Klystron Development](#)
- ▶ Many other opportunities available here.



# New technologies: Thin Film SC RF

- ▶ **Bulk niobium cavities** have been the choice for SC RF cavities for the last 50 years
- ▶ Use a considerable amount of natural material
- ▶ Performance limit of niobium has been reached
- ▶ Costly to produce
- ▶ Run at a temperature of 2 K
  - ▶ A considerable cryogenic demand and energy load
  
- ▶ Thin films open up the possibilities to
  - ▶ Use a copper supporting cavity - better thermal properties and cheaper material and production
  - ▶ Using different superconducting materials (e.g. Nb<sub>3</sub>Sn, NbN and MgB<sub>2</sub>)
  - ▶ Higher operation temperature of new alloys
  - ▶ Theoretical higher accelerating gradients
  - ▶ Using high  $T_c$  superconducting materials allows RF cavities to operate at **4.2 K**, instead of the **1.9 K** used for high-performance Nb cavities
    - ▶ more than doubling the efficiency of the cryogenic system



# Newer technologies: Permanent Magnets (PMs)

- ▶ Is it better to use PMs over electromagnets (EM)?
- ▶ ASTeC Zero-Power Tunable Optics
  - ▶ PM alternative to EM
- ▶ Proposed 3 TeV version of CLIC would require 582 MW
  - ▶ 124 MW would be used by resistive EMs.
- ▶ One magnet replacement could save 136 kg CO<sub>2</sub>/yr.
- ▶ Great example of power vs. material impacts
- ▶ NdFeB is a rare earth magnet with non-negligible environmental impacts
  - ▶ 27.6 kg CO<sub>2</sub>e / kg of virgin NdFeB magnet



Table 3. Life cycle impacts of producing virgin and recycled NdFeB magnets.

Impact category	Unit	Virgin	Recycled
Global Warming	kg CO <sub>2</sub> eq	27.602	12.453
Acidification	H <sup>+</sup> moles eq	20.524	11.320
Carcinogenics	benzene eq	0.069	0.035
Non carcinogenics	toluene eq	249.382	136.075
Respiratory effects	kg PM2.5 eq	0.124	0.059
Eutrophication	kg N eq	0.011	0.004
Ozone depletion	kg CFC-11 eq	1.25E-06	4.89E-07
Ecotoxicity	kg 2,4-D eq	94.285	45.345
Smog	kg NO <sub>x</sub> eq	0.109	0.034

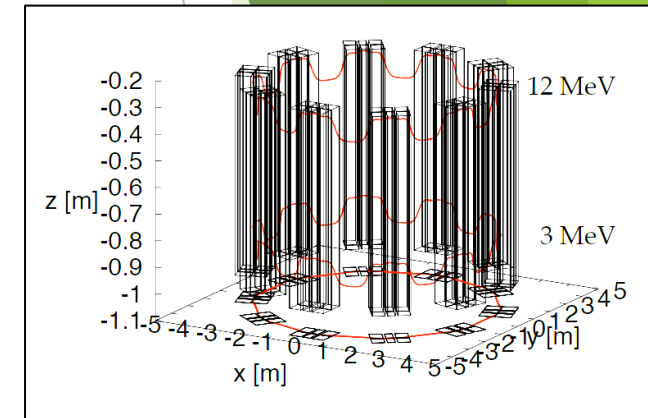
Tunable permanent magnets for sustainable particle accelerators

Comparative Life Cycle Assessment of NdFeB Magnets



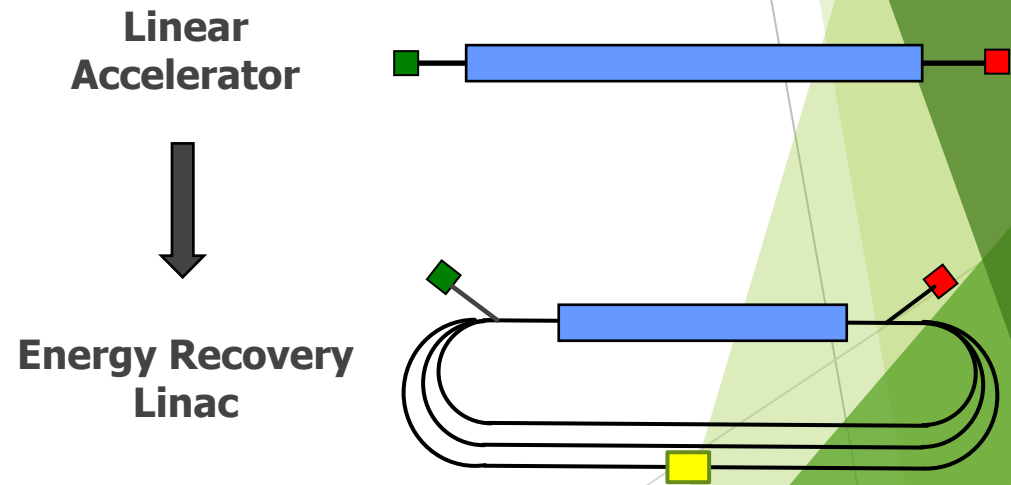
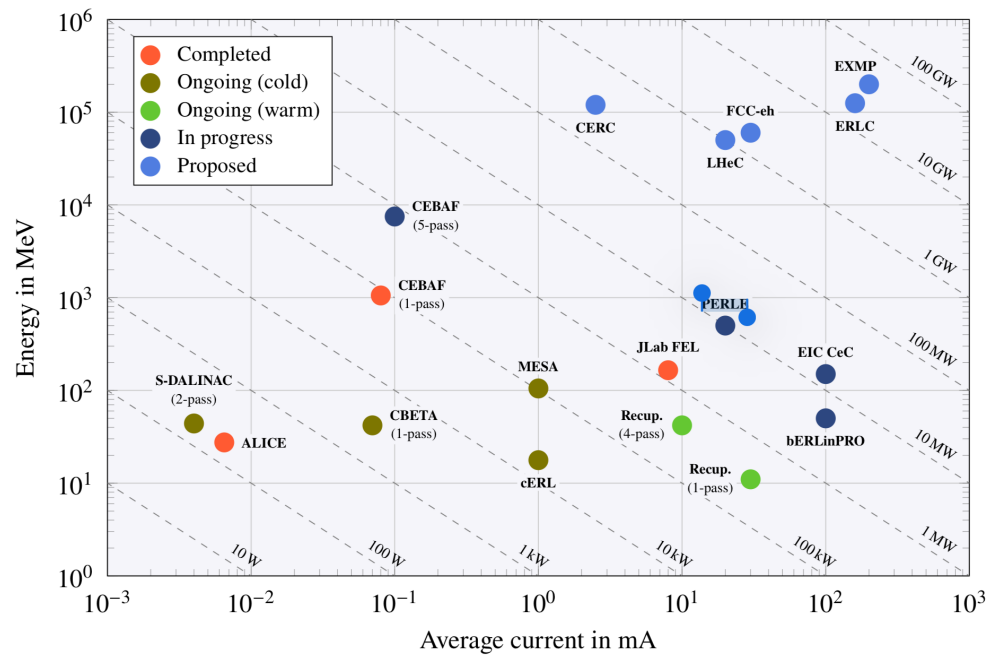
# Newer technologies: Fixed Field Alternating gradient (FFA) rings

- ▶ High energy efficiency possible due to super-conduction or permanent DC magnets
- ▶ Can deliver a high average beam current
  - ▶ The acceleration pattern is not constrained by the B field ramping speed (as in synchrotrons)
  - ▶ Solely determined by the RF voltage and frequency
- ▶ The high repetition rate could be used to deliver pulsed beams to multiple target stations at different rates
  - ▶ Leads to neutrons being able to be generated with a variety of time structures.



# Newer technologies: Energy Recovery Linacs (ERL)

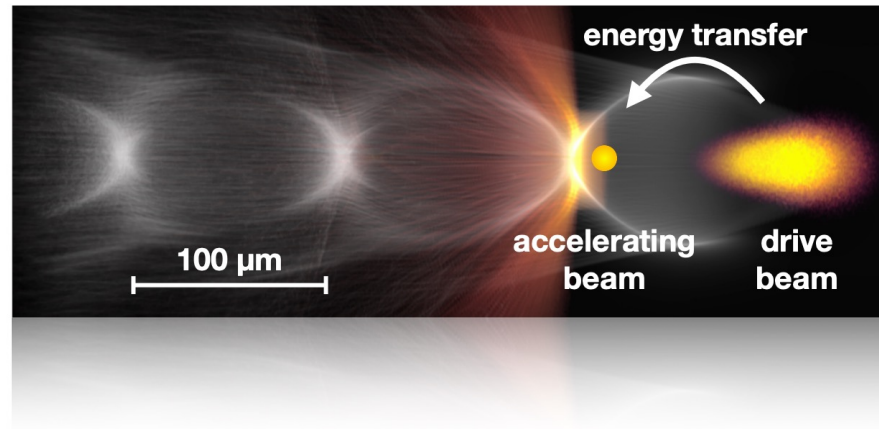
- ▶ Utilise the kinetic energy of unused particles in increasing the RF field intensity
- ▶ Accelerate → use → decelerate
- ▶ More energy efficient
- ▶ Largest energy consumption will be the cryo



<https://arxiv.org/pdf/2207.02095.pdf>

# New technologies: Plasma accelerators

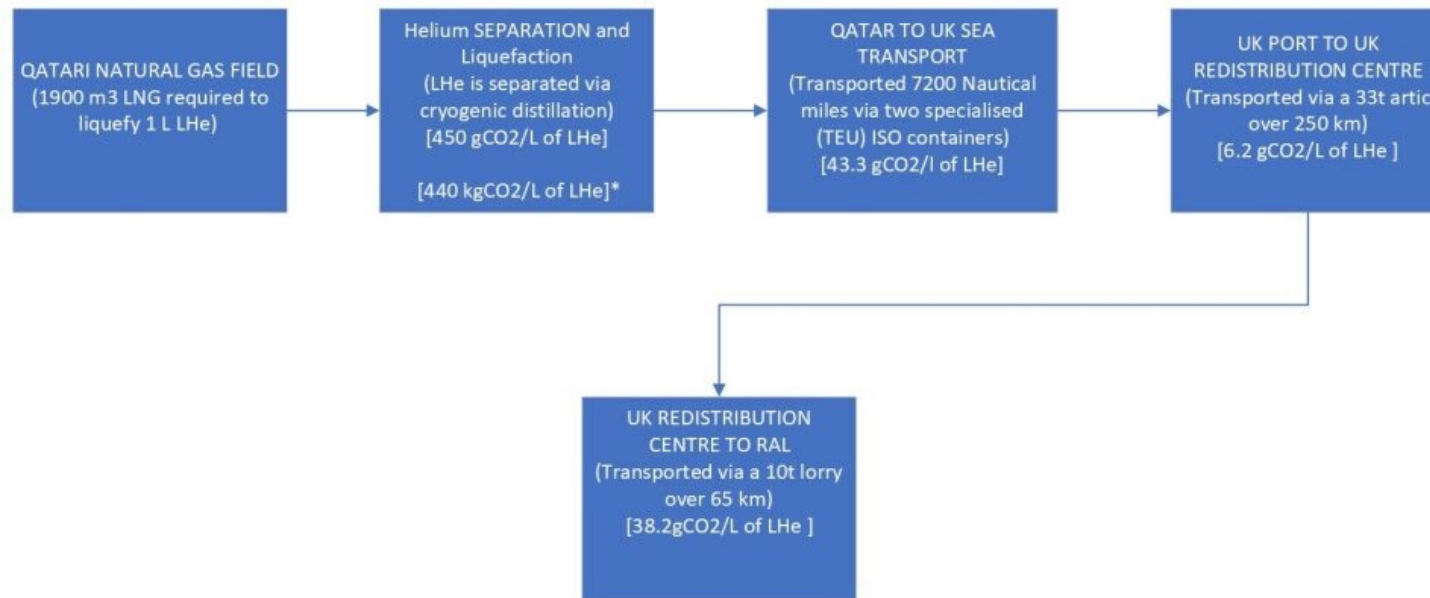
Charge-density wave in plasma



- ▶ High power-transfer efficiency
- ▶ Potential for wall plug power to beam power efficiency of 50%?

# Reduction in resource consumption: Helium

- ▶ Increasingly rare and expensive!
- ▶ Also comes with associated environmental impact



Helium source	Production footprint (g CO <sub>2</sub> /l He)	Transportation footprint (g CO <sub>2</sub> /l He)	Boil-off losses (%)	Total footprint (g CO <sub>2</sub> /l He)
ISIS helium recovery system	450	0	10	500
Gas company (excluding LNG production)	450	87.7	25	712
Gas company (including LNG production)	440,000	87.7	25	587,000

0.08% of gas company inc. Liquid Natural Gas (LNG) production

The authors have applied an assumption that ~25% of the gas suppliers' liquid helium boils off during transport, compared to ~10% at ISIS.

# Particle accelerator waste

- ▶ Waste occurs throughout lifetime
- ▶ Many types of waste, and lots of it
  - ▶ Especially at decommissioning



# Reducing radioactive waste

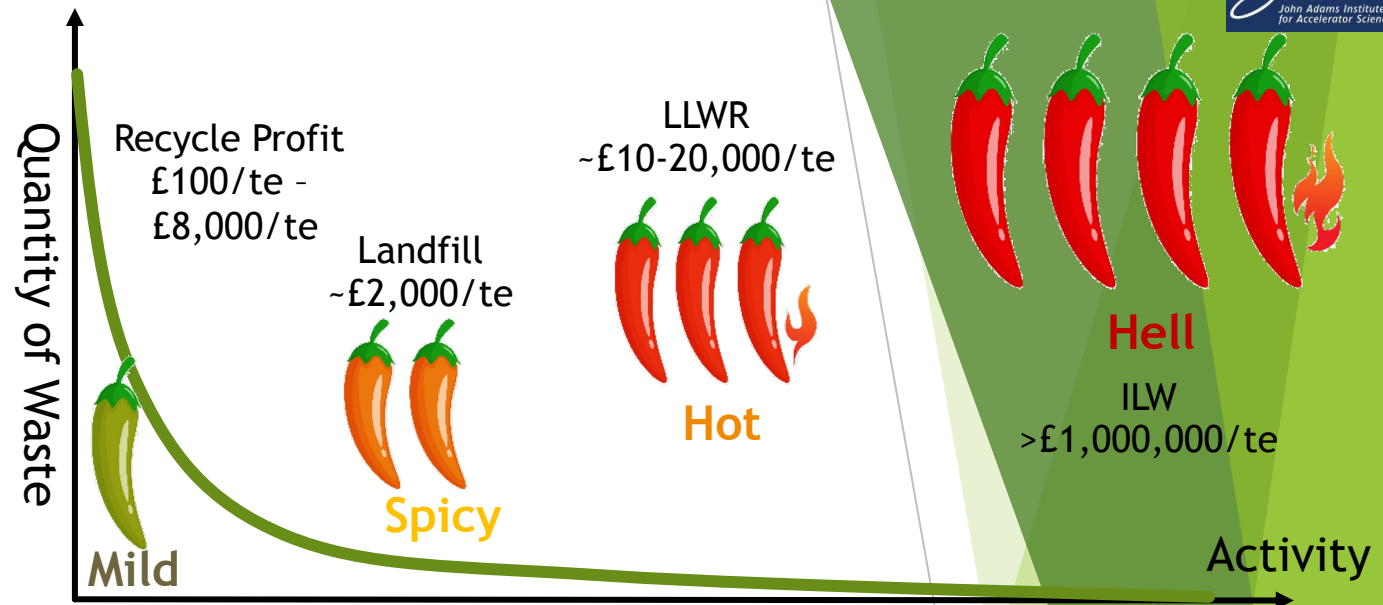
- ▶ Accelerators can generate some highly active hazardous waste
  - ▶ Operational and End Of Life
- ▶ Long lived radionuclides are the relevant topic for waste management at accelerator facilities
- ▶ Electron accelerators:
  - ▶ Not (usually) significant  $< 13$  MeV
  - ▶ Radioactivity comes from secondary photo-nuclear interactions
- ▶ Proton/ion accelerators:
  - ▶ Threshold reactions can occur at almost all energies
    - ▶ Leads to activation of accelerator components
  - ▶ Spallation and neutron production
    - ▶ Also activates surrounding materials!



# Reducing radioactive waste

- ▶ The UK currently lacks enough capacity for disposal of ILW and High Activity Waste (HAW)
- ▶ Geological Disposal Facility (GDF) is in early planning stages
  - ▶ GDF schedule 2040-2108
- ▶ Waste must safely store for ~20-90 years...

**ISIS radioactive waste**  
150 - 300 tonnes of radioactive waste per year  
~30,000 - 35,000 tonnes decommissioning



Low Activity Low Level Waste      Low Level Waste      Intermediate Level Waste

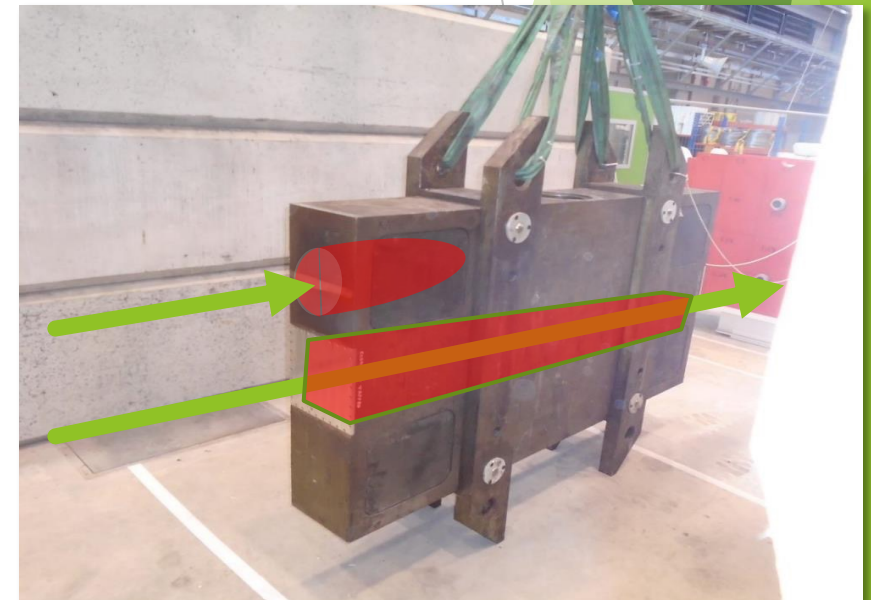
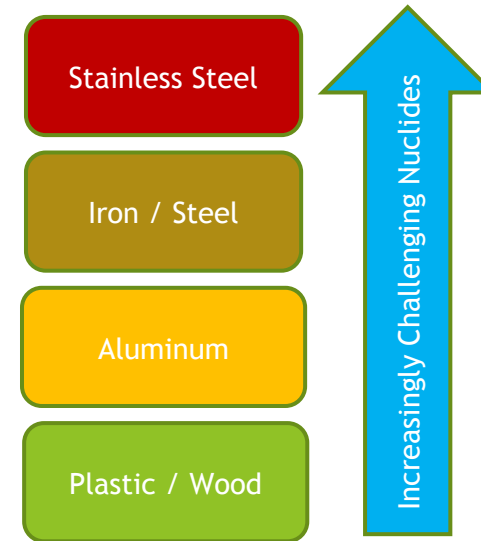
What would it cost to dispose ISIS current waste right now?

Waste Category	Current Volume	Disposal Cost
LA-LLW	1,140 te	~ £2.2 M
LLW	100 te	~ £1.5 M
ILW	70 te	~ £ 70 M

*This is just disposal cost*

# Reducing radioactive waste

- ▶ Understand what you expect to generate
- ▶ Plan and manage through the full lifecycle
  - ▶ Minimise (beam losses, material selection)
  - ▶ Segregation
  - ▶ Characterise
  - ▶ Storage
  - ▶ Disposal
- ▶ Adequate facilities (remote waste handling)
- ▶ Plan for site legacy after operation





# Other optimization

e.g. could machine learning aid us?

## 1. Simulation

- ▶ enhance simulation and modelling of particle accelerator processes for more accurate predictions of performance and energy usage such that researchers could identify ways to improve efficiency and reduce environmental impact before physical implementation.

## 2. Optimise Energy Use

- ▶ analyze data on energy consumption patterns of particle accelerators and reduce energy without compromising performance. Potential here for real-time adjustment of machine parameters.

## 3. Optimise Material Use

- ▶ optimize materials used and component design in particle accelerators to improve efficiency and reduce environmental impact.

## 4. Beam Control

- ▶ predict and control beam characteristics such as intensity, position, and stability using ML models to operate more efficiently, reduce energy consumption and minimize radioactive waste.

## 5. Fault Detection

- ▶ proactively detect anomalies using sensors and predict potential failures in particle accelerators to prevent unexpected downtime and environmental impact associated with spares and repairs.

# Evaluating environmental impacts

There are many methods to evaluate various environmental impacts

- ▶ “Back of envelope”
- ▶ Environmental impact reports
- ▶ Carbon emission/footprint reports
- ▶ Life Cycle Assessments/Analyses
  
- ▶ What is important is
  - ▶ Appropriate level
  - ▶ Documentation/Methodology
  - ▶ Reproducibility

# Antec Magnet Carbon Footprint

## Materials:

		kgCO <sub>2</sub> e/kg	Source
Oxygen free copper	Copper, Finland	0.400	Northey, 2012
Magnetic Steel: M270-50A	Steel, Germany	1.708	Hasanbeigi, 2016
G11 plates	Fibreglass, Europe	1.500	PwC, 2016
Epoxy resin	Epoxy resin, World	6.700	Venkatesh, 2009

## Supplies (location):

			kgCO <sub>2</sub> e/t.km	km	kgCO <sub>2</sub> e/kg
Copper	Finland	Road freight, Europe	0.1	3800	0.531
Magnetic Steel	Germany	Road freight, Europe	0.1	1700	0.238
G11	Spain	Road freight, Europe	0.1	410	0.057
Epoxy resin	Spain	Road freight, Europe	0.1	410	0.057

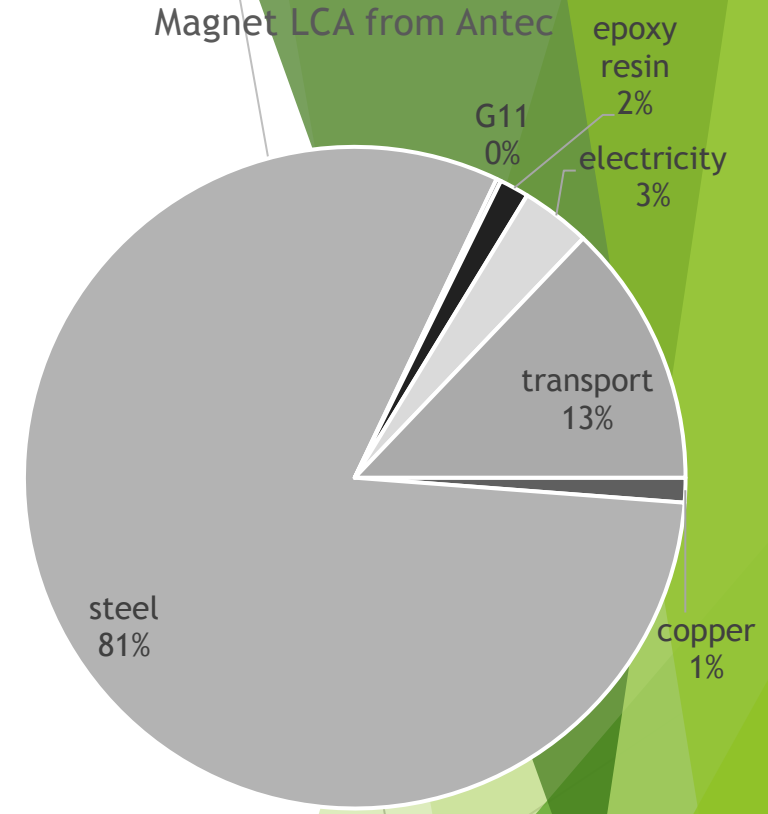
## Use of materials (quantities/surplus):

	end use [kg]	consumed [kg]	kgCO <sub>2</sub> e	transport kgCO <sub>2</sub> e
Copper: 70kg (100% utilization)	70	70	28	37
Magnetic Steel: 1100 kg of material consumed to use 700 kg (63.6% utilization)	700	1100	1879	261
G11: Consumed 3.5 kg material to use 2.5 kg (71.5 %)	2.5	3.5	5	0
Epoxy resin: 5 kg per coil	5	5	34	0
Other materials in commercial parts not considered				
<b>Totals</b>	<b>777.5</b>	<b>1178.5</b>	<b>1946</b>	<b>299</b>

## Energy consumption (per magnet) (\*):

	kWh/kg
Manufacture/yoke stacking and curing: 0.25 kWh/kg	0.25
Winding: 0.1 kWh/kg	0.1
Impregnation and curing: 0.3 kWh/kg	0.3

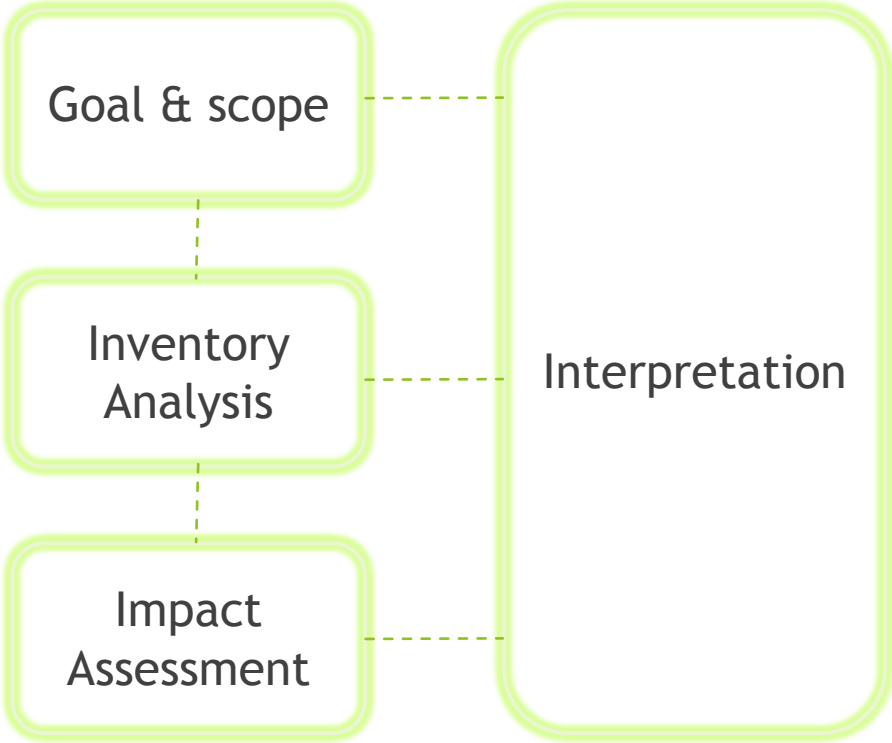
<b>Total</b>	<b>0.65</b>	<b>505 kWh</b>
Spain, 2020	156	gCO <sub>2</sub> e / kWh
	79	kgCO <sub>2</sub> e
<b>Overall total</b>	<b>2324</b>	<b>kgCO<sub>2</sub>e</b>
	<b>2.99</b>	<b>kgCO<sub>2</sub>e/kg finished product</b>



Scenario	kgCO <sub>2</sub> e	% change
Baseline	2324	0%
Mexican steel	1449	-38%
Rail freight for steel	2091	-10%
EU-average for copper	2393	3%

# A Life Cycle Analysis/Assessment (LCA)

► ISO 14040/44 standard



LCA steps.

# Goal & Scope

## Goal

- ▶ What is the goal of this study? Are you trying to compare designs? Identify hotspots of impact? Report on a specific component/material?

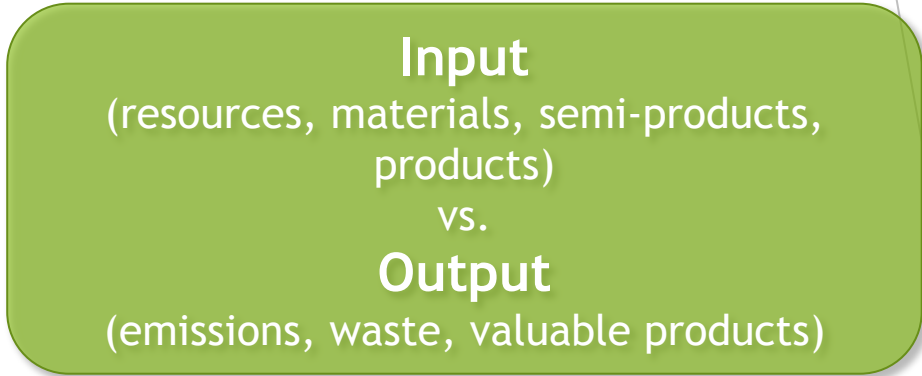
## Scope

- ▶ What will the study cover? What will it ignore? What assumptions are made?
- ▶ Decide on a functional unit, e.g., "user hours delivered over 40 years of operation at an energy of 1.2 GeV".
- ▶ Define impacts considered.
  - ▶ Environmental impact is not just CO<sub>2</sub>e (toxicity, biodiversity, human health, ...)

# Inventory Analysis

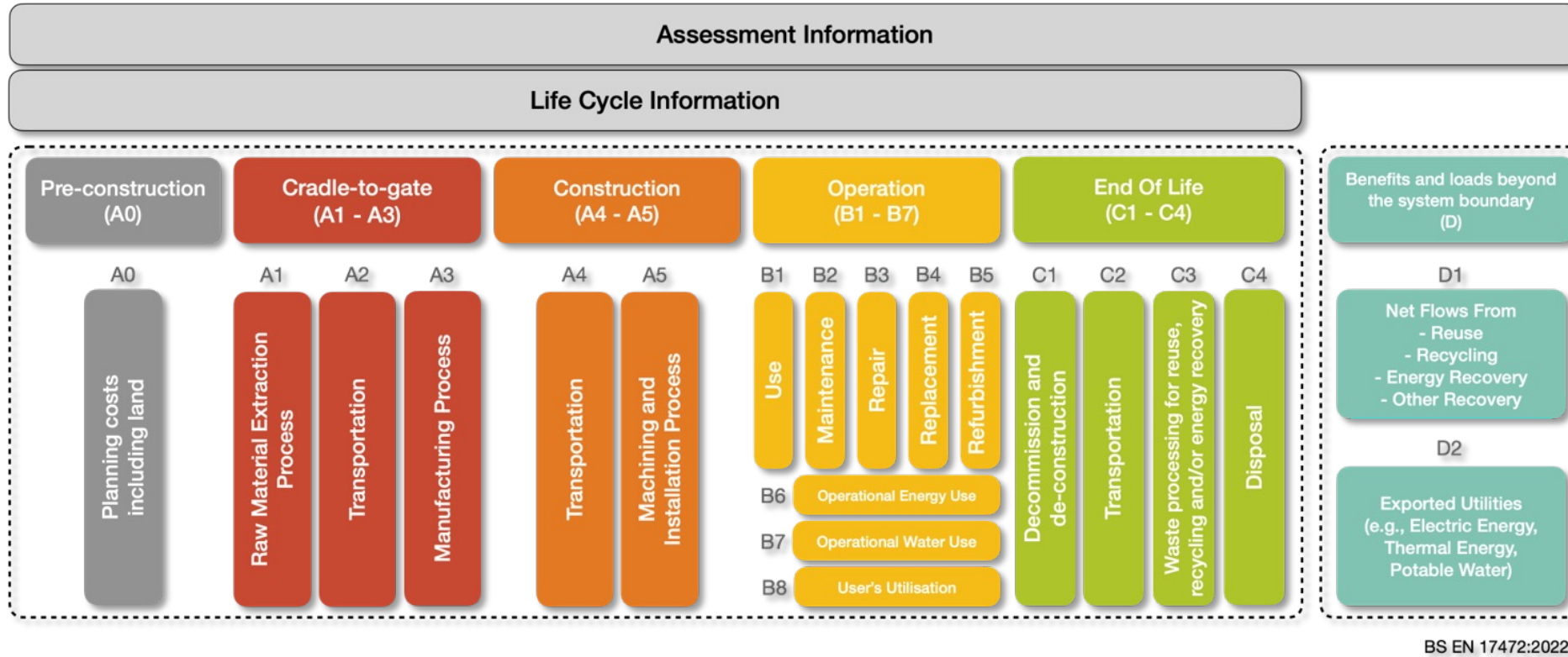
## Data collection and quality control:

- **Construction**
  - Facility
  - Machine
  - Shielding
  - Computing
  - Location
- **Operation/Active life**
  - Energy consumption
  - Resource consumption inc. leakage
  - Failure likelihoods/risks inc. replacement/repair
- **Decommissioning**
  - Storage of radioactive materials



# Impact Assessment

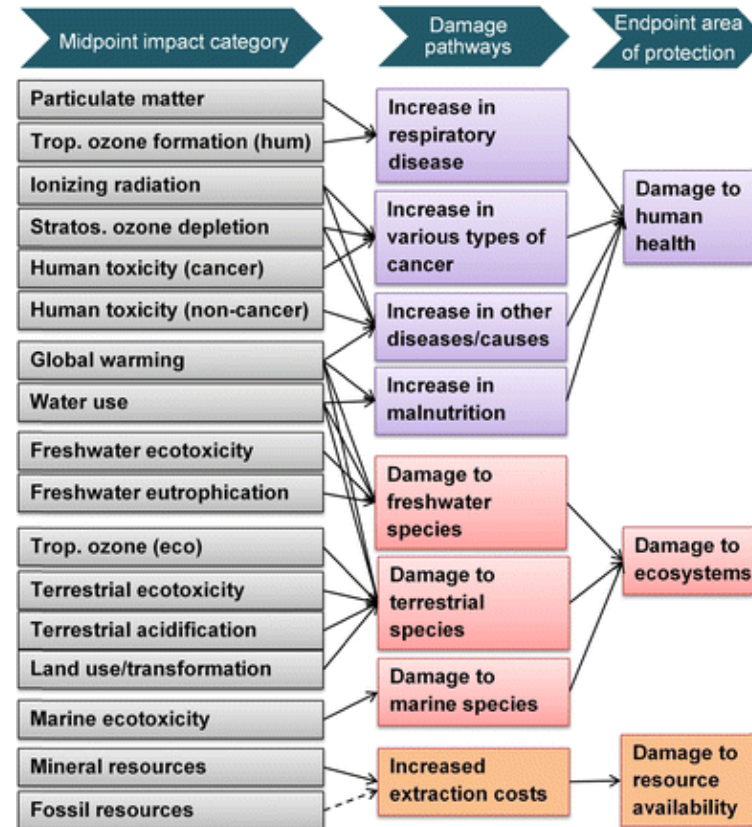
- A. Construction
- B. Operation
- C. Decommissioning



- ▶ EN 17472:2022 is an engineering standard which we can use as a basis.

# Impact Assessment

- ▶ Many impact assessments exist, no standard yet set within our field
- ▶ ReCiPE:2016 Midpoint (H) Life Cycle Impact Assessment Method





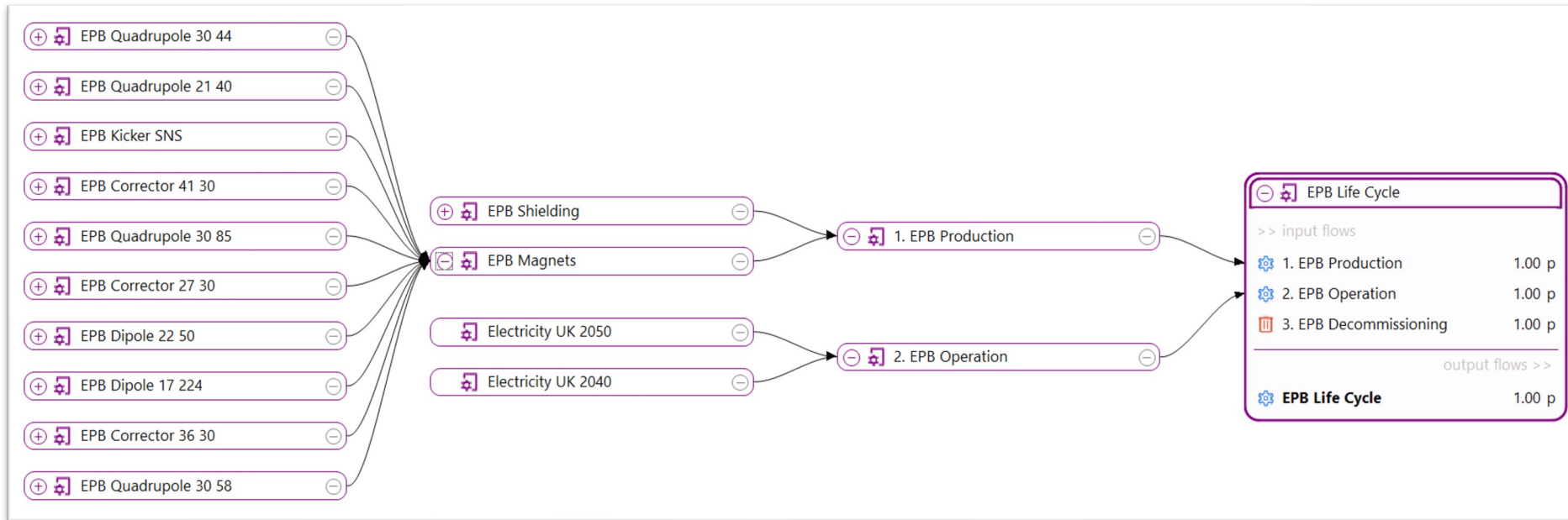
# LCA Software

- ▶ OpenLCA
- ▶ Simapro
- ▶ OneClick LCA
- ▶ Ansys Granta Eco-audit
- ▶ ...

# LCA Software

## ► OpenLCA

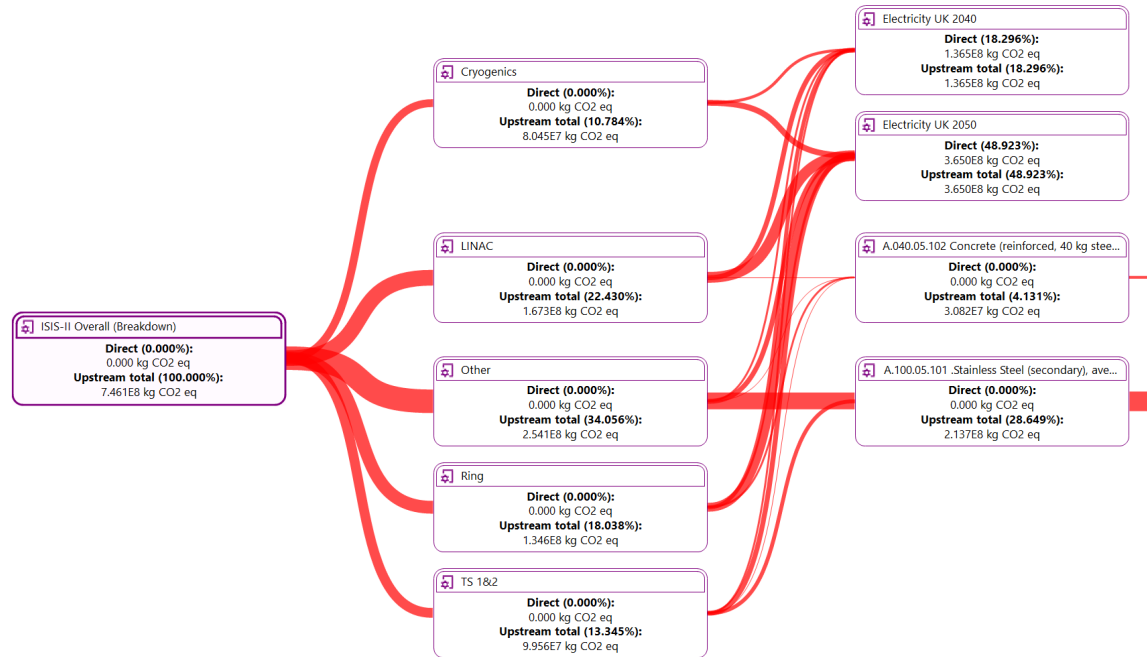
- Idemat database free for academics



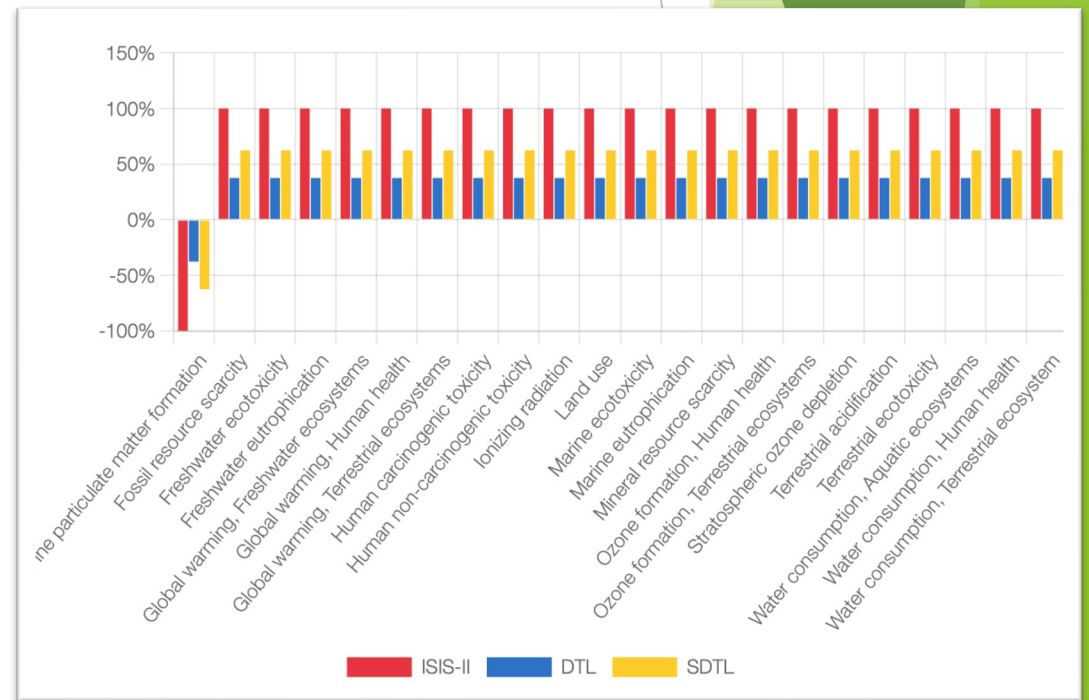
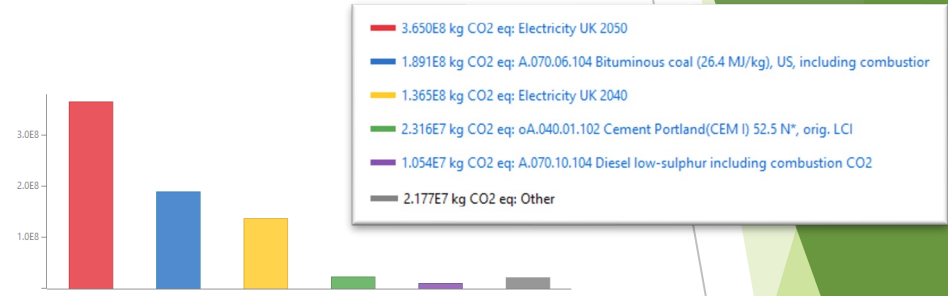
# LCA Software

## OpenLCA

- ▶ Idemat database free for academics
- ▶ Open Source
- ▶ Compatible with Python
- ▶ Enables fast calculation of component lifetime impacts
- ▶ Enables comparison of components, different designs etc.



Contribution	Process	Total result [kg C...]
100.00%	ISIS-II Overall (Breakdown)	7.46052E8
> 34.06%	Other	2.54073E8
> 22.43%	LINAC	1.67336E8
> 18.04%	Ring	1.34572E8
> 13.35%	TS 1&2	9.95621E7
> 10.78%	Cryogenics	8.04518E7
> 01.35%	Support Buildings	1.00565E7



## Conclusion and summary

- ▶ Particle accelerators have an environmental impact
- ▶ We should reduce it
- ▶ There are endless opportunities to do so
- ▶ Each have different levels of impact themselves
- ▶ Evaluation allows identification of next steps

# Backup slides

# The Energy Crisis

- ▶ Humanity's power consumption is growing, and still growing, to the point of an energy crisis.
- ▶ David MacKay TED talk: [How the Laws of Physics Constrain Our Sustainable Energy Options](#)
  - ▶ Book! ([free pdf and other versions](#))
- ▶ Energy crisis has many possible solutions and *opinions*:
  - ▶ “Renewables! Only renewables.”
  - ▶ “Slow down our development.”
  - ▶ “Technology will save us.”
- ▶ Realistically, none of these on their own is our single saviour.

# Established groups, organizations and events to be aware of

EuCARD2 - EnEfficient, WP3 Energy Efficiency

High Energy Physics, Cosmology, Astroparticle Physics, Nuclear and Hadron Physics (HECAP+) Initiative

i.FAST

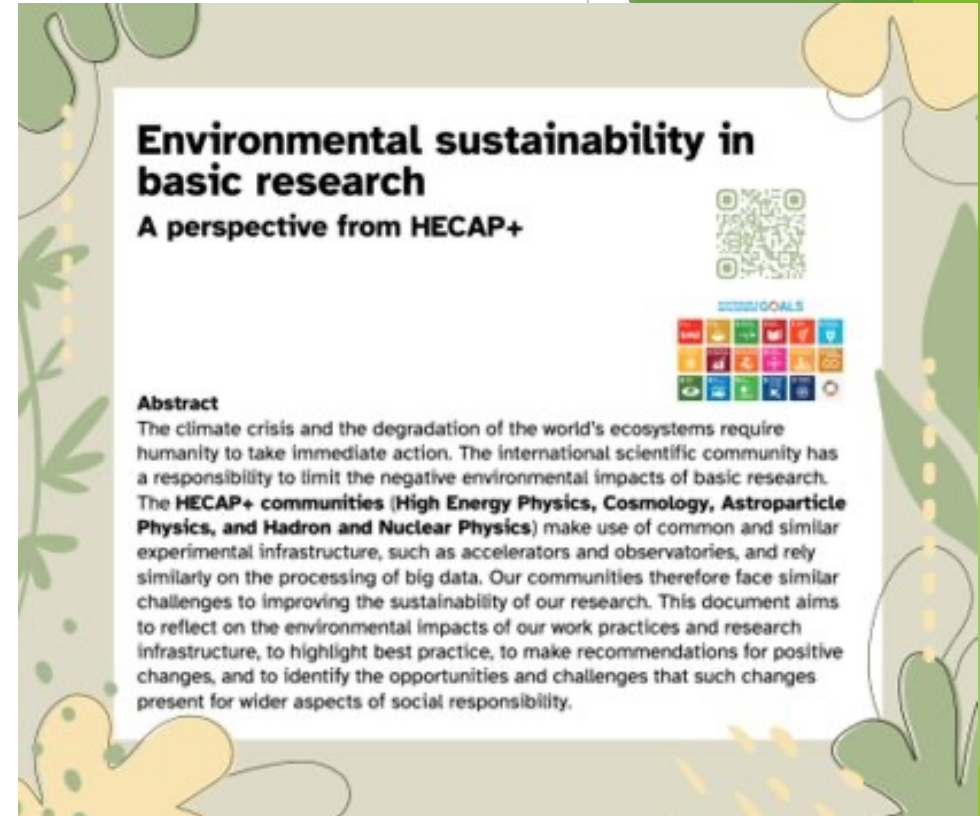
ESSRI Workshops [previous 2022 workshop](#) , [next workshop: Madrid 25-27 Sep 2024](#)

EAJADE Workshop [on Sustainability in Future Accelerators \(WSFA2023\) \(25-27 September 2023\)](#)

Sustainable HEP 2024 (**upcoming!**): [Sustainable HEP 2024 – 3rd Edition \(10-12 June 2024\)](#)

# The Sustainable HECAP+ reflective document

- Reflects on sustainability in the context of HECAP+ (High Energy Physics, Cosmology, Astroparticle Physics plus Hadron and Nuclear Physics).
- Initiative conceived at the 2021 Sustainable HEP workshop, hosted online by CERN.
- Broken down by key areas for our research, with best practice examples, case studies and recommendations.
- Relevance across big science, and all those engaged in it: scientists and non-scientists alike.
- You can show your support of this document through endorsement at the website!



<https://sustainable-hecap-plus.github.io>



# Additional Resources

- ▶ [\[2203.12389\] Climate impacts of particle physics](#)
- ▶ [\[2307.04084\] Sustainability Strategy for the Cool Copper Collider](#)
- ▶ [Fraunhofer CLIC Energy Study: Energy Load and Cost Analysis](#)
- ▶ [ARUP CLIC and ILC Life Cycle Assessment Final Report](#)