Accelerator Facility Sustainability

JAI AB | University of Oxford | April 2026

Dr. Hannah Wakeling

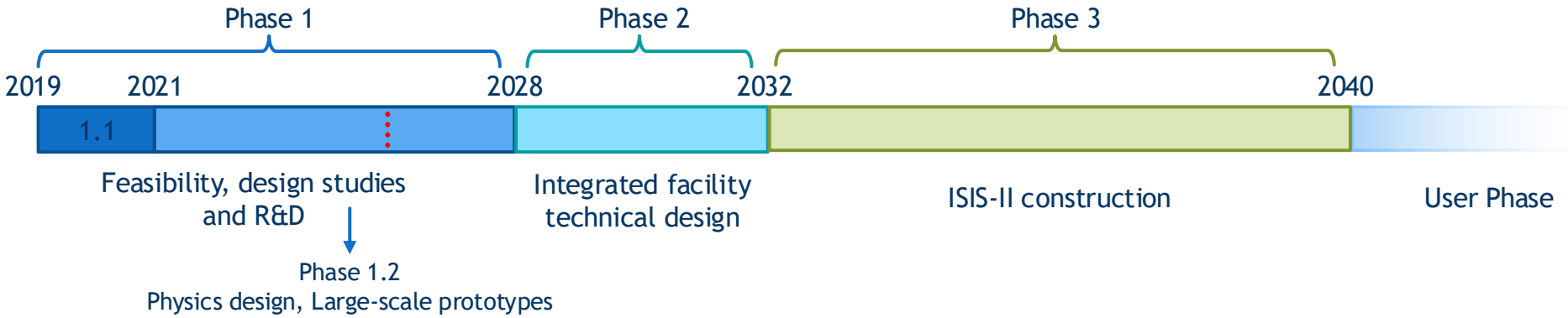
John Adams Institute for Accelerator Science

Overview

- ISIS-II Neutron and Muon Source and environmental sustainability
  - Life Cycle Assessment (LCA)
  - Sustainability Strategy
- Open Research Life Cycle Assessment (ORLCA) repository
- High-level environmental sustainability guidelines for large accelerator facilities
- Communication, collaboration and education
- Future

ISIS-II Life Cycle Assessment (LCA) of Phase 1.2a

- LCA considering construction (2032-2040), operation (2040-2100), and decommissioning (2100-2170)
- Phase 1.2a (1.25 MW, 1.2 GeV), Greenfield option, RAL
  - Future: consideration of Phase 1.2b (2.4 MW, 1.2 GeV)
- Original proposed timeline (to resume as soon as the opportunity arises):

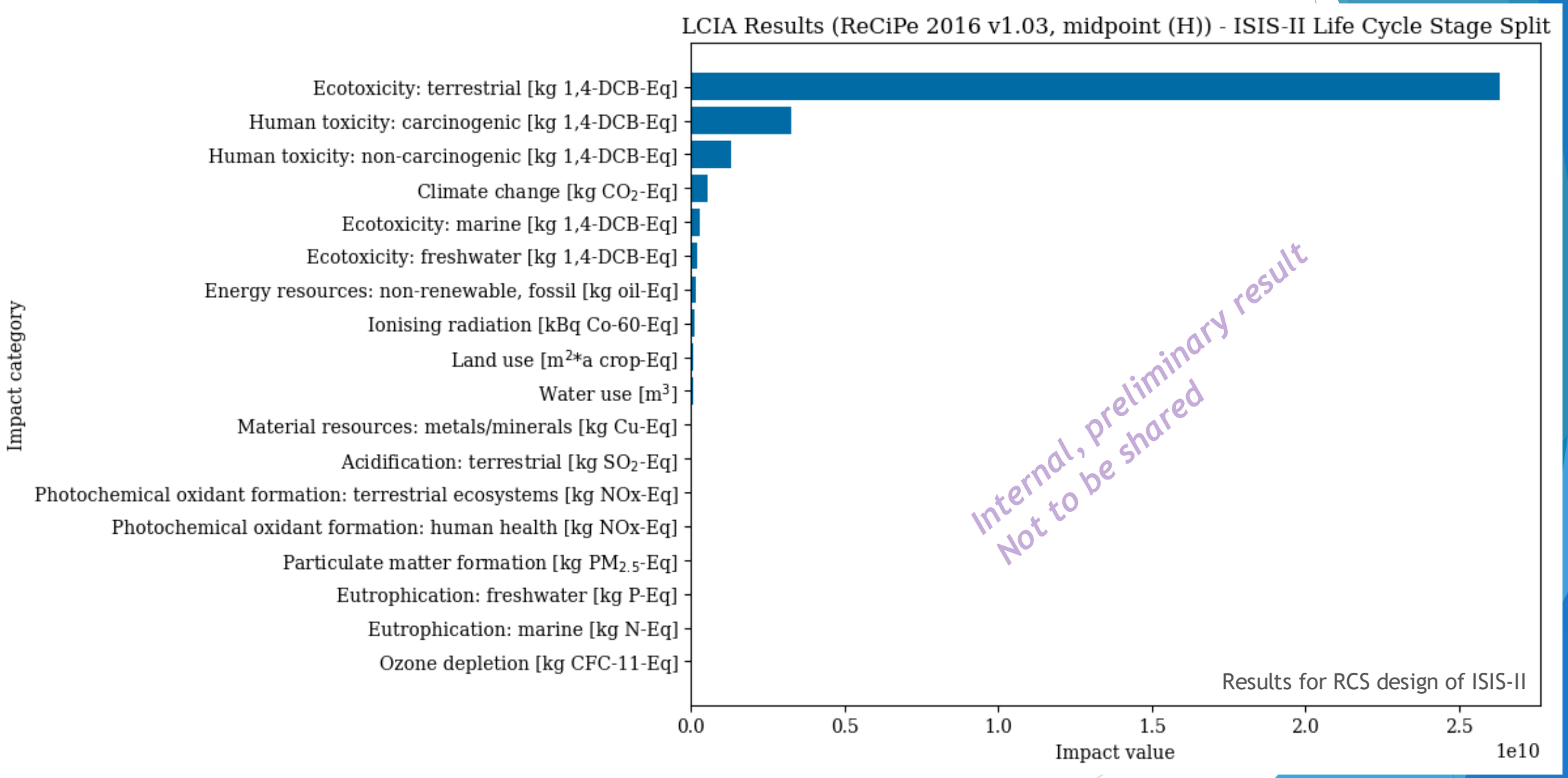


- Question: How to perform an LCA of a full accelerator facility?
  - Utilise the iterative nature of LCAs to continually improve the understanding of the environmental impact of ISIS-II as designs evolve, and as LCA inventories, databases etc. develop.

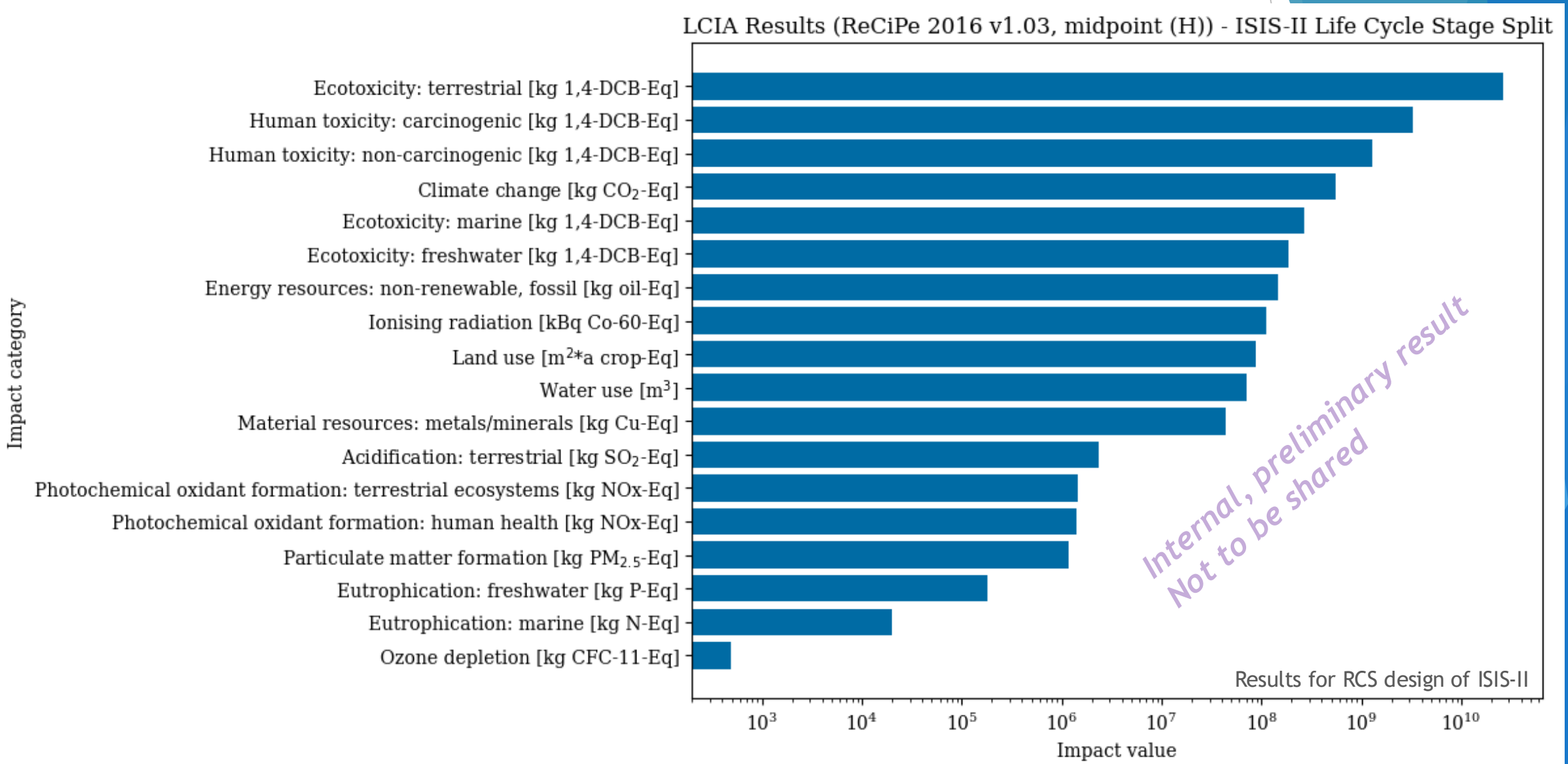
(Simplified) Life Cycle Assessment

- Construction/production, operation + decommissioning
- Goal & Scope: To identify the lifetime environmental impacts of a Rapid Cycling Synchrotron (RCS) and Accumulator Ring (AR) and the corresponding linear accelerator (linac) designs necessary to deliver a beam of protons at an energy of 1.2 GeV to the neutron and muon community over a period of 60 years -> *functional unit*.
- Life Cycle Inventory: OpenLCA, ecoinvent allocation cut-off by classification model and unit process database, using BS EN 17472 standard as guidance.
  - Sources of data including but not limited to:
    - Internal technical documentation (Phase 1.2a)
    - Extrapolation/sampling from similar facilities: SNS AR (1.4 GeV) and J-Parc RCS (3GeV)
- Life Cycle Impact Assessment: ReCiPE 2016 midpoint (H)
  - with a focus on Climate Change impact factor [kg CO_2e] referred to as Global Warming Potential (GWP) or Global Warming Impact (GWI)

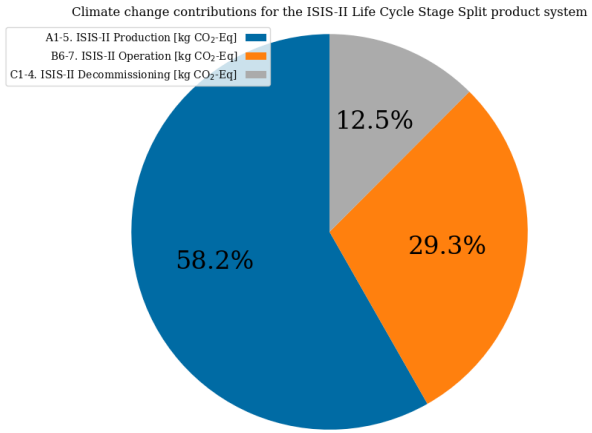
(Simplified) Life Cycle Assessment Results

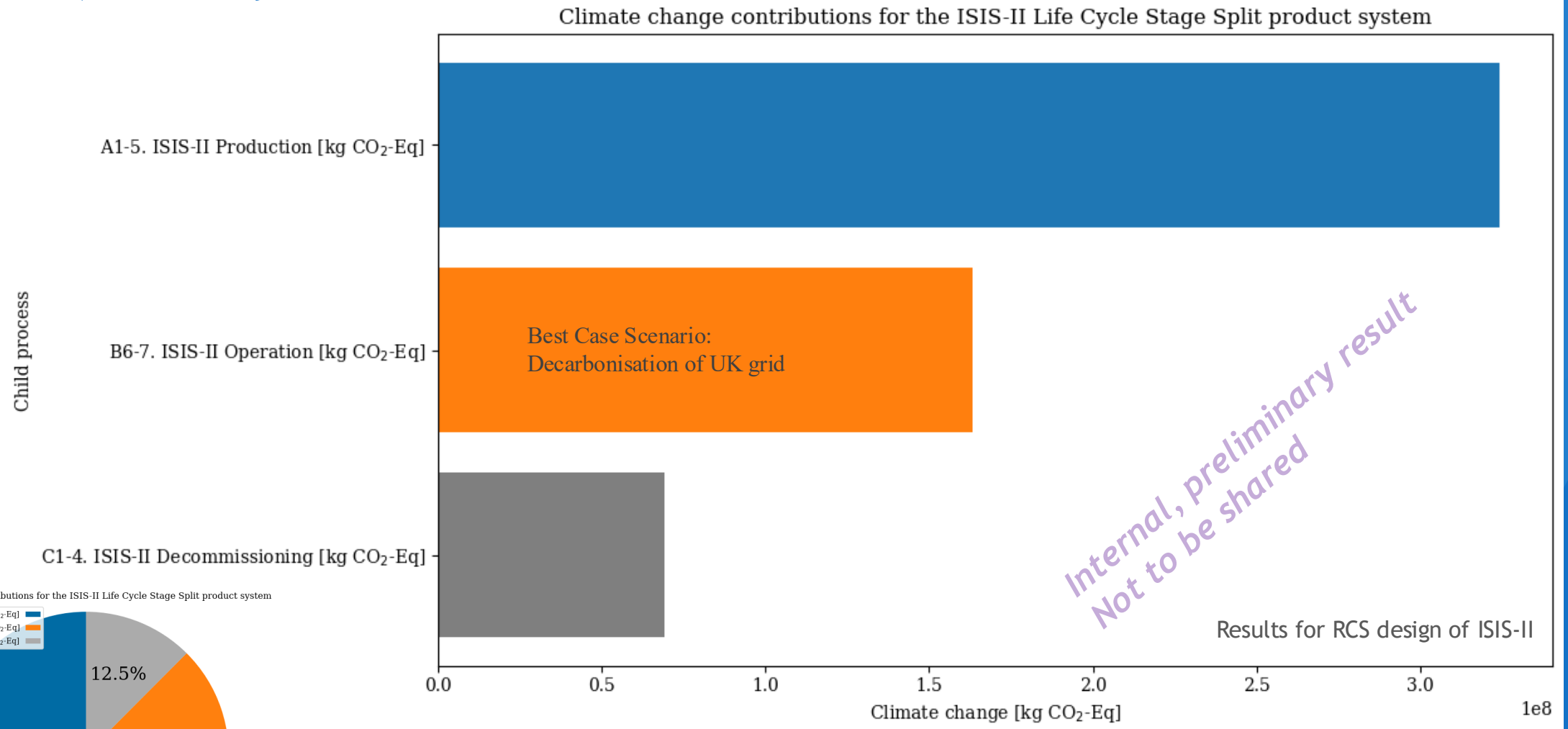


(Simplified) Life Cycle Assessment Results

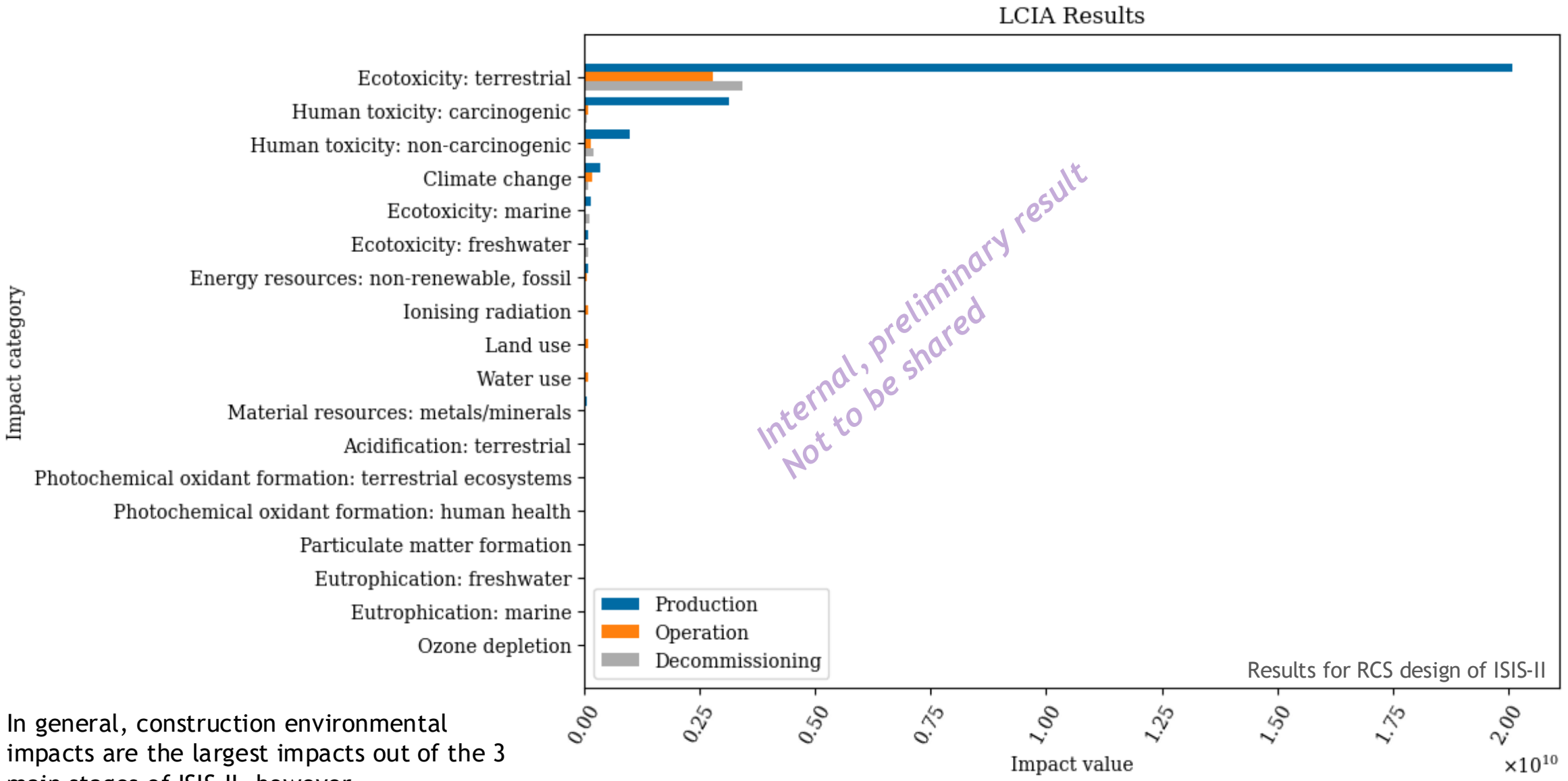


(Simplified) Life Cycle Assessment Results



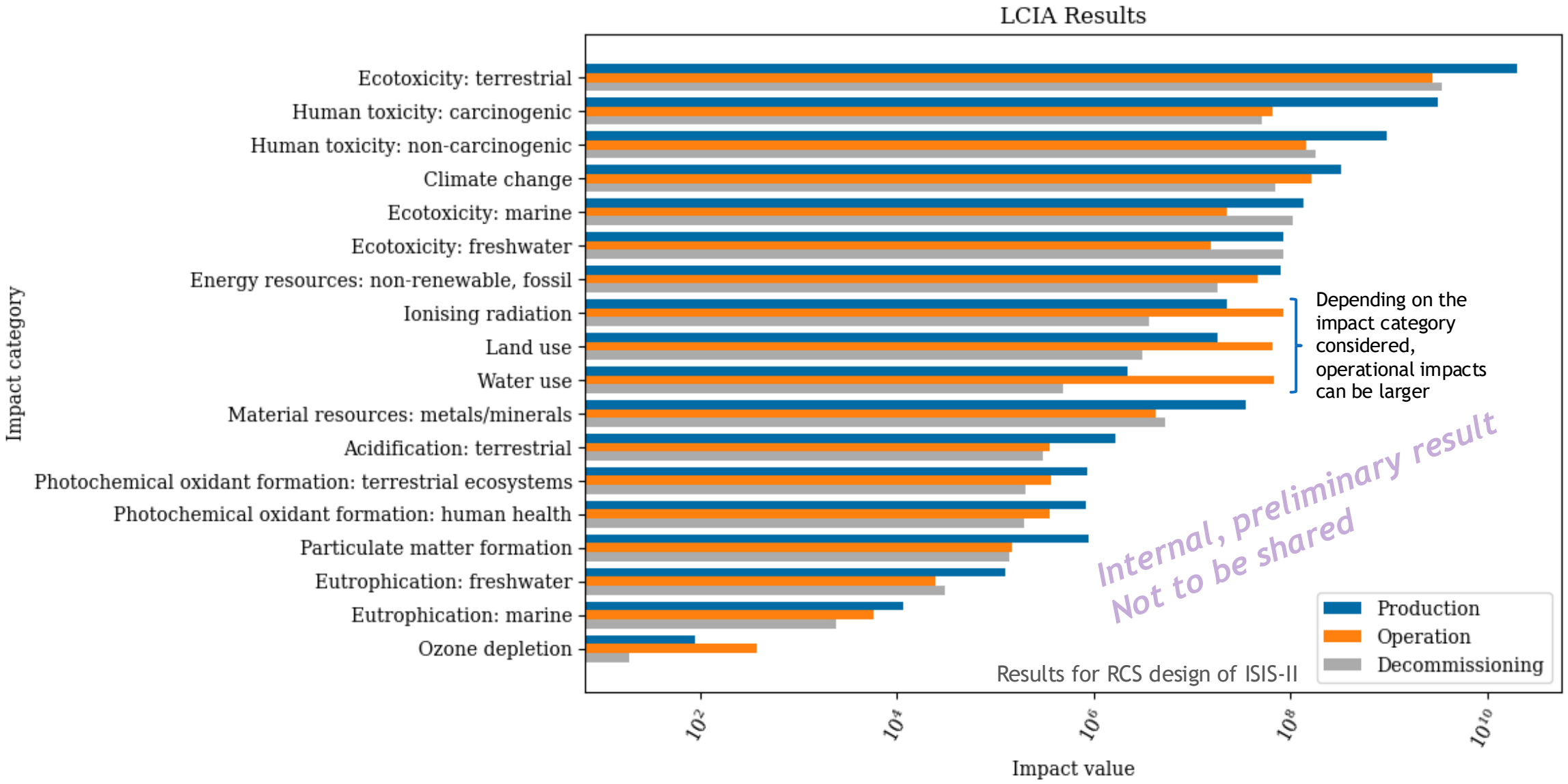


(Simplified) Life Cycle Assessment Results



In general, construction environmental impacts are the largest impacts out of the 3 main stages of ISIS-II, however…

(Simplified) Life Cycle Assessment Results



Results of ISIS-II LCA for Phase 1.2a (baseline study)

Which of the design options of ISIS-II would be least environmentally impactful: an Accumulator Ring (AR) or a Rapid Cycling Synchrotron (RCS)?

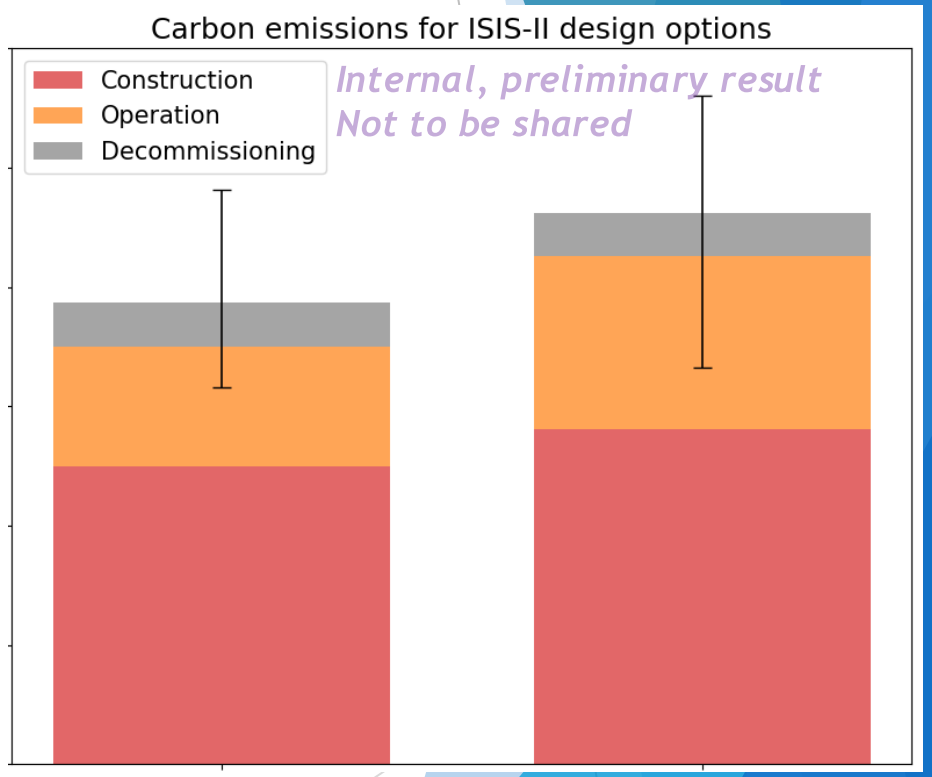
- First estimations show the AR design option *could* have a lower lifetime impact
  - Similar order of magnitude
  - Power consumption causes largest difference

- Presented to the UKRI Facility Strategic Advisory Group (FSAG)
  - December 2025

- Critical review required for publication of results

*LCA: "When a comparative study is intended to conclude on the superiority… of the compared alternatives… and to make these conclusions publicly available... **a critical review [must be] performed by a panel of interested parties**".*

- Life Cycle Assessment: Theory and Practice



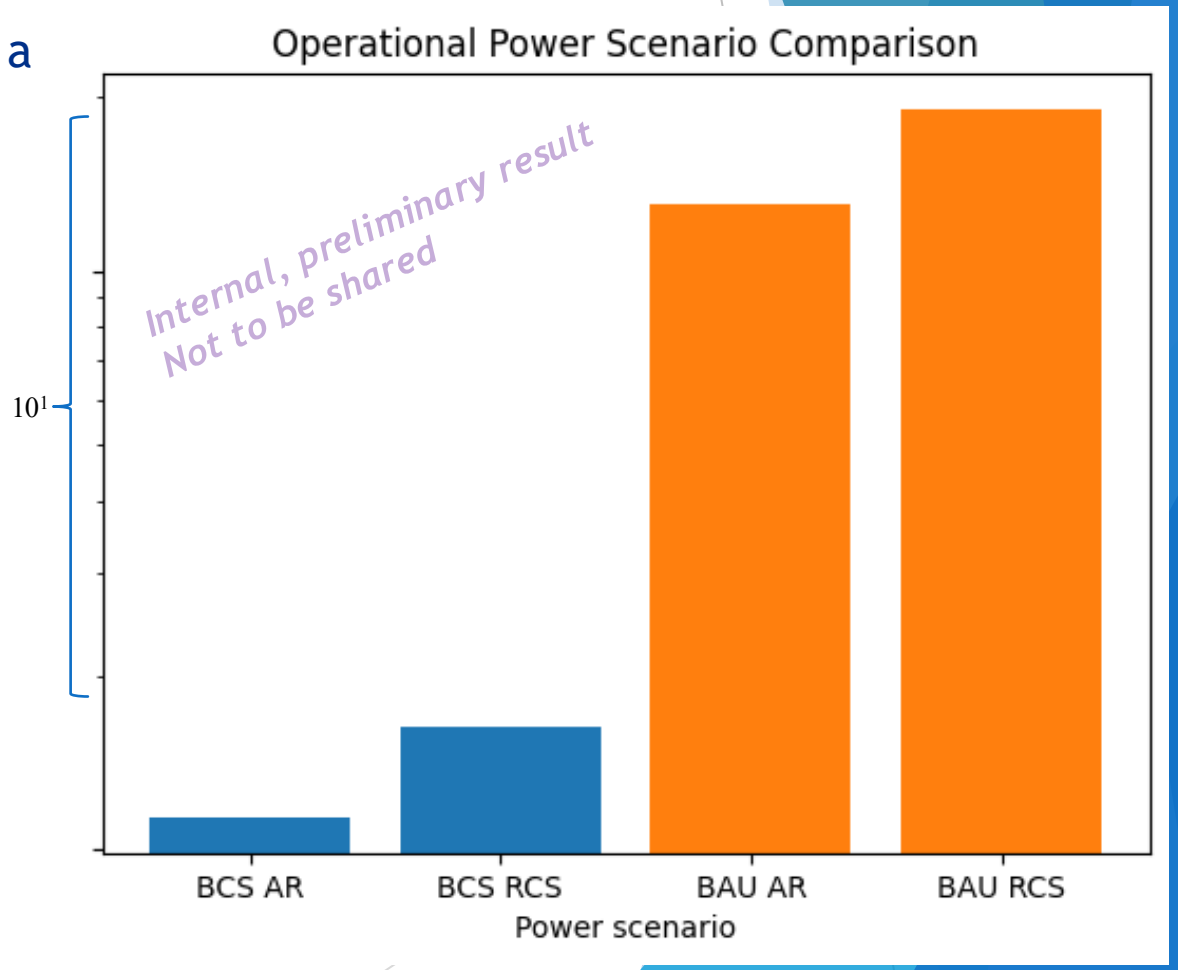
Note: Grid decarbonisation uncertainty is not included in error bars (very large uncertainty, see Slide 11)

Results of ISIS-II LCA for Phase 1.2a (baseline study)

Which of the design options of ISIS-II would be least environmentally impactful: an Accumulator Ring (AR) or a Rapid Cycling Synchrotron (RCS)?

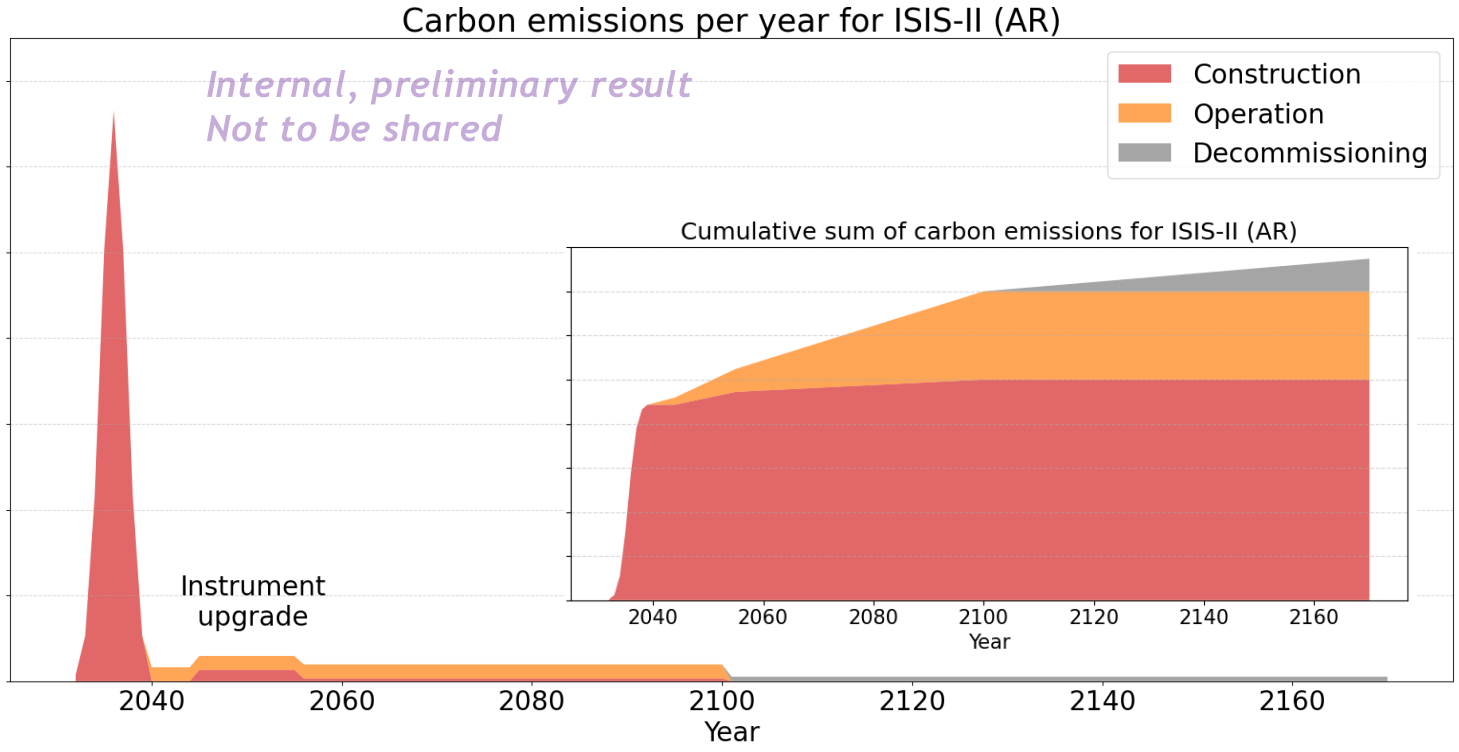
- First estimations show the AR design option *could* have a lower lifetime impact
  - Similar order of magnitude
  - Power consumption causes largest difference

- High level of uncertainty
  - Highly uncertainty of decarbonisation of UK grid
    - Comparing with impacts of using today's grid carbon factor in a Business as Usual (BAU) scenario = 10x carbon impact
  - Modelled using existing accelerators which were not built to optimise sustainability
    - Can be considered a BAU or worst-case scenario (WCS)

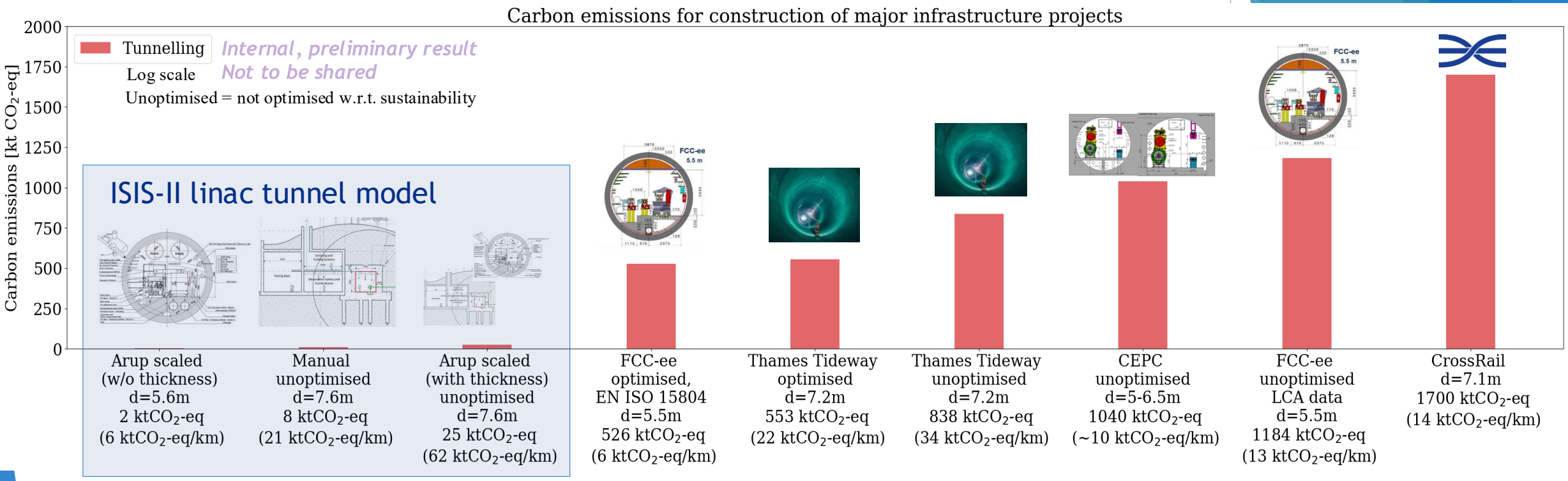


Results of ISIS-II LCA for Phase 1.2a (baseline study)

- Construction: ISIS-II and instrument upgrade in 2045
- Operation: ISIS-II and instrument upgrade start in 2055
- Decommissioning from 2100 averaged over 70 years



Comparison of tunnelling impacts



- ISIS-II requires walls of 1.6 m thick of concrete for shielding.
- ISIS-II tunnelling impact calculated manually using geometrics as no adequate model was available to scale from.
- Modelling differs between each impact report. Difficult to compare without comparing apples to oranges.

How do particle accelerator facilities compare in their environmental impacts?

Next step is to “lift the hood” to understand impacts better.

- How do various reports compare?
- What is included and excluded?
- What is an assumption versus a measurement?
- What is needed in the future to be able to compare?

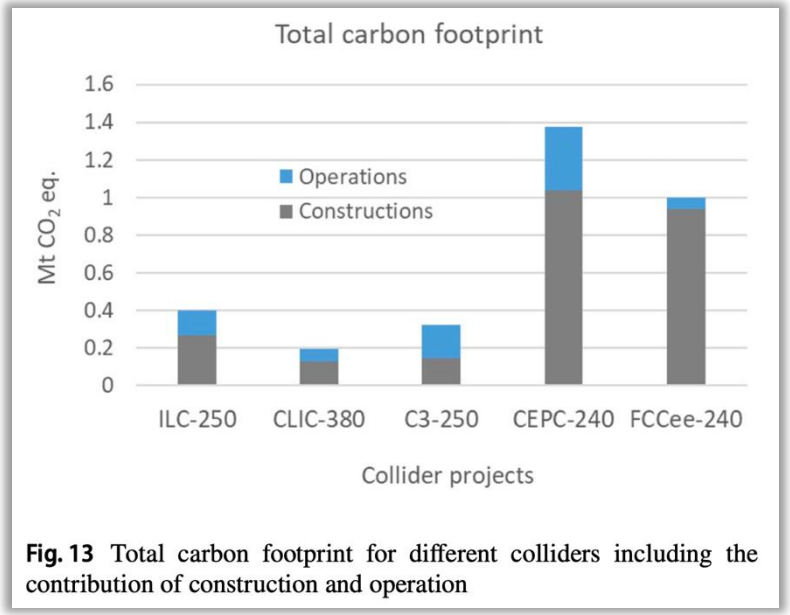


Fig. 13 Total carbon footprint for different colliders including the contribution of construction and operation

Source: The carbon footprint and CO2 reduction optimization of CEPC

Open Research LCA database (ORLCA)

Proposal: creation of an open-source repository containing:

- Field specific LCA inventories, processes and products
- Generic LCA processes, products and inventories relevant to the fields

Status:

- ArXiv concept published:
  - https://arxiv.org/abs/2509.08901
- Great feedback received
- HORIZON-INFRA-2026-01-TECH-01
  - Watch this space!

High-level environmental sustainability guidelines for large accelerator facilities – Version 2!

- Generic sustainability guidelines, recommendations and opportunities exist.
- Yet a common issue is that specific recommendations are not available for bespoke and niche areas.
- Living document created
  https://arxiv.org/abs/2501.14979
- Nature Reviews Physics Comment (Published)
  https://www.nature.com/articles/s42254-025-00878-6
- Presented invited talk at IPAC'25
- **Version 2 accepted for publication in EPJ RI Journal!**
  - As of April 3rd 2026

Communication, collaboration, education

- **ESPPU contributions:** https://cds.cern.ch/record/2957411/

9. Sustainability and environmental impact

Environmental considerations, in particular those relating to climate change, are driving the community's efforts to reduce the environmental impact of particle physics research and to develop sustainable solutions, which may also benefit society. Assessing and mitigating environmental impact is important at all levels: institutional, project and individual.

Energy consumption and emissions must be minimised when realising and operating facilities and projects. This requires the implementation of sustainability strategies, many of which can be coordinated among particle physics laboratories, environment protection, preservation of local biodiversity, energy reuse and climate-change resilience.

A. *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.*

B. *The particle physics community should continue and intensify its efforts to develop and adopt sustainable solutions.*

Communication and collaboration are at the core of the scientific life and productivity of the particle physics community, but must be balanced against the environmental consequences.

C. *An effective balance between in-person and online meetings should be considered in order to mitigate the environmental impact of carbon-intensive travel.*

Communication, collaboration, education

- ESPPU contributions: https://cds.cern.ch/record/2957411/
- Sustainable Accelerator Design Group (ISIS)
- Sustainable HECAP+ (Environmental Sustainability in Basic Research)
- Sustainable HEP conference
  - July 8th - 10th : https://indico.global/e/susthep26

Collaboration

Communication, collaboration, education

- ESPPU contributions: https://cds.cern.ch/record/2957411/
- Sustainable Accelerator Design Group (ISIS)
- Sustainable HECAP+ (Environmental Sustainability in Basic Research)
- Sustainable HEP conference
- **JAI Graduate Lecture Course: incorporation of sustainability into final project**
  - 3rd year of sustainable accelerators lecture
  - 2nd iteration of problem set (in the style of a thought exercise)
  - Goal: To encourage students to think about their environmental impact throughout the project and to exhibit the importance of evaluating and reducing their environmental impact in the design stages of the project.
  - Students considered environmental and social considerations
    - See this afternoon's student talk

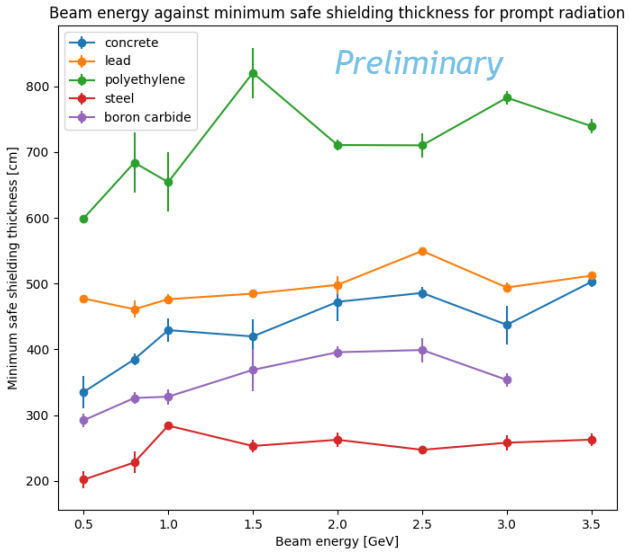
Communication, collaboration, education

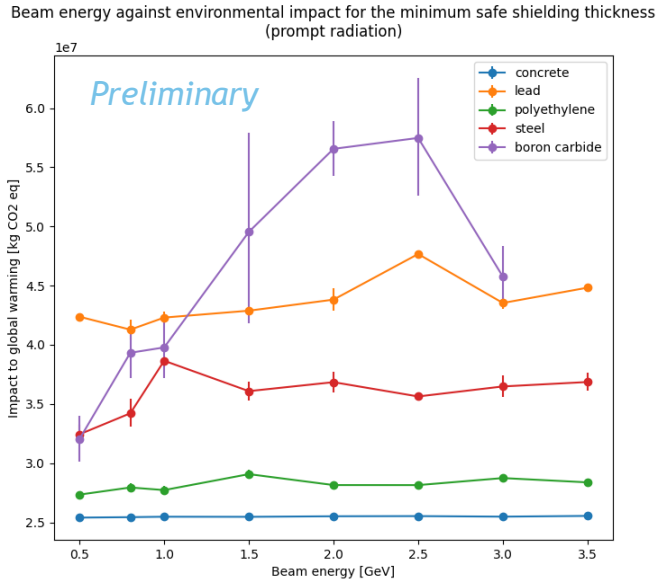
- ESPPU contributions: https://cds.cern.ch/record/2957411/
- Sustainable Accelerator Design Group (ISIS)
- Sustainable HECAP+ (Environmental Sustainability in Basic Research)
- Sustainable HEP conference
- JAI Graduate Lecture Course: incorporation of sustainability into final project
- **Summer intern:** Sustainability R&D in accelerators, focusing on optimisation of shielding for various accelerator scenarios

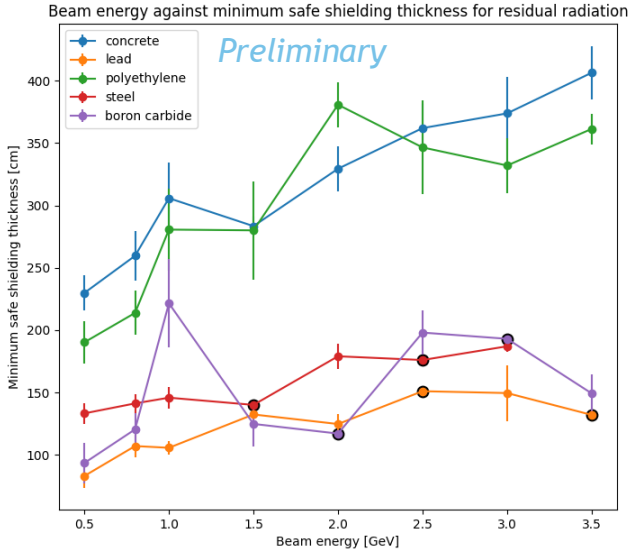
Summer Intern – R. Jackson

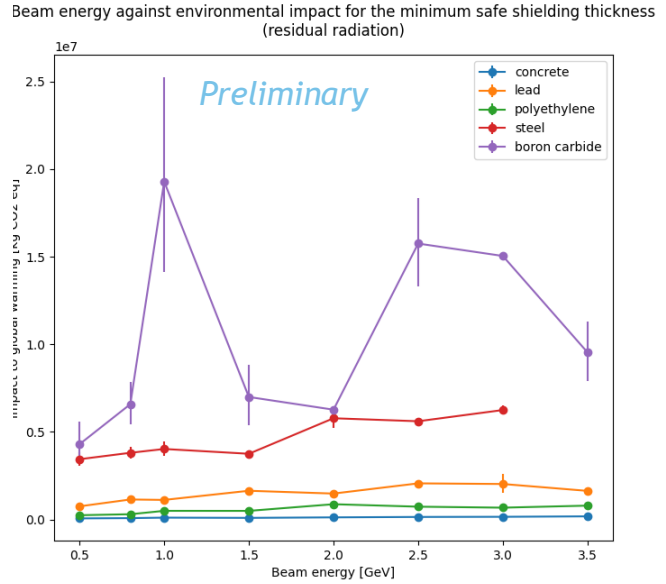
Development of a tool for Fluka to evaluate shielding environmental impacts through LCA integration

- Concrete is the lowest carbon impacting shielding material of those studied.
- Steel (prompt) and lead (residual) are effective but higher carbon impact shielding materials.
- B4C has the highest carbon impact for thickness required.
- Polyethelene is the least efficient protection but is low carbon impact.
- A combination of materials is likely the best method for maximising safety and minimising carbon impact.





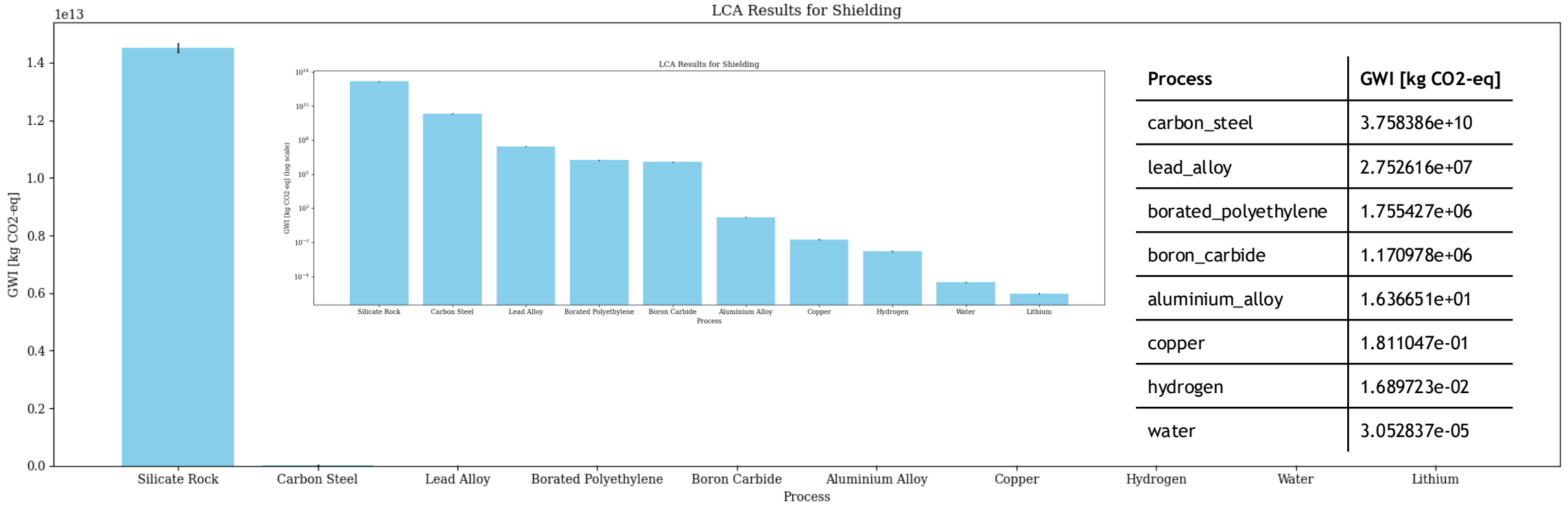




Sustainable Shielding Tool

Development of a **generic** tool (not just Fluka) to evaluate shielding environmental impacts through LCA integration

Collaboration with ISIS Radiation Experts



Process	GWI [kg CO2-eq]
carbon_steel	3.758386e+10
lead_alloy	2.752616e+07
borated_polyethylene	1.755427e+06
boron_carbide	1.170978e+06
aluminium_alloy	1.636651e+01
copper	1.811047e-01
hydrogen	1.689723e-02
water	3.052837e-05

Communication, collaboration, education

- ESPPU 2025 contributions: https://cds.cern.ch/record/2957411/
- Sustainable Accelerator Design Group (ISIS)
- Sustainable HECAP+ (Environmental Sustainability in Basic Research)
- Sustainable HEP conference
- JAI Graduate Lecture Course: incorporation of sustainability into final
- Summer intern: Sustainability R&D in accelerators, focusing on optimis accelerator scenarios
- **IUPAP Accelerator Ambassador**
  - Develop “Accelerating Sustainability” talk
  - Provide resources to the community
  - US$1000 budget

Communication, collaboration, education

- ESPPU 2025 contributions: https://cds.cern.ch/record/2957411/
- Sustainable Accelerator Design Group (ISIS)
- Sustainable HECAP+ (Environmental Sustainability in Basic Research)
- Sustainable HEP conference
- JAI Graduate Lecture Course: incorporation of sustainability into final project
- Summer intern: Sustainability R&D in accelerators, focusing on optimisation of shielding for various accelerator scenarios
- IUPAP Accelerator Ambassador
- **EPITA - Enabling Partnerships for Innovation and Accelerator Technology Advancement**
  - 3 key technology tracks: Accelerating Systems, Magnets and Beamlines, and Frontier Technologies
  - WP: Development of Methodologies and Technical Strategies for Sustainable Research Infrastructures
  - "To develop, harmonize, and validate science-specific methodologies for assessing and improving sustainability in large-scale RIs, including LCA, Design for Sustainability (D4S), and feasibility testing within technical systems. … and aims to embed sustainability principles without compromising scientific excellence or operational functionality."

Communication, collaboration, education

- ESPPU 2025 contributions: https://cds.cern.ch/record/2957411/
- Sustainable Accelerator Design Group (ISIS)
- Sustainable HECAP+ (Environmental Sustainability in Basic Research)
- Sustainable HEP conference
- JAI Graduate Lecture Course: incorporation of sustainability into final project
- Summer intern: Sustainability R&D in accelerators, focusing on optimisation of shielding for various accelerator scenarios
- IUPAP Accelerator Ambassador
- **EPITA - E**nabling **P**artnerships for **I**nnovation and Accelerator **T**echnology **A**dvancement
- **GEAR-NG - G**lobal **E**xchange for **A**ccelerator **R**esearch – **N**ext **G**eneration
  - Training, education, and staff exchange in accelerator research for HEP
  - WP on Global Sustainability including *proposed* deliverables such as the organisation of the first in-person, hybrid Sustainable HEP conference at CERN and surveys leading to derivation of sustainability best practices

Communication, collaboration, education

- ESPPU 2025 contributions: https://cds.cern.ch/record/2957411/
- Sustainable Accelerator Design Group (ISIS)
- Sustainable HECAP+ (Environmental Sustainability in Basic Research)
- Sustainable HEP conference
- JAI Graduate Lecture Course: incorporation of sustainability into final project
- Summer intern: Sustainability R&D in accelerators, focusing on optimisation of shielding for various accelerator scenarios
- IUPAP Accelerator Ambassador
- **EPITA - E**nabling **P**artnerships for **I**nnovation and Accelerator **T**echnology **A**dvancement
- GEAR-NG
- **RI-SPOND**
  - The project unites leading European RIs with academic and industrial partners to co-develop innovative, replicable solutions across three pillars: sustainability, digitalisation, and flexibility.
  - ORLCA project

Future

- Life Cycle Assessment
  - Now recommended by ESPPU
  - Can always and iteratively be improved
  - Tools needed to facilitate
  - Design options comparison: technology, down/dark time, power grid carbon factors
- “Lift the hood” on the accelerator proposals environmental sustainability reporting
- Collaborations with environmental sustainability projects
  - Tools and resources

Thank you

Sustainable HEP Conference 2026
July 8th - 10th
https://indico.global/e/susthep26

John Adams Institute for Accelerator Science

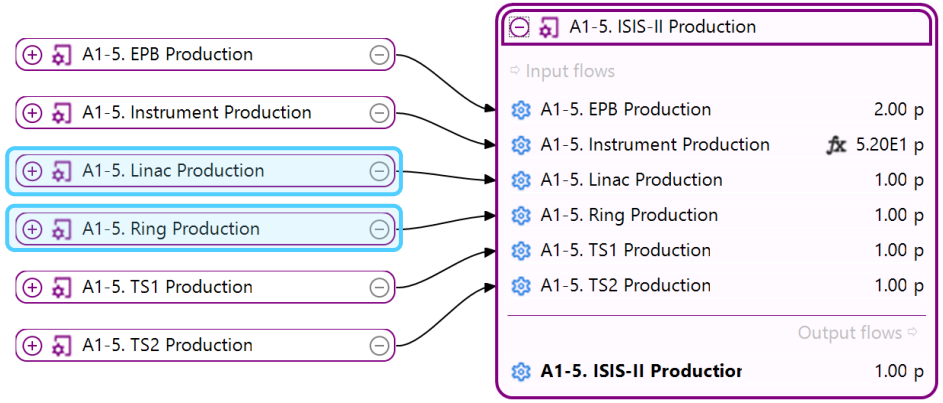
UKRI Science and Technology Facilities Council

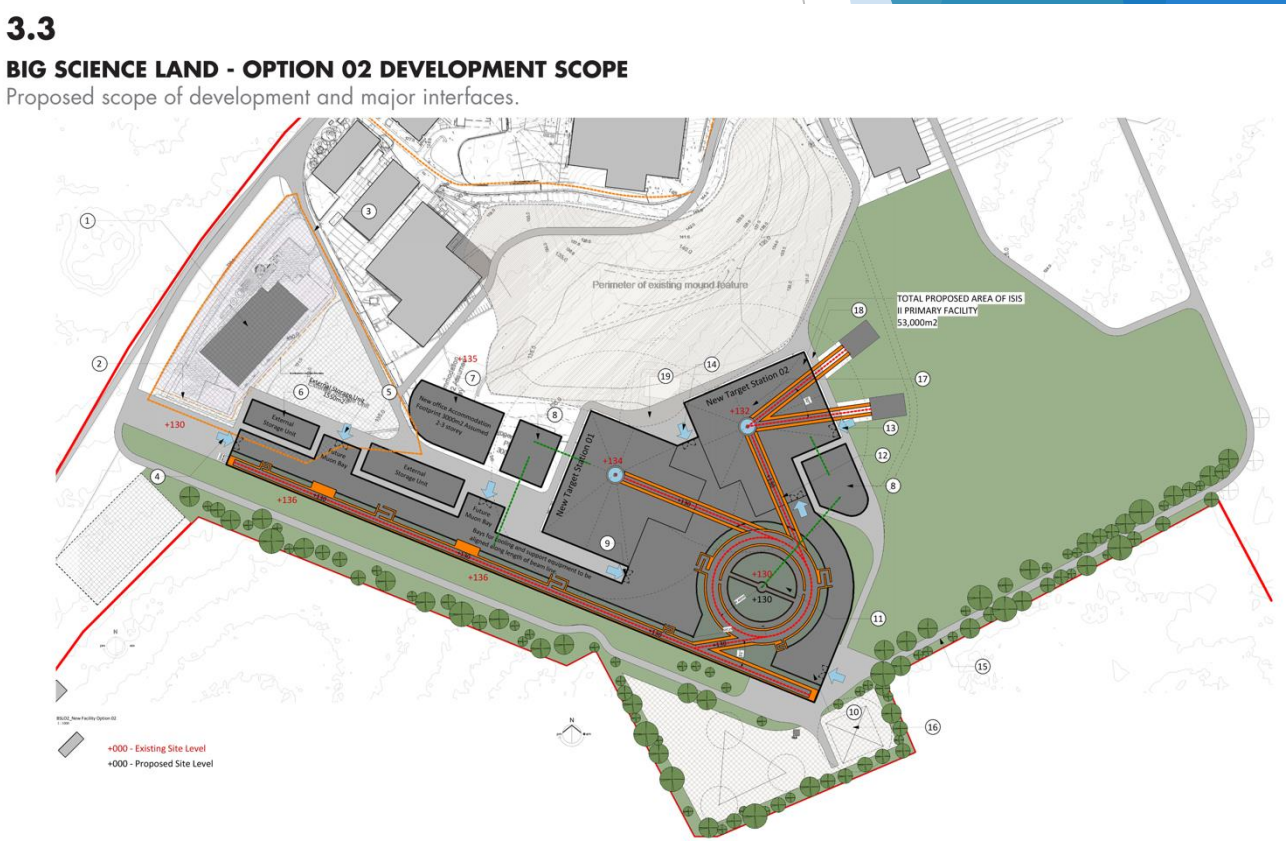
ISIS Neutron and Muon Source

Backup slides

Life Cycle Inventory of an accelerator facility that doesn't exist yet

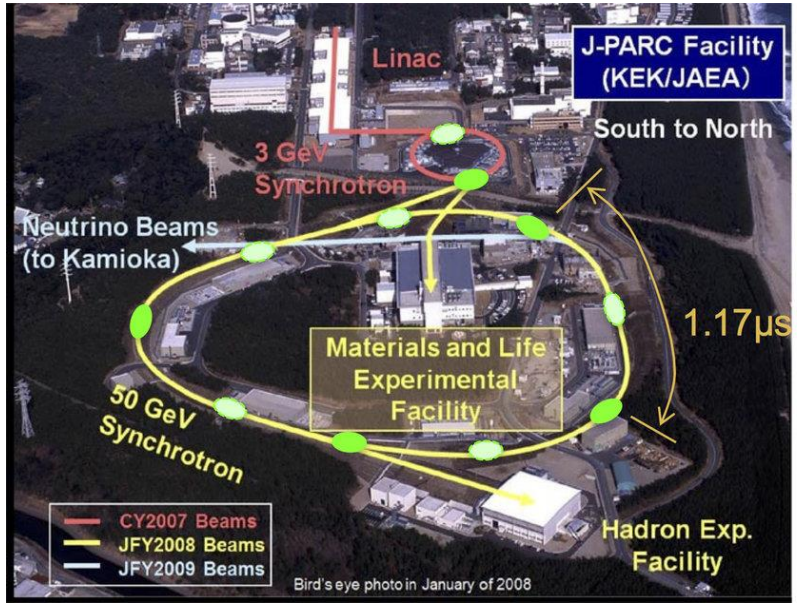
- How do you model a state-of-the-art mega-project?
- 2 major proposed design options
  - Comparison of two rings: Rapid Cycling Synchrotron and an Accumulator Ring
- Hundreds of design options to take into account
  - Emerging technology that may be incorporated



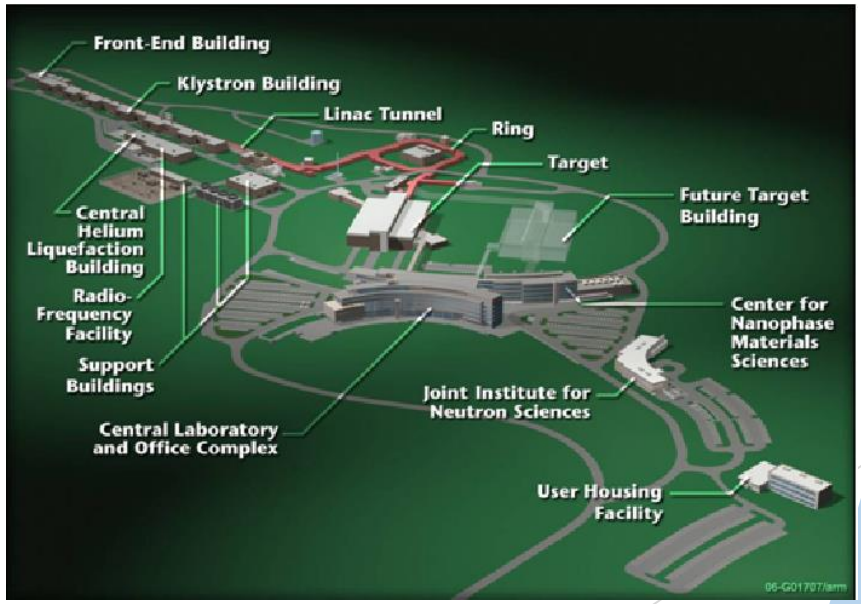


Modelling using existing facilities

- Modelling performed using existing facilities such as SNS and J-PARC, where ISIS-II designs not yet available.
  - Some similar areas/components which may be used as a basic model
  - ISIS-II will be built decades after; change in techniques, material and policy



J-PARC facility - photo source

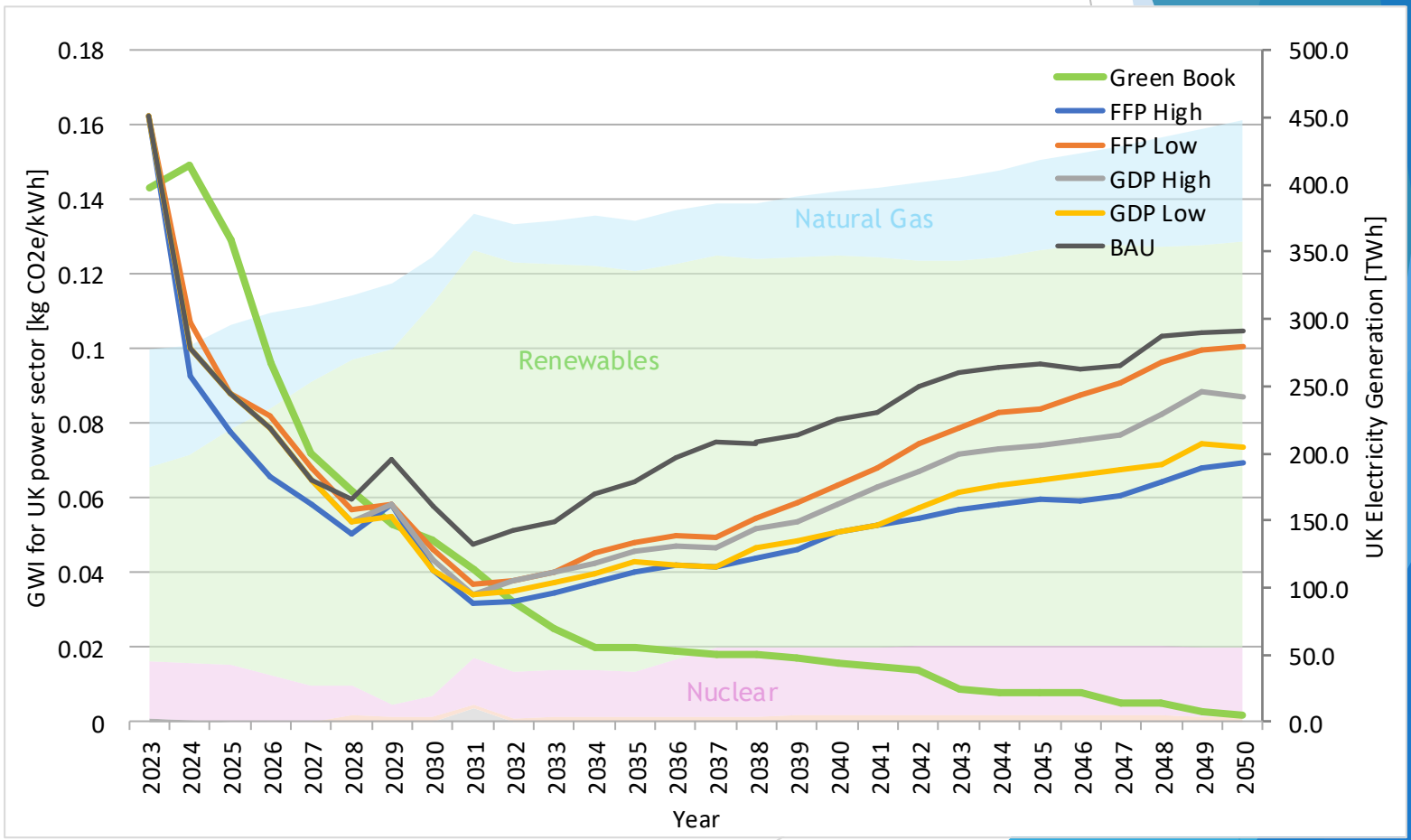


Spallation Neutron Source - photo source

ISIS-II Operational Impacts

With the net-zero goals of UK grid power generation, construction of ISIS-II is naturally the largest proportion of the carbon impact of the facility, however, depending on energy scenarios of the UK, this varies between models.

How does one model electricity supply from 2040-2100?

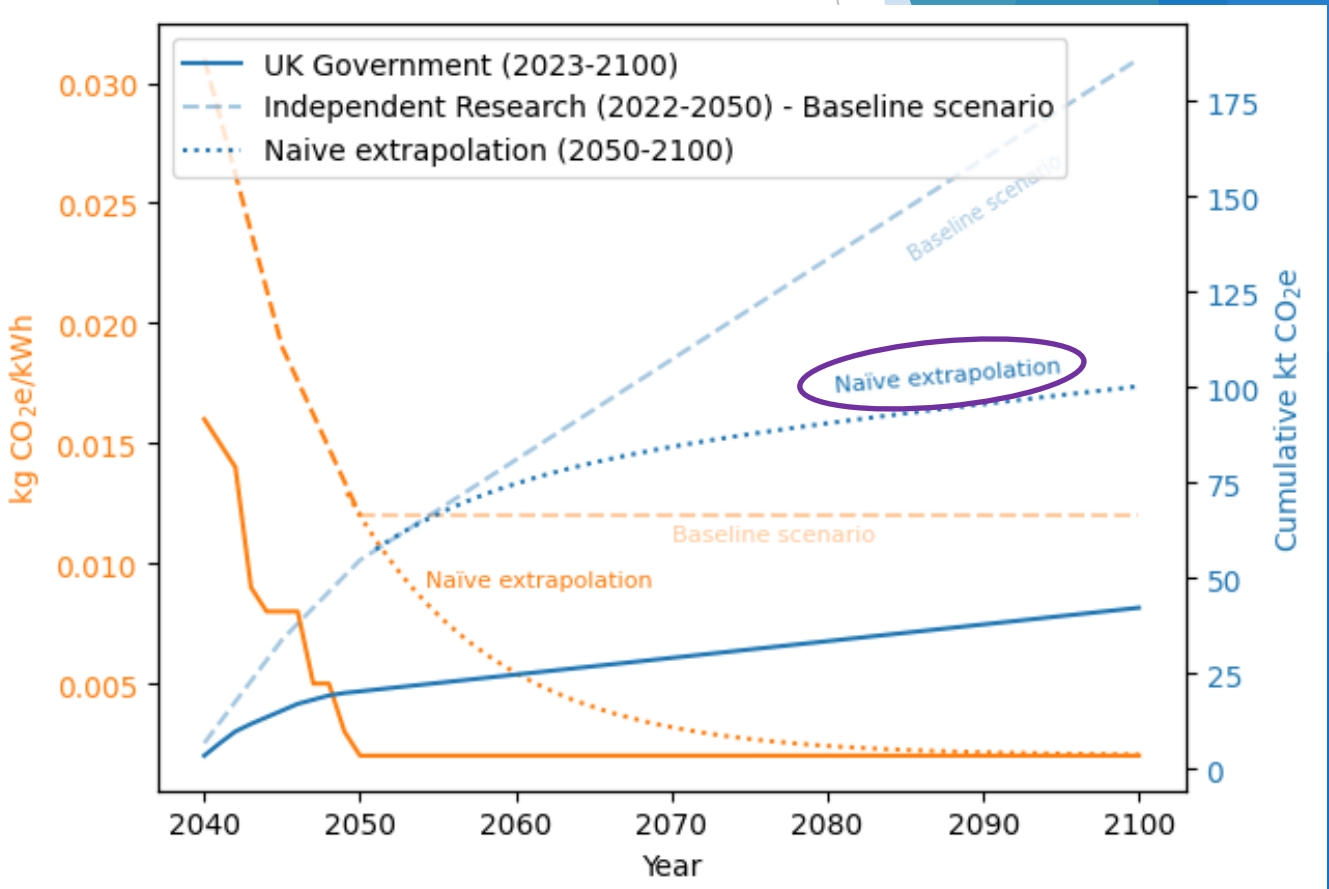


ISIS-II Operational Impacts

With the net-zero goals of UK grid power generation, construction of ISIS-II is naturally the largest proportion of the carbon impact of the facility, however, depending on energy scenarios of the UK, this varies between models.

Year	kg CO_2e / kWh
2050	0.013
2051	0.012
2052	0.011
2053	0.010
2054	0.009
2055	0.008
2056	0.008
2057	0.007
2058	0.007
2059	0.006
2060	0.006
2061	0.005
2062	0.005
2063	0.005
2064	0.004
2065	0.004
2066	0.004
2067	0.004
2068	0.004
2069	0.003
2070	0.003
2071	0.003
2072	0.003
2073	0.003
2074	0.003
2075	0.003

Year	kg CO_2e / kWh
2076	0.003
2077	0.003
2078	0.003
2079	0.002
2080	0.002
2081	0.002
2082	0.002
2083	0.002
2084	0.002
2085	0.002
2086	0.002
2087	0.002
2088	0.002
2089	0.002
2090	0.002
2091	0.002
2092	0.002
2093	0.002
2094	0.002
2095	0.002
2096	0.002
2097	0.002
2098	0.002
2099	0.002
2100	0.002



Minimum of 438 tCO_2e per year of operation from 2050

ISIS-II sustainability strategy

The ISIS-II facility will set SMART goals as part of its sustainability strategy.

Two specific overarching objectives and prioritise them based on feasibility and environmental impact, namely GWI.

1) Design the world-leading ISIS-II Neutron and Muon Source facility with state-of-the-art technology, fully optimised for environmental sustainability by 2032.
2) Contribute significantly to the UKRI's 'net-zero' target by 2040 by minimising operational greenhouse gas (GHG) emissions, strive to meet net zero GHG emissions of operational power consumption and reduce construction impacts by X%* from the ISIS-II LCA baseline value.

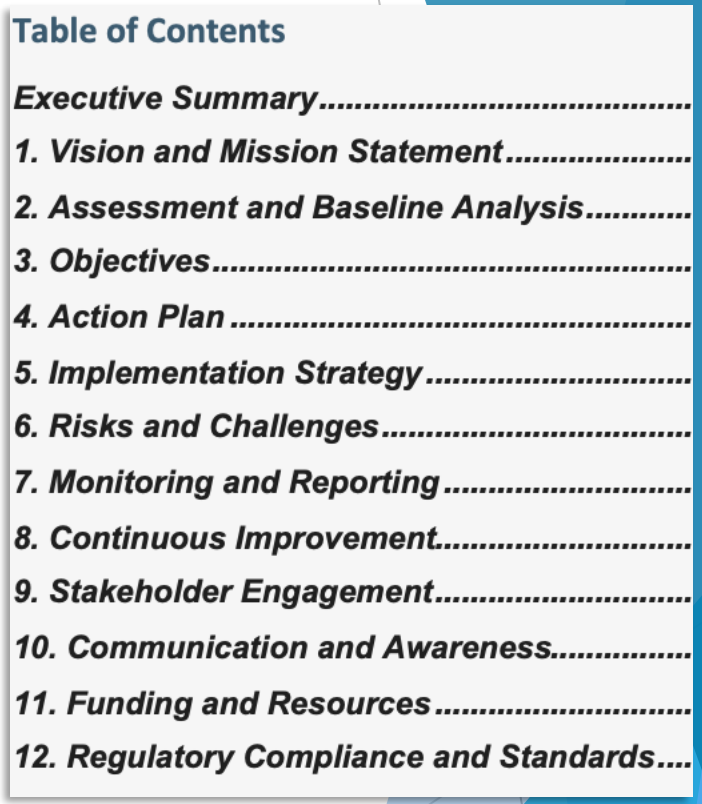


Table of Contents

SMART: Specific, measurable, achievable, relevant, and time bound.
*Where X is a percentage to be determined in upcoming studies.

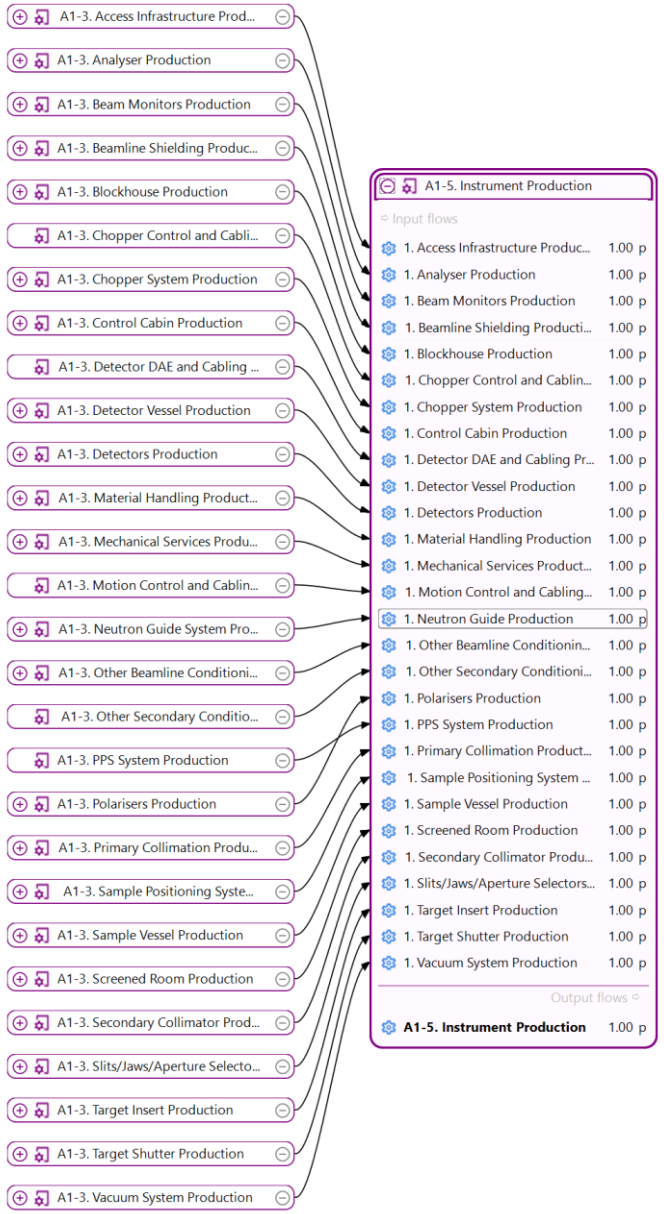
Uncertainty analysis

- Input variable uncertainty based on “Bilan Carbone” uncertainties defined as:

Data	Uncertainty
Emission factor from a direct measurement	0-5%
Reliable non-measured data	15%
Calculated data	30%
Approximated data (statistical data)	50%
Order of magnitude estimate	80%

- Database quality entry: Ecoinvent Data Quality System with base uncertainty of Bilan Carbone uncertainty
- Uncertainties then evaluated using Monte Carlo standard deviation (under re-evaluation)

Example: LCI of an ISIS-II instrument/experiment



- Most accurate area of the Life Cycle Inventory (LCI) at this point in time is for an ISIS-II instrument
- Usual lifetime of 30 years before upgrade/replacement
- Modelled using 1 “generic” instrument
- However, ISIS-II would likely have 26 varying instruments
  - E.g., 1 in 10 instruments will have a Beryllium filter