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Updated results of a life cycle assessment of the ISIS-II neutron and muon source

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The ISIS-II Neutron and Muon Source is the proposed next generation of, and successor to, the ISIS Neutron and Muon Source based at the Rutherford Appleton Laboratory in the United Kingdom. Anticipated to start construction in 2032, the ISIS-II project presents a unique opportunity to incorporate environmental sustainability practices from its inception. A (simplified) Life Cycle Assessment (LCA) will examine the environmental impacts associated with each of the ISIS-II design options across the stages of the ISIS-II life cycle, encompassing construction, operation, and eventual decommissioning. This proactive approach will assess all potential areas of environmental impact and seek to identify strategies for minimizing and mitigating negative impacts, wherever feasible. This talk will provide insights into the motivation, methodology, and first results of the environmental impact and LCA of the entirety of the ISIS-II project.

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1. Introduction

Humanity is faced with the fact that the emission of six more years of carbon dioxide equivalent (CO_2e) emissions at the current global rate will limit us to a 50% chance of keeping the Earth below a 1.5°C temperature increase from pre-industrial baselines [1]. In this scenario, global tipping points could occur as soon as the 2030s [2]. As a result of this, many members of the research community are stepping up to the task of altering practises and increasing efforts to reduce the direct environmental impact of research activities.

The proposed ISIS-II Neutron and Muon Source could be the UK's next generation source for the international neutron and muon user community. The project itself is currently at the feasibility and optioneering stage of design. At this stage, there is huge potential to reduce the overall environmental impact of the facility for its entire lifetime [4]. To identify the areas of high environmental impact and potential for reduction, and to inform on the varying impacts of design options for ISIS-II, a simplified Life Cycle Assessment (LCA) is underway.

Previously, the Global Warming Impacts (GWI) from the LCA for the low-energy (<180 MeV) linac were reported on [5]. This study extends that report to present an order-of-magnitude GWI of the Accumulator Ring (AR) design option of the ISIS-II facility.

2. A simplified Life Cycle Assessment at ISIS-II

A LCA is a standardized method for assessing the environmental impact of a product or process throughout its entire life span. This approach involves a cyclical process divided into four key stages:

1. defining the Goal and Scope,
2. conducting a Life Cycle Inventory (LCI) analysis,
3. carrying out a Life Cycle Impact Assessment (LCIA), and
4. interpreting the results [6, 7].

To conduct a LCA, detailed data on the resources used to construct and operate all parts of the accelerator facility are necessary. Since the ISIS-II facility is currently in the feasibility and design phase, performing a comprehensive LCA for a facility that is yet to be fully designed introduces various uncertainties. This is especially true regarding the preliminary estimates of the materials and resources needed for the facility, which are subject to significant uncertainty. Therefore, the iterative approach to conducting an LCA is advantageous as it allows for continuous evaluation throughout the evolving design process of ISIS-II.

Additionally, a comprehensive LCA of a large accelerator facility can be quite complex and could delay the delivery of actionable results. For this reason, a "simplified" LCA will be performed. Initially, this involves focusing on the most significant impacts. Gradually more detail will be added to the LCA as it becomes available.

Furthermore, the LCA will aim to account for more than 90% of the materials and resources required for the ISIS-II facility, whilst ensuring that any remaining materials are considered and accounted for within uncertainties. Careful attention will be given to these additional materials to ensure that they would not significantly influence the final outcomes of the LCA for ISIS-II.

2.1 Goal

To identify the lowest lifetime environmental impact between the proposed designs of the compression ring for ISIS-II.

2.2 Scope

The proposed ISIS-II facility aims to deliver a 2.4 MW beam of 1.2 GeV protons to serve the neutron and muon research community. The construction of ISIS-II is projected to commence in the 2030s. Following the completion of construction, the operational lifespan of ISIS-II is anticipated to be from 2040 to 2100, based on the expected 60-year lifespan of the current ISIS neutron and muon source. Decommissioning is expected to take approximately 70 years due to constraints related to the storage of radioactive isotopes (2100-2170). Therefore, the functional unit for the final LCA is defined as: "One ISIS-II facility delivering a 1.2 GeV proton beam to the international neutron and muon community over 60 years, followed by a 70-year decommissioning period".

The ISIS-II LCA will cover the Cradle-to-Grave life cycle of the facility and its components. The BS EN 17472 standard [8] is being used as a reference for compiling the life cycle inventory. The ReCiPe:2016 [9] LCIA method has been selected to evaluate the Midpoint (H) impact categories[1].

To demonstrate the LCA process for a particle accelerator facility using open-source tools and databases available to academics, OpenLCA software (v2.0.3) [10] and the Idemat [11] LCA database were employed for this stage of the LCA. The Idemat database offers a wide range of products suitable for a first-order evaluation of a particle accelerator, but notably does not includes some key materials, such as beryllium or niobium. Missing materials are manually added to the project from external sources where possible, or substituted for other materials with a reliably similar impact profile. For the next iteration of the LCA, the study will transition to using the Ecoinvent database [12], due to the need for more up-to-date and accurate data that reflect specific temporal and geographical boundaries.

Uncertainties in the inventory data are quantified following guidelines from Bilan Carbone [13], with uncertainty levels assigned as follows: 0%-5% for direct measurements, 15% for reliable non-measured data, 30% for calculated data and extrapolations, 50% for approximations, and 80% for order-of-magnitude estimates. During the LCIA phase, a Monte Carlo simulation using a log-normal distribution will be conducted to assess the results, accounting for both the uncertainties in inventory data and the database data quality from the Ecoinvent Data Quality System [12].

2.3 Life Cycle Inventory (LCI)

The inventory collection involves assessing all materials and resources utilized in the construction, operation, and decommissioning of the ISIS-II facility. Given that the designs for ISIS-II are still at an early stage, the LCA has been assembled by focusing on one specific area of the facility at a time. Consequently, this study concentrates on one of the ISIS-II design options with an AR and corresponding linac. Where specific designs are not yet available for ISIS-II, existing facilities and components are used as reference models for the LCA:

- Ion source (Model: RAL Front End Test Stand (FETS) [14])

[1] Additional assessment methods may be required to adequately evaluate radionuclides from the operation and decommissioning stages.

- Low Energy Beam Transfer (LEBT) (Model: FETS)
- Radio-Frequency Quadrupole (RFQ) (Model: FETS)
- Medium Energy Beam Transfer (MEBT) (Model: FETS)
- Drift Tube Linac (DTL) (Model: ISIS-II)
- Separated Drift Tube Linac (SDTL) (Model: ISIS-II)
- Superconducting Linac (SCL) (Model: SNS [15])
- High Energy Beam Transfer (HEBT) (Model: SNS)
- Accumulator Ring (AR) (Model: SNS)

This assessment includes specific ancillary equipment such as klystrons, moderators and vacuum pumps, as well as shielding, cut-and-cover tunneling, and building infrastructure.

The calculated operational impact uses CO_2e emissions factors for UK grid electricity generation projected up to the year 2050, which are then used as baseline values for the remaining operational years of ISIS-II [16]. Therefore, the operational impact results are likely to be overestimated, especially given ongoing efforts to decarbonize the UK grid by 2050.

For the building data, a worst-case scenario of 1,000 kg CO_2e per m^2 of gross internal area is assumed [17] until more detailed information on building suppliers and construction methods becomes available.

3. Results

First order-of-magnitude estimates of the GWI from the ReCiPe:2016 LCIA results are presented for one design of ISIS-II facility with an AR. The results align with EN17472 [8] stages A1-3 and B6. Data for the End of Life stage (C), including decommissioning of ISIS-II, is not yet available.

The results showed that the construction materials used in shielding could have a significantly higher GWI than those used in the fabrication of the accelerator components. Additionally, the GWI of the specified ISIS-II linac components indicates that construction (A1-3) and operation (B6) could be of comparable magnitude, as seen in Table 1.

Table 1: GWI of ISIS-II design with an AR for the construction (A1-3) and the lifetime operational energy use (B6)

Life Cycle Stage	**GWI [kt CO_2 eq]**
A. Construction	$\mathcal{O}(300)$
B. Operation	$\mathcal{O}(100-500)$

This analysis effectively identifies potential GWI hotspots, highlighting the need to focus on reducing the environmental impact of the shielding, buildings and structures associated with ISIS-II. It also highlights the importance of the UK grid meeting the net-zero goals set.

4. Conclusion

The initial LCA results for the ISIS-II design option with an AR show that the GWI of construction and operation could be of a similar order of magnitude, depending on the GWI of the UK grid power supply. With the UK grid's transition towards net-zero emissions, it is anticipated that the environmental impact from constructing the ISIS-II facility would surpass that of its entire operational lifespan. Ongoing investigations are focused on strategies to mitigate and reduce these environmental impacts.

Ultimately, this study has provided an initial insight into the GWI of a large accelerator facility and initiated discussions on considerations for the design of ISIS-II with a focus on its environmental impact. As the LCA expands to encompass more design options of the ISIS-II facility, integrates additional life-cycle stages, reduces uncertainty in inventory estimates, and gains access to more accurate models, it will enable a more comprehensive evaluation of the facility's full lifetime environmental impact.

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