# The increasing overlap of environmental sustainability with particle accelerators

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Particle accelerator facilities provide significant societal and economic benefits; however, these advancements come with an environmental cost. Recognising this, the accelerator and particle physics communities are actively working to reduce their environmental impacts. As a first step towards this, environmental impact assessments are being conducted to identify key areas of concern. Alongside this, there are research and design efforts ongoing that aim to develop effective environmental impact mitigation strategies.

Through engagement with colleagues, we received numerous expressions of interest from individuals eager to incorporate environmental sustainability into their work. However, many faced common barriers: a lack of dedicated time within their projects; insufficient funding for environmental sustainability initiatives; environmental sustainability recommendations that were either too generic, inapplicable or unspecialised; or too much uncertainty about how to incorporate environmental sustainability into their work. Some were also concerned that their efforts might unintentionally ”shift the burden" of their existing environmental impacts to new sources of impact (whilst reducing existing ones). Efforts to reduce one impact often entail trade-offs with others. For example, changing a critical material to reduce carbon emissions could lead to use of a material that is more toxic towards the environment, increase resource scarcity, or have dire, direct human impacts (e.g. modern slavery); a facility switching from conventional to superconducting magnets may reduce operational power demands but increase embodied impacts due to cryogenic infrastructure and exotic materials like niobium; substituting a high-GWP gas in a detector system may reduce climate impact but raise safety or toxicity concerns; replacing concrete with lower-carbon alternatives can affect shielding efficacy or introduce lifecycle uncertainties. Further research is required in each of these areas to fully understand the consequences of any shifts to, what one might *think*, is working towards being more sustainable.

Many of these challenges are not unique to particle accelerator science, but their scale and technical complexity often amplify them. Large accelerator facilities epitomise what is sometimes termed ”big science": long-lived, resource-intensive infrastructure supporting international collaborations. Though these challenges are not limited to accelerator physics, this feedback highlighted two key points:

1. There is still considerable research required to fully understand and address environmental challenges within the realm of accelerator physics.

2. There is a clear need for a centralised resource tailored to large accelerator facilities – one that offers practical guidance, provides specialised recommendations, and shares existing tools.

In response, we created a *living* document designed to gather and share resources and information for those working with particle accelerators. Alongside this, we continue to invite contributions from across the community to ensure this resource remains relevant, comprehensive, and impactful. We are committed to providing regular updates as new insights, technologies and best practices emerge. Version 1 is now published on the arXiv[1]. Version 2 is already underway and is expected to be published this year (2025).

## Particle accelerators deliver and encourage progress

Particle accelerators have revolutionised science and technology in the last century. While they are best known for probing the structure of matter at the smallest scales, their applications extend far beyond fundamental physics. In medicine, accelerators produce isotopes for cancer diagnostics and therapy, enabling treatments such as proton beam therapy for targeting tumours with remarkable precision. There are also many industrial applications, including sterilising medical equipment and improving the durability of materials. In the energy sector, accelerators support research into nuclear fusion and advanced materials for renewable technologies. Furthermore, accelerators provide insights into climate science by allowing scientists to study atmospheric particles and develop models for environmental systems.

These facilities are critical hubs of innovation. Technologies developed for accelerators, such as superconducting magnets and advanced cooling systems, have been adapted for use in MRI machines and energy-efficient power systems. Additionally, particle accelerators enable breakthroughs in other fields such as chemistry, biology, and materials science, which helps address pressing global challenges.

Given their enormous contributions to science and society, it is important that particle accelerators remain at the forefront of innovation - not only in research but also in environmental responsibility.

## Is it possible to make particle accelerators and colliders environmentally sustainable? It depends!

Despite their benefits, large-scale particle accelerator facilities require substantial electrical power to operate. The energy supply – whether drawn from renewable or fossil fuel sources – heavily influences an accelerator facility's environmental footprint. In addition, their impact extends beyond energy consumption:

- **Land use**: Large accelerator facilities require land for tunnels, infrastructure, and surrounding facilities. This can alter local ecosystems or displace wildlife.
- **Infrastructure**: The design and construction of buildings, tunnels, and access routes involve significant material and resource consumption, including concrete, steel, and excavation.
- **Materials**: Accelerator facilities rely on specialised materials, such as superconducting wires, rare metals, and advanced cooling agents, which often have significant environmental costs.
- **Computing**: Data centres that process the vast amounts of experimental data generated by the accelerators require substantial electrical power, generating considerable carbon footprints.
- **Consumed resources**: Power demands for magnets, cryogenics, and cooling systems are significant. Water consumption for cooling and the use of specific gases or liquids in detector systems further contribute to resource depletion and can themselves contribute directly to climate change.
- **Radioactive material storage**: While modern facilities manage this responsibly, long-term storage and handling of activated materials pose environmental and safety challenges.
- **Travel**: Particle accelerator research is highly collaborative, requiring frequent international travel for meetings, conferences, and experiments, adding to carbon emissions.

Increased environmental sustainability is achievable, but it requires proactive steps. Energy-efficient cooling systems, improved power management, and sustainable infrastructure design can all reduce the environmental burden. Innovative approaches like energy recovery linear accelerators and beam recycling strategies could also offer promising solutions for reducing waste and energy usage.

## Toward a greener future for particle accelerator facilities

In recent years, the particle accelerator community has become increasingly active in reducing its environmental impact. Facilities are actively exploring ways to reduce energy consumption, manage resources more efficiently, and adopt greener technologies. However, we recognised a gap in the existing guidance for achieving these goals. While there are many general environmental sustainability resources available, the particle accelerator community lacked tailored recommendations specific to the unique challenges of large accelerator facilities. This observation inspired us to create the *High-level Guidelines for Large Particle Accelerator Facilities*[1].

Our living document provides practical advice designed specifically for the accelerator field. It addresses key areas such as energy management, sustainable infrastructure, and best practices for reducing environmental impact during both construction, operation and decommissioning. By developing these targeted guidelines, we aim to support accelerator facilities in making informed decisions that balance scientific advancement with environmental responsibility. We aim to update the living document as new information and technologies becomes available.

Accelerator facilities worldwide are already demonstrating positive change, including implementing ambitious strategies to improve energy efficiency, integrating renewable energy sources and exploring ways to adopt greener technologies. By continuing these efforts and facilitating future efforts with dedicated guidelines, we believe our field can lead by example and contribute meaningfully to global environmental sustainability efforts.

## Call to action

The responsibility to advance our environmental sustainability practices extends to all scientific disciplines but each field faces unique challenges in minimising its environmental footprint. Tailored guidance will facilitate each of these communities to balance scientific advancement with environmental responsibility.

Therefore we encourage all fields to develop or continue to develop their own dedicated environmental sustainability recommendations. By sharing strategies, best practices, and innovative solutions, the broader scientific community can collectively reduce its impact on the environment and influence environmental sustainability globally. We invite scientific communities worldwide to continue this commitment to environmentally sustainable research, ensuring that future science is not only groundbreaking but also environmentally responsible.

## References

**1.** Wakeling, H. *et al.* High-level environmental sustainability guidelines for large accelerator facilities (2025). 2501.14979.