Sustainability for Particle Accelerators: RUEDI - A Case Study

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Abstract

Particle accelerators are inherently energy-hungry facilities. As the effects of human-induced climate change become obvious, it's clear that institutions must take action to make their facilities as sustainable and energy-efficient as possible to minimise their impact on the environment. In this report, we undertake a review of the subsystems required to build a modern particle accelerator, and arrive at an estimate of the carbon footprints for construction and operation of each individual subsystem. The review uses the proposed RUEDI facility in the UK as a case study, but the aim is to produce a more generic toolkit for assessing the climate impact of accelerators, to provide some indications of the best areas to target for emissions reductions.

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1 Introduction

Particle accelerators are powerful machines that enable scientists to study the fundamental building blocks of matter and the laws that govern the universe. These machines have revolutionised our understanding of physics, leading to breakthrough discoveries such as the Higgs boson and the development of life-saving medical technologies. However, particle accelerators are also energy-intensive and can have significant environmental impacts.

As the global community becomes increasingly focused on sustainability, it is important to assess the sustainability of particle accelerators and identify opportunities for improvement. This review aims to provide an overview of the current state of sustainability in particle accelerators, including energy consumption and the use of resources. By highlighting best practices and areas for improvement, this review can serve as a guide for researchers, policymakers, and industry leaders working to promote sustainability in this important field.

The aim of this review is to look at each subsystem of an accelerator in turn, assessing the impact of manufacture and operation of these systems. We use the proposed RUEDI facility as a case study so that specific information about components in each subsystem can be included. There are other accelerator components that are not included in RUEDI; these will be considered in a more general future report. Identification of the major sources of emissions will enable accelerator designers to focus their efforts in reducing overall emissions.

2 Scope

2.1 The need for sustainability

It is now well accepted by a consensus of scientific research that humanity's technology progress has brought with it a significant effect upon the Earth's climate, that is likely to have a number of consequences upon the Earth's ecology and thereby upon humanity's ability to sustain itself. 'Global warming' is often used as a simplified term for climate change but is a distinct concept; however, it is a useful indicator of the effect of people upon the planet they live on. 'Sustainability' is a third issue linked to climate change and global warming, that we will discuss a little later.

'Global warming' refers to the increase in the mean temperature of the Earth due to human activity since the beginning of the industrial age, commonly pinpointed to James Watt's 1776 invention of the steam engine in Britain and which ushered in the use of machines to carry out work previously done by human hands. Building upon the outlook of the Enlightenment and the earlier agricultural revolution in farming methods, the industrial revolution used the burning of fossil fuels – initially coal – to sustain an ever-increasing population and give them eventual access to the modern benefits we all enjoy today: plentiful food, warmth and light, effective medicines, travel, and freedom from drudgery. As we all know, the burning of coal, gas and oil to achieve these benefits has released enormous quantities of carbon dioxide (CO_2) into the atmosphere, up from pre-industrial levels of around 280 ppm (parts per million) to over 400 ppm today. Loosely put, the carbon that was once trapped by dead plants in the ground (in the form of coal, gas and oil) is now in the air, and as CO_2 it is very effective at trapping the heat from the Sun; this is known as anthropogenic ('human-caused') carbon emission. It is a principal driver of the warming of the Earth and the climate change that accompanies it, but it also has other negative consequences. For example, it is predicted that a collapse in the Gulf Stream current could occur in the next several years [1], bringing about drastic changes to weather patterns and hence agriculture in the UK.

The world of the 21st century is quite different to what it was one hundred years ago. The population of the Earth will not inexorably rise for ever – as the Malthusian myth proposed – but is likely to peak at around 10.5 billion people toward the end of this century, due mainly to human prosperity bringing smaller families. These people will still want the things we enjoy today – more so, even, since the developing countries of the world want access to the things that the developed world already has: clean water, washing machines, cars, medicine and so on. To enable that, the world must transition from the 'consume and dispose' system of the past, and to a world where the world's resources are maintained or even improved from what they are today. We must become *sustainable*.

The creation of the things we use (cars, toothbrushes, tinned tomatoes) involves two important components: energy and resources. Resource usage is a complex topic in itself, and involves ideas such as whether a particular resource (such as water, copper, helium etc.) are depleted by use or not, and the degree to which that resource can be used again. This idea of reusing resources – instead of a once-through linear process of use and disposal – underlies the idea of the *circular economy*. At the consumer end the idea of the circular economy is reflected in the tenets: 'reduce, reuse, recycle'. At the production end the circular economy includes other concepts, such as: modularity in design; choice of materials that enable reuse and/or re-manufacturing; choice of materials that limit disposal and recycling issues. But we always need *energy* whatever our manner of using or reusing resources; a key idea in sustainability is therefore the sustainability of the energy being used to carry out all the steps in the use of technology.

The importance of sustainability in energy production was already well understood fifty years ago, and epitomised in Fred Hoyle's well-known book 'Energy or Extinction' [2]. Hoyle's book advocated for nuclear energy over coal on the basis of single-use resource depletion, but today we also recognise that nuclear energy gives us – somewhat obviously – much lower CO_2 emissions than does coal. We also have today more well-developed sources of so-called renewable energy, famously wind power and solar power but also for example tidal generation and biofuels. These renewable sources essentially 'collect' energy embodied in ongoing natural processes that are inherently constantly replenished from a combination of the rotation of the Earth and the heating from the Sun, rather than using the stored biological energy in coal and oil whose build-up is much too slow to keep up with its current usage. Whilst renewable sources are well known to be inherently intermittent, demanding either changes to our pattern of usage or smart grids/energy storage to balance production and load, their potential generating capacity is now nearly on a par with traditional, more-centralised sources such as coal-fired, gas-fired and nuclear power stations.

The capacity of different sources to fulfil the UK's energy needs has been well explored in David MacKay's book (and accompanying website) 'Sustainable Energy - Without the Hot Air' [3, 4], and the CO_2 emissions of different generating sources are well summarised by a number of bodies that include the IEA [5–8]. This data highlights an important issue when comparing the sustainable credentials of activities carried out in different countries: those countries may have quite different energy generation methods that cascade down into differences in the embodied CO_2 emissions in manufacturing – for example, working out how much CO_2 is emitted when an object such as a frying pan is made. This total 'embodied' CO_2 is commonly known as the carbon footprint of the object or activity.

The carbon footprint of an activity (manufactured object or otherwise) can arise from surprising sources. For example, it is commonly supposed that the carbon footprint of a person living in a domestic dwelling is primarily from the natural gas usage (mainly heating and cooking) and from electricity usage. But this is not true. Using the metric of consumed kWh embodied in different activities – which is somewhat related to carbon emissions if all the energy comes from similar sources (e.g. fossil fuels), MacKay has estimated that most of an individual person's domestic energy usage comes from the manufacturing of the goods they use, not their direct energy (heating and lighting) usage [4]. Translated into current terminology, we distinguish three so-called Scopes of emissions. Scope 1 emissions are those that arise from the *direct* activities that occur in a domestic or industrial setting; for example, the gas burnt in a company's boilers that are used to heat its buildings. Scope 2 emissions are *indirect* emissions that arise elsewhere as a consequence of an activity; for example, when electricity is used by a company there are emissions generated elsewhere when that electricity is generated. Scope 3 emissions are also *indirect* and are those incurred when an item or process is carried out elsewhere on behalf of a person or company; for example, when a computer is purchased by a company, energy and resources are used that both give rise to equivalent CO_2 emissions. MacKay points out a notable fact about domestic energy usage (and therefore CO_2 emissions): Scope 3 emissions are in general much higher than Scope 2 emissions. In other words, the CO_2 emissions from buying things are much larger than the CO_2 emissions from things like heating and cooking. Formal Scope 1/2/3 emissions are discussed more below.

One other point is worth mentioning here, that will not be developed later, is that there is also a human cost consequence that goes along with sustainability and climate change considerations. Energy is central to all arguments about sustainability, and different forms of energy production involve different rates of human fatalities. Contrary to much popular public belief, the production of nuclear energy involves far fewer deaths than, say, coal-fired generation; the coal power station itself does not cause many deaths directly, but the mining of the coal and the air pollution do [9, 10]. A wind turbine in operation gives little risk to the people around it, but building many such turbines requires a lot of concrete and the rare-earth metals used in the generator permanent magnets involve extensive mining. To quantify this properly to compare different energy sources, a common metric is 'deaths per GWh'; it is outside the scope of the present report to discuss this more, but it should be considered alongside sustainability in a wider consideration of the overall burden of having a modern, industrialised civilisation.

2.2 UK strategy and policy

The realisation that all countries - particularly those in the developed world – have to contribute to limit the climate change caused by anthropogenic CO_2 emissions has led to a number of actions. The first coalesced the world around the United Nations Framework Convention on Climate Change (UNFCCC) which came into force in 1994. This was followed by the 1997 Kyoto Protocol which came into force in 2005 and was signed by 192 countries including the UK. At UN COP21, the so-called Paris Agreement was enacted: this commits the UK to reducing economy-wide greenhouse gas emissions by at least 68 % by 2030, compared to 1990 levels. This commitment is enshrined in the UK's Nationally Determined Contribution, which communicates and details what the UK economy aims to achieve by 2030; it includes not only CO_2 but also other greenhouse gases such as methane. The Department for Energy Security and Net Zero (DESNZ) is responsible for the strategic oversight of the climate policy that will bring about these greenhouse gas reduction targets.

The UK Climate Change Act of 2008 set legally-binding targets on net greenhouse gas emissions to be 80 % lower in 2050 than their 1990 levels, and aims to enable the UK to become a so-called low-carbon economy. In 2019 the UK enacted legislation that commits to a 100 % reduction in greenhouse gas emissions by 2050, and thereby became the first major economy to commit to this 'Net Zero'. The 2008 Act established the Climate Change Committee which oversees the progress toward the UK's climate change targets, and that work is based on Carbon Budgets that set statutory caps on greenhouse gas emissions [11]. Carbon Budgets 1 and 2 were met and the UK is on track to meet the third; it is not on track to meet the fourth (CB4, 2023-2027) or fifth budget (CB5, 2028-2032).

The UK's Net Zero strategy published in 2021 [12] sets out how the UK will deliver on Carbon Budgets 4,5, and 6 [13], and the National Determined Contribution [14]. The recent war in Ukraine led the UK Government to undertake a review of the 2050 targets, published early in 2023 [15]; this review recommended '25 policies by 2025', and so-called Mission Zero missions. Of the 129 recommendations, some notable ones for the present report are the aims to create a consumer carbon calculator and to create standardised charter marks and eco-labelling methods. Other relevant documents are the Industrial Decarbonisation Strategy [16] and The Ten Point Plan for a Green Industrial Revolution [17]. Overall, the legislation and associated policy documents set the context within which the public sector and private sector will work in the coming years.

2.3 Achieving Net Zero

The UK has a strategy to reach 'Net Zero' by 2050, in other words to eliminate net greenhouse gas emissions completely. Whilst the UK has met its targets for reductions in the first two carbon budgets (2008-17), the planned reductions will become increasingly difficult to meet as the 'easy wins' are steadily eliminated as time goes on.

For the purposes of accounting, carbon emissions are divided into three scopes as defined by the widely-used WBCSD/WRI Greenhouse Gas Protocol [18]:

- **Scope 1.** Emissions from a source that an organisation owns or controls directly, for instance petrol burned in combustion-powered cars in the organisation's fleet, or leaked refrigerants from cooling systems.
- **Scope 2.** Emissions associated with energy purchased and used by the organisation, for instance gas burned in power stations connected to the electrical grid.
- **Scope 3.** Everything else. This means emissions associated with the manufacture and disposal of products used by the organisation, but also commuting and business travel associated with the organisation.

One related standard BSI PAS2060:2014 [19], which is a specification for how to demonstrate carbon neutrality; criteria are available by which an organisation can demonstrate their achievement of such neutrality. BSI PAS2080:2023 is another standard [20], which specifies requirements for the management of whole life carbon in buildings and infrastructure.

Scope 3 emissions are clearly the hardest to quantify, since it's difficult to know *a priori* how many carbon emissions are associated with producing (for instance) a tonne of steel, not to mention the processes required to turn those raw materials into components and devices that are ready to use. Raw materials are often sourced from many different countries, and suppliers are not always ready to divulge information about their sources or their internal processes. Particle accelerators utilise a great many different components sourced from a wide variety of manufacturers, located all over the world; some of these components use rare or very energy-intensive materials (neodymium for magnets, niobium for superconducting cavities, and so forth). Therefore, Scope 3 emissions are likely to be an important contributor to the overall carbon footprint.

Net Zero aims at eliminating net greenhouse gas emissions across the UK economy as a whole, but it is likely to be also needed sector by sector; in other words, it will probably not be possible to make a special case for particle accelerator infrastructures. For example, one might argue that a scientific facility may conduct research that brings about products that reduce or eliminate carbon emissions when used as replacements for previous versions of those products; an example might be a scientific facility that is used to develop a new generation of batteries to be used in a (green) smart grid economy. It has been suggested that this might be considered akin to so-called greenwashing and thus be perceived negatively. That said, STFC is commissioning work to quantify the environmental benefits of the research carried out at its major infrastructures, including the ISIS Neutron Source which is notable in the STFC estate as being the infrastructure with the largest associated carbon emissions (due mostly to the present carbon intensity of the electricity it uses).

Here, we argue it is incumbent on any technology area to critically examine the embodied CO_2 and energy usage in its products; particle accelerator manufacture is no different to car manufacture, and one should look critically at the options available to reduce the CO_2 embodied in the manufacture, operation, recycling and eventual disposal of research facilities. This concept of examining the CO_2 emissions of technology over the full span from creation to disposal is termed *Life Cycle Assessment* (LCA). This outlook is in line with UKRI's recently-published Environmental Sustainability Strategy [21], which by 2025 will embed sustainability across all of UKRI's operations. UKRI's strategy reflects the UK Government's 'Greening Government Commitments' policy which addresses Government departments' environmental impacts, which includes greenhouse gas emissions amongst other factors [22]. Similarly, the Cabinet Office has published guidelines for achieving Net Zero on UK Government estates (of which UKRI is one) in the form of a 'Playbook' [23]. Within STFC there are similar aims, that separate the broader scientific goals of funded research that may enable net-zero-relevant technologies from the more direct goal of reducing the carbon footprint of the STFC estate.

As part of the UKRI Infrastructure Fund that is now a major route for the development of research infrastructures [24], UKRI has commissioned Arup [25] to conduct operational carbon forecasting using standardised reporting. An Arup report has been generated for the RUEDI project [26], and our estimates below are in line with Arup's. Arup has also carried out an LCA on behalf of CERN for the Compact Linear Collider (CLIC) and International Linear Collider (ILC) projects [27]. The conclusions of Arup's LCA analysis are discussed further below. Arup's analyses may be set against the framework of the UNFCCC campaign "Race to Net Zero" [28] which aims on a sector-by-sector basis that each partner (e.g. company, institute, region) will halve their emissions by 2030; this is one aim in the UN's so-called "2030 Breakthrough". The aim of Race to Net Zero is to ensure that countries and non-state actors are on track to achieve Net Zero by 2050.

STFC's goals are laid out in its Environmental Sustainability Action Plan [29]. Importantly, *STFC aims to reach net zero carbon emissions by 2040*. STFC has adopted an energy hierarchy framework to reduce its emissions burden; the framework, in order of priority, is:

1. Energy reduction, particularly by energy-intensive infrastructures such as particle accelerators, data centres, and high-power lasers;
2. Improving processes and infrastructures to give greater energy efficiency;
3. Energy substitution to utilise lower-carbon sources of energy such as solar, either generated within the STFC estate or utilised by cooperation with low-carbon smart grid schedules;
4. Compensation/offsetting, which is considered a low-priority 'last resort' within STFC's strategy.

The present report aims to contribute to fulfilling the first two of these aims; STFC will develop an Energy Roadmap and Decarbonisation Plan toward the end of 2022. As part of STFC's decarbonisation, procurement of components and infrastructures will in future embed sustainability into the selection criteria; STFC's Estates Strategy includes the publishing of a Sustainable Building design standard during 2023. STFC is also developing guidelines for sustainable design, procurement/manufacture and use in engineering; this would apply to the design and manufacture of all accelerator subsystems and components. STFC's activities in this area have been collected under the umbrella of the SPADE project [30].

In recent years STFC has made some progress in reducing the emissions due to its direct activities, for example reducing overall CO_2 emissions from 60 kt in 2017/18 to 29 kt in 2022/23 [31]. This data points out a basic feature of energy consumption within the UKRI estate: the major UK scientific facilities naturally account for the bulk of electricity consumption and hence CO_2 emissions, and most of those facilities are either particle accelerators or high-performance computing infrastructures; STFC consumed 107 GW h of electricity during 2022/23. There is therefore a naturally strong impetus to limit emissions from those facilities; the first of those – particle accelerator infrastructures – is the subject of the present report. In parallel there have been significant initiatives to help decarbonise the electricity usage within the STFC estate, using funds from the Public-Sector Decarbonisation Scheme [32] to install large-scale photovoltaic panels to offset some of the energy usage by the organisation; this will be transitioned into deploying solar solutions as a matter of course on new and refurbished buildings.

STFC has also recently signed up to the UCL-defined Laboratory Efficiency Assessment Framework (LEAF) standard [33]. Although focused on smaller items such as disposable/single-use plastic items, the framework is accompanied by calculator tools for the assessment of environmental impact of practices and equipment use.

STFC has committed to the following specific aims, which echo the Greening Government Commitments [22]:

- Be net zero by 2040 (ten years ahead of the date set by the GGCs);
- 100 % electric vehicles by 2027;
- 30 % reduction in domestic business flights by 2025;
- Increase recycling to 70 % by 2025;
- Remove all consumer single-use plastic.

2.4 Global warming potential

Global warming is caused by the release of a number of different gases into the atmosphere; their effect is quoted relative to that of CO_2 and the overall effect from a given process which may emit various different pollutants is represented by a single figure; so the overall global warming potential (GWP) is measured in kg CO_2 equivalent or kgCO_2e. In this report, we use the terms *global warming potential*, *carbon footprint*, and *carbon impact* interchangeably. The term *carbon intensity* represents the relative GWP contribution of a given process or material, and is typically measured in kgCO_2e/kg for materials and kgCO_2e/kWh for energy.

2.5 STFC and the UK by the numbers

Given the inherent complexity of calculating equivalent CO_2 emissions, it is useful to try to simplify things by giving approximate figures. These are meant to be indicative so that the detailed calculations later can be set in context.

A useful benchmark is the per capita CO_2 emissions of a person in a developed country such as the UK or elsewhere in Europe [34]. Whilst there is some variation, a guideline is around 6 tCO_2e, i.e. this is the amount of CO_2 incurred due to one person over one year. Net Zero ambitions seek to reduce that number to zero by 2050; loosely put, they also demand that workplace emissions do not contribute either. In other words, Net Zero implies a major change to workplace activities.

To show the scale of the problem, we refer to the HECAP+ report ("Striving towards Environmental Sustainability in High Energy Physics, Cosmology and Astroparticle Physics (HECAP), and Hadron and Nuclear Physics") [35]. This report tabulates typical recent per-capita GHG emissions for staff at European physics laboratories (which are similar to STFC). Workplace emissions are typically around 5 tCO_2e, and for CERN staff it's as much as 15 tCO_2e. Being a working physicist doubles your CO_2 emissions. The source of those emissions varies, but for the most part is either energy usage by facilities, the equipment to build those facilities, and travel to and from those facilities. Physics is a highly-mobile field, which will be an area where great change will be needed. Airline travel emits around 0.5 tCO_2e per hour of flight time – much more than train travel, for example – and so the GHG emissions of a scientist can be dominated by those flights.

Across STFC, GHG emissions across Scopes 1, 2 and 3 were 29 ktCO_2e in 2022-23 [31]. This is around 17 tCO_2e per staff member. Of course, there are many users that access STFC facilities and other resources each year (around 3500), but even including them the emissions per capita from STFC activities is around 6 tCO_2e per year – around the same as domestic emissions.

In 2022-23 STFC consumed 107 GW h of electricity. This equates to 22.1 ktCO_2e using the current conversion factor of 207 gCO_2e/kWh [36]. In other words, fully two-thirds of STFC carbon emissions are from its electricity use. GHG emissions from electricity production are forecast to decrease massively by 2040 [37] which will greatly assist STFC's Net Zero ambitions (see Appendix A for some discussion on these numbers). However, this should be placed against the occasional large capital projects (i.e. accelerators) which must aim also to be Net Zero. Greening electricity alone will not be enough.

2.6 Comparison with other initiatives

STFC is of course not alone in considering the impact upon the environment of its activities and the sustainability consequences that may bring. A number of other laboratories and institutes are building sustainability into their activities, and many initiatives are underway that are considering how to achieve good sustainability and Net Zero impact from their research.

There is a broad literature in which the CO_2 emissions of scientific activities have been considered. We identify three research areas which are comparable in nature to particle accelerator science:

- Particle physics, particularly the construction and exploitation of large particle detectors for colliders and neutrino physics [35, 38, 39];
- Astronomy and astrophysics, particularly the construction and exploitation of land-based telescopes (whether optical, radio or otherwise) [40, 41];
- High-performance computing infrastructures that support science [42, 43].

Important concepts which emerge from the literature are:

- Life Cycle Assessment is the standard methodology adopted to quantify emissions, and the ISO 14001:2015 international standard, itself part of the wider ISO14000 series of environmental standards, sets out a common approach for quantifying emissions and reporting them [44]. In addition, sustainability assessment can be divided into stages as defined in BS EN 17472:2022 [45];

- It is important to consider sustainability throughout the design cycle, but particularly at the 'optioneering' phase where key choices are made that may have far-reaching consequences for sustainability;
- The most important issues for sustainability may be unexpected ones. For example, several projects have concluded that the travel conducted by staff, users, and/or collaborators is the dominant component in their CO_2 emissions.

The authors of the HECAP+ report [35] have conducted a broad review illustrated with numerous case studies. These include a number of relevant estimates for similar laboratories and projects elsewhere.

2.7 Comparison with other laboratories

Most major physics-based and accelerator-based laboratories now have sustainability plans in place. Fermilab [46] is considering many different aspects of sustainability across all its operations [38]. CERN has now published two Environmental Reports [47, 48] that summarise the environmental emissions of CERN's activities; these broadly follow the same Scope 1/2/3 emissions estimates followed in the UK. These initiatives mirror the guidance of the recent 2020 Update of the European Strategy for Particle Physics [49], which states *"A detailed plan for the minimisation of environmental impact and for the saving and reuse of energy should be part of the approval process for any major project."*

CERN has also conducted project-specific preliminary estimates of CO_2 emissions and other sustainability issues for possible future collider projects CLIC [50], ILC [27], and Future Circular Collider (FCC) [51]. Indeed, comparative estimates of the emissions associated with the construction and operation of electron-positron Higgs factories vary widely depending on location and construction types [51].

Loosely put, the analyses above show that a Higgs factory will consume around 1 TWh of energy each year. Using a possible future carbon intensity for French electricity production of $16\,\mathrm{gCO_2e/kWh}$, this corresponds to $16\,\mathrm{ktCO_2e}$ per year or around $1.6\,\mathrm{tCO_2e}$ for each of the world's approximately 10 000 high-energy physicists. The assumed carbon intensity of electricity production is very important in assessing the differences between the candidate collider projects (e.g. circular vs. linear) and technologies (e.g. X-band vs. superconducting), and it is crucial to understand those assumptions – which vary by country, operation period and national rules.

In addition, construction is likely to require around 50-100 km of tunnel at around $6\,\mathrm{tCO_2e/m}$ of tunnel construction (very approximate figures); concrete tunnels are likely to be the single largest source of CO_2 emissions involved in the construction of a collider [39, 50], although the accelerator within will still be significant (perhaps $5\,\mathrm{tCO_2e/m}$, of which around half may be mild steel usage). Construction emissions will therefore be around 300-600 $\mathrm{ktCO_2e}$, or around 12-24 $\mathrm{ktCO_2e/year}$ spread over a 25-year operating life. This is around the same scale as the electricity consumption. The summary is simple: building a collider such as a Higgs factory will involve large carbon emissions that must be weighed against the benefits that will be realised during the operations phase.

2.8 Ongoing Sustainability Projects

In addition to initiatives by individual institutes, there are a number of larger, multi-partner coordinated programmes investigating technologies and concepts around sustainable accelerators. The most prominent of these activities are supported by Horizon 2020 (H2020) or Horizon Europe funding.

The current Horizon Europe Innovation Fostering in Accelerator Science and Technology (iFAST) programme [52] builds on technologies investigated in H2020 ARIES and includes a dedicated work package (WP11) looking at both discrete sustainable technologies and broader concepts for improving operational efficiencies. The programme also directly funds the development of two technology demonstration prototypes - high efficiency klystrons and advanced permanent magnet systems. iFAST additionally funds R&D into thin film superconducting radio frequency (SRF) technology, which has the potential to achieve sizeable reductions in emissions in both the manufacturing and operations phases of SRF-driven accelerators.

The recently-approved Horizon Europe Innovate for Sustainable Accelerator Systems (iSAS) [53] programme is dedicated to exploring innovative concepts for tackling the energy demands of future large scale research systems, including work on superconducting RF, energy recovery linacs and efficient cryogenics.

These highly-resourced pan-European activities underline the prominence of sustainable accelerators in the research landscape and the coordination required to deal with forthcoming national carbon budgets for research.

2.9 Life Cycle Stages

BS EN 17472:2022 defines the stages in LCA (Life Cycle Analysis), and particularly for civil construction, as follows:

- A: Before use stage (Planning, Manufacture and Construction)
- B: Use stage (Use and Operation)
- C: End of life stage (Demolition and Disposal)
- D: Benefits and Loads (Reuse and Recycling)

These are broken down into more detailed steps that can be considered separately:

- A0: Preliminary studies
- A1: Raw material supply
- A2: Transportation
- A3: Manufacture
- A4: Transport to works
- A5: Construction

- B1: Use
- B2: Maintenance
- B3: Repair
- B4: Replacement
- B5: Refurbishment
- B6: Operational energy use
- B7: Operational water use
- B8: User utilisation of infrastructure

- C1: Deconstruction and demolition
- C2: Transport for disposal
- C3: Waste processing
- C4: Disposal

- D: Reuse and recycling

These concepts are mirrored in the UKRI Infrastructure Fund definitions of categories and in the information solicited when estimates of carbon emissions are made.

Life cycle assessments encompass several stages. After a clear definition of goals and scope of a project, a Life Cycle Inventory (LCI) is first compiled to quantify foreseen inputs and outputs. A Life Cycle Impact Assessment (LCIA) is then performed. Various LCIA frameworks exist that include ReCiPe 2016 [54]. Software tools exist to assist in LCIA, including OpenLCA [55] and SimaPro [56].

The assessment of each stage depends on a number of parameters that may have uncertainties. For example, the carbon emissions incurred during electricity production vary from country to country, and will change over time. Hence, there are standardised guidance available. The UK Government has published a guidance to be used for GHG assessments in infrastructure, known as the HMT Green Book supplementary guidance [37], that defines assumed conversion factors to be used when calculating the carbon emissions incurred by e.g. Scope 2 activities. Accompanying these are the UK Government conversion factors that allow organisations to report equivalent GHG (greenhouse gas) emissions [36].

A very important overriding concept in sustainability is to embed the concept of the *waste hierarchy*; this establishes an order of priority for utilisation of goods, and follows the lifecycle steps above:

- **Prevention.** Can use be avoided or reduced, for example by good design?
- **Preparing for reuse.** Can good design allow an item to be used multiple times?
- **Recycling.** Can an item be conveniently recycled, e.g. can its components be separated and re-manufactured?
- **Other Recovery.** For example, can waste heat be recovered and used to aid the main use or be applied for a different use?
- **Disposal.** Can items be disposed of in a way that minimises environmental impact, or potentially be used at a later date?

This hierarchy was established in UK legislation [57], adopting an EU directive [58]; Government guidance is available on its use [59], and several authors have commented on how the terminology and methods should be used [60].

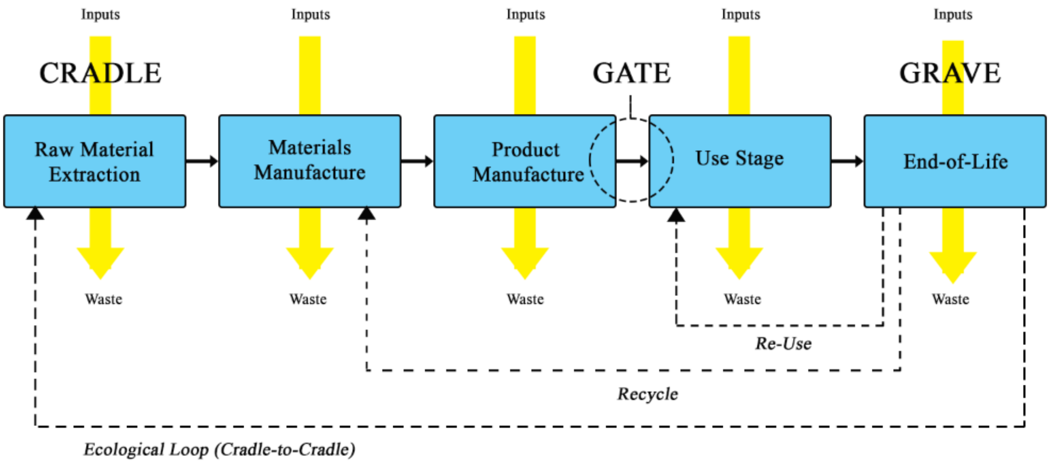


Figure 1: Stages of Life Cycle Assessment (LCA) for a given product.

2.10 Our methodology

Tools and methodologies, e.g. lifecycle analysis (LCA), are available to carry out assessments. For this first report, we have decided not to carry out a formal LCA using a commercial software package and databases. As indicated above, accelerators are complex infrastructures, and to carry out a top-down review will always require some approximations. So for each machine area, we aim to break down the work as follows:

1. Take an inventory of the key components and their primary materials;
2. Contact suppliers to find where materials are typically sourced, and (if possible) the amount of energy used in manufacture;
3. Find values in published literature and guidance for carbon intensities associated with production;
4. Estimate how much power is used in operation of each component.

In this way, we can build up carbon footprints associated with the **materials** and **operation** of each part of the machine. The obvious missing piece here is **disposal**; what happens to components at the end of their life. We take the view that many components can be repurposed or reused, and in fact there are many instances of this kind of reuse of accelerator components [61–63]. For electron machines, with low levels of activation, the end-of-life components are usually non-radioactive, and so we assume that the carbon footprint of disposal and recycling is relatively low. For facilities dealing with heavier particles such as protons, this may be a more significant factor, and this should be addressed in a future report.

We use RUEDI as a case study for this report, in order to give a reasonable scope and to enable the calculation of carbon footprints for a single facility. Where possible, we aim to make general points about environmental impacts of accelerator systems that can be applied more widely to a variety of different accelerator types. RUEDI is a relatively small and simple facility, and as such there are many different technologies (for instance, superconducting RF) that are not considered here. Our hope is that this general approach can be adopted and adapted by other institutions looking to reduce their carbon footprints, and that there are useful takeaways from this report that can be widely applied.

There are standardised approaches to LCA, including ISO 14001 [44]. LCA usually gives a variety of different metrics relating to the impacts of human activities on the environment, including human toxicity, ocean acidification, eutrophication, and global warming potential (GWP). Clearly these are all important; however, for the purposes of simplicity and clarity, in this report we concentrate solely on global warming potential.

Figure 1 shows the stages of a product's lifecycle usually considered in LCA. In this report, we aim to consider the footprint associated with material extraction and manufacture, product manufacture, and the use stage. As mentioned previously, we do not generally consider the end-of-life stage here; this is a question for a future report.

3 RUEDI

RUEDI, the Relativistic Ultrafast Electron Diffraction and Imaging facility, is a proposal to build an electron diffraction national user facility sited at Daresbury Laboratory in the northwest of England [64]. It aims to be a globally unique high-brightness electron diffraction and imaging facility with simultaneous high temporal and spatial resolution. It is designed to observe, quantify and understand fundamental ultrafast processes, including complex irreversible reactions that are far from equilibrium. RUEDI will conduct experiments under five research themes: energy generation, transformation and storage; biosciences; dynamics of chemical change; quantum materials and processes; and matter under extreme conditions.

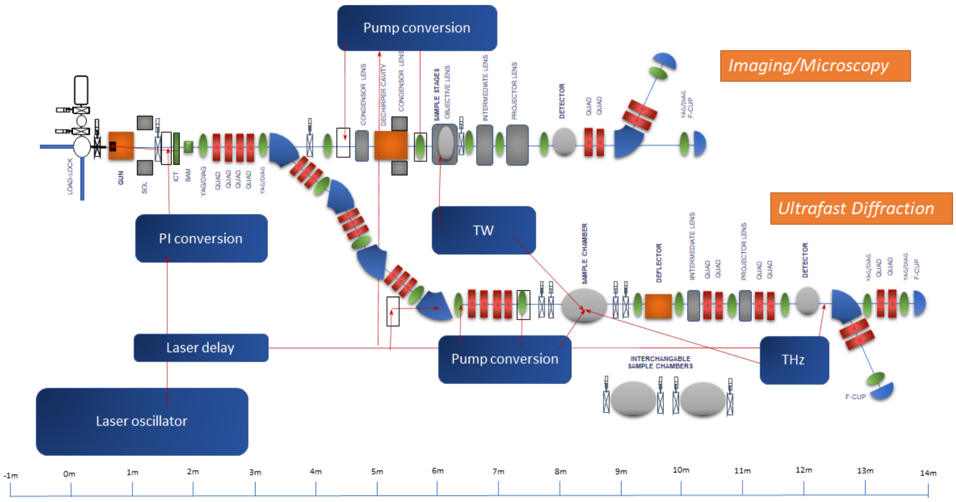


Figure 2: The layout of the imaging and diffraction beamlines on RUEDI.

The RUEDI instrument (Figure 2) consists of a normal-conducting S-band RF photocathode gun, producing bunches of electrons at 4 MeV [65]. The electron beam is transported to one of two beamlines: one for imaging, and one for diffraction. The laser system is based on using a single oscillator and amplifier, enabling inherent synchronisation of the photoinjector, TW pumps for the beamlines, and THz diagnostics.

In the straight-on imaging beamline, the beam is decelerated to a reduced energy of 2 MeV in a dechirper cavity. This is the maximum energy consistent with using a series of solenoid lenses to focus the beam. The beamline acts as a 16-64 megapixel electron camera, with magnification factors between 600-6500. The diffraction beamline is optimised for excellent time resolution, and consists of a four-dipole magnetic arc that suppresses the electron bunch jitter and provides bunch compression. Large sample chambers can be used, since the sample does not have to be located inside a lens. A series of solenoids magnify the diffraction pattern whilst retaining axial symmetry, and a suite of diagnostics are used to measure the final properties of the electron beam.

RUEDI is currently at the Technical Design Review stage. The top-level schedule, should the project be approved, is as follows [66]:

- **2022:** Conceptual Design Review (CDR)
- **2023:** Technical Design Review (TDR) and capital funding bid
- **2024:** Final detailed design
- **2025-26:** Procurement
- **2026-29:** Construction and assembly
- **2028-29:** Technical systems commissioning
- **2029-30:** Science commissioning and initial user programme
- **2031-35:** First five-year operational run

During an operational run, the plan is to run for five days per week with one 8 h shift per day [64]. There will be 180 days per year of EPSRC-funded operations, with another 60 days for set-up time and machine development. Commercial access will be available outside of these times. This report assumes a standard operating year of 250 days, with 10 hours of operation each day (to take into account startup and shutdown time), i.e. 2500 hours per year. For the purposes of emissions analysis, it is envisaged that RUEDI will have an operational lifespan of at least 10 years.

4 Machine Areas

Our aim here is to look at what components are needed for a given area of the machine, in the broadest sense. We do not aim to be comprehensive and get down to the level of nuts and bolts, but rather to provide an inventory of the major materials required for each section, and in what quantities they are required. We then calculate the carbon footprint for manufacture of these components, based on likely countries (or even continents) of origin of those materials, sourcing carbon intensity values from the published literature. Information on the carbon impact of processing materials at the factory to build up components (e.g. machining of steel) is included where possible, but manufacturers are often unwilling or unable to provide this information.

We also consider the carbon impact of the operation of the RUEDI facility, broken down by machine area. This is primarily electricity use. The carbon intensity of UK electricity generation during the 2030s is projected to be 77.4 $kgCO_2e/kWh$ - for more details, see Appendix A. Some subsystems require active water cooling, which adds an overhead for refrigeration and pumping of the cooling water, estimated at around 35 % of the base power requirement for each water-cooled component. Many systems (notably RF and magnets) are only required to be online when the machine is on; others (vacuum and diagnostics) will be running 24 hours a day.

STFC has adopted a common labelling method to describe uncertainties in emissions estimates. Given that it is difficult to state quantified error bars on individual emissions values, we use a Red/Amber/Green (RAG) uncertainty rating that is now commonly applied in these analyses. These ratings can be summarised as:

- **Green**: A well-understood uncertainty in the value (often used as a 10 % error);
- **Amber**: Some understanding of the uncertainty, but with caveats (which is often used as a 20 % error);
- **Red**: Little understanding of the degree of uncertainty (which is often used as a 50 % error).

Broadly speaking, most estimates in this report correspond to an Amber rating.

4.1 Laser systems

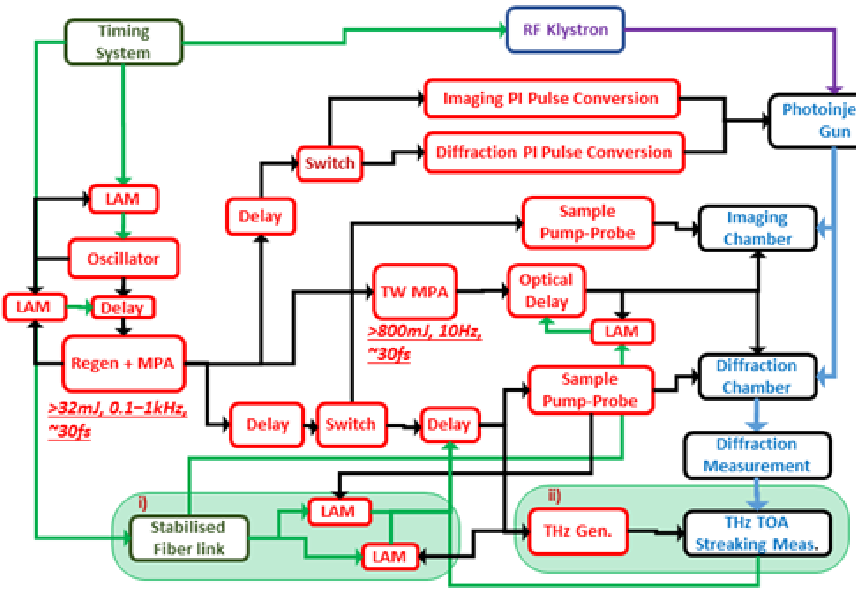


Figure 3: Schematic overview of laser and timing system. Laser systems are shown in red, electron beam and RF in blue, and timing and synchronisation systems in green. TOA refers to time-of-arrival measurements. LAM refers to the laser arrival monitors. The output of the oscillator is split into six creating the pulses for the photoinjector (PI), THz diagnostic branch and the pump-probe pulses for beamline experiments. Part of the main output is further amplified by a separate TW multi-pass amplifier (MPA).

The RUEDI laser and timing system is extremely complex due to the large number of wavelengths required (extreme UV to THz). It should be noted that in the case of RUEDI, the laser system is likely to make a much more significant impact on the overall carbon footprint of the facility than is typical. Figure 3 depicts a block diagram of the overall laser and timing system. Figure 4 shows the stages required for the generation of the UV pulses for the photoinjector. Figure 5 details the wavelength conversions required at one of the end stations. The imaging end station will also require a set-up producing a very similar range of wavelengths, though will not include the extreme UV wavelengths. This means there will be multiple of almost every wavelength conversion unit. The contributions to the overall carbon footprint from both the power consumption and the manufacturing of the system has been assessed.

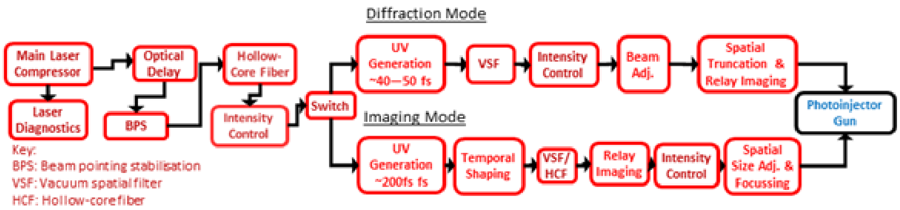


Figure 4: Schematic overview of the photo-injector pulse conversion system. It will consist of two lines for producing UV pulses, as each line requires slightly different pulse parameters.

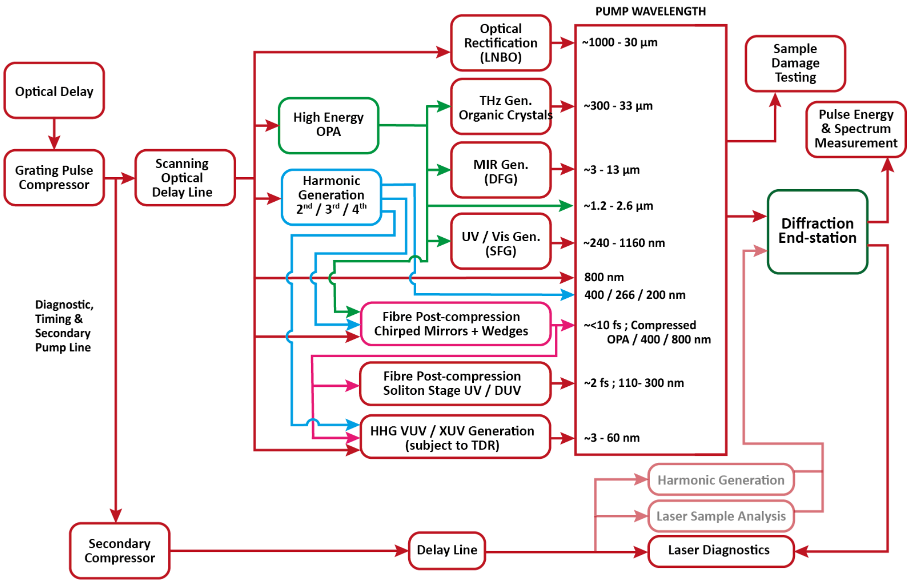


Figure 5: Outline of the pump-probe scheme specific to the diffraction line. This shows the nonlinear stages required for creating pump-probe pulses with wavelengths spanning from around 3 nm to 1 mm. The imaging line will also have a separate pump-probe scheme producing wavelengths spanning a similar range. Semi-transparent boxes have not been included in the analysis, as decisions on whether these will be included in the facility will be made at the technical design report stage.

4.1.1 Manufacturing

Due to the complexity of the laser and timing system, some assumptions had to be made. The contribution to the carbon footprint from the manufacturing of electronics – for example, computers, cameras, power supply units, chillers, and spectrometers – have not been included. Previous work into rack-mounted servers suggest that the operational carbon footprint far exceeds the production and manufacturing by orders of magnitude [67]. We assume this conclusion can be applied to all electronics in the laser system and that manufacturing contributions are negligible. Translation stages have been included in the manufacturing carbon footprint but have assumed to be made entirely from aluminium.

As RUEDI is in the design phase, the exact laser system that will be procured or the supplier is unknown. This makes determining the number of components, materials, and location in which they are manufactured very difficult. The majority of the laser system will likely be made of aluminium 'black boxes' of optical components, though this won't be true for every supplier. For this reason many of the systems will be simplified to a number of optical components, diodes, crystals, metres of fibre cable, and kilograms of aluminium. The amount of each of these has been estimated from typical layouts for each subsystem seen in literature and commercial system documentation.

All fused silica optical components have been assumed to weigh 42 g, the weight of a 2-inch diameter fused silica lens [68, 69]. This is estimated to be the average weight of an optical component within the whole system. The carbon footprint of the fused silica components has been taken to be 0.72 $kgCO_2e/kg$ produced. This is the carbon intensity found for special glass in 2007 by Schimitz et al [70]. This does not include the coating process which will be applied to almost every component, primary production of coating materials, transportation of the components after manufacturing or any end of life processes. Information about coating materials and energy intensity of the coating process is very limited and we anticipate transportation of the components will contribute negligibly to the total carbon footprint of the item. The end-of-life of all components will be discussed separately. Much of the carbon released in the glass making process is in the burning of natural gas in furnaces. This means the value quoted for Europe can be applied to glass manufactured around the world.

The laser crystals were treated separately from optical components as the manufacturing process produces a lot more carbon dioxide. Large single crystals are required for lasers and are grown using the Czochralski method. This involves heating the components to around 2000 °C, dipping in a seed crystal attached to a rod, then slowly rotating and pulling the rod out of the crucible over many hours. The majority of the carbon emissions are as a result of this manufacturing stage. Each crystal was assumed to be 4 g, though many of the crystals used will be much smaller than this. The carbon intensity value per kg of crystal was found to be 943 $kgCO_2e$. This has been calculated from energy and material usage estimated for manufacturing 6 g sapphire wafers in [71]. It is assumed that crystals are manufactured in Europe, where the carbon intensity for electricity production is currently 334 gCO_2e/kWh [72]. In common with other regions, Europe is gradually decarbonising its electricity supply and so this figure is somewhat conservative.

Ti:sapphire is the main crystal used in the laser oscillator and amplifiers. The main component in Ti:sapphire is alumina which has a carbon intensity of 0.71 $kgCO_2e/kg$ [73]. Though the primary production of the base compounds of the various laser crystals used will be different, one carbon intensity value will be used for all crystals. This is due to the lack of information on the carbon footprint of the obscure compounds used to grow other crystals.

In the oscillator and amplifiers, the light is first generated by large diode arrays or flash lamps before being converted into laser light of the correct frequency for pumping Ti:sapphire. The carbon footprint of manufacturing these has been found by scaling the values found for an LED array and compact fluorescent lamp (CFL) by the input power of the arrays and lamps in the laser units. CFLs are manufactured in a comparable way to flash lamps. The diodes in the amplifier pump lasers have a combined output power of 80 W. The diodes are assumed to be 40 % efficient giving 200 W of input power. The two terawatt amplifier pumps contain flash lamps. The power input of these flash lamps has been estimated to be 660 W and 2500 W assuming 50 % of the input power to the amplifier pump unit goes into powering the flash lamps. In Scholand and Dillion [71] it was found that 0.71 kg of CO_2 is produced in the manufacturing of a 1 W LED and 1.83 $kgCO_2e/W$ for CFLs. These values were calculated excluding disposal and energy in use as these will be discussed separately.

Table 1 shows the carbon footprint of the components within the laser system. These calculations are based on assuming all aluminium and steel comes from China and therefore has a carbon intensity of 20 $kgCO_2e/kg$ [74] and 2.15 $kgCO_2e/kg$ [75] respectively. The laser crystals are assumed to be manufactured in Europe. These are likely to be the most representative values for the carbon footprint as more than 50 % of the world's aluminium and steel is produced in China [76, 77], and the most common crystal manufactures are based in Europe. An evaluation will be done into the benefit of the location of manufacturers.

Item	**Carbon intensity** [$kgCO_2e/kg$]	**Mass used** [kg]	**Total emissions** [$kgCO_2e$]
Aluminium	20	847	16942
Steel	2.15	6775	14553
Flash lamp	1.83 $kgCO_2e/W$	3160 W	5775
Diodes	0.71 $kgCO_2e/W$	2700 W	1927
Laser crystal	943	0.17	158
Fibre cable	7.29	2.26	16.5
Glass	0.72	20.6	14.8
		Total	39.4 tCO_2e

Table 1: Amounts and contributions to the carbon footprint from materials in the laser and timing system.

4.1.2 Reducing carbon emissions from manufacturing

The carbon footprint of manufacturing the laser systems totals 39 tCO_2e. Approximately 43 % of this is attributed to the aluminium in the system, 37 % is due to the emissions from steel production, and around 20 % is from the diodes and flash lamps. There are negligible contributions from the laser crystals, optical fibre, and glass within the system totalling less than 1 % of the carbon footprint.

It has been assumed that all aluminium is sourced from China. The carbon intensity of aluminium can be reduced by sourcing from a 'greener' country. Utilising recycled aluminium could mean even greater carbon savings. Europe produces aluminium with a carbon footprint of 6.70 $kgCO_2e/kg$ of aluminium [74], compared to China's 20 $kgCO_2e/kg$. Recycling aluminium produces 0.5 $kgCO_2e/kg$ [78]. If all aluminium within the laser system was produced in Europe rather than China, the carbon footprint would be reduced by almost 11 tCO_2e. A saving of 16.5 tCO_2e could be made using recycled aluminium. These alternatives could reduce the total carbon footprint from manufacturing by 66 % and 97 % respectively. Therefore, where possible aluminium should be made from recycled sources or sourced from Europe or other countries with low carbon footprints for aluminium production. This should be relatively easy to achieve as all the laser 'black boxes' will be supplied by only two or three companies. Confirmation from one laser company has been obtained that their aluminium is likely manufactured within Europe; however it is clear that transparency in supply chains is a concern. Therefore, the values quoted in the table represent a worst case for the manufacturing carbon footprint. In future tender processes a request from each company about the source of their aluminium could be added and would aid in reducing the laser system footprint.

Steel is the next biggest source of carbon. The most significant contribution to the amount of steel in the system are the optical tables, accounting for 79 % of all the steel in the system and 29 % of the total carbon footprint from manufacturing. Therefore, the footprint of the laser system should be made as compact as possible, though this does limit room for potential upgrades in the future. The carbon footprint of the steel in the system can be reduced by over 7 tCO_2e by sourcing from Mexico for example. The carbon intensity of steel from Mexico is 1.08 $kgCO_2e/kg$ compared to 2.15 $kgCO_2e/kg$ from China [77]. Similarly to aluminium, it is likely only one supplier will be used for the optical tables and a requesting the source of the steel would be beneficial for making more sustainable choices.

Since 2007, the year in which the value used for the carbon footprint of glass was calculated, progress is likely to have been made on reducing emissions. One of the largest suppliers of speciality glass, Schott, have recently announced a commitment to becoming carbon neutral by 2030 [79] and are in the process of converting all their gas furnaces to electric as well as exploring hydrogen powered furnaces. All electricity supplied to Schott facilities across the world is 100 % green since the end of 2021. However, the contribution to the carbon footprint of RUEDI from glass is approximately 15 $kgCO_2e$, meaning even if the glass manufacturing were carbon-neutral no significant carbon saving would be made.

The most energy-intensive material within the laser system are the laser crystals with a carbon intensity of 943 $kgCO_2e/kg$ of crystal. This is assuming the crystals are manufactured in Europe. Despite the high intensity value, the laser crystals only contribute 160 $kgCO_2e$ to the overall footprint. This is because it has been estimated that the laser system contains less than 200 g of crystal. If crystals are manufactured in China assuming a carbon intensity of 549 $kgCO_2e/kWh$ for electricity [80], the contribution increases to 260 $kgCO_2e$. This difference only represents 0.25 % of the total carbon footprint from manufacturing. Therefore, the supplier of the laser crystal does not have a significant impact. Laser crystals are grown using the same method as silicon. Improving the sustainability of silicon crystal production is an area where significant work is being done due to their use in photovoltaic panels. Between 2015 and 2020, carbon emissions from single crystal silicon has reduced by 50 %; this improvement is mainly attributed to reduction of waste [81]. It is anticipated that the silicon sector will continue to improve on carbon emissions and that this will positively impact the adjacent laser crystal sector.

The disposal, end of life, and repairs/replacement of components have not been included in our analysis. Most of the replacement components will be optics and not whole laser units. The optics contribute negligible amounts of carbon to the total, so replacement parts will not be considered. Much of the laser system will be repurposed when RUEDI is no longer operational, as the components are not highly specific to the application. When components do break, it is difficult to calculate the impact of their disposal. The majority of the glass in the system is coated, meaning it cannot be recycled by traditional means. It is difficult to determine whether the aluminium and steel in the laser system will likely be recycled. The metal may not be easily isolated from other components. The most impactful form of recycling can only be done by manufacturers themselves, who may be able to reuse the parts. This practice is, however, extremely uncommon in the laser industry. In future we hope companies will work towards a more circular economy for their products. If all the aluminium in the system was recycled, this would add 423 $kgCO_2e$ to the total. This represents less than 1 % of the total carbon footprint from manufacturing. For these reasons we have assumed there is no contribution to carbon footprint from disposal.

4.1.3 Power Consumption

Lasers are notoriously inefficient, usually only converting a few percent of the input power into output light power. The energy consumption of the laser system has been calculated assuming the amplifiers will be running for 10 h per day, 250 days a year. The oscillator, vacuum pumps and cooling systems are assumed to be running 24 hours a day, 7 days a week. A summary of the power consumption can be seen in Table 2.

Item	Location	Power consumption [W]	Energy usage [MWh/yr]	Total carbon footprint [kgCO_2e/yr]
Pump power supply	Oscillator	750	6.57	509
Controller	Oscillator	110	0.964	75
Chiller	Oscillator	600	5.26	407
Controllers	Regen and MPA0 amplifers	990	2.48	192
Chillers	Regen and MPA0 amplifiers	5520	48.4	3745
Pump power supply x10	Regen, MPA0, cryo amplifiers	4400	11.0	851
Controller	Cryo MPA	330	2.89	224
Cryo chiller	Cryo MPA	7900	69.3	5360
Diaphragm pump	VSF	336	2.95	228
Turbo pump	VSF	250	2.19	170
OPA controller	OPA	240	0.600	46
Pump power supply 1	TW pump	1320	3.3	255
Pump power supply 2	TW pump	5000	12.5	968
Controller	TW MP1 and MP2	240	0.600	46
Chiller	TW pump	1440	12.6	977
Backing pump x2	TW	2640	23.1	1791
Vacuum pump	TW compressor	600	5.26	407
Timing laser	Timing laser	15	0.131	10
Computers	Misc	1140	9.99	773
Total		33.8 kW	220	17.0 tCO_2e

Table 2: Power consumption of the RUEDI laser and timing system. MPA stands for multipass amplifier, VSF: vacuum spatial filter, OPA: optical parametric amplifier and TW: terawatt.

4.1.4 Reducing power consumption

The power consumption of the RUEDI laser system has a GWP of 17 tCO_2e/yr. Over 10 years of operation this will dwarf the contributions from the manufacturing of the system. This means a large impact can be made by using electricity from more carbon-neutral sources (considered elsewhere in this report).

Around 57 % of the total energy consumption is due to the chillers, 21 % is attributed to the pump power supplies, and the remaining contributions are from the controllers, computers and vacuum pumps. Water cooled chillers generally consume less power than air cooled though the amount of energy saved is dependent on the application [82]. Chillers waste a lot of energy when working at part load; for a significant proportion of the time the chillers will be working in this state. Efficiency can often be improved with smarter control of the chillers and variable-speed drivers. It has been shown that using smart controllers can reduce the energy consumption of a chiller plant by 14 % [83]. Over 10 years of operation this could result in a 37 t saving in CO_2 for RUEDI. Unfortunately this would require one integrated chiller system for all the laser units. This is very uncommon, since laser systems are typically built up in modules depending on customer requirements, meaning that subsystems generally have individual chillers. These chillers are supplied by the manufacturer of the laser and so we have little influence over either the chiller choice or its control.

The second biggest contributors to the carbon footprint are the pump lasers. Many of the pump lasers already utilise efficient diode arrays to pump their laser medium. The inefficiencies are introduced in the stimulated emission process. The energy input required for a given energy output is dictated by the laser medium. Therefore, significant improvements to the power consumption of the pump lasers are unlikely. Ti:sapphire has been used as a lasing medium since the 1980s and yet a more efficient laser medium has not taken its place. Conversion efficiency in Ti:sapphire can be improved by 25-30 % through cryogenic cooling [84]. Unfortunately, cryogenic systems are much more expensive than traditional cooling systems, and analysis into whether the improvements in efficiency result in a saving in electricity overall would be required. The initial energy requirement for the oscillator and amplifiers is dictated by the energy required by the branches as well as efficiency of the laser transport and manipulation. Ensuring the highest reflectivity optics are used, identifying any units not performing at the efficiencies designed and optimising them as well as manipulating the beam as little as possible could significantly reduce the energy requirements for the laser system. For example, a laser reflected by ten 97 % reflectivity mirrors has a final energy of 74 % of the initial, using 99 % reflectivity mirrors this value increases to over 90 %. Therefore, ongoing maintenance has the potential to reduce energy consumption significantly.

Recently developments have been made into ytterbium-doped laser gain media which can be direct diode pumped. The Ti:sapphire systems require a pump wavelength of 532 nm, meaning diodes need to pump a crystal; this light is then frequency doubled in another crystal before the light can be utilised by the Ti:sapphire. Removing these two stages will significantly improve the efficiency of the pump by potentially 50 % [85, 86]. Unlike: Ti:sapphire, ytterbium can be added to fibres which can significantly reduce the cooling requirements of the laser improving the power savings further. However, an assessment has been done into the suitability of this type of system for RUEDI and it was concluded that Ti:sapphire will be used. Due to smaller bandwidth, ytterbium systems require complex compression systems to reach the desired pulse length. Ytterbium systems also have poorer intensity stability, beam pointing stability, and are currently double the price of an equivalent Ti:sapphire system. Despite this, these developments are promising. As the ytterbium-based laser matures, this system has the potential to greatly reduce laser system power consumption in future projects.

4.1.5 Conclusions

Over 10 years of operation the total carbon footprint from the laser and timing system is 170 tCO_2e. This is likely to be disproportionately large compared to most facilities of this size due to the sheer complexity of the laser system. The electricity consumption accounts for 81 % of the laser system's carbon footprint and 19 % is attributed to manufacturing. Despite this, considerable carbon savings can be made in the manufacturing. The most significant of these will be ensuring that steel and aluminium in optical tables and laser units are sourced from countries where the carbon impact of manufacturing is lower or from recycled sources. This lower-carbon sourcing could save around 18 tCO_2e of emissions.

It is difficult to reduce the energy consumption of the laser as the conversion efficiencies are dictated by the different laser media properties. However, optimising the efficiency of the components that interact with the laser through using the highest reflectivity mirror available, ongoing maintenance and monitoring of the system could lead to a significant reduction in electricity required. Due to laser inefficiencies a large proportion of the energy is needed to cool the systems. Slight improvements can be made to chiller power usage through favouring water cooling over air, though this choice may not be available for all sections of the laser system. Unfortunately much of the technology which has the potential to make a significant impact on laser efficiency is currently inferior to the standard laser used, in the case of ytterbium-based laser systems, or requires a detailed further investigation into whether carbon savings can be made through cryogenic cooling.

It has been clear throughout this work that sustainability is not at the forefront of thinking in laser manufacturing, although the industry is focused on improving laser efficiencies. Currently no scientific laser manufacturers have a recycling policy. By developing a more circular economy within the laser industry vast improvements could be made to laser unit carbon footprint; however, there are likely issues with laser safety when reusing parts. There is also a particular issue with transparency about the geographical origin of sourced materials. Requesting information about this in future tenders could improve transparency.

4.2 RF systems

4.2.1 Definition

The RUEDI design has 3 RF systems: the RF photoinjector gun, the transverse deflecting cavity (TDC), and the dechirper cavity. All three RUEDI RF systems have a standard top-level design. For the purposes of this report, this consists of:

- Low level RF electronics
- High-power RF amplifier
- Waveguide RF transport system
- Cavity
- Water cooling/stabilisation systems
- Cabling

The power source for some RF systems, the high-power RF amplifiers, is currently under review for the RUEDI RF systems and is dependent upon the peak RF power and the repetition rate requirements for the machine (100 Hz or 1 kHz). Currently, the baseline design consideration is for each of the high-power RF systems to consist of a high voltage (HV) modulator containing a solid-state amplifier and with a klystron as the final stage of amplification. However, the peak power requirements for the TDC may be low enough that the RF power can be provided by just a solid-state amplifier, removing the need for a HV modulator and klystron. Additionally, it may be possible to replace the waveguide transport system with a coaxial cable RF transport system. The top-level requirements for each of the RF systems are shown in Table 3.

RF system	**Cavity requirement**	**Cavity power** [MW]	**Repetition rate** [Hz]	**RF pulse length** [μs]
Photoinjector	2-4 MeV acceleration	5.75	100	1
TDC	0.1 MV deflection	0.12	100	3
Dechirper	32 MV/m peak field	1.1	100	3

Table 3: RUEDI RF systems.

4.2.2 System assembly

Some items in the RF system such as the waveguides and cavities are made of only 1-2 different materials; others such as the electronics-based items have many more. Estimates for the main material usage and their emissions are shown in Table 4 for the RUEDI RF systems. It should be noted here that it has not been possible to ascertain from the suppliers of the equipment the source of their materials, so in general averages for the carbon intensity figures have been assumed. For example, for the aluminium used in the modulators there will be various grades of aluminium required depending on its usage (i.e. high quality for the transformer tank, lower quality for the side panels) so could be sourced from either Europe (6.7 $kgCO_2e/kg$) and China (20 $kgCO_2e/kg$), thus a carbon intensity figure of 13.5 $kgCO_2e/kg$ has been assumed.

Item	**Material**	**Estimated mass** [kg]	**Emissions** [$kgCO_2e$]
2 x modulators	Copper	570	935
	Steel	760	1298
	Oil	342	1112
	Aluminium	190	2537
	Silica	19	124
	Fibre glass	19	38
	Total	1900	6043
2 x klystron and solenoid	Copper	420	689
	Steel	180	307
	Total	600	996
4 x solid state amplifier and LLRF units	Copper	21	34
	Steel	27	46
	Oil	3	10
	Aluminium	6	80
	Silica	2	13
	Fibre glass	1	2
	Total	60	185
3 x cavity	Copper	71	116
	Steel	4	7
	Total	75	123
Waveguide	Copper	84	174
	Steel	13	22
	Total	97	196
Grand total		2732	7544

Table 4: Materials used for the RF systems in RUEDI.

4.2.3 Operation

For a standard RF system, the main power requirement is the modulator system. The power required for the modulator depends on the efficiency of every component in the system. Here we will work backwards from the cavity up the chain to the modulator.

The cavity is the most inefficient part of the system. For each pulse the cavity must be filled with RF and a flat top in voltage provided, which takes 1-3 µs. The single RUEDI bunch passes through in nanoseconds, so the voltage achieved in the cavity is unused for the vast majority of the time. The bunch is low charge, and consequently the beam power is also low.

Taking the RUEDI photoinjector baseline design as an example, with an RF pulse length of 1.37 µs, peak power of 5 MW and the RUEDI repetition rate of 100 Hz, it has an average power consumption of 685 W. The 50 pC bunch is accelerated through 4 MV, giving a beam power of 20 mW. This represents an efficiency of 0.003 %.

Good cavity design principles can increase the efficiency of the structure somewhat, but for a low current accelerator like RUEDI the power transfer from the RF to the electron beam will always be very low.

The RUEDI waveguide transport lines between the klystron and the cavity will include straight waveguides, waveguide bends, directional couplers, pumping ports and a circulator to protect the klystron. Currently the full waveguide design for each of the RF system has not been completed; however the design principles will be similar to those used for CLARA, thus for the purpose of assumptions and calculations we will consider information from the CLARA Linac 1 RF transport line [87]. This waveguide has theoretical losses of 18.9 %, using the VSWR values for each component along with the RF attenuation in each length of waveguide. This value measures (25 ± 5) % during operation. A reasonable estimate for the power transport efficiency is therefore 70-80 %, which means for the RUEDI photoinjector the klystron must be able to provide a peak RF of at least 6.25 MW, an average RF power of 856 W.

Typically, klystron efficiencies will be in the range of 43-45 % [88]. Here it should be noted that there are programmes of work to improve the efficiencies of klystrons. However, for RUEDI there will very little opportunity to influence the design of a new efficient klystron, as the number of klystrons required for the RUEDI facility is low and would not justify the cost and time to develop a bespoke klystron. The modulator provides the DC voltage to the klystron, but the pulse length needs to be approximately 2 µs longer than the klystron RF pulse length to enable a flat top to be achieved for the RF pulse and to allow for the rise and fall times. Thus, for the photoinjector klystron the peak beam power will be 14.4 MW and the average beam power will be 4.87 kW. However, the modulator provides power for the klystron filament, solenoids, solid state RF amplifier and ion pump, as well as ancillary supplies. Approximate power consumption values for the filaments, solenoids, and amplifier are respectively 530 W, 4060 W, and 150 W (the power for the ion pump is negligible). The total power for the ancillary supplies is therefore around 4.74 kW. Thus, the overall average power consumption for the modulator to power the klystron is around 9.6 kW. Modulators typically run at 85-90 % efficiency, giving an overall average power consumption for the photoinjector of 11.4 kW. Table 5 shows the power consumption and the total carbon footprint for each RF system, assuming 10 hours operation per day and 250 days of operation per year.

RF system	**Electrical power consumption** [kW]	**Water cooling overhead** [kW]	**Annual energy usage** [MWh/yr]	**Annual carbon footprint** [tCO_2e/yr]
Photoinjector	11.4	4.0	38.5	2.98
TDC	0.09	0.03	0.3	0.02
Dechirper	6.71	2.35	22.7	1.75
Total	18.2	6.37	61.4	4.75

Table 5: Power consumption for each of the RUEDI RF systems. The systems are water-cooled, which we assume adds a 35 % overhead.

4.3 Magnets

Accelerator magnets fall into one of three broad categories:

- Normal conducting;
- Superconducting (SC);
- Permanent magnet (PM).

This review concentrates on normal conducting magnets since they are the baseline for RUEDI. Consideration will be given to superconducting and PM-based magnets in a future report.

4.3.1 Manufacture

The primary materials used in normal conducting magnets are copper and steel. Low-carbon steels in the AISI 10XX range are typically used [89], where the XX represents the fraction of carbon (for example, AISI 1010 steel contains 0.1 % carbon by mass). Copper for current-carrying cables is usually oxygen-free high-conductivity copper, often with a central channel for cooling water. Other materials are used as well, for instance epoxy resin to insulate the coils and aluminium for non-magnetic structural components. However, the mass contribution of these is negligible compared to the copper and steel.

A typical example is illustrated here, using data furnished by Tesla Engineering in the UK [90]. A 2 t quadrupole magnet is produced using 2.85 t of steel and 150 kg of copper. The steel is manufactured in Germany, and the copper in Finland. Both are taken by road freight to a factory in the UK. Electricity consumption at the factory has been estimated for various different processes. An overview of this is shown in Table 6 and visualised in Figure 6. Overall, 6138 $kgCO_2e$ are emitted, which corresponds to 2.86 $kgCO_2e/kg$ of finished product.

Materials	**Origin**	**Carbon intensity** [$kgCO_2e/kg$]	**Mass used** [kg]	**Total emissions** [$kgCO_2e$]
Copper	Finland	0.400 [91]	150	60
Steel	Germany	1.708 [75]	2850	4868
Transport	**Transport method**	**Carbon intensity** [$kgCO_2e/tkm$]	**Distance** [km]	**Total emissions** [$kgCO_2e$]
Copper	Road freight, Europe	0.14 [92]	3000	63
Steel			900	359
Energy		**Carbon intensity** [$kgCO_2e/kWh$]	**Energy used** [kW h]	**Total emissions** [$kgCO_2e$]
Yoke machining		0.212 [93]	606	129
Pole machining			1080	229
Coil winding			1453	308
Assembly			82	17
Testing			492	105
Total				**6138**

Table 6: An example of the CO_2 emissions produced in manufacturing an electromagnet. This allows us to derive a value of 2.86 $kgCO_2e/kg$ of manufactured product.

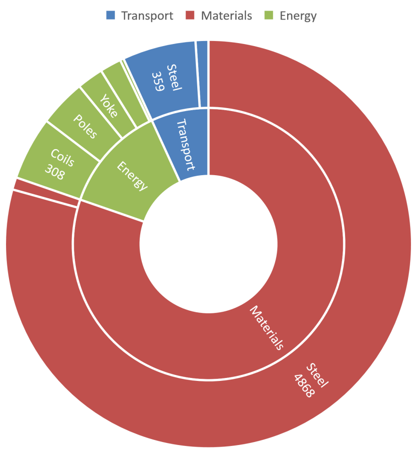


Figure 6: CO_2 emissions produced in manufacturing an electromagnet.

It's clear to see that the largest impact comes from the production of the steel, and that the next largest impact is from the energy used during manufacture. Steel production emissions vary considerably by country; if the steel for this magnet was produced in Mexico rather than Germany (reported carbon intensities of 1.080 and 1.708 $kgCO_2e/kg$ respectively [75]), overall emissions could be reduced from 6138 to 4187 $kgCO_2e$, a reduction of 32 %, even taking into account the longer transportation distance. Another way to reduce emissions could be to run manufacturing processes at times when the grid carbon intensity is lower (i.e. the fraction of electricity produced by renewables or nuclear is higher); reducing the grid intensity by 50 % in these calculations results in an overall emissions reduction of 6 %, so the gains to be made from this are are more modest.

A relevant analysis was carried out for production of a prototype tidal power generator from Antec, a Spanish magnet manufacturer [94]. The results were very similar to the analysis above, with the bulk of emissions coming from the steel production and an overall emission rate of 2.99 $kgCO_2e/kg$ for finished product.

4.3.2 Emissions from operation

Figure 7 shows a set of quadrupole magnets produced for the CLARA front end [87]. These magnets are designed to operate at low beam energy (up to 60 MeV), and so are broadly similar to those expected to be used on RUEDI. Operating data for a single magnet is shown in Table 7. An operating lifetime of 15 years was assumed for CLARA, over which the predicted operational CO_2 emissions from energy use amount to 4.8 tCO_2e. This dwarfs the emissions from manufacture, which (assuming a similar intensity to the analysis above) comes to 107 $kgCO_2e$.

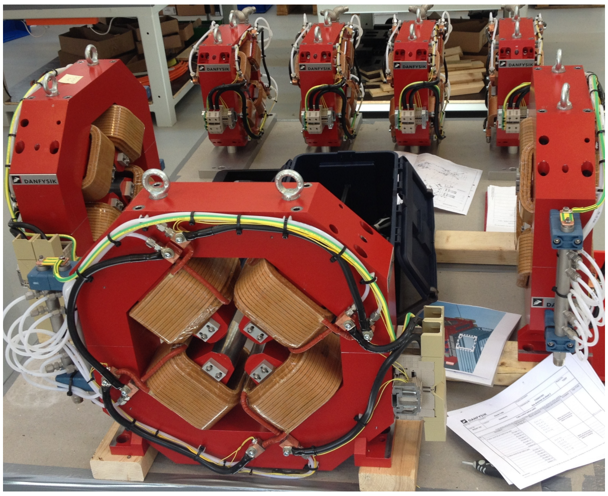


Figure 7: Quadrupole magnets produced by Danfysik for the CLARA front end.

4.3.3 Scaling laws for quadrupole magnets

In general terms, the footprints for manufacture and operations of normal conducting quadrupole magnets depend on a number of factors.

- **Aperture.** The steel and copper mass, and the electrical power required, all scale with r^2 in quadrupole magnets, where r is the aperture radius of the magnet. Reducing r to the minimum possible value will drastically reduce the amount of materials required, and the power consumption of the magnet.
- **Current density.** The electrical power has a linear dependency on the current density J, but the steel and copper mass are both inversely proportional to J. For a typical magnet the operations footprint will vastly outweigh the construction footprint, so decreasing the choice of current density in the magnet will likely result in a reduction in the overall footprint. Of course, it means that a larger magnet will be required with fatter coils to provide the same amount of total current, so space concerns may come into play as well.
- **Integrated gradient.** Expressions for the material mass and the electrical power consumption also all contain a linear dependency on G, the quadrupole gradient, and on L, the quadrupole length. The quantity GL is the integrated gradient, which provides a constant focusing strength for a given beam energy. So a significant reduction in GL is not possible without also reducing the beam energy.

Similar arguments apply for other types of magnets, though the scaling laws may be somewhat different in each case.

Quantity	Value	Unit
Power	425	W
Cooling power	124	W
Daily usage duration	16	h
Daily energy use	8.79	kW h
Annual usage duration	6	months
Annual energy use	1.61	MW h
Lifetime	15	years
Total energy use	24.1	MW h
Electricity carbon intensity	199	gCO_2e/kWh
Carbon emissions from operation	4.79	tCO_2e
Steel mass	51	kg
Copper mass	9.6	kg
Steel carbon intensity	1.71	$kgCO_2e/kg$ [75]
Copper carbon intensity	2.07	$kgCO_2e/kg$ [95]
Emissions from materials	107	$kgCO_2e$

Table 7: A summary of the lifetime CO_2 emissions produced in manufacturing and operating a Type 1 CLARA quadrupole magnet. Electricity carbon intensity is averaged over the 15-year period starting in 2014. See Appendix A for details. Emissions from manufacturing only consider the materials footprints for copper and steel, and so are likely to be an underestimate.

4.3.4 Magnets for RUEDI

The ‘shopping list’ of magnets for RUEDI is shown in Table 8. Outline designs have been produced [96] for some components. We can estimate the mass and the power consumption for each one, and therefore produce rough estimates for the materials and operational footprints for the magnets. It’s clear from this data that the CO_2 emissions are dominated by the operation of the lenses, which are large solenoid devices drawing several kW each. This is where efforts to reduce the energy consumption should be concentrated. It’s not entirely clear what form those efforts could take, as the design of the focusing lenses is more complex than for the more standard dipoles and quadrupoles used for beam transport (which give a much smaller contribution to the energy consumption, despite being greater in number). The lens design must allow for sample chamber insertion as well as interaction with lasers, and therefore making changes such as reducing the aperture or increasing the number of windings (both of which may reduce the power requirements) may be difficult. We recommend that a full design should pay careful attention to the power consumption, and consider whether low-power alternatives such as permanent magnets or hybrid magnets may be viable.

Magnet type	Quantity	Mass [kg]	Total mass [kg]	Materials footprint [$kgCO_2e$]	Power consumption [W]	Operational footprint [$kgCO_2e/year$]
Gun solenoid	1	79	79	147	12124	3167
Quadrupole	30	15	435	803	13	75.5
Arc dipole	4	47	186	338	11	8.51
Spectrometer dipole	2	49	98	177	34	13.2
Sextupole	4	25	100	185	20	15.5
Corrector	12	8	96	199	2	4.64
Lens (diffraction line)	3	79	237	442	12124	9501
Lens (imaging line)	4	119	475	883	6062	6334
Objective lens	1	160	160	302	5000	1306
Total				3.48 tCO_2e		20.4 tCO_2e

Table 8: Bill of materials for RUEDI magnets [97]. Materials footprints are estimated using the carbon intensities quoted for steel and copper in Table 7. Operational footprints are estimated using the standard RUEDI usage pattern of 10 h days, 250 days per year, over a lifetime of ten years. All magnets are passively cooled except the lenses, which are water cooled; the assumption is that this adds 35 % on top of the quoted power consumption. The carbon intensity of electricity is assumed to be 77.4 gCO_2e/kWh - see Appendix A.

4.4 Diagnostics and Controls

Diagnostics and Controls are the systems that allow operators and scientific users of a machine like RUEDI to identify what the accelerated beam is doing and control the beam to carry out experiments. They are therefore vital to the operation of the machine. The RUEDI diagnostics and control system includes two main types of components: Diagnostic devices mounted on the accelerator beamline and computing hardware mounted in a rack room to process data and control hardware.

Based upon reviews of the sustainability of servers and data centres [67, 98] we conclude that over the lifetime of an accelerator, the emissions generated by the manufacture, assembly and delivery of diagnostic and control systems make up less than 5 % of the systems, with the vast majority of emissions resulting from the consumption of electricity.

Based on this finding, only devices which continuously consume electricity are included in this analysis. This includes processing crates, front-end electronics, oscilloscopes, network switches and servers. The manufacturing cost has been included where this is available in literature for illustration. The devices considered are listed in Table 9, with the number of devices based on a scaling from CLARA.

Device	**Number**	**Total manufacture impact** [tCO_2e]	**Total operation impact** [tCO_2e/yr]	**Data source**
Front-end electronics	8 (1U ea)	2.04	1.47	[99]
Processing crate	6 (3U ea)	4.60	3.32	[99]
Oscilloscope	2 (6U ea)	3.07	2.21	[99]
Network switch	5 (1U ea)	0.698	0.364	[100]
Rack-mounted server	6 (2U ea)	3.07	2.21	[99]
Totals	27	13.5	9.58	

Table 9: Table of devices considered in the control and diagnostics system. Operations impact for the network switches are calculated using a figure of 174 W for operation [100], with 24 h operation assumed. For the other components, power consumption figures are calculated from the figure of 748 $kgCO_2e$ given for operation in the EU in 2014 [99, 101]. The carbon intensity of electricity is assumed to be 77.4 gCO_2e/kWh - see Appendix A.

For rack-mounted servers and network switches, literature was used for the life cycle assessments. Dell has carried out an LCA for a 2U PowerEdge R710 rack server [99], which is representative of the servers used in the control system. It found that over 90 % of the total life cycle impact over a six year lifetime came from electricity consumption. The remainder was mainly caused by the production and assembly of the server. The Dell white paper agrees with the findings in [67] and [98]. For network switches, [100] found less disparity between manufacture and operation. The rack-server estimate is used as a representative example of other systems, such as processing crates and oscilloscopes, which are effectively specialised rack-mounted servers with similar components, manufacturing steps and use patterns. Therefore 255.5 $kgCO_2e$ and 745 $kgCO_2e/yr$ for the impact of manufacture and operation per rack unit, respectively, was used as an estimate for those devices.

Based on these assumptions, it is estimated that the manufacture and assembly of the RUEDI diagnostics system will generate approximately 13.5 tCO_2e and each year of operation will generate approximately 9.6 tCO_2e. As discussed above, this figure is based on 24/7 operation of many electronic devices; it may be possible to achieve significant reductions by putting devices into a low-power state when the accelerator is not running.

4.5 Vacuum

To propagate accelerated particles within an accelerator, a vacuum is required to maintain the beam quality. Depending on the particle type, beam specification and beam energy required by the machine design, different vacuum levels are dictated. Accelerators normally have several vacuum regions with different specification levels; this is no different for RUEDI.

To achieve the required vacuum levels, attention has to be given to the design and preparation of the vacuum system. The operation of vacuum systems should also come under scrutiny as this is an area which historically has not been considered.

4.5.1 Achieving Vacuum

The higher the vacuum specification, the more effort is required to prepare the vacuum vessels. This is to reduce the vessel material outgassing, reducing the residual gas continually desorbing into the system. All vacuum components must be degreased to remove hydrocarbons. This is done using a detergent and water wash and a chemical solvent degrease and drying time. To reduce the outgassing further, a vacuum bake is undertaken to remove water vapour from the surfaces of the vessel; some benefit is gained through an *ex situ* bake before installation. To achieve ultra high vacuum (UHV) levels, an *in situ* bake is required. This adds a further level of complication to the accelerator design. To drive hydrogen from stainless steel, required to achieve the lowest outgassing vessels and reach extremely high vacuum (XHV), vessels must be vacuum fired - heated to 950 °C in a vacuum for several hours.

The environmental impact of preparing vacuum vessels is predominately down to the electricity used and should only need carrying out once for the lifetime of the accelerator, if the components are handled and stored with care. A baked-out UHV system can be maintained under vacuum with continual pumping and controlled procedures for operation. This is an area where new design philosophies around control and standby modes could reduce the baseline carbon footprint. An accelerator which reduces its power consumption when there is no beam by turning off pumps to match outgassing levels could prove beneficial.

Once UHV is achieved, vacuum levels can be maintained using pumps which capture molecules, such as ion pumps. These only require a high voltage supply and typically use only a few tens of watts in steady state at UHV conditions. Non-evaporable-getter (NEG) cartridge pumps, once activated (heat cycled), do not require any power to operate. In certain environments NEG cartridges can be very effective, but if exposed to poor vacuum conditions they cannot be recovered immediately. NEG pumps are often used in tandem with ion pumps as their strengths complement each other. NEG thin film coating can also be used as a barrier on the surface of vessel walls to reduce outgassing and provide a small amount of distributed pumping. This technology is essential with narrow bore vacuum vessel tubes.

Vacuum regions which are required to handle a large gas load cannot use such capture pumps mentioned above, as the quantity of gas would soon overwhelm them. These systems use pumps such as turbo-molecular pumps and scroll or screw backing pumps. Both of these types of pump contain moving parts and require some form of motor to drive shafts. This is therefore where the largest operational carbon usage is seen. Approximate power usage of general vacuum pumps is tabulated in Table 10. It is widely accepted that the operation carbon impact of a motor far outweighs its manufacture. The production carbon cost of a motor is between 1-5 % of its total lifecycle carbon cost. It is therefore critical that any motors designed into the vacuum system should have standby and power reduction where possible to manage energy consumption.

Pump	**Item mass** [kg]	**Materials footprint** [kgCO_2e]	**Max power consumption** [W]	**Power consumption at ultimate pressure** [W]
Ion pump, 75 l/s	19	280	100	10
NEG cartridge	5	165	200 (Activation only)	0
Turbo, 2000 l/s	50	335	750	150
Turbo, 300 l/s	12	95	400	120
Large backing, 280 m^3/h	370	1529	7500	4500
Small backing, 15 m^3/h	25	169	300	220

Table 10: Approximate power consumption and estimated materials footprint of various general pumps which might be used on RUEDI.

4.5.2 Mechanical Vacuum Vessels

The vacuum system for an accelerator consists of passive components and active ones. Using the outline design for the RUEDI facility, we have estimated lengths of stainless steel vacuum chamber required, together with the associated flanges, YAG screen six-way crosses, and sample holders. An overview of this is shown in Table 11. The largest single contribution is from the sample chambers: only six of these are required but together they amount to almost half a tonne of stainless steel. Again, we are only considering the raw material footprints here; no allowance is made for manufacturing procedures or preparation for use in a vacuum environment.

Consideration should be given to the material of the vacuum system. It is quite often found that chambers are made from stainless steel for its mechanical properties; it also has a relatively low CO_2 impact. However, some vacuum systems are made with copper or aluminium. To reduce the vacuum outgassing, titanium is an excellent material to use; although it has a higher carbon cost for manufacture than stainless steel, it could reduce the number of ion pumps required throughout the system, lowering the operational carbon cost.

During the mechanical design, the surface area of the vacuum vessels should be considered and trade-offs can be made. It may be desirable to reduce the beam pipe diameter to accommodate smaller magnet apertures, which will result in lower carbon emissions for magnet production and operation - see section 4.3.3. However, this can create a vacuum conductance problem, meaning the vacuum between pumps may not achieve the specified

Item	Quantity	Item mass [kg]	Total mass [kg]	Materials impact [$kgCO_2e$]
Vacuum tube (38 mm diameter)	18 m	1.37	25	42
Flange (70 mm diameter)	140	0.2	28	48
Sample chamber	6	70	420	717
YAG station	18	15	270	461
Vacuum tube (100 mm)	30 m	4.91	147	252
Flange (150 mm)	40	1.5	60	102
Totals			950	1623

Table 11: An inventory of the vacuum chambers and associated equipment for RUEDI, showing the carbon footprint for each one. All components are made from stainless steel, and a carbon intensity figure of 1.708 $kgCO_2e/kg$ is used [75].

base pressure. This can be overcome via several methods to reduce the outgassing of the beam pipe surface - for example, choice of material (titanium over stainless steel), *in situ* bake, or NEG coating. The NEG coating also has the benefit of providing distributed pumping, reducing the amount of lump pumps needed.

4.5.3 RUEDI Vacuum

RUEDI will require several different vacuum regions which meet different specifications and operations. At the time of writing, the specification for RUEDI has not been fixed, so a best approximation for the vacuum levels has been used based on initial calculations and experience. The first key areas are the gun cavity and electron beam pipe; these need to be optimised so as to not degrade the electron bunch properties, enabling the best performance of the gun and cathode. The waveguide systems delivering RF power to the cavities should be considered to be vacuum vessels primarily to eliminate electrical breakdown in the place of SF_6 gas. The sample chambers need to be able to handle changes of samples and provision to allow experiments on environmental samples with minimal impact on the accelerator vacuum. Finally, the numerous laser systems require transport under vacuum and will need to be coupled to the accelerator vacuum. Some of the laser systems have components working at pressures close to atmosphere, so a considerable amount of differential pumping will be required.

To provide the best conditions to achieve a well-conditioned gun which operates at the expected accelerating gradient, the cleanliness, residual gas, and vacuum base pressure need to be to UHV specification. This requires the first section of the machine to be baked *in situ* to remove water vapour and achieve a base pressure better than 1×10^{-9} mbar. In order for the electron beams to be transported throughout the machine with little interference from residual gases in the vacuum system, a base pressure of 8×10^{-9} mbar or better is required.

The RUEDI electron beamline is a total of 18 m of pipe with 18 chambers for YAG diagnostics and 6 sample and detector chambers. Predominately this needs to be held at a base pressure of 8×10^{-9} mbar; this will be achieved by initially processing the vacuum components to a UHV standard before installation. Ion pumps (with optional NEG cartridges) will be used for maintaining vacuum during normal operations. According to calculations, a minimum of 22 ion pumps (75 l/s) will be required to achieve the specified base pressure. This is for a stainless steel vessel which has been UHV cleaned and baked *ex situ*. The gun will require an *in situ* bake to 150 °C to remove water and achieve the more demanding vacuum levels below 1×10^{-9} mbar.

Vacuum is used as an electrical insulator in RF waveguides in place of SF_6 gas. SF_6 is an extremely potent greenhouse gas (with a global warming potential 23 500 times greater than CO_2) and where possible should be avoided. To enable this, the waveguide for the systems should be designed as vacuum vessels to UHV specifications; this should allow a base pressure in the region of 10^{-9} mbar. An estimated 9 ion pumps are needed for the RUEDI waveguides.

The transport of the UV laser for the photoinjector is required to be in vacuum but only at a level of 10^{-7} mbar. This would be achieved by the use of 2 small turbos and a backing pump. Two of the sample chambers require exchange of samples though the use of a load-lock system and the requirement of a turbo and backing pump.

All these system items are listed in Table 12 as part of the core accelerator vacuum which must operate continuously. The power consumption and operational footprint is therefore calculated for a full year of operation: 8766 hours.

The sample and detector chambers will require additional pumping capacity. Depending on the experimental specification, they may require differential pumping to maintain accelerator vacuum if gas jets are used. Differential pumping would consist of a series of turbos and large backing pumps to handle the gas load. As this could

Pump	**Quantity**	**Materials footprint** [tCO_2e]	**Power consumption** [MWh/year]	**Operational footprint** [tCO_2e/year]
Ion pump	31	6.43	2.72	0.21
Turbo pump, 300 l/s	4	0.206	4.21	0.325
Scroll pump	3	0.289	5.79	0.448
Total		6.92	12.7	0.984

Table 12: Core accelerator vacuum system operational demand and carbon footprint for one year. Calculated using ultimate pressure consumption, ignoring initial start up. The carbon intensity of electricity is assumed to be 77.4 gCO_2e/kWh - see Appendix A.

be switched on when additional pumping is required, it is included in Table 13 which shows additional pumping during operation.

The high power laser systems (IR and TW) need to be under vacuum to reduce scattering and preserve beam quality. This requires a vacuum in the region of 10^{-7} mbar. This level of vacuum is normally achieved with scroll and turbo-molecular pumps, but additional ion pumps could be used to couple the vacuum to the accelerator vacuum.

The final vacuum challenge is around laser systems which use gas to generate the desired wavelength of light. These need to be directly coupled into the accelerator and therefore differential pumping is required to preserve the accelerator vacuum. This is undertaken by a significant number of turbos and large backing pumps. RUEDI could acquire several of these systems for different wavelengths, for example deep UV soliton, HGG gas jet, hollow core fibre systems. The carbon footprint of three of these envisaged systems is calculated as an indication, and the results are shown in Table 13.

Pump	**Quantity**	**Materials footprint** [tCO_2e]	**Power consumption** [MWh/year]	**Operational footprint** [tCO_2e/year]
Sample chamber differential pumping				
Turbo pump, 2000 l/s	5	0.944	1.88	0.145
Backing pump	3	3.05	33.8	2.61
Total		4.00	35.6	2.76
Laser systems transport: IR and TW				
Ion pump	4	0.83	0.1	0.008
Turbo pump, 300 l/s	6	0.309	1.8	0.139
Scroll pump	3	0.289	1.65	0.127
Total		1.43	3.55	0.274
Laser systems differential pumping				
Turbo pump, 2000 l/s	18	3.40	6.75	0.522
Backing pump	12	12.2	135	10.4
Total		15.6	142	11.0
Grand totals		21.0	181	14.0

Table 13: Additional vacuum system operational demand and carbon footprint for one year of operation considered as 10 hours run a day for 250 days. Calculated using ultimate pressure consumption, ignoring initial start up. The carbon intensity of electricity is assumed to be 77.4 gCO_2e/kWh - see Appendix A.

The evaluation of the RUEDI vacuum systems identifies two distinct areas. The core accelerator vacuum system has a large initial materials carbon impact to build, and a much smaller operations impact, taking approximately 7 years to equalise. On the other hand, the operational cost for the vacuum system of the laser transport is almost the same as the material costs to build. This is a key area to mitigate.

The laser vacuum system should be an area of scrutiny to identify if the laser system needs to operate in such a way using differential pumping, or whether certain areas can be de-scoped or isolated. If the direct coupling to the accelerator vacuum is specified, this should undergo stringent modelling to maximise engineering controls such as apertures and bends to reduce the pumping capacity required to maintain accelerator core vacuum. It is clear that this area needs careful operation control with significant standby modes to reduce operational costs.

4.6 Shielding

4.6.1 Shielding considerations

In the UK, the regulations governing the occupational exposure of workers are the Ionising Radiations Regulations 2017 (IRR17) [102]. Made under the Health and Safety at Work Act 1974 [103], these regulations are a translation of European Directive 2013/59/Euratom [104] into UK law. This established the three principles of protection against ionising radiation:

- **Justification.** The practice using ionising radiation must have benefits which outweigh the detriments of the exposure.
- **Optimisation.** If radiation exposures are justified, they must be optimised. The widely accepted linear no-threshold model of the stochastic effects of exposure to ionising radiation [105] suggests there is no "safe" exposure. Doses are therefore optimised to a level considered As Low As Reasonably Practicable (ALARP), which practically means balancing the cost, time and effort of establishing exposure control methods against the reduction in exposure provided. Importantly, sustainability arguments should also feature in this decision.
- **Dose limitation.** Finally, occupational exposures must be below legal dose limits established in regulation.

When optimising exposures from significant external sources of ionising radiation, in addition to considering exposure duration and distance, application of radiation shielding is often an essential control measure. Adhering to the hierarchy of controls evident in all health and safety legislation (radiation safety being no different), the placement of fixed radiation shielding is an engineered control measure, which is preferred over procedural methods.

High-energy particle accelerator facilities present a significant external ionising radiation hazard, generating unshielded dose rates of the order of hundreds of Sv/h. Therefore, in order to optimise exposures and certainly prevent doses in excess of statutory limits, facilities are typically enclosed in substantial quantities of shielding material. Through this, the ionising radiation hazard is confined to the inside of the shielded enclosure and dose rates external to facilities are at levels consistent with natural background sources. At Daresbury Laboratory, to restrict doses to levels that are ALARP, facilities are constructed with a 1 μSv/h external dose rate design goal; depending on the beam energy and power, this can result in shielding that is metres in thickness.

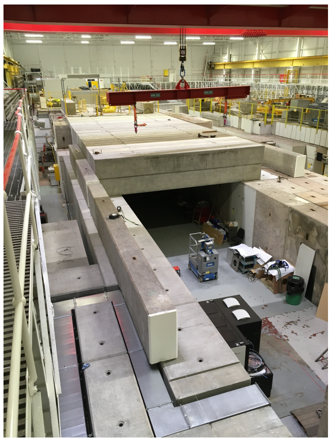
4.6.2 Advantages of concrete

There are many benefits of using concrete as a shielding material:

- **Neutron and gamma shielding**. The neutron shielding is due to the large fraction of hydrogen atoms in the concrete material, around 17 % in Portland concrete, and the gamma shielding from the heavier atoms such as oxygen, silicon and the metal content.
- **Durability.** Concrete is resistant to fire, weathering and corrosion, and it is not very susceptible to activation. Typical concrete blocks will easily last for 30 years or more - longer than the typical lifespan of an accelerator facility.
- **Ease of manufacture.** It can be homogeneously produced and is relatively inexpensive compared to lead and other materials with comparable shielding capabilities.
- **Structural capability.** Concrete can act as a structural material, allowing it to form part of the floor, building or roof structure as well as acting as a radiation shield; this sets it apart from most other shielding material options.

However, a significant drawback to the use of concrete is the environmental impact of its manufacture. Concrete dominates worldwide materials use in construction - around 17 Gt per year of which over 5 Gt is of cement [106] - and concrete production contributes around 8 % of anthropogenic CO_2 [107] emissions, largely due to the high temperatures of the manufacturing process.

(a) Concrete blocks for bunker walls



(b) Installation of roof beams

Figure 8: Reused concrete shielding blocks in Daresbury Laboratory's Electron Hall.

4.6.3 Reducing and reusing

To establish a more sustainable approach to the use of radiation shielding in high-energy particle accelerator facilities, it is prudent to consult with the waste hierarchy, which similar to IRR17 has a basis in European law through directive 2008/98/EC [57]. Given the high durability of concrete, significant advantages can be made in the waste management stages of 'reduce' and 'reuse'.

Reusing concrete shielding that has had a previous life on a facility is a viable and significant option to decrease the environmental impact of a new facility; it reduces the usage of newly-manufactured material, in addition to preventing old concrete from ending up as disposed waste. These sustainability arguments do need to be balanced against the safety implications of reusing shielding that has become damaged and/or activated, and any costs of refurbishment that are necessary. An important recommendation that arises from the desire to reuse concrete is that shielding materials should be constructed from blocks of standardised sizes, with suitable and persistent documentation that enables the long-term information about the concrete construction to be preserved in the long term; *concrete blocks are likely the longest-lasting and most reusable component of any accelerator*.

It is notable that significant use has been made of recycled concrete blocks at Daresbury Laboratory. The CLARA facility (and other shielded enclosures within the Electron Hall) makes use of hundreds of concrete blocks that were previously used for the SRS accelerator, and before that the NINA facility which was built in 1964. On the RUEDI facility, there are significant emissions savings achieved by the effective reuse of the existing Electron Hall (primarily the emissions associated with the main foundation slab) and by the reuse of existing blocks. Figure 8 shows the construction of bunkers within the Electron Hall using a mixture of old and new concrete blocks.

A preferred management option higher up the hierarchy is opting to reduce the amount of material produced. One way of achieving this is to employ local shielding closer to the sources of ionising radiation produced by high-energy particle accelerators (e.g. beam loss points, beam dumps). Applying shielding closer to the source of ionising radiation would require less shielding material within the outer walls of particle accelerator enclosures. In practice, this must be explored during the design phase of a facility and should not have a detrimental impact on the normal operation of the facility. If local shielding is portable and not fixed, this also adds procedural control into the radiation safety programme of a facility, which may not be appropriate when a less sustainable, but fixed, shielding is available as an engineered control. The idea of using localised shielding has notably been explored in the context of the self-shielded cyclotron [108], where local small-volume shielding can greatly reduce the requirement for larger volumes of shielding for the main vault construction. Again, a key idea here is to *utilise modular shielding blocks as re-configurable structural elements*.

4.6.4 Carbon footprint reduction

There has been some research conducted into reducing the amount of waste generated, such as mixing of regular concrete constituents with waste materials, such as discarded metal and glass (see for example [109] which examines the use of waste material to construct Magnetite concrete). Reusing materials initially used for other purposes both reduces waste volumes and improves the sustainability of the concrete manufacturing process. It may also help to lower the calcination temperature used in manufacture; calcination accounts for around half the energy usage in concrete production. Some studies report improved shielding capability, including increases in the linear attenuation coefficients, when using concrete-waste product hybrids. However, these mixes can negatively affect the durability, susceptibility to activation (especially mixes with iron) and homogeneity of the shielding material; these factors must all be considered when selecting a shielding material for a high-energy particle accelerator.

In short, radiation shielding material cannot be selected on sustainability grounds alone, but it should be a factor in the optimisation process. There are a number of positive steps that can be established in this area on the road to a more sustainable particle accelerator: some relatively simple (for example, reusing old shielding), and some more involved and requiring further research (for example, using concrete mixes that incorporate waste materials). In addition, the concrete industry is also actively examining methods to reduce the carbon intensity involved in cement manufacture; notable are the efforts to conduct the energy-intensive calcination process using alternative fuels (e.g. biologically-derived fuels such as plant waste products) or such things as solar concentrators.

4.6.5 Alternative materials

Concrete is considered here as the default material choice for radiation shielding, but it is not the only one. In general, radiation shielding materials are used not only for shielding but also as structural elements in accelerator facilities (concrete and cement are dominant materials in construction generally, not just in accelerators). Replacing concrete as a shielding material with other materials therefore has significant consequences on the construction assumptions.

The primary materials used for shielding are earth, concrete and steel [110, 111], with other materials used to a more limited extent; the latter include in particular materials used for localised shielding such as lead, polyethylene and boronated materials. Neutrons are generally produced as the principal secondary radiation, and therefore hydrogen-containing materials must be used in conjunction with materials that stop primary particles such as electrons and gammas in the case of RUEDI. High-Z materials such as lead and tungsten are used to attenuate or stop x-rays, and weight-for-weight offer similar attenuation to materials such as concrete. However, tungsten as a refractory metal is both expensive to produce and involves large associated emissions during primary production and manufacture. Lead is more emissions-friendly, but is more difficult to handle and dispose of due to its toxicity; it is also very poor structurally. Lead is also rather transparent to neutrons, making it not suitable for many shielding applications.

Earth is often used due to its material constituents (silica and water content), but must be handled carefully because of the natural variations in its composition and the potential for activation. This issue must be balanced against any potential cost or sustainability benefits obtained at the beginning of a facility's life. Earth is often used as partial shielding, bounded by structural elements such as concrete and/or steel. The ability to use earth also typically depends on local availability and site conditions; one must also pay attention during construction to ensure voids are removed by suitable compaction, and that later inadvertent movement/removal of the bounded earth is prevented. For large accelerator infrastructures, construction cost pushes the design choice to be a tunnel or cut-and-cover; smaller infrastructures such as RUEDI typically use accelerator vaults built above ground using concrete.

Water shielding (using plastic or metal containers) has occasionally been used in the past as a beam stop. The main disadvantage of water-based shielding – apart from the obvious need to provide structural support – is the integrity of the containment. Another issue is the inherent build-up of 2 MeV gamma production through neutron capture in the hydrogen atoms, which is a general feature of all hydrogenous shielding; it can be mitigated with sufficient thickness or by utilising a composite (layered) construction using e.g. steel; concrete does not suffer from this issue due to its non-hydrogen constituents. Boron may be added to water but in limited amounts – boronated cooling water is used for example in controlling neutrons in the moderators of pressurised water reactors. As an alternative to water, polyethylene sheet is used in limited quantities (for example, it is used at STFC's Central Laser Facility), and boron-doped polyethylene sheet is commercially marketed as an 'add-on' shielding material; lithium and lead may also be added to polyethylene sheet. We do not consider these materials due to the design complexity of using them, both structural and shielding. Similarly, other hydrogenous materials used in the past – such as paraffin wax, plastics and oils – are also excluded.

Concrete has both advantages and disadvantages over other materials besides its shielding properties, principally its use as a structural element. Poured and cast concrete typically will utilise steel rebar that will augment the shielding capability; however, cast concrete has an effective lifespan equal to that of the facility since it may not easily be reused.

4.6.6 Types of concrete and their environmental burden

There are a variety of concrete types and densities that are commonly used in accelerator shielding, but they generally fall into one of two classes:

- **'Ordinary' concrete** that uses ordinary aggregate/ballast such as locally-sourced gravel. These concretes typically have a density around 2.1-2.3 g/cm^3.

- **'Heavy' magnetite or baryte concrete** that utilise heavier aggregates such as blast furnace slag. These concretes have a much higher iron content which increases both their density (3.5-4.0 g/cm^3 is typical) and their shielding attenuation.

Compared to ordinary concretes, heavy concretes are more efficient at providing shielding for a given thickness; more expensive per unit mass; and have similar CO_2 emissions per unit mass. Because of their greater cost, heavy concretes are much less frequently used; here, we consider only ordinary concretes.

Ordinary concretes have somewhat different activation and shielding qualities depending upon the relative quantities of metallic content in their aggregates; this is reflected in the composition data used in radiation modelling, for example the compendium of materials given in PNNL 15870-Rev. 1 or 15870-Rev. 2 [112] that is popularly used by many regulators. Activation will affect eventual disposal, but here we assume that concrete is reused and there is no CO_2 burden from disposal.

PNNL-15870-Rev. 2 defines compositions for Portland concrete which is obtained in manufacture by using ordinary Portland cement (OPC), the basic cement material used for all concrete production; OPC composition is defined in BS EN-197 [113]. There are various standard types of cement, which have varying amounts of OPC and additive content.

- **CEM-I**: 100 % OPC
- **CEM-II**: OPC and a mixture of fly ash, slag, and limestone, up to a maximum additive content of 35 %
- **CEM-III**: OPC and blast furnace slag, with 40-90 % depending on the grade

Each type has further sub-classifications (grade and class) denoting the strength, rate of strength gain, and additive content.

The eventual emissions associated with production of CEM-I concrete are around 0.148 $kgCO_2e$ for each kilogram of finished concrete [114]. Since the emissions are primarily associated with cement production, increasing the additive content will decrease the emissions in proportion.

Different grades of concrete have differing structural properties. Ordinary concrete for accelerators typically specifies 100 % OPC, and is an upper bound on the CO_2 emissions for a given mass of concrete. In the construction of its dedicated building, the STFC EPAC project used 75 % Ground Granulated Blast Furnace Slag (GGBS) in place of 100 % OPC [115]. An analysis by the engineering contractor concluded:

- GGBS usage increased costs somewhat.
- GGBS usage reduced carbon emissions to around half that of 100 % OPC usage.
- GGBS usage means different strength profiles over time, which must be considered in any structural analysis.

The UK-based cement trade body, the Cementitious Slag Makers Association (CSMA), has published figures on GGBS concrete [114], showing that including 50 % GGBS decreases the carbon intensity of structural concrete by 42 % (i.e. from 148 $kgCO_2e/t$ to 86 $kgCO_2e/t$).

Hottle *et al* conducted a review of the environmental impact of concrete production in the USA [116] and estimated emissions from cement production. OPC production averages around 0.96 $kgCO_2e/kg$. Hottle also quantifies well-established facts about concrete production:

- CO_2 emissions from concrete production are primarily due to the cement constituent production; transport, mixing, installation and disposal are much smaller proportions of the environmental burden.
- Cement production CO_2 emissions are primarily due to the high-temperature processes needed, particularly the calcination step at around 1450 °C that creates the lime.

Trends in the production of so-called 'green' concretes are summarised well in several reviews [117].

In conclusion, if we wish to reduce CO_2 emissions associated with concrete production, we should examine whether it is structurally possible to use non CEM-I concrete, similar to the process adopted for EPAC; this has the potential to reduce CO_2 emissions associated with concrete production by around 50%. Also, we recommend modular construction and reuse, with a consideration of how to account for possible reuse in the carbon budget for a facility.

4.6.7 Emissions due to concrete use in RUEDI

The RUEDI baseline has the following assumptions that are relevant for CO_2 emissions estimates:

- Reuse of an existing building, in other words no new floor slab is required; this is a significant emissions advantage for the facility.
- Use of ordinary concrete with 100 % OPC, with new block construction for all walls and ceilings.

Table 14 shows the calculation basis for CO_2 emissions estimates for the RUEDI baseline, assuming that cement production dominates, and using layout and shielding information summarised in PA/SA/STFC/2022/003, the RUEDI Infrastructure and Layout PDR [96], and the RUEDI CDR OID [65].

Item	**Value**
Shielding perimeter x height x thickness	$84\,\mathrm{m} \times 4\,\mathrm{m} \times 0.7\,\mathrm{m}$
Wall volume	$235\,\mathrm{m}^3$
Roof beams area	$240\,\mathrm{m}^2$
Roof beams thickness	0.7 m
Roof beams volume	$168\,\mathrm{m}^3$
Total concrete volume	$403\,\mathrm{m}^3$
Total concrete mass	927 t
Carbon intensity	$0.148\,\mathrm{kgCO_2e/kg}$
Total RUEDI concrete emissions	$137\,\mathrm{tCO_2e}$

Table 14: Parameters used for CO_2 emissions arising from concrete usage in the RUEDI baseline. Values given are the one-time emissions arising from the production of concrete.

It is instructive to compare the RUEDI baseline with the situation if a new building were provisioned. Assuming the building footprint is comparable to the experimental area layout (i.e. around $30\,\mathrm{m} \times 12\,\mathrm{m}$), and assuming a concrete slab thickness of 1.2 m, the addition of a floor slab roughly doubles the required volume of concrete and therefore the associated carbon emissions, taking them from around $137\,\mathrm{tCO_2e}$ to around $284\,\mathrm{tCO_2e}$.

It is also useful to compare the embodied CO_2 emissions from concrete production from RUEDI with those of other facilities. Using a RUEDI accelerator length of around 20 m, the new concrete construction emissions per unit length of accelerator are around $6.9\,\mathrm{tCO_2e/m}$. Using the same assumptions for CLARA - a comparable-scale accelerator infrastructure (at Daresbury) that utilised existing floor slab but significant utilisation of new shielding walls and roof - we obtain a concrete emissions value of $6.6\,\mathrm{tCO_2e/m}$; CLARA has thicker walls but fewer divisions between the different areas. Interestingly, these emissions values are broadly in line with the estimates for collider tunnel emissions, i.e. around $6\,\mathrm{tCO_2e/m}$ [50]; one may use this as a rule-of-thumb. It should be noted that CLARA shielding construction utilised a significant quantity of recycled blocks, showing the potential in a modern facility of re-using concrete.

In conclusion, the concrete emissions estimates for RUEDI confirm the experience of other facilities, which is that creation of concrete is a significant component in the overall emissions burden of a facility. Comparing the concrete emissions with those of other components (see Table 18), we find:

- Concrete-related emissions are equivalent to 54 % of the total of all procurement items added together;
- Concrete-related emissions are equivalent to the emissions arising from almost 1 year of operation.

Mitigation methods may be summarised as follows:

- Reuse an existing building to house the RUEDI facility, with estimated savings of $147\,\mathrm{tCO_2e}$. *This is in the baseline design.*
- Use low-carbon concrete. Replacing the carbon intensity quoted in Table 14 with the figure quoted above for concrete using 50 % GGBS results in a saving of $57\,\mathrm{tCO_2e}$.
- Reuse old blocks. If the required volume of concrete could be made up of reused blocks, this represents a saving of $137\,\mathrm{tCO_2e}$ (assuming the blocks are sourced locally, and transport emissions are negligible).
- Any new blocks manufactured should be constructed of a standard size so they can be reused in a later project. A method of accounting for the CO_2 savings needs to be developed.

Without any of these mitigation strategies (new building, ordinary concrete shielding), concrete usage in RUEDI would account for around 15 % of full lifetime emissions assuming a 10-year operational life. By using an existing building and GGBS concrete, the impact of concrete usage can be reduced to $80\,\mathrm{tCO_2e}$, around 5 % of the lifetime emissions. By reusing old blocks, this figure can be reduced still further (perhaps even to zero), depending on the quantity of blocks available.

4.7 Cooling infrastructure

All electrical equipment produces waste heat in addition to useful energy output. Components are either cooled passively, using heatsinks to dump excess heat into the air, or actively, using water pumped around a cooling circuit. Refrigeration of the cooling water has already been considered as part of the relevant sections above. The infrastructure required for this cooling is substantial as well. Estimates have been produced of the amount of cooling infrastructure required for RUEDI; this is detailed in Table 15. This is all assuming that metric pipework is used; the same calculations were carried out using Schedule 10 (Imperial) pipework, which resulted in a 27 % higher overall footprint due to a larger amount of steel being used in the pipes. RUEDI requires a total of eleven air handling units (AHUs) for its air conditioning system, which come in three different sizes depending on the size of the room to be ventilated.

Item	**Mass** [t]	**Materials footprint** [tCO_2e]
Air handling units	4.59	8.34
Pumps and valves	1.8	3.07
Heat exchangers	0.3	0.512
Water chiller, 500 kW capacity	3.2	5.47
25 mm diameter pipe, 200 m length	0.2	0.342
50 mm diameter pipe, 100 m length	0.26	0.444
100 mm diameter pipe, 600 m length	3.06	5.23
Total	13.4	23.4

Table 15: Bill of materials for RUEDI air conditioning and water cooling infrastructure. All elements apart from the AHUs are assumed to be made of stainless steel, with a carbon intensity of 1.708 $kgCO_2e/kg$ [75]. The AHUs are assumed to be composed of 70 % steel and 30 % copper (2.069 $kgCO_2e/kg$ [95]).

Based on the power rating of the fans in the AHUs, the total power demand is 36.5 kW. Since these systems will run constantly, the total energy usage over a year is around 320 MW h. A water chiller with an overall cooling capacity of 374 kW provides the cooling for these AHUs; the total power demand for this, based on an energy efficiency ratio (EER) of 3.89, is 96.1 kW. Pumps for cooling water have been specified with a total power rating of 22.5 kW. Since these pumps will also run 24/7, the overall energy usage over a year is 197 MW h. Refrigeration of the cooling water for the RF and magnet systems has been considered as part of the relevant sections above. The total carbon emissions for the operation of RUEDI's heating and cooling systems are summarised in Table 16.

Note that a major function of the air conditioning system is to maintain the *stability* of the temperature in the accelerator hall, not simply to remove the heat from the system. Temperature stability is critical to the reliable running of a modern accelerator; temperature variations of more than 0.1 °C can have deleterious effects on the spatial and temporal resolution of the RUEDI instrument.

Item	**Power demand** [kW]	**Operating hours per year**	**Energy usage** [MWh/year]	**Carbon emissions** [tCO_2e/year]
Air handling units	36.5	8766	320	24.8
Chiller	96.1	2500	240	18.6
Pumps	22.5	8766	197	15.3
Total	155		758	58.6

Table 16: Carbon emissions associated with the operation of RUEDI's heating and cooling systems.

Diamond Light Source has in recent years enacted a programme of energy efficiency improvements [118]. In 2022, the total savings from these schemes was estimated at 10.2 GW h, around 20 % of Diamond's total consumption. Quantified energy savings from various different interventions are shown in Figure 9. The largest savings arise from installing variable-speed drives for the air conditioning system and replacing always-on fluorescent lighting tubes with motion-sensitive LED panels. These enhancements would be considered as standard features for new facilities being built today, rather than being retrofitted later.

During periods of colder weather, it may be possible to use free cooling to assist with RUEDI's cooling requirements. A modulating valve would allow some or all of the water to bypass the chiller and go through the free cooling system instead, which uses the ambient air temperature to assist in the cooling. This can potentially result in using around 75 % less energy in the cooling system in the colder months of the year. In 2018, a study was commissioned at Daresbury Laboratory to investigate the feasibility of using a borehole system to extract

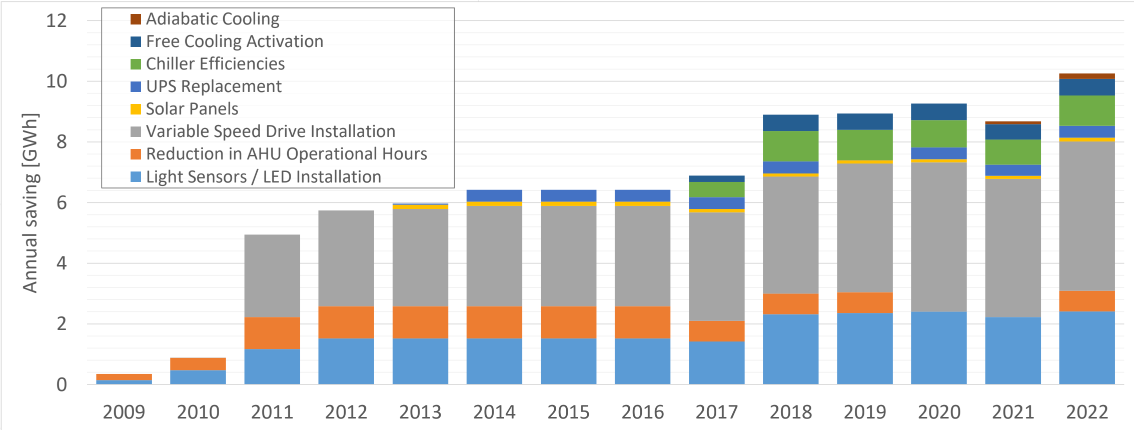


Figure 9: Energy saved on a yearly basis using measures introduced at Diamond Light Source between 2009 and 2022. UPS refers to Uninterruptible Power Source. For reference, Diamond's energy consumption in 2022 was around 42 GW h.

free cooling from ground water. It was found that this had the potential to provide 2 MW of cooling power to the laboratory, which would reduce electricity consumption by 4 GW h. The scheme has not been pursued any further as yet.

Further reduction of the energy usage associated with RUEDI's temperature stabilising systems may be possible. Variable-speed fans are in the baseline design; however, the effect of changing the fan speed (perhaps reducing it during non-operational periods) on the overall stability of the machine needs to be investigated. In general, pumps driving the chilled water circuits operate at a fixed-pressure set point. Operating at a fixed flow speed will reduce the overall energy usage, but this needs to be carefully balanced, as there is a minimum pressure required to pump water through each individual component. Pumps for the inhibited water cooling the AHUs are temperature-controlled, so they only run when required to keep the water below 18 °C. A buffer tank is used for the chillers, which reduces the amount of time they need to be switched on for. Work is ongoing to find more ways of reducing energy usage in this area; clearly it's a big part of RUEDI's overall operational footprint, so more study is required.

4.8 User and staff travel

RUEDI is envisaged as a national facility for the UK. Its users will travel from locations across the UK, bringing samples for their particular experiments. As part of the RUEDI operational carbon forecasting carried out by Arup [26], estimates have been made of the annual number of trips using various different modes of transport (Table 17).

Mode of transport	**Number of trips per year**	**One-way trip distance** [km]	**Total distance** [km]	**Carbon intensity** [gCO_2e/km]	**Carbon footprint** [tCO_2e]
Rail	40	300	24000	13.3	0.318
Car: petrol	30	300	18000	164	2.95
Car: electric	30	50	3000	9.68	0.029
Short-haul flight	6	1500	18000	183	3.29
Long-haul flight	3	10000	60000	200	12.0
Totals	109		123000		18.6

Table 17: RUEDI annual travel emissions, broken down by means of transport. Flights represent conference attendance for staff working at the facility. Intensity data is sourced from UK government reporting factors [36], with minor changes applied: the rail intensity is scaled down to account for 2030 grid electricity intensity, and figures for electric vehicles (EVs) are based on an efficiency of 8 km/(kW h), state-of-the-art in 2023. Uptake of EVs is a little pessimistic in these estimates.

The dominant source of emissions for travel is long-haul flights, even though these represent a small fraction of the overall number of trips. Presenting work at international conferences is a key part of the process of science, and the networking that takes place at these meetings is vital for the health of the field, particularly for early-career researchers. There clearly needs to be a balance, however, and sensible restrictions must be placed on the number of overseas trips taken per year per researcher. STFC's 'virtual first' policy puts into place a clear hierarchy of business travel: virtual meetings at the top, low-carbon transport next, and air travel as a lowest priority. RUEDI, as with other modern user facilities, will have a 'sample by post' mode where researchers can send in samples to undertake standardised experiments, as a low-carbon alternative to researchers travelling in person to the laboratory.

5 Systems in other accelerators

RUEDI, as an example of a small low-energy facility, clearly does not represent the full range of components found in accelerator facilities worldwide. Some notable omissions are briefly listed below.

5.1 Linacs

We have looked at the RF cavities for RUEDI, and a normal-conducting RF system would be a scaling-up from this, particularly in terms of operational carbon. For high-energy accelerators, a high proportion of the energy costs are attributed to the RF system [119]. Efforts to reduce this cost will therefore result in significant savings for larger facilities. These include high-efficiency klystrons [120] and fast reactive tuners (for SRF) [121].

5.2 Superconducting RF

This is well outside the scope of this report; however, SRF is a critical technology for many larger accelerators so it should not be neglected. In this case, niobium rather than copper cavities are usually used, so the manufacture footprint of the cavity will be dramatically increased. The manufacture and operation of a cryogenic system to cool the cavities to 2 K is significant as well. In recent years, advances have been made in thin film technology, using a thin film of superconductor on a bulk copper cavity rather than a solid niobium cavity. This has several advantages for sustainability: reducing the carbon impact of manufacture; increasing the accelerating gradient of a given cavity (thus reducing the overall number of cavities required to reach a given energy); increasing the operating temperature from 2 K to 4 K, which could halve the energy used by the cryogenic system.

5.3 Insertion devices

Undulators and wigglers are a critical part of storage ring and FEL-based light source facilities, and are usually based on arrays of permanent magnets or superconducting wire, to generate a magnetic field which varies sinusoidally along the longitudinal beam axis. In the case of PM undulators, the manufacture footprint will dominate over the (very low) operating footprint; for superconducting devices, the bulk of the carbon emissions are likely to be due to the operation of the cryogenic system.

5.4 Pulsed and AC magnets

Non-DC magnets are required for various different types of accelerator, for instance when accelerating a beam from low to high energy in a booster ring. The manufacture footprint will be similar to that described in the electromagnet section above, but AC power supplies tend to be larger and more complex than DC ones. Overall power consumption of AC magnets will be greater than that of DC magnets, due to eddy current losses. Replacing a non-DC magnet with a permanent magnet is much more challenging as well - although not impossible: some development has gone into PM-based septum magnets [122], which are traditionally pulsed devices.

5.5 Other particles

RUEDI is an electron accelerator, and although shielding is clearly a major concern, ionising radiation is only present when the accelerator is in operation, and long-term activation of components is not a major issue. Heavier particles such as protons can penetrate to a much greater depth within materials, and this can result in longer-lasting radiation issues. From the point of view of this report, this will have an impact on policies for maintenance, disposal, and recycling of components. The end-of-life carbon impact has not been considered in this report, and this will be much greater for a machine with activated components that need to be stored safely for many years.

5.6 Data analysis

Accelerators built for user experiments will generate data during operation: controls history, diagnostics readouts, screen images and so on. All this data must be stored and processed, and there is clearly an energy cost associated with this. Accelerator design and simulations will take a significant amount of computing power both before and during operation. Facilities like the LHC are built around experiments which generate enormous volumes of data, requiring large data centres to be built for storage and processing. Increasing the efficiency of data centres is a separate field, and not considered by this report.

5.7 Ancillary facilities

Everything considered in this report could be said to be part of a 'beam delivery system', i.e. systems whose purpose is to produce and control a beam of charged particles. Naturally, a complete accelerator facility encompasses much more than the beam delivery system. There are user experimental hutches, laboratories, and offices, and other associated facilities. None of this has been explicitly covered in this report.

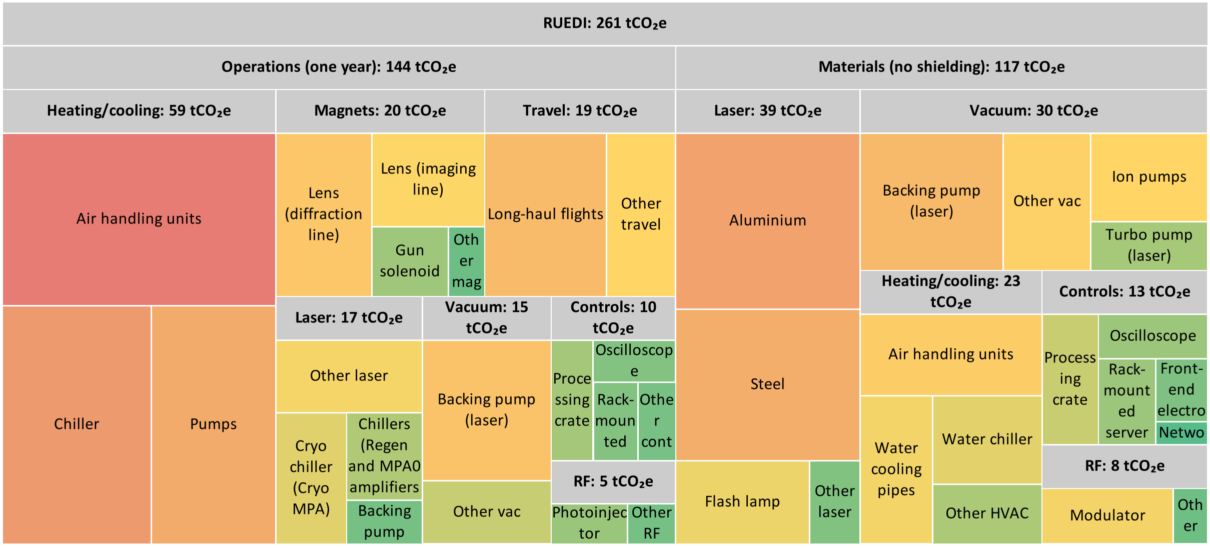
6 Summary

In this report, we have made an inventory of the components required to build and operate RUEDI, a small accelerator-based electron diffraction and imaging facility. None of the choices made thus far in the design process have been aimed towards a 'low-carbon' facility, and so this report in some way represents the facility before taking any mitigating action. We have broken the machine down into technology areas, and tried to highlight the main sources of carbon emissions in each area. The hope is that this approach gives a reasonable idea of the largest sources of emissions involved in building and operating the beam-delivery system of an accelerator facility. There are ancillary facilities that would be included in an overall scientific research complex - for instance, detectors, user end stations, offices, laboratories, and of course the building itself. In an effort to simplify matters, these are not considered in the scope of this report.

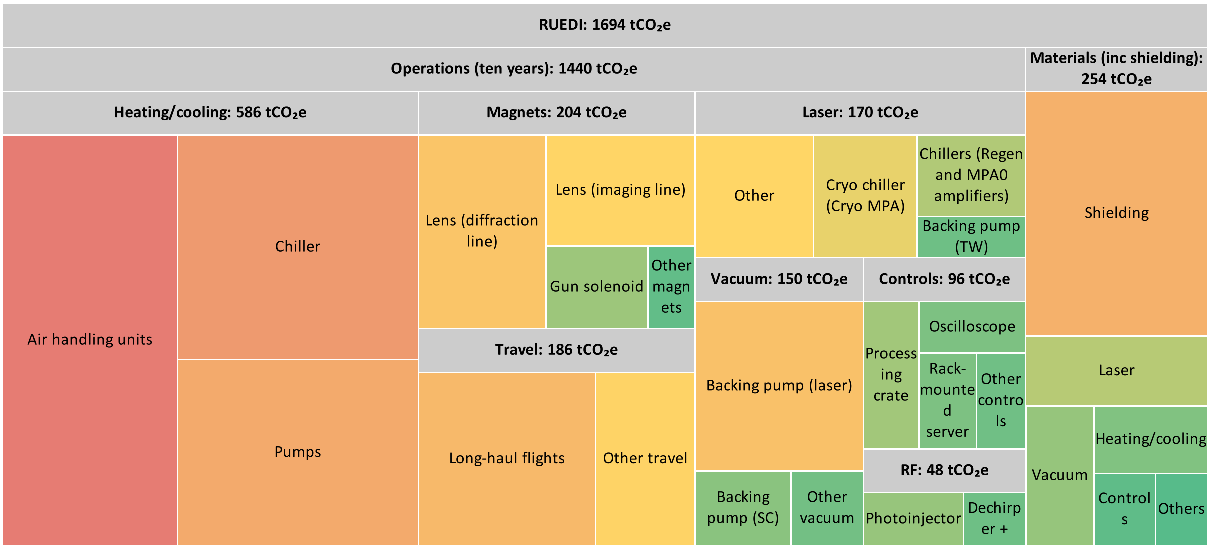
Table 18 and Figure 10 show carbon emission totals by area. The figures for operations refer to a single year of operations. Clearly a facility such as RUEDI is expected to operate for much longer than that - perhaps ten or twenty years. It's easy to see that emissions from operations will dwarf those from manufacturing over this period of time.

Machine area	**Manufacture totals** [tCO_2e]	**Operation totals** [tCO_2e/yr]
Laser	39.4	17.0
RF	7.54	4.75
Magnets	3.48	20.4
Vacuum	29.6	15.0
Controls	13.5	9.58
Heating/cooling	23.4	58.6
Shielding	137	
Travel		18.6
Totals	254	144

Table 18: Total emissions by area for manufacture and one year of operation. Note that water cooling is added to each machine area separately.



(a) One year, no shielding included



(b) Ten years, including shielding

Figure 10: Visualisation of the overall emissions from manufacture and operations. The top figure compares one year of operations with manufacture of everything *except* concrete shielding, whereas the bottom figure represents ten years of operations and is inclusive of concrete shielding on the manufacture side.

7 Reduction strategies

We have shown that the carbon footprint of RUEDI is dominated by the carbon cost of the electricity used to power the machine during operation. The emissions generated in manufacturing the component parts are approximately equal to the emissions produced during 3.5 years of operation. For a facility with an expected lifetime measured in decades, this implies that we should focus our efforts on making its operation as energy-efficient as possible, whilst also aiming to limit emissions from manufacture and disposal. To this end, the following recommendations are targeted towards RUEDI and other facilities at a similar scale.

1. **Reusable shielding.** Large volumes of concrete are required for radiation shielding. There is some scope for reducing the associated carbon emissions, by switching to different grades of concrete. Additionally, by building shielded enclosures using standardised concrete blocks, the enclosures can be reconfigured according to the needs of facilities as they evolve over time. STFC has a long history of adhering to this practice.

2. **Temperature stability.** A large fraction of the operational footprint is used in management of heat loads. Even a modest reduction of this energy usage would have a large impact. Work is ongoing to determine whether any further reductions would be possible without negatively affecting RUEDI's performance as a scientific instrument, for instance variable-speed drives and free cooling.

3. **Permanent magnets.** Many of the steering and focusing magnets used in beam transport lines operate with a fixed field, with only small adjustments needed when tuning up. Replacing electromagnets with fixed-field PM-based devices could potentially result in large energy savings, as well as removing the need for power supplies, large current-carrying cables, and water cooling. Careful design is required to ensure that there is still enough scope for operational adjustments to the beam transport.

4. **Laser system cooling.** Modern accelerators make increasing use of complex laser systems, for beam generation, acceleration and diagnosis. These systems are often built from modular components provided by different laser manufacturers, each of which comes with its own chiller system. Typically, not much consideration is given to integrating the cooling requirements of individual laser systems. By enabling more centralised and intelligent cooling systems, substantial energy savings could be made.

5. **Reuse of waste heat.** Clearly energy is not 'used up' during operation - it is converted to useful energy and heat. If possible, we should make use of the waste heat produced by accelerator operations. It could be used indirectly to provide heating and hot water for office buildings in the same campus, or for homes in the immediate neighbourhood.

6. **Demand shifting.** As the electricity grid shifts from fossil-based to renewable sources, the carbon intensity of electricity will vary on a daily and seasonal basis. It may be possible to time-shift some of the power demand for an accelerator facility, in order to use electricity when the carbon intensity is at a minimum. This is probably not possible for most systems, but it may be possible to set up 'smart' controls for items such as vacuum pumps and secondary water circuits that respond to changes in the electricity grid. There is also the potential to set up 'green scheduling', perhaps avoiding running the accelerator during carbon-intensive periods of the day, and timing shutdowns to coincide with longer periods of low renewable availability (e.g. winter).

7. **Submetering.** Adding more instrumentation to measure the energy used during operation will not lead to immediate reductions; however, it is a vital tool to assist with finding 'hot-spots' of energy consumption. As more energy-efficient technology is developed, this data will help with deciding what interventions to put in place during the operational lifetime of the facility to make further improvements.

8 Conclusions

Accelerators are large, complex, power-hungry machines. To design and build them takes years of effort from teams of multi-disciplined, highly skilled people, working within a global research and development community that consists of government-funded institutes, universities, and private industry. They also span a huge range of sizes and applications, from room-sized particle therapy machines to city-sized particle physics machines. With all this in mind, answering the question "what is the carbon footprint of a particle accelerator?" is quite difficult. In this report, we have taken an example of a small accelerator currently in the technical design phase – RUEDI. This approach enabled us to have a reasonable amount of certainty about the kinds of components that would be needed. The final specifications are not set in stone, which makes things more difficult but also lends itself to implementing measures to reduce the overall emissions before the next phase of the project.

We have shown that the emissions from manufacturing the main components required for RUEDI add up to approximately 254 tCO_2e, and the corresponding figure for operations is about 144 tCO_2e/yr. In other words, the operational emissions dominate the manufacture emissions even after an operating period of three years. Typically, accelerator facilities have lifetimes measured in decades - so a key recommendation is to reduce the operational footprint, even if this increases the manufacture footprint somewhat. These figures are based on realistic assumptions about the electricity grid in the 2030s, assuming a near-total transition from fossil-based to renewable sources of energy, and assigning small but non-zero carbon intensity values for those renewable sources. See Appendix A for full details.

This is far from a comprehensive survey, and there are many technologies that make up modern accelerators that are not considered here. This report provides an overview of the major sources of emissions for RUEDI, as well as some suggested mitigation strategies. We have laid out the groundwork and some methodologies for assessing carbon emissions in the manufacture and operation phases. This should allow future accelerator designers to concentrate their carbon-reduction efforts on the most likely sources. Consideration of the carbon footprint of any new facility will be a critical part of its design in the future.

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Appendix A Electricity carbon intensities

Carbon emissions for electricity consumption depend strongly on time of day and season, particularly in the UK where there has been a strong push for renewables in the past decade. Average intensity figures have been published by the UK Government on an annual basis since 2002 [36]. With more installation of renewable generation and shutting down of coal-fired power stations, the carbon intensity involved in electrical generation has dropped significantly over the past few years (see for example the ESO Dashboard [123]).

As discussed in the introduction, the UK Government's targets for climate change mitigation are enshrined in law via a series of 'Carbon Budgets', the sixth of which covers the period 2033-37. The UK Government published carbon intensity projections along with the Sixth Carbon Budget (CB6) [124], and has also published its Energy and Emissions Projections (EEP) on an annual basis since then [125]. The carbon intensity of electricity clearly depends on a number of factors: domestic, commercial, and industrial usage patterns; roll-out of nuclear and renewable generation and retirement of fossil-fuel generation; weather and climate patterns; global geopolitical events. There are a number of different available sources to calculate the carbon intensity of each type of electricity generation, each of which take into account different factors. For instance, one might naively expect the carbon intensity of solar power to be zero; however, there is an impact associated with manufacture, installation, and maintenance of photovoltaic panels. We include this, and also include the carbon cost associated with building a 'traditional' coal- or gas-fired power plant.

Here, we have used two sources for carbon intensity of generation: the Intergovernmental Panel on Climate Change (IPCC) [126], and Staffell [127], the numbers from which are used to generate 'live' carbon intensity figures from the UK's Energy System Operator [123]. The main difference between these two methodologies is that the IPCC figures are lifecycle emissions - so that renewable and nuclear technologies have a finite (but small) value for emissions. Table 19 shows selected intensity figures for different types of power generation.

Technology	**Carbon intensity** [gCO_2e/kWh]	
	Staffell [127]	**IPCC** [126]
Gas (combined cycle)	394	490
Nuclear	0	12
Coal	937	820
Offshore wind	0	11
Onshore wind	0	12
Solar	0	48

Table 19: Carbon intensity for selected types of power generation from two sources. Other technologies such as hydrogen are not considered here, and are not expected to have a large impact on the overall intensity figures.

Estimates for power consumption levels also vary between CB6 (613 TWh in 2040) and EEP (448 TWh in 2040). A summary of the overall energy mix expected in 2030 in either case is listed in Table 20. Note that EEP has a much higher percentage of renewables but lower contributions from nuclear and gas, and EEP expects to import some power from Europe (as is the case now), whereas CB6 has the UK exporting a surplus.

Technology	**Contribution**	
	CB6	**EEP**
Gas	18 %	12 %
Nuclear	15 %	10 %
Renewables	52 % (wind)	72 %
	10 % (solar, other)	
Imports	−6 %	6 %
Other	11 %	0
Total consumption [TWh]	**389**	**369**

Table 20: Projected energy mix in 2030, according to the UK Government's CB6 and EEP reports. The negative number on the CB6 import figure means that the UK is expected to be a net exporter of energy. 'Other' generation sources for CB6 include hydrogen, biomass, and geothermal.

The conflicting projections and differing carbon intensity values mean that picking an overall grid intensity figure is not straightforward. Table 21 gives a list of intensities calculated using various different datasets. There seems to be an overall increasing trend, indicating perhaps that initial optimistic estimates have been revised upwards in later publications. This leaves us with a choice for this report - to be optimistic about the rollout of renewable energy and corresponding decrease in emissions, or to err on the more conservative side and assume that energy will still have a considerable impact during the 2030s. We choose the latter approach, and have adopted the upper quartile value from the list in Table 21 (note that this seemingly pessimistic strategy gives a reasonably accurate figure for 2023). Thus, the carbon intensity for electricity for the initial RUEDI operation period of 2030-40 is taken to be 77.4 gCO_2e/kWh. It is important to note that we assume a carbon intensity based upon using the UK-averaged carbon intensity across the whole Grid. When assessing business cases for new infrastructures, some Government analyses use *marginal* emissions factors – i.e. the carbon emissions associated with *increases* in generating need – rather than whole-Grid values. Those emissions for the period 2030-40 are significantly lower at 25.9 gCO_2e/kWh (see HMT Green Book Supplementary Guidance, Table 1 [128]). The difference between those two assumptions materially changes the conclusions outlined in this report.

Scenario	**Grid intensity** [gCO_2e/kWh] 2023	2030-40
CB6 (figure in report)	136	18
CB6, Staffell	230	35
CB6, IPCC	192	53
EEP 2017	145	79
EEP 2018	111	63
EEP 2019	119	77
EEP 2021, IPCC	164	77
EEP 2021, Staffell	177	85
Green Book [128]	248	47
Upper quartile of estimates	192	77.4
Real value	200	

Table 21: Average grid carbon intensities for 2023 and the period 2030-40 using various different sources of figures. The top line is from Figure 3.4b in the CB6 report, but we could not reproduce those numbers using credible intensity figures. The EEP publications from 2017-19 are listed, since they also provide intensity figures. The EEP 2021 update provided power generation figures only, and intensities have been calculated using IPCC and Staffell numbers. The 'Green Book' is a UK Government publication which provides a toolkit for estimating future emissions. Note that using the upper quartile of the estimates from all of these sources seems pessimistic, but it comes close to the actual value from grid data in 2023.

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