



DIGITAL RESEARCH INFRASTRUCTURE AND NET ZERO PROJECT SUMMARY REPORT

**Net zero computing:
Scoping UKRI's journey to sustainable digital
research infrastructure**

August 2023

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SUMMARY

The need for urgent action to avert climate disaster has been clearly stated by the UK parliament and the UN Secretary General has underscored the need to reach net zero emissions by 2040. UK Research and Innovation (UKRI), funded by the UK Government, has a duty to set out a roadmap of actions that will ensure the emissions it is responsible for are net zero by no later than 2040.

Escaping carbon dependency will require a tremendous programme of change across the research community and wider society. Digital Research Infrastructure (DRI) requires carbon-intensive technology production processes and substantial energy consumption. While not the largest driver of emissions in the UK research community, it is an important contributor. It is also emblematic of the challenges that face research organisations and of the capacity to deliver radical change.

The UKRI Net Zero Digital Research Infrastructure Scoping Project (the Project) was undertaken during 2021-2023 to establish the scope of applicable knowledge currently available. By collating the best available evidence, this report describes how to approach operating the DRI while achieving net zero. A more detailed Technical Report¹ is also available.

The Project was undertaken to:

- Collect evidence to inform UKRI DRI investment decisions
- Provide UKRI and their community with an outline roadmap for achieving net zero in their DRI by 2040 or sooner
- Enable UKRI to play a positive and leading role in the national and global transition to a sustainable economy

The Project found that significant emissions derive from four main areas:

- Production of the electricity used by DRI
- Production of hardware (including the associated manufacture of hardware and the mining of minerals going into the hardware)
- Use of DRI, including user devices
- The impact of the UKRI DRI on societal emissions through research and innovation outcomes

The Project produced a set of recommendations for UKRI to implement, directly or through influence with partners, peers, and stakeholders to achieve net zero for DRI. This complex work will require the collective efforts of leaders and staff at all levels of the organisations involved.

The recommendations are organised into an overarching Net Zero Delivery Framework, encompassing a Roadmap and a Toolkit. The Roadmap comprises three Delivery Pathways, reflecting the actions required and the mechanisms available to effect change. The Toolkit contains research findings organised into themes that reflect the challenges likely to be faced as organisations embark on their net zero journey.

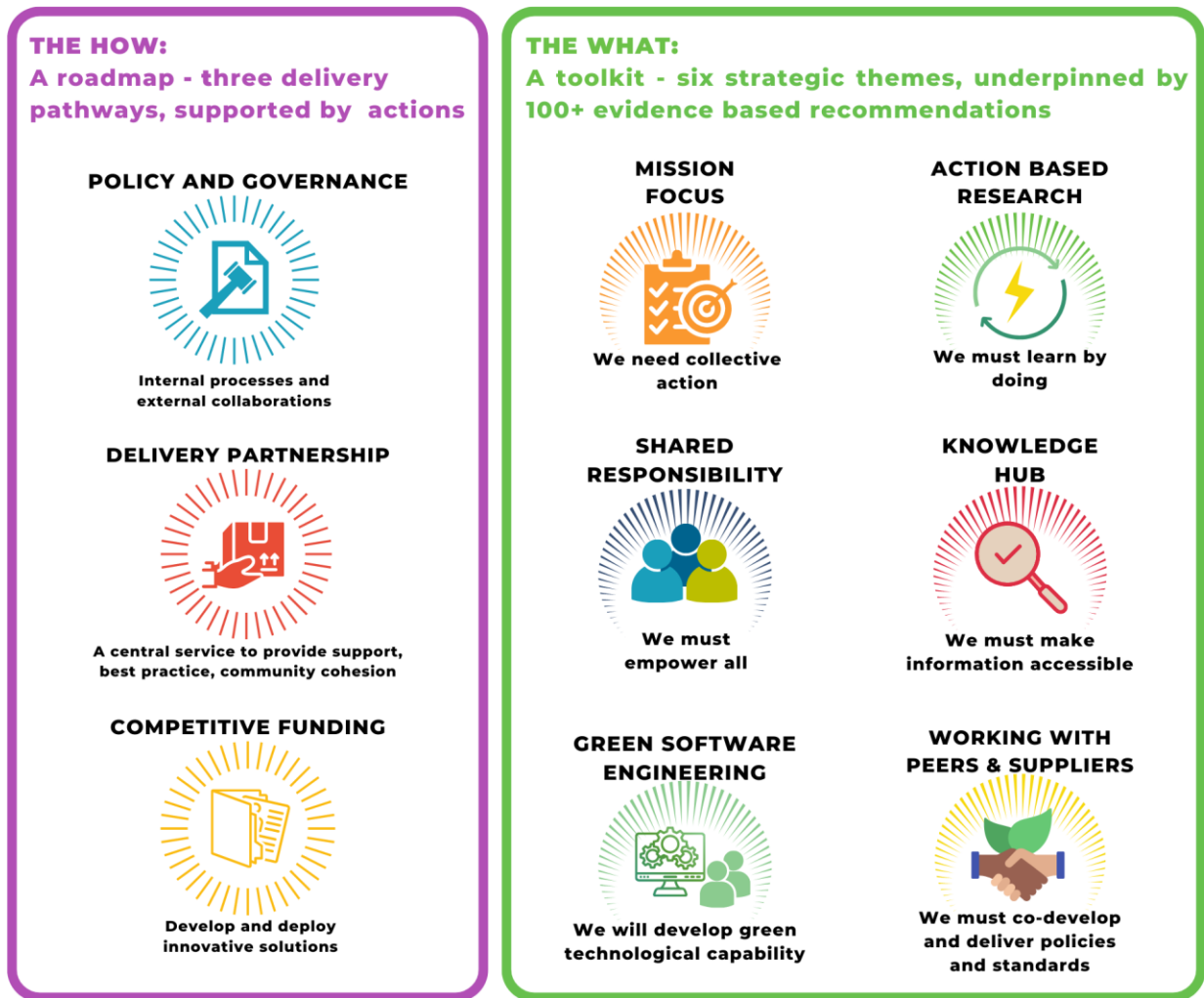


Figure 1: Summary of Project Recommendations

The recommendations emerging from the Project have been organised via a dual approach into a net zero delivery framework. The roadmap shows 'how' to tackle the problem, the toolkit sets out 'what' can be done.

The delivery pathways are:

- i. A Governance and Policy Framework, covering both internal processes and external partnerships and collaborations.
- ii. A net zero DRI Delivery Partnership, comprising a centralised service to:
 - (a) support decision makers,
 - (b) establish and disseminate best practice as it applies to the UKRI DRI,
 - (c) foster community cohesion through meetings and communication activities, and
 - (d) maintain a map of the UKRI DRI and its carbon footprint.
- iii. Competitive Funding leading to a portfolio of projects to allow the community to develop and deploy Net Zero solutions, including the creation of a national resource of green software engineers.

This study represents an authoritative review of expert and stakeholder opinion within the UKRI community and of the scientific literature on how we might collectively tackle the challenges of accomplishing net zero in our digital research environments by 2040.

The results give us grounds for optimism yet also reveal the sheer scope and scale of work to be done. There are uncertainties, and there are gaps in our knowledge. Some problems remain to be solved. These are not, nor must they be allowed to be seen as, reasons for inaction.

The time to act is now.

THE PROBLEM

Confronting the Climate Crisis

There is a climate crisis. The time for talking has passed; now is the time for action. UN Secretary General Antonio Guterres recently warned of the “climate time bomb” and the need to reach net zero emissions by 2050 as part of “a survival guide for humanity” (and indeed all life on the planet). In response, widespread commitments to achieving the goal of net-zero by 2050 have been adopted. In some sectors, ambitious earlier targets have been set².

“Without urgent, effective, and equitable mitigation and adaptation actions, climate change increasingly threatens ecosystems, biodiversity, and the livelihoods, health and wellbeing of current and future generations.”
IPCC, 2023

On 1st May 2019, the UK parliament declared an environment and climate emergency, underlining the urgency of the situation. The UK government’s plans for net zero greenhouse gas (GHG) emissions by 2050 came into effect in June 2019, updating the Climate Change Act 2008.

The preferred approach of the Climate Change Committee (CCC) is the *balanced pathway* to net zero^{3,4}. This requires high levels of innovation and moderate behaviour change to reduce emissions without significant economic disruption. Success will require

significant changes to existing habits, values, and behaviours across the research community and wider society. Achieving net zero without disrupting services will require complex changes, designed and implemented consistently across multiple facilities operating with a huge range of technical, staffing and governance systems. Significant progress has been made, although a March 2023 report from the CCC found no sector in the UK adequately prepared for the climate risks facing the country⁵.

The scientific community recognizes the need to be at the vanguard of enabling and shaping evidence-based responses. UKRI, funded by government, has a duty to ensure the emissions it is responsible for are net zero by 2040 or sooner⁶. The UKRI Net Zero Digital Research Infrastructure (DRI) Scoping Project (the Project) was established to provide recommendations to enable UKRI DRI to play a leading role in the national and global transition to a sustainable economy and to achieve net zero in their own emissions by 2040 or before. This strategic objective, outlined in the 2020 UKRI Environmental Sustainability Strategy⁷, is extremely challenging. The Project uncovered strong determination to meet that objective.

Digital systems are a vital component of the UK research infrastructure, supporting the nation’s ability to respond to 21st century challenges, including climate pressure and decarbonization. Carbon-intensive technology production processes and substantial energy consumption requirements mean digital systems are a significant challenge in the mission to accomplish net zero.

Solving the problem of how to accomplish net zero for DRI is emblematic of other crucial national systems that are dependent on high levels of power and constructed of technologies requiring substantial carbon emissions to create.

DRI is complex in both its governance and its technology, ranging from large scale compute facilities to data storage, to mechanisms for access such as networks, to software and to the people who use, develop, maintain and fund these powerful resources. The pathway to net zero computing requires transformational change which can deliver huge benefits as part of the broader transformation to a new generation of digitally enabled research. The transition to sustainable research computing must follow and support the national transition to a sustainable economy, as outlined by the CCC balanced pathway.

By 2040, it is likely that the term 'net zero' will mean something different to what it does today. Net zero is well defined at the global scale but cannot always be clearly defined at the organisational scale (this is discussed further in the Interim Report⁸). Arguably, the goal is less numerical and instead one of clear and effective leadership in the national transition to a sustainable society and the global transition to net zero carbon balance.

Between now and 2040, the solutions, goals, and terminology will have changed. These are dynamic concepts shaped by the social, economic and climate contexts of the time. They have already changed greatly in the last 10 years. But we cannot wait. The scale of challenges presented by the climate crisis can overwhelm us, but it is also creating opportunities. The collective focus created by a shared national and international goal can bring people from many different backgrounds together and generate new inspiration and creativity.

Emissions per year for digital research infrastructure

Large scale computing facilities:

40 kiloton CO₂e/yr

UKRI DRI facilities average estimate



Server rooms and laptops:

35 kiloton CO₂e/yr

Non-facilities equipment average estimate



15 kiloton CO₂e/yr
(UKRI funded equipment)

plus:

20 kiloton CO₂e/yr
(not UKRI funded equipment)

Both are equally important contributors to emissions from UKRI funded research.

There is a large uncertainty on these figures. Averages have been used for the purpose of this infographic.

Figure 2: Estimated carbon emissions per year for UKRI DRI ecosystem components

THE RESEARCH

Gathering evidence from across the UKRI community

The Project was commissioned by NERC, on behalf of UKRI, to establish the scope of knowledge currently available^{9,10} and provide recommendations to achieve net zero by 2040. Over approximately 18 months, the Project involved in-depth research literature reviews, technical studies, community engagement activities (surveys, workshops, an art commission), and stakeholder events. DRI is used across research councils and is a trans-disciplinary resource, used increasingly within traditionally digital fields (such as computer sciences, medical research and engineering) and also research domains such as the arts and humanities.

The Project aimed to:

- Collect evidence to inform UKRI DRI Investment decisions.
- Provide UKRI and their community with an outline roadmap for achieving carbon neutrality in their DRI by 2040 or sooner.
- Enable UKRI to play a positive and leading role in the national and global transition to a sustainable economy.

The Project had a budget of £1.86 million which funded evidence gathering activities that covered both the technical and behavioural aspects of the challenges and solutions associated with a net zero DRI.

The Project sought to address the heterogeneity of the physical DRI and of the user communities accessing DRI resources¹¹. The scope of evidence gathering was therefore necessarily broad and defined in consultation with the Project's Scientific Advisory Board and key stakeholders across the DRI.

Scoping Studies

Scoping reviews are "useful for examining emerging evidence when it is still unclear what other, more specific questions can be posed and valuably addressed by a more precise systematic review. They can report on the types of evidence that address and inform practice in the field and the way the research has been conducted."

Munn et al (2018)

In addition to an extensive literature review, and with guidance from the Scientific Advisory Board and key stakeholders, several in-depth research projects were also undertaken, which are referred to as 'Sandpit Projects' and 'Consortium Projects'.

Sandpit projects

These arose from open invitations to researchers to submit ideas which addressed the Project goals. Selected applicants were invited to shape their ideas over a 3-day online workshop, where participants could 'play with ideas' (hence 'sandpit'), rapidly-iterating on research concepts to develop proposals and teams. Project teams were formed around shared areas of interest, and at the end of the workshop each submitted outline proposals, which were presented to, reviewed and assessed by a panel of experts. This process

resulted in seven Sandpit projects which ran for 6 months, covering both technical and behavioural aspects of the challenge of reaching net zero DRI.

Project Research Methodology at a glance

The Project involved:

- An in-depth literature survey
- Sandpit Projects:
 - Research project ideas developed by the UK research community
 - Funded competitively via online ‘sandpit’ events
- Consortium projects:
 - Ideas initiated by the core team, and drawn from the original project proposal
 - Identified from knowledge gaps via the literature review process
 - Funded via consortium agreements
- Community and consensus building activities

Consortium projects

These arose from specific challenges identified as knowledge gaps through the literature review. The Project Team commissioned consortia to address these, and of the 9 consortium projects, 5 reflected case studies of HPC UKRI facilities and focused on technical challenges relating to hardware, software, energy usage and job scheduling. The DRI mapping project responded to the absence of a comprehensive database representing all UKRI owned or majority funded DRI; establishing a list of significant DRI facilities is a prerequisite to capturing the current situation and to future monitoring and

evaluation of progress. The remaining consortium partners provided expertise and guidance to the Project team.

The Project team partnered with 20 different institutions, consisting of over 40 researchers, to undertake evidence gathering activities (Figure 1). These activities generated action-based recommendations, which were framed by additional input from groups of general and expert stakeholders engaged with the DRI. Owing to the requisite technical expertise needed, stakeholders representing the Science, Technology and Facilities Council (STFC) were often over-represented in early activity. Efforts were made - successfully - to ensure that perspectives arising from all of the UKRI research councils were captured in the course of evidence gathering activity (for example, an art commission was added at a later stage to ensure representation from the arts and humanities communities).

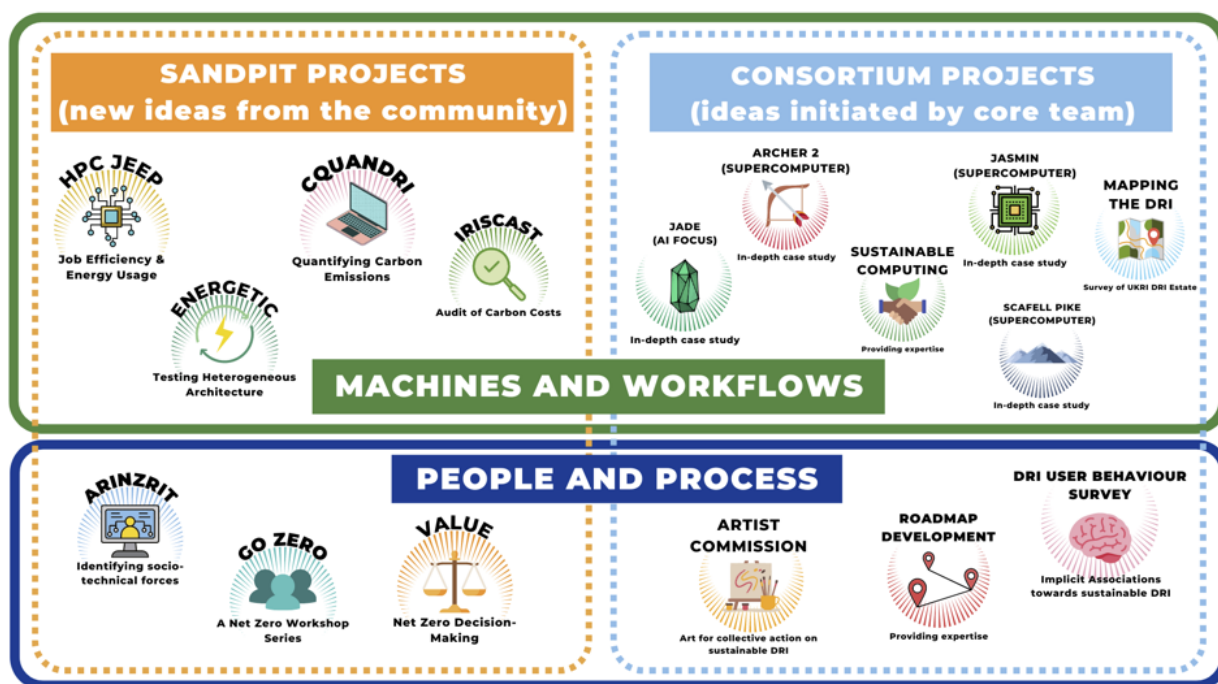


Figure 3: Research areas in the Project

The research undertaken during this Project revealed an extensive evidence-base, enabling us to identify a number of key actions that must be undertaken. The outputs of the sandpit and consortium projects, combined with evidence from a literature review and feedback from stakeholder events, have been synthesised into a Net Zero Delivery Framework comprising a [Roadmap](#) (see page 12) and a [Toolkit](#) (see page 15).

The *Roadmap* is an overarching timeline of actions, organised into *Delivery Pathways*, that will be needed to accomplish net zero operations, which involve UKRI directly and the various entities comprising the UK research community.

The *Toolkit* is a curated collection of specific recommendations that may be applied in various situations and at different levels of an organisation to help accomplish the journey. The Toolkit provides a broad range of recommendations and optional actions, collected into 6 *Thematic Areas*.

The Delivery Framework embodies the evidence collected and reviewed in this study which underpins the recommendations made. A more detailed Technical Report, with full details of the evidence base and recommendations, is available in addition to this report.

RESEARCH INTO ACTION

Mapping our journey to net zero

Having undertaken this thorough review of existing knowledge, what have we discovered and how can it be put into action?

A central conclusion of this research is arguably the most obvious: adequate progress to net zero DRI is unlikely without a clear plan to get there. There is no simple solution to the challenge of creating the net-zero DRI that can simply be adopted and implemented to assure success by 2040. It will require assent, action and change across multiple entities, many of which lie beyond the immediate control of UKRI and some of which extend into society as a whole. This calls for a wide-ranging set of processes that can inspire, cajole, monitor, activate and adapt throughout the remaining time to the target date.

We do not anticipate that detailed plans will all be developed centrally; rather that plans to achieve net zero will be developed at various levels within the overall UK research community. Some will be DRI-specific, others will exist within larger efforts to accomplish net zero at the level of an entire institution. The framing of the work as a 'journey' provides a model for thinking about the timeline and the steps required.

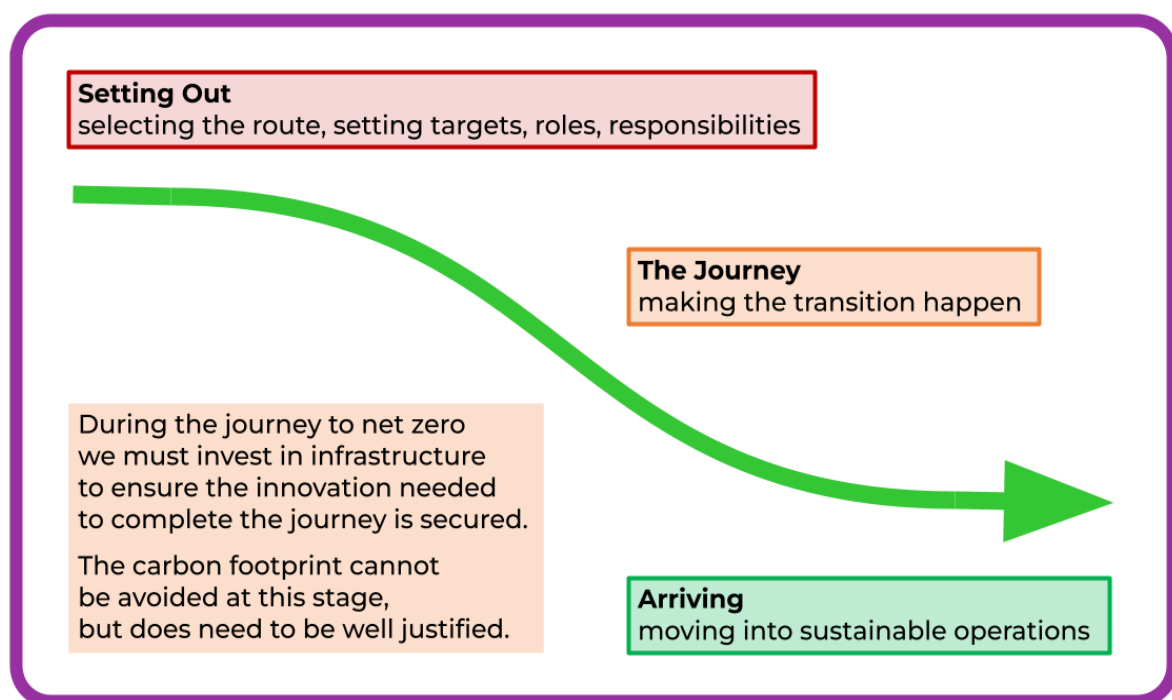


Figure 4: The Net Zero Journey

The Net Zero Journey entails three distinct phases:

- *Setting out:* preparing, route planning and allocating associated responsibilities.
- *The journey:* undertaking the transition to net zero.
- *Arriving:* successful accomplishment of the transition to continuing operations on a sustainable, zero-carbon basis.

During the journey there will be tension between reducing the carbon footprint of DRI and using DRI to enhance innovation towards net zero research. To bring coherence to the many instances of this journey and the myriad efforts to accomplish net zero across the DRI infrastructure, we have created a *Net Zero Delivery Framework* (Figure 5). The intent of the delivery framework is to enable coordinated efforts where local and national undertakings align, overlap or intersect, and how central resources may be leveraged to bolster local efforts to help ensure optimal effectiveness. These steps are organised into a *Roadmap*, encompassing the three *Delivery Pathways*, and provide an approach to deploying the findings represented in the *Toolkit*.

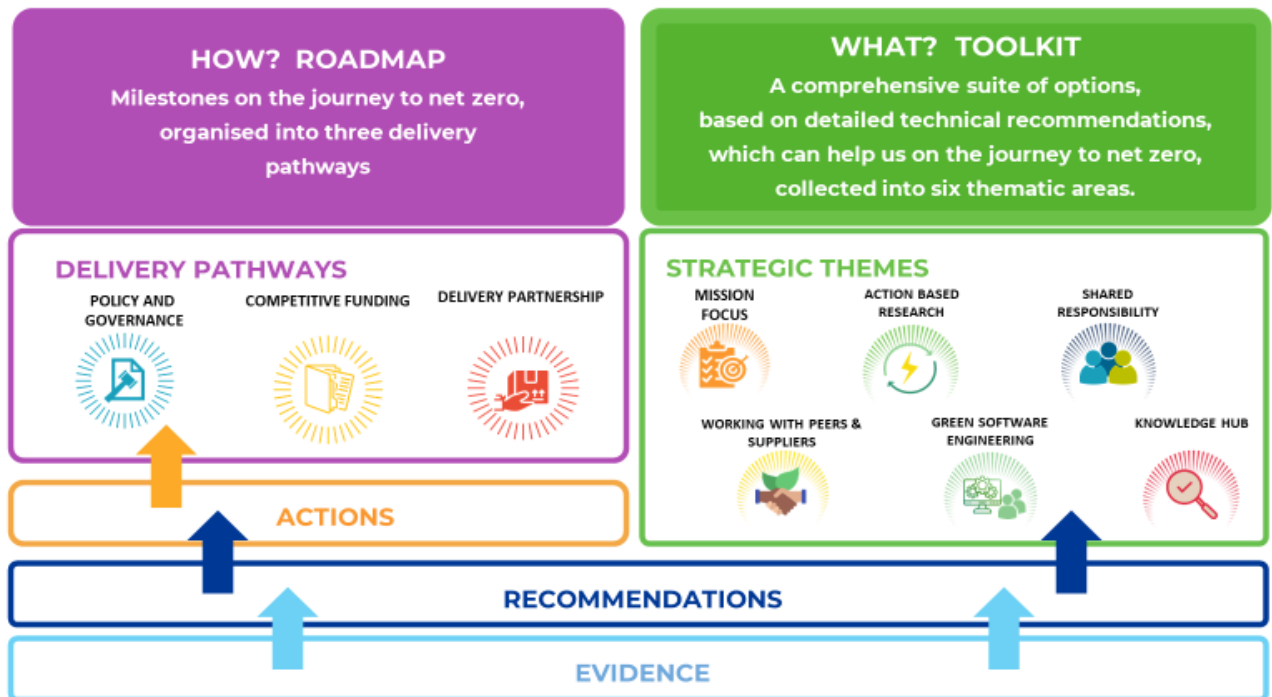


Figure 5: Net Zero Delivery Framework

This report is not intended to represent a detailed “how to” guide for every individual assigned the task of developing a net zero plan for DRI in their organisation. Each will have to approach their responsibilities following a sequence that broadly matches this model. They must prepare to set out and then embark on the journey; undertake the journey, with course-correction as required, and arrive at the destination of operations that may be sustained without net carbon output.

Implementing these recommendations and following this roadmap (outlined in Appendix A) will entail considerable effort, spread across several years.

ROADMAP DELIVERY PATHWAYS

An undertaking as large and dispersed as the creation of a net zero DRI will require several mechanisms of intervention, which we have described as Delivery Pathways (Table 1).

The three Delivery Pathways - Policy and Governance, Delivery Partnership, and Competitive Funding - represent the approaches to effecting change in how DRI functions. It is the recommendation of this report that UKRI should implement the Roadmap and pursue these three delivery pathways as interdependent courses of action. Together, they constitute the proposed way forward for UKRI and the bodies it funds.

Delivery Pathway	Description	UKRI delivery area
Policy and Governance	Creating a policy framework which can deliver the steps needed to achieve the net zero ambition.	UKRI Direct Operations
Delivery Partnership	Funders and facility leads or service providers work together to implement the fundamental changes required.	Lead procured
Competitive Funding	Develops the necessary capabilities and tools drawing on the creativity, diversity and strength in depth of the UK academic community	Funded

Table 1: Delivery pathways

The Delivery Pathways correspond to the three delivery areas referred to in the UKRI Environmental Sustainability Report; respectively: UKRI Direct Operations, Lead Procured, and Funded. An overall governance framework will be required, to track progress towards net zero.

1.) *Policy and Governance:*

To achieve net zero DRI by 2040, UKRI should develop a policy framework to apply to organisations within its funding orbit. This should entail standard policy guidance on internal processes and external partnerships and collaborations. This policy framework should also stipulate that individual institutions are to create net zero strategies and action plans for their own digital research infrastructure. Applying the research findings to action plans for specific situations will require local knowledge combined with specialist expertise. For example, the challenges faced by supercomputers (such as ARCHER2¹²) will be different from the management of servers at a smaller humanities-focused university.

The policy framework should describe the realms of responsibility that are expected to be centralised (such as the transformation of the National Grid to zero-carbon electricity), and those that are the responsibility of individual entities (universities, high-performance computing centres, departments within universities).

2.) *Delivery Partnership:*

A net zero DRI Delivery Service should be established, to help all parties charged with contributing to achieving the goal. This Service should be a central resource, established to support the work of institutions. It will be a foundational plank of the support UKRI will need to provide to decision-makers at all levels, from policy makers to individual computing systems managers at institutional level.

This service should establish and disseminate best practice as it applies to the DRI, maintain community cohesion through meetings and communication activities, and maintain a map of the UKRI DRI and its carbon footprint. The body of work created as a result of this study, along with the expertise gained by the individuals involved in the work, may play a key role in establishing the foundations of such a capacity.

Part of the work of the Delivery Service should be to develop, maintain and extend a central Knowledge Hub. This should begin with the results of the Scoping Study and be extended as new research emerges. Thus, the Hub should include the ability to capture and disseminate future learnings as the DRI community responds. Continuing research by the Delivery Service will constantly add new information which should be curated in a central, but accessible, location. Established industry best practice for the management of knowledge management systems should apply.

UNESCO (2021)¹³ notes the urgency of “fostering equitable access to scientific information” in order to create resilience and the capability to respond to global emergencies. The Knowledge Hub could also serve as a valuable place for sharing best practices around the world, not only for DRI but other wider applications facing the same challenges.

3.) *Competitive*

Funding

As work begins, preparing to embark on the journey to net zero, challenges will be encountered, such as lack of solutions to specific problems, or the lack of key systems or tools. Examples include further development of best practices in *green software engineering*. This aspect of the delivery service and the curated knowledge management system will also represent a national resource of green software engineering skills. Others may include the production of specific software tools that may support the work to accomplish net zero. Examples such a ‘green scheduler’ and a series of energy-related reporting tools have been proposed.

The actions undertaken within the framework of these Delivery Pathways represent a significant program of change that will affect the entire UK research community and the

community of collaborators, partners, suppliers, and other stakeholders. The high-level framework outlined here will help to communicate expectations to these organisations. These actions represent a flexible programme of immediate and continuing activity coupled with continuing research and plan-adaptation as required. To support organisations - at various levels within the research community - as they undertake the work needed, the research findings of this project have been organised into a toolkit. The Toolkit, described in the next section, represents a rich knowledge resource to be applied to specific situations and contexts encountered as the Roadmap is implemented.

TOOLKIT

Six strategic themes

The evidence gathered in the Project suggested that several common challenges will be faced by every organisation aspiring to net-zero operations. While the evidence suggested many approaches to such challenges, the specific scenarios faced by institutions and departments comprising UKRI will be different.

Over 160 recommendations were identified, which can be considered guidance, tools and techniques that may be applied within institution-specific plans to accomplish net zero. They represent a *Toolkit*, a curated resource in support of achieving net zero goals.

The detailed recommendations, their derivation and the situations to which they may apply are discussed in the Technical Report and supporting partner reports. These have been grouped around six themes, which align with the challenges likely to be faced and the ways they may be met:

- a) Maintaining a mission focus: ways of demonstrating leadership and creating clear and cohesive narrative.
- b) Demanding shared responsibility: methods of fostering responsibility at individual and group levels.
- c) Undertaking action-based research: initiatives to learn quickly, emphasising progress not perfection.
- d) Working with peers and suppliers: approaches to developing a low-carbon supply chain.
- e) Providing support and advice: components of a knowledge base to share information and best practice.
- f) Developing green software engineering: techniques for the sustainable management of digital infrastructure and software development.

The point of mission focus is to counter the possibility of distraction. Shared responsibility is about emphasising that everyone has a part to play and nobody should be tempted to think it's all down to others. Action-based research is intended to stop the perfect becoming the enemy of the good. Working with peers and suppliers demands consideration of the consequences of activity both up and down the supply chain. Support and advice concern the free-flow of information and trying to ensure avoidable mistakes do not arise because of a lack of it. And green software engineering is about the fundamentals of how UKRI DRI is implemented.

Each theme is explored in more detail below, with a discussion of each theme, reflecting the challenges likely to be faced as organisations embark on their net zero journey and how the specific findings may support addressing these challenges. We anticipate that these findings will represent the initial contents of the 'Knowledge Hub' described in the previous section and will serve as a basis for local action and also as a resource for the Delivery Service. They might also represent ideas for funding calls for competitive projects to address specific knowledge gaps or tool development requirements.

THEME 1:

Mission Focus

Why is a “mission focus” necessary? Reacting to the emergency requires enhanced innovation, restrained use of energy and global cooperation. The need to act might seem to outstrip our knowledge of how to act, which necessitates a flexibility of response as we act and learn. As we do so, the overarching mission must always be at the heart of our planning.

A strong mission focus is needed to ensure that this transformation stays on track to achieve sustainability. Nor is this purely a scientific and engineering problem. Solving it will require harnessing economics, the social sciences, arts and humanities to understand the range of societal views that may accelerate the transition, or conversely, block change.

To harness the support and resources required to effect change at the scale contemplated, we must all understand that we are in a climate emergency. Accomplishing net zero goals will require ways of demonstrating leadership and creating clear and cohesive narrative, and then adjusting plans as required - as circumstances change and new information becomes available - to accomplish the mission. The research outlined in this section points to techniques that may help maintain that organisation-wide mission focus.

THEME 2:

Recognising Shared Responsibility

Every organisation within the overall research community must engage towards net zero. To harness these collective endeavours, we must maintain the mission focus explored above, and ensure there is an understanding that everyone needs to engage and play their part. This requires organisation leaders to consider methods of fostering responsibility at individual and group levels.

Shared responsibility means that each person in an organisation, no matter their position, shares in the responsibility to take action to reach net zero. This responsibility should be recognised by each person and by each entity within the UKRI ecosystem. UKRI can support such efforts to raise awareness and encourage that sense of shared responsibility within all Research Councils, embedding net zero principles at all layers of UKRI with active engagement with each Research Council. Creating this shared sense of responsibility will require an education and learning program to help staff understand that a range of appropriate actions can be taken, and to provide the wider context of the organisational plan. When people are energised by a sense of responsibility, a culture of action can form, encouraging meaningful change. That sense of responsibility, however, may be disheartening unless people know what they can do. An explicit expectation that all areas of UKRI will participate in developing & sharing best practices, coupled with the availability of knowledge resources (e.g., via a central knowledge hub, as discussed in the previous section), can support this effort.

THEME 3: Undertaking Action-Based-Research

It has become crucial that work on decarbonising the UKRI DRI starts immediately, with a resolve to focus on progress not perfection by making small steps and learning from experience. It is equally important to recognise this will be an iterative process where regular checks and adjustments will likely be needed.

The challenge of creating an effective net zero environment is complex. It involves a huge number of ever-changing factors and unknowns. To achieve the target and remain on the timeline, we do not have the luxury of striving for perfection in design. The imperative must be to learn quickly, embracing the necessity sometimes to make mistakes and readjust along the way. It is more important that we continue to make progress against the overall goal than that we are faultless in every step. Therefore, it is important that initiatives are undertaken with a goal of learning quickly, emphasising progress not perfection.

We will need to become comfortable with pragmatic compromises rather than ideal solutions. The most efficient way forward will involve trial and error, and some extent of only partial success. Many recommendations show how much can be achieved by getting started now, allowing much more to be achieved by learning and adjusting as progress is made.

THEME 4: Working with Peers and Suppliers: *Developing a low-carbon supply chain*

Meaningful progress towards net zero cannot be achieved by focusing just on the activities under the direct control of UKRI DRI. It will be necessary to develop a low-carbon supply chain that minimises carbon emissions across all contingencies associated with UKRI, from the people undertaking the research through to the suppliers of the suppliers within the chain. A comprehensive lifecycle analysis will be needed for everything from tea bags to servers.

The computers required for DRI, and the electricity required to power them, represent major components of the overall DRI carbon footprint. The challenges involved are not unique to the UK research community, and research peers in other countries are also facing similar challenges. It is essential, then, that the research community engage with suppliers to engage with them in collaboration towards net zero operations, and with peers to gain and share insights

Achieving net zero is challenging for a unified commercial organisation; the nature of UKRI DRI creates additional difficulties. The range and scope of systems and facilities involved in providing the DRI for the research community covers a wide range of activities spanning compute facilities, software, data storage, access to networks, users, maintenance specialists and funders.

THEME 5:

Providing Support and Advice: Components of a knowledge base to share information and best practice.

The Project has identified and curated a large body of research that forms the basis for the recommendations made. This information, and other resources created during the course of the Project, represent an important collection of guidance that may be deployed in a range of ways and scenarios.

This material should be seen as the foundation for a knowledge base that can be accessed by the research community seeking ideas and guidance.

The roadmap to net zero will pass through unexplored territory, and new findings will emerge. The knowledge hub will need to be regularly updated with lessons learned from exploratory pathfinder projects at UKRI and elsewhere.

THEME 6:

Developing Green Software Engineering: Creating a body of expertise, providing training, developing tools, metrics, expert assessment, and standards.

The use of computers creates carbon emissions. The carbon emitted in connection with computing infrastructure is not simply a consequence of machine use. Computing requires software, and the manner in which the software controls the hardware affects carbon emissions. Not all software is well written. Not all computing hardware is wisely acquired or optimally managed. Therefore, sometimes, carbon is emitted that need not have been. Green software engineering refers to the specialist skills, expertise and frameworks required to tackle these issues.

The term “software” covers a wide spectrum of digitised instructions and knowledge systems, whether a code used or developed by a researcher, or the environment within which such codes run (e.g. from schedulers on multi-user machines to use of ChatGPT as a tool). The term “software engineering” typically covers the whole lifecycle of development of software, from gathering requirements, through design, implementation and deployment, and the science of doing so in an efficient manner. Traditionally, software engineering has focussed on functionality, reliability, extensibility and how well the software product performs in terms of time, hardware resources and people to maintain it.

Reducing the carbon footprint of the computational resources required to support the UK research community will require novel approaches to both hardware and software. This includes understanding and applying software-writing techniques that reduce the energy demands of the software at run-time, and approaches to hardware management that minimise the energy consumption.

Approaches to the sustainable management of DRI and optimal techniques for software development and deployment are referred to as ‘Green Software Engineering’. This term encompasses both the writing of software, and the whole-lifecycle management of computing infrastructure. Several specific techniques were recommended as a result of the research undertaken, each of which may play a role in ensuring less carbon intensive use of DRI.

These operate at various 'levels' of the computing environment:

- Selection and implementation of hardware
- The management of the hardware infrastructure
- Development of efficient, well-behaved software
- Management of software operations
- Instrumenting infrastructure to assess carbon impact
- Continuous learning and knowledge dissemination

Many technical recommendations have been made that overlap with the discussion of Green Software Engineering. For example, recommendations relating to procurement, considered under "Working with Peers & Suppliers" also apply when considering Green Software Engineering.

CONCLUSIONS

Any project of scale risks failure to accomplish its goals, and this risk increases with project complexity and uncertainty of the environment in which the project is pursued. In addition, there may be obvious barriers to progress that must be considered from the start. Some risks and barriers are well known; complex projects involve risks and barriers that fall into the categories of known unknowns and unknown unknowns.

Achieving net zero is a gargantuan undertaking, of such a scale that it runs an inherent possibility that it will fail to accomplish at least some of its goals. Some of these risks can be seen in the individual themes outlined in the Toolkit above. But beyond these specific themes, there are further overarching risks and barriers. A key area is the interpretation and specificity of the language that is used. The net zero target has a clear objective meaning when applied to global emissions, but precise interpretation becomes ambiguous and controversial when applied to specific organisations because of fundamental ambiguities about allocation and compensation measures through offsetting and capture. The 'net zero' objective is often treated as an objective and physically measurable target, but there is an increasing body of literature treating it as an emerging social norm.

Commercial hyperscale data centres can provide significant advantages of scale, and many providers have well-developed reporting on emissions and sustainability. However, quantitative comparison between different institutions remains challenging because of a lack of standards to ensure consistent interpretation of reported data. All this ambiguity has even led some to conclude that the objective of demonstrating leadership is a safer guiding principle than any specific quantitative metric.

There are also unavoidable tensions that need to be managed. For example, there is potential conflict between the desire to minimise the carbon expenditure on DRI use at the individual project level and decisions made about scheduling jobs to minimise energy consumption at the collective facility level. At the facility level, managers could schedule CPU intensive software (the kind that needs additional cooling) during periods where the electricity supply from the grid is powered with a greater proportion of renewable energy (less carbon intensive). Conversely less CPU intensive software could be preferentially scheduled during periods of high carbon intensity electricity supply.

There is a conflict at the heart of all net zero aspirations for UKRI DRI. The Climate Change Committee report on pathways to net zero highlights the importance of restrained or constrained energy consumption. They recommend a balanced pathway which involves some restraint in energy usage but at the same time requires innovation to power the transition. This balance creates a tension between the need for innovation and restraint on energy use which could dampen innovation. Some contributors have taken it for granted that this constraint will be passed down to the UKRI and the UKRI DRI while others assume that the UKRI DRI is a special case for which, by virtue of the large societal benefits it delivers, should be allowed an exemption from this constraint. Neither the extreme of unfettered innovation nor that of excessive restraint provides a satisfactory outcome. To steer between the two we need to have regular reviews of the course.

Finally, there is a clear imperative to resist self-deception concerning progress made and the pace of change. Success can only be achieved by sustained vigilance over a coming period of almost two decades. And it is essential for people not to become susceptible to the obstacles that arise from the likes of greenwashing, mis-use (or misunderstanding) of terms such as net zero, and political posturing.

The past is not characterised by an absence of concern for the environmental damage being wrought by our unsustainable carbon footprint. But until now, good intentions have consistently fallen short when it comes to delivering real change. It is no longer an option to continue following that path. We need meaningful action, not just willing words.

CALL TO ACTION

Urgency and Transformation

The need for urgent action to avert climate disaster has been clearly stated by the UK parliament. The UN Secretary General also underscored the need for the developed economies to reach net zero emissions by 2040. These strong words call for strong and immediate action. UKRI, funded by the UK Government, has a duty to ensure the emissions it is responsible for are net zero by 2040 - preferably sooner, and set out a roadmap of actions to accomplish this.

This study represents an authoritative survey of the state of scientific literature, coupled with new research and expert consultation, on how we might do so. It addresses how to tackle, collectively, the challenges of accomplishing net zero in our digital research environments by 2040. The results give us grounds for optimism yet also reveal the sheer scope and scale of work to be done. DRI is not the largest driver of emissions in the UK research community but represents an important contributor and is emblematic of the challenges that face research organisations.

There are uncertainties, and there are gaps in our knowledge. Some problems remain to be solved. These are not, nor must they be allowed to be seen as, reasons for inaction.

The time to act is now.

APPENDIX A: Roadmap

Actions proposed to reach net zero DRI by 2040

Number	Actioned by (Year)	Delivery Pathway	What	Outcomes and impacts
1	2024	Policy and Governance	Review policy areas across UKRI and integrate net zero principles	Net zero ambition integrated into all areas of policy resulting in consistent and effective action
2	2024	Policy and Governance	Create net zero action plans for DRI facilities, considering active and embodied carbon, and including decommissioning	Consistent and transparent approach enables rapid transition without disrupting competitive and collaborative working
3	2024	Policy and Governance	Develop a timeline for the elimination of onsite fossil fuels	Clarity about deadlines will result in timely procurement decisions and minimise disruption
4	2024	Delivery Partnership	Establish net zero DRI task-force from within research community to provide guidance and support on policy development and implementation	A task-force with the capacity to maintain current and authoritative information will enable consistent decisions which take advantage of best knowledge available.
5	2024	Delivery Partnership	Create a map of DRI resources and their environmental impact profile	A clear understanding of current footprints, UKRI DRI stakeholders will be able to make effective decisions about priorities for decarbonisation
6	2024	Competitive Funding	Run responsive-mode funding calls and research fellowships focused on sustainable DRI.	Creation of a robust body of expertise around green software engineering will enable optimal use of resources.
7	2024	Competitive Funding	Fund research into carbon impact of heterogeneous hardware and software combinations and use patterns	Clear understanding of carbon impact related to heterogeneous hardware/software combinations and use patterns

8	2024	Competitive Funding	Fund research into carbon accounting tools and methodologies	A robust and effective framework for monitoring carbon impacts
9	2024	Competitive Funding	Fund research into strategies for behaviour change at all levels of DRI	A clear understanding of the measures that UKRI must take to facilitate change to more sustainable working patterns
10	2028	Policy and Governance	Implement UKRI policy on use of contracts and conditionalities to reduce emissions in scopes 2 and 3 via procurement contracts and power-purchase agreements	Establish clear and legally binding commitments from suppliers that will take us to net zero in scope 3 emissions
11	2028	Policy and Governance	Implement UKRI policy on re-use of waste heat and recycling of hardware.	Minimisation of waste ensures that the net zero strategy is also aligned with other sustainability goals.
12	2028	Policy and Governance	Establish a financial and legal framework to facilitate multi-institution collaborations to support sharing of resources and efficient use of capacity	Greater flexibility leads to enhanced collaboration among UKRI funded institutions.
13	2028	Delivery Partnership	Provide training in low-carbon DRI use to early career and established researchers, research software engineers, facilities managers etc	Habits of efficiency adopted early by new generations of researchers
14	2028	Delivery Partnership	Develop technical standards for monitoring, evaluation and accreditation of DRI usage	Consistent reporting on energy and carbon footprints becomes possible
15	2028	Delivery Partnership	Develop standards for Open Science principles	Open Science becomes common in the UKRI research community, leading to greater research efficiency
16	2030	Policy and Governance	Shift from voluntary to mandatory environmental sustainability reporting and accreditation across research grant funding, UKRI majority funded facilities, and procurement	A comprehensive approach to reporting gives greater clarity about areas of progress and areas where greater efforts are needed

17	2030	Policy and Governance	Integrate sustainable computing within DRI career development pathways	A workforce motivated to enhance sustainability leads to rapid progress in elimination of waste
18	2030	Delivery Partnership	Adopt standards for Open Science research practice using DRI	Open Science enables greater efficiency in scientific workflows
19	2030	Delivery Partnership	Ensure training in best practices for low-carbon use accompanies software, hardware and facility development	When new hardware arrives, the user community is well prepared to make full use of it
20	2030	Delivery Partnership	Establish a centralised net zero DRI hub to provide support and advice to UKRI research communities and ensure visibility of low-carbon initiatives within DRI	All operators and users will have easy access to consistent and up-to-date information.
21	2030	Competitive Funding	Develop carbon emissions tracking capability and make connection between user activity and carbon impact	Establishing the capability at a facility or service level will enable design of a system wide approach and start the process of gathering data systematically
22	2040	Policy and Governance	Implement a procurement framework that guarantees a sustainable supply chain; Prioritise sustainability in DRI design and investment decisions and develop DRI resources in partnership with the research communities	Supply chain element of scope 3 emissions reduced to near zero.
23	2040	Competitive Funding	Develop a single DRI interface reporting energy use and environmental footprint per job	Clear and accessible metrics facilitate detection of inefficiencies by users and operators of facilities
24	2040	Competitive Funding	Develop and deploy green schedulers to enable optimal distribution of computational workloads and carbon efficient energy usage across facilities	Reduction in resources wasted by running on inappropriate hardware or underused facilities.

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⁴ <https://www.theccc.org.uk/wp-content/uploads/2023/01/CCC-Insights-Briefing-Determining-a-pathway-to-Net-Zero.pdf>

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