NETZERO

Net-Zero and Circular Economy Federation: Evidence-based Policy Roadmap for Carbon-Aware Compute in the Built Environment

Prepared for

National Federated Compute Services (NFCS)

Prepared by

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Executive Summary

The NETZERO project was undertaken to support the National Federated Compute Services (NFCS) by generating evidence, metrics, and policy recommendations to embed sustainability principles within federated compute and data services. Using the built environment as a high-impact pilot sector, the project addressed the growing environmental and governance challenges associated with compute-intensive digital workflows, including artificial intelligence (AI), digital twins, whole-life carbon assessment (WLCA), Digital Product Passports (DPPs), and other data-intensive applications. The project contributes directly to the NFCS Community, Technology, and Governance pillars while supporting the UK's Net Zero ambitions and the UN Sustainable Development Goals (SDGs 9, 11, 12, 13 and 17). The project adopted a mixed-methods and co-creation approach, combining evidence review with organisational survey data, stakeholder engagement, expert consultation and Rapid Delphi validation. In total, over 250 stakeholders contributed to the project, including 214 valid survey responses from academia, industry, government, infrastructure providers, professional bodies and built environment organisations. This generated one of the first organisational evidence bases for sustainable federated computing within the UK built environment. The evidence demonstrated that advancing sustainable federated computing is not solely a technological challenge but also requires coordinated improvements in governance, interoperability, sustainability measurement, workforce capability and organisational readiness. Stakeholders identified strong demand for harmonised sustainability metrics, trusted governance arrangements, interoperable data ecosystems and practical decision-support to support sustainable federation. These findings informed the development of five integrated project outputs. The project produced a Harmonised Sustainability Vocabulary establishing a common language for sustainable federated computing; a National Sustainability KPI Framework comprising 124 validated KPIs across five sustainability domains; an evidence-based package of governance and policy recommendations supported by a phased five-year implementation roadmap; SustainFed, an adaptive sustainability assessment and decision-support platform that operationalises the project's evidence within a practical assessment environment; and a Transferable Engagement and Co-Creation Toolkit to support the replication of the NETZERO evidence-to-action approach across future NFCS communities. Collectively, these outputs provide NFCS with an integrated evidence-to-action pathway for advancing sustainability across federated compute and data services through common terminology, harmonised measurement, trusted governance, practical decision-support and transferable implementation methods. Although developed using the built environment as a pilot sector, the approach is designed to be transferable across other research domains and digital infrastructure initiatives. By combining robust organisational evidence with practical frameworks, strategic guidance and an operational prototype, NETZERO provides a strong foundation for embedding sustainability within the future evolution of the UK's federated compute ecosystem.

1. Introduction

1.1 Background

The UK's NFCS programme aims to develop a nationally coordinated ecosystem of federated compute and data services that enables secure, scalable and collaborative access to HPC, cloud resources and research data infrastructures across disciplines. By federating distributed digital infrastructure rather than relying on isolated computing environments, NFCS seeks to improve resource utilisation, interoperability, research collaboration and innovation while supporting the UK's broader digital research infrastructure ambitions.

As demand for compute-intensive research continues to grow, federated computing infrastructures are becoming increasingly important for supporting AI, large-scale simulation, digital twins, data analytics and other compute-intensive digital workflows. However, these capabilities also increase energy consumption, carbon emissions, long-term data storage requirements and governance complexity. While significant progress has been made in improving computational performance and data federation, sustainability considerations, including carbon-aware computing, resource efficiency, lifecycle impacts, interoperability and governance, remain insufficiently integrated into the planning, operation and evaluation of federated digital infrastructures. Therefore, there is a growing need for evidence-based approaches that embed sustainability considerations. within the future development of national federated computing services. Although several national initiatives are advancing federated computing and digital research infrastructures, there remains limited evidence to support the systematic integration of sustainability considerations into federated compute planning, governance and decision-making. In particular, there is a lack of harmonised sustainability terminology, consistent performance indicators and practical implementation guidance that can support sustainability-aware infrastructure development across research communities.

The built environment was selected as the pilot sector because it represents one of the UK's most data- and compute-intensive research and industrial domains while contributing significantly to national carbon emissions, resource consumption and infrastructure investment. Digital transformation within the sector is accelerating through the adoption of AI, Building Information Modelling (BIM), digital twins, whole-life carbon assessment (WLCA), Digital Product Passports (DPPs) and smart infrastructure systems, all of which depend on increasingly sophisticated computing and data federation capabilities. These characteristics make the built environment an ideal testbed for developing and validating sustainability-aware approaches that are directly relevant to NFCS while providing transferable lessons for other research domains. The NETZERO project was established to address this gap by generating the evidence, metrics, governance guidance and practical tools required to integrate sustainability principles into federated compute and data services.

1.2 Project Aim

The NETZERO project aimed to generate the evidence, frameworks, tools and policy recommendations needed to support the National Federated Compute Services (NFCS) in embedding sustainability principles within federated compute and data services.

1.3 Project Objectives

The project was structured around four interconnected objectives that collectively support the sustainable development of federated computing within NFCS.

- **Community Building and Stakeholder Engagement (Community)**
Engage stakeholders from academia, industry, government, infrastructure providers, and the built environment to identify sustainability priorities, establish a cross-sector community of practice, and ensure broad representation in the development of sustainability-aware federated computing.
- **Vocabulary and KPI Harmonisation (Community/Technology)**
Develop a harmonised sustainability vocabulary and a standardised KPI framework to improve interoperability, benchmarking, and consistent sustainability assessment across NFCS and related national initiatives, including NetDRIVE, DAFNI, and UKCRIC.
- **Evidence Generation and Transferable Toolkit Development (Technology/Community).** Generate evidence on representative compute-intensive built environment workflows and develop a transferable engagement toolkit, including the SustainFed decision-support platform, to support sustainability assessment and evidence-based decision-making.
- **Governance Co-Creation and Roadmap Development (Governance)**
Co-develop and validate governance recommendations, implementation actions and a five-year roadmap to support sustainable, interoperable and inclusive federated computing within NFCS.

1.4 Project Deliverables

The project delivered four integrated deliverables that collectively support the sustainable evolution of federated computing within NFCS:

1. A Harmonised Sustainability Vocabulary to improve consistency and interoperability across technical, policy, and practice communities.

2. A National Sustainability KPI Framework comprising 124 validated indicators across five sustainability domains for benchmarking and performance assessment.

3. An Evidence-Based Governance and Policy Roadmap containing six strategic recommendations and a phased five-year implementation plan for NFCS.

4. SustainFed, a transferable sustainability assessment and decision-support platform that integrates the project's vocabulary, KPI framework, governance principles and recommendations within a single assessment environment.

5. A Transferable Engagement Toolkit to support the reproducible development, validation and implementation of sustainability frameworks across NFCS and other research communities.

1.5 Project Partners

The NETZERO project was led by the University of the West of England (UWE Bristol) and supported by an interdisciplinary partnership of academic, industry and professional organisations with expertise in digital infrastructure, sustainable construction, governance, policy and federated computing. The project also benefited from engagement with the wider NFCS community and national digital infrastructure initiatives throughout its delivery.

Table 1. NETZERO Project Partners and Their Roles

Project Partner	Affiliation	Role / Expertise

Ms Amanda Williams	Chartered Institute of Building (CIOB)	Professional body; stakeholder engagement, industry collaboration and policy dissemination
Dr Abid Mehmood	Cardiff University	Governance, policy, sustainability and stakeholder engagement
Mr Philip Reid	VINCI Construction	Industry partner; digital construction and infrastructure practice
Professor Muhammad Shafiq	Heriot-Watt University	Digital construction, BIM and digital transformation
Dr Muhammad Qasim Rana	University of Built Environment	Sustainable built environment and digital innovation
Professor Bankole Awuzie	University of Johannesburg	Sustainability, circular economy and stakeholder engagement
Dr Kaveen Perera	Northumbria University	Digital engineering, data analytics and computing systems

1.6 Structure of the Report

The remainder of this report is organised as follows. Chapter 2 describes the project methodology and stakeholder engagement process. Chapter 3 presents the national evidence base. Chapter 4 summarises the principal project outputs. Chapter 5 presents the strategic recommendations, followed by the five-year implementation roadmap in Chapter 6. Chapter 7 discusses the project impacts, while Chapter 8 concludes the report and outlines future opportunities.

2. Project Approach and Methodology

2.1 Methodology

The NETZERO project adopted a mixed-methods, stakeholder-centred and evidence-driven approach to develop practical resources for embedding sustainability within the NFCS. The methodology combined secondary evidence, primary stakeholder engagement, collaborative co-creation, expert validation and iterative platform development to ensure that all project outputs were evidence-based, transferable and aligned with national priorities.

Project delivery followed eight sequential but interconnected phases (Figure 1). The process began with a comprehensive review of academic literature, UK policies, international standards and existing digital infrastructure initiatives to establish the project's evidence base. This informed the design of the stakeholder survey and engagement activities. Survey findings were subsequently explored through workshops and co-creation sessions to identify stakeholder priorities, refine sustainability concepts and develop the initial vocabulary and KPI framework.

A Rapid Delphi process was then undertaken to validate, cluster and refine the proposed sustainability indicators and governance concepts. Findings from all evidence sources were synthesised to develop the project's principal outputs, namely the Harmonised Sustainability Vocabulary, National Sustainability KPI Framework, Governance and Policy Recommendations, SustainFed sustainability assessment platform, and the Transferable Engagement Toolkit. These outputs were subsequently evaluated through scenario-based testing, stakeholder validation workshops and expert review before being consolidated into the final recommendations and Five-Year Implementation Roadmap for NFCS.

The stakeholder engagement methodology, templates and facilitation materials developed during the project have been consolidated into the Transferable Engagement Toolkit (Appendix B) to support transparency, reproducibility and future adoption by other NFCS communities.

Figure 1. Overview of the NETZERO mixed-methods research methodology and project workflow

2.2 Stakeholder Engagement

Stakeholder engagement formed the core of the project methodology and was designed to ensure that all outputs reflected the priorities and practical needs of the NFCS community. Engagement activities combined surveys, workshops, co-creation sessions, Rapid Delphi validation and platform testing, enabling evidence to be progressively refined throughout the project lifecycle.

Stakeholder engagement combined a national survey comprising 214 organisational responses with 13 workshops involving more than 50 individual participants across stakeholder engagement, co-creation, validation and dissemination activities. Together, these complementary evidence sources ensured that the project outputs reflected diverse organisational perspectives and expert knowledge spanning academia, industry, government, professional institutions, infrastructure providers and the wider built environment community.

Table 2. Summary of stakeholder engagement activities

Activity	Purpose	Participants/ Respondents	Period	Key Outputs
Evidence Review	Review academic literature, policies, standards, NFCS initiatives and sustainability frameworks	Project team	Dec 2025–Feb 2026	Baseline evidence, conceptual framework and initial sustainability domains
National Survey	Assess organisational awareness, adoption, readiness, sustainability priorities, barriers and future requirements	214 organisational responses	Jan–Apr 2026	National organisational evidence base and quantitative findings
Stakeholder Engagement Workshops	Gather requirements, identify sustainability priorities, and explore federation challenges through multidisciplinary stakeholder engagement	13 workshops involving 90 participants from academia, industry, government, infrastructure providers and professional institutions	Feb–Jul 2026	Stakeholder requirements, sustainability priorities and implementation challenges
Co-Creation and Expert Validation	Co-develop and validate the Harmonised Sustainability Vocabulary, National Sustainability KPI Framework, governance recommendations and SustainFed	Researchers, policymakers, industry practitioners, infrastructure providers and sustainability experts	Mar–Jul 2026	Refined vocabulary, validated KPI framework, governance recommendations and SustainFed platform
Rapid Delphi and Expert Review	Review, refine and build consensus on KPI domains, governance concepts, recommendations and implementation priorities	Multidisciplinary expert panel	Apr–Jul 2026	Consensus-based KPI framework, governance principles and implementation recommendations
Scenario Testing and Platform Validation	Evaluate SustainFed through representative decision scenarios and stakeholder validation workshops	End users, infrastructure providers and subject experts	May–Jul 2026	Validated decision-support logic, implementation roadmap and final project recommendations
Project Dissemination and Knowledge Exchange	Disseminate project findings, obtain final stakeholder feedback and promote wider adoption across the NFCS ecosystem	Researchers, industry practitioners, policymakers, infrastructure providers and professional communities	Jul-26	Dissemination of project outputs, stakeholder knowledge exchange, implementation awareness and future collaboration opportunities

Detailed information on stakeholder engagement activities, workshop attendance, participant profiles, Research Council representation, locations and workshop outputs is provided in Appendix A.

2.3 Stakeholder Profile

The project engaged a diverse range of organisations and individual participants to ensure that the evidence, outputs and recommendations reflected the perspectives of both research and practice. The national survey captured 214 organisational responses, representing organisations from academia, industry, government, professional institutions, infrastructure providers and the built environment. These organisational responses provided evidence on institutional awareness, digital maturity, sustainability priorities, implementation barriers and future requirements for sustainable federated computing.

Complementing the survey, more than 50 individual experts engaged in stakeholder workshops, co-creation sessions, expert reviews, validation activities and dissemination events. Their expertise spanned sustainability, digital construction, federated computing, data management, governance, policy, digital infrastructure and high-performance computing, supporting the refinement and validation of the project's outputs.

Together, the organisational survey responses and stakeholder engagement activities provided broad representation across organisational types, sectors, professional expertise and research communities, strengthening the credibility, applicability and transferability of the project's findings and recommendations.

The report summarises the characteristics of the participating organisations and stakeholder communities through a series of figures, including:

- Organisation Type (e.g. academia, industry, government, professional institutions and infrastructure providers).
- Sector Representation (built environment disciplines and related sectors).
- Research Council Representation (where available and consistent with ethics approval).
- Professional Expertise represented by workshop participants (e.g. sustainability, digital construction, AI, data management, governance, HPC and digital infrastructure).
- Geographical Distribution of participating organisations and stakeholder engagement activities.

Detailed information on stakeholder engagement activities is provided in Appendix A. The organisational characteristics of the national survey respondents are presented in Section 3 alongside the corresponding survey findings, while the stakeholder engagement methodology, templates and supporting materials are presented in the Transferable Engagement Toolkit (Appendix C).

3. National Evidence Base

This section presents the national organisational evidence base generated through the NETZERO project and synthesises quantitative survey findings with qualitative evidence from stakeholder engagement, co-creation activities, Rapid Delphi validation and SustainFed platform evaluation. Together, these evidence sources inform the development of the project's outputs, recommendations and implementation roadmap.

3.1 Organisational Landscape

The NETZERO project established a national organisational evidence base to examine sustainability awareness, organisational capabilities and readiness for sustainable federated computing. The survey generated 214 valid organisational responses from organisations operating across the built environment, infrastructure, research, technology, sustainability, policy and professional sectors. This quantitative evidence was triangulated with stakeholder workshops, co-creation activities, Rapid Delphi validation and SustainFed platform evaluation, providing complementary qualitative and expert insights across the Community, Technology and Governance dimensions of NFCS.

The organisational sample was intentionally designed to be cross-sectoral and multidisciplinary, capturing both users of compute-intensive digital workflows and organisations responsible for their development, management, governance and implementation. This breadth is important because sustainable federation depends not only on computing infrastructure but also on organisational capability, data governance, interoperability, sustainability assessment and operational decision-making. Sections 3.1.1 and 3.1.2 examine this evidence base through its sectoral composition and geographical distribution.

3.1.1 Organisational Sector, Expertise and Capability Representation

The 214 participating organisations represented a broad cross-section of the built environment and its wider digital, sustainability, research and governance ecosystem. As shown in Table 3.1, the sample spans the full built-asset lifecycle, from design, engineering and construction to asset operation, while also incorporating the specialist capabilities required for sustainable federated computing.

Table 3. Organisational sector, expertise and capability representation

Organisational Sector	Number	%	Relevant Expertise and Capabilities Represented
Construction and Project Management	45	21.0%	Construction delivery; project and programme management; procurement; planning; cost and resource management; digital project delivery
Design and Architecture	41	19.2%	Architectural and engineering design; computational design; BIM; information modelling; digital design workflows; sustainability-led design
Asset and Facilities Management	36	16.8%	Asset and facilities management; lifecycle information management; operational data; asset performance; maintenance; smart building applications
Engineering and Infrastructure	27	12.6%	Civil and infrastructure engineering; infrastructure planning and delivery; simulation and modelling; infrastructure asset management; resilient infrastructure
Digital Built Environment and Automation	23	10.7%	BIM; digital twins; AI-enabled built environment applications; automation and robotics; sensing/IoT; digital construction; integrated digital workflows

Research and Education	14	6.5%	Research and innovation; education and training; interdisciplinary research; knowledge exchange; emerging digital and sustainability methods
Sustainability, Energy and Climate Resilience	12	5.6%	Carbon and sustainability assessment; energy performance; whole-life carbon; lifecycle assessment; resource efficiency; climate resilience
Technology, Computing and Data Analytics	8	3.7%	HPC and cloud computing; AI/ML; data analytics; data management; computing infrastructure; software and digital platforms
Policy, Standards and Governance	5	2.3%	Policy and regulation; standards; data and information governance; compliance; institutional governance; strategic implementation
Industry Bodies and Professional Institutions	3	1.4%	Professional standards; industry guidance; skills and competency development; professional practice; sector engagement and knowledge dissemination

The evidence base is strongly grounded in organisations directly involved in built-asset delivery and operation. Construction and Project Management (21.0%), Design and Architecture (19.2%), Asset and Facilities Management (16.8%), and Engineering and Infrastructure (12.6%) collectively represented 69.6% of the sample. This provides substantial lifecycle coverage from design and project delivery through to infrastructure and asset operation, where compute-intensive workflows increasingly influence planning, delivery and management decisions. A further 10.7% represented Digital Built Environment and Automation, bringing capabilities in BIM, digital twins, AI, robotics, IoT and integrated digital workflows. Together, these five groups accounted for 80.3% of participating organisations, providing a strong empirical basis for using the built environment as the project pilot.

The remaining 19.7% provided strategically important complementary perspectives from Research and Education (6.5%), Sustainability, Energy and Climate Resilience (5.6%), Technology, Computing and Data Analytics (3.7%), Policy, Standards and Governance (2.3%), and Industry Bodies and Professional Institutions (1.4%). Although individually smaller, these groups broadened the evidence base beyond built-environment practice by contributing expertise in carbon and lifecycle assessment, HPC and cloud computing, data analytics, interoperability, research and innovation, standards, governance and professional implementation.

Collectively, the organisational profile provides a robust evidence base for examining sustainable federation as a socio-technical challenge involving technology, governance, organisational capability and sustainability, and underpins the subsequent analysis of technology maturity, sustainability measurement, implementation barriers and future NFCS priorities.

3.1.2 Geographical Distribution

Beyond sectoral diversity, the geographical distribution of participating organisations demonstrates that the NETZERO evidence base achieved UK-wide coverage while remaining strongly aligned with the national context of NFCS. As shown in Figure 2, organisations from England represented the largest share of the sample (73%), complemented by representation from Scotland (11%), Wales (8%) and Northern Ireland (3%). A further 5% of participating organisations were international.

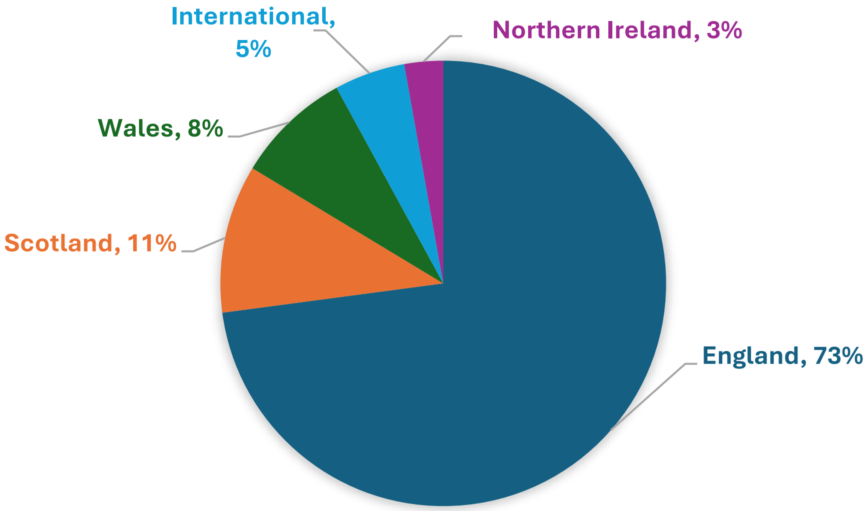

Figure 2. Geographical distribution of organisations represented in the NETZERO survey

The distribution provides representation across all four UK nations, which is important for a project intended to inform a national federated computing ecosystem. While the concentration in England reflects the larger scale of its built environment, research and digital infrastructure communities, participation from Scotland, Wales and Northern Ireland broadens the evidence beyond a single national or regional context. This is particularly relevant because organisational access to digital infrastructure, institutional capacity, research ecosystems and implementation conditions can vary geographically.

The 5% international representation provides an additional comparative perspective without diluting the project's UK focus. These organisations contribute experience from different institutional, digital infrastructure and sustainability contexts, supporting critical reflection on the transferability of the approaches developed through NETZERO. Importantly, the evidence base remains predominantly UK-derived (95%), ensuring that the findings and resulting recommendations are principally grounded in the organisational and policy environment relevant to NFCS.

Taken together with the sectoral diversity presented in Section 3.1.1, the geographical profile strengthens the evidence base in two complementary dimensions: sectoral breadth and national coverage. The sample captures organisations operating across different parts of the built environment and digital infrastructure ecosystem while also incorporating perspectives from across the UK. This provides an appropriate foundation for interpreting subsequent findings on organisational maturity, sustainability practices, governance, interoperability and readiness for sustainable federated computing.

The geographical distribution should nevertheless be interpreted as broad national coverage rather than a geographically proportional sample of the UK. Accordingly, the findings are intended to inform strategic NFCS development rather than comparative analysis between individual nations or regions.

Key Evidence

- 214 organisational responses across ten sectors established a broad evidence base for sustainability-aware federated computing.
- 80.3% of organisations represented construction, design, asset management, engineering/infrastructure and digital built environment sectors, providing strong coverage across the built-asset lifecycle.
- The remaining 19.7% contributed complementary research, sustainability, computing, governance and professional expertise relevant to all three NFCS pillars.
- 95% of organisations were UK-based, with representation across England (73%), Scotland (11%), Wales (8%) and Northern Ireland (3%), complemented by 5% international participation.
- The combined sectoral, capability and geographical diversity provides a robust evidence base for the subsequent analysis of organisational maturity, sustainability practices and readiness for sustainable federated computing.

3.2 Technology Awareness, Adoption and Organisational Readiness

Sustainable federated computing depends not only on access to advanced digital infrastructure but also on organisations having the knowledge, capability and readiness to adopt it effectively. The NETZERO survey therefore examined organisational maturity across three complementary dimensions: technology familiarity, technology adoption and readiness to implement carbon-aware compute governance. Collectively, these findings provide an evidence-based assessment of current organisational preparedness for sustainable federation and identify where capability gaps remain across the transition from awareness to implementation.

3.2.1 Technology Awareness and Familiarity

Organisations assessed their level of awareness and familiarity with twelve digital, sustainability and compute-intensive technologies and workflows using a five-point scale from Very Low to Very High. The results, presented in Figure 3, reveal substantial variation in organisational familiarity and a clear gradient from established built-environment information practices towards more advanced compute- and federation-dependent capabilities.

BIM and Information Modelling demonstrated the highest level of familiarity (RII = 78%), with 71% of organisations reporting High or Very High familiarity and only 10% reporting Low or Very Low familiarity. This confirms BIM as the most established digital capability within the organisational sample. A second tier comprised Lifecycle Carbon and Sustainability Assessment (RII = 65%), Large-Scale Geospatial and Environmental Data (RII = 65%), and Operational Energy and Building Performance Simulation (RII = 62%). These results indicate comparatively strong familiarity with sustainability assessment and data-intensive workflows already embedded within built-environment planning, design and performance evaluation.

Familiarity declined for more advanced digital applications. AI and Machine Learning achieved an RII of 58%, followed by Advanced Engineering Simulation and Modelling (54%), Digital Twins (53%), and Urban-Scale Modelling (51%). For Digital Twins, for example, only 26% reported High or Very High familiarity, compared with 50% reporting Low or Very Low familiarity. The results therefore suggest that visibility and sector interest in emerging technologies do not necessarily translate into widespread organisational familiarity.

The clearest maturity gap occurs in technologies most closely associated with automation, distributed data and advanced computing infrastructure. Automation and Robotics (RII = 46%), Data Federation (45%), DPPs and Lifecycle Data (43%), and particularly HPC and Cloud Computing (38%) recorded the lowest familiarity. For HPC and Cloud Computing, 74% of organisations reported Low or Very Low familiarity, while only 12% reported High or Very High familiarity. Similarly, 63% reported Low or Very Low familiarity with Data Federation, compared with only 16% at High or Very High levels.

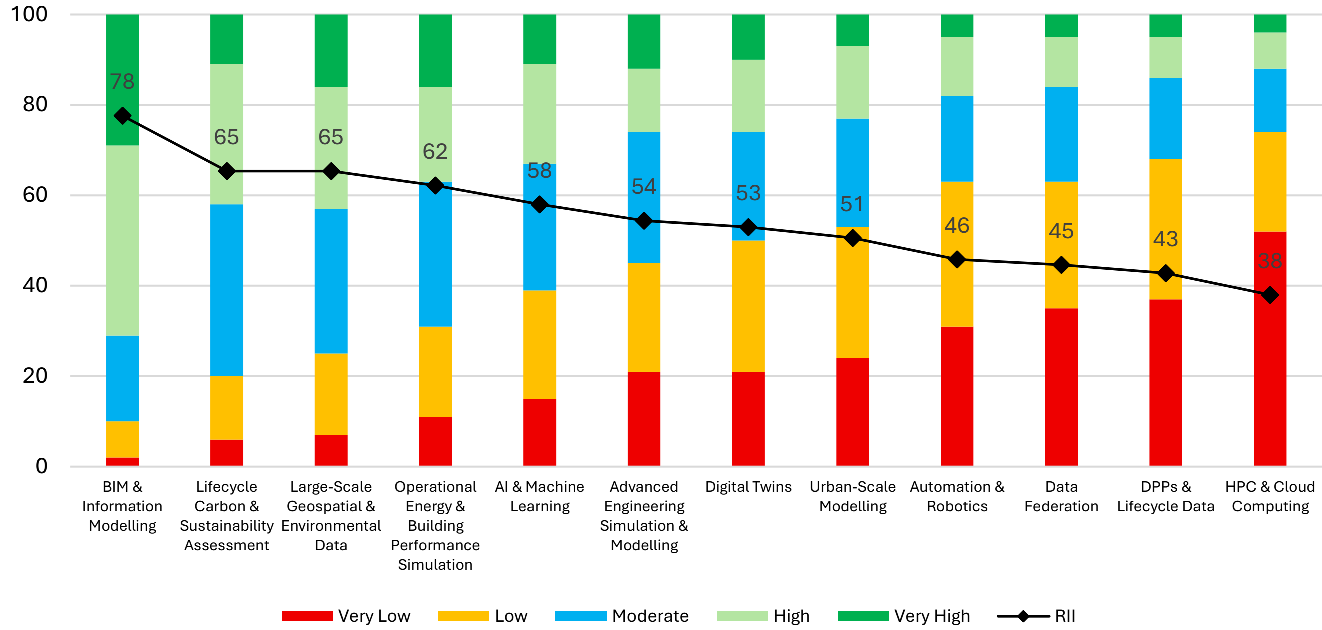

Figure 3. Organisational awareness and familiarity with digital and compute-intensive technologies and workflows

Taken together, the findings demonstrate that organisational familiarity declines progressively from well-established built-environment applications towards the data federation and advanced computing capabilities required for sustainable federation. This provides an important baseline for examining whether familiarity is reflected in actual organisational adoption, which is explored in the following section.

3.2.2 Technology Adoption

While familiarity indicates organisational awareness, it does not necessarily reflect operational implementation. The survey therefore assessed the extent to which organisations currently utilise the same twelve digital, sustainability and compute-intensive technologies examined in Section 3.2.1. As shown in Figure 4, adoption follows a clear maturity gradient, with established built-environment applications substantially more embedded in practice than advanced modelling, automation, federation and computing infrastructure.

BIM and Information Modelling showed the highest level of adoption (RII = 76%), with 68% of organisations reporting Extensive or High utilisation and only 14% reporting no or limited utilisation. Lifecycle Carbon and Sustainability Assessment (RII = 67%) and Large-Scale Geospatial and Environmental Data (RII = 65%) also demonstrated relatively mature adoption, with 46% and 41%, respectively, reporting extensive or high utilisation. Operational Energy and Building Performance Simulation (RII = 59%) and AI and Machine Learning (RII = 57%) occupied an intermediate position, indicating growing but not yet consistently embedded organisational use.

Adoption declined substantially for more specialised and emerging digital workflows. Advanced Engineering Simulation and Modelling achieved an RII of 50%, while Digital Twins fell to 44%, with 45% of organisations reporting no utilisation and only 19% reporting extensive or high utilisation. Automation and Robotics (RII = 40%) showed an even greater implementation gap, with 57% reporting no current utilisation.

The lowest adoption occurred among capabilities most directly associated with large-scale data integration and advanced computing. Data Federation (RII = 34%), Urban-Scale Modelling (33%), DPPs and Lifecycle Data (30%), and HPC and Cloud Computing (29%) were all weakly embedded in current organisational practice. Notably, 69% reported no utilisation of Data Federation, 72% no utilisation of DPPs and Lifecycle Data, and 76% no utilisation of HPC and Cloud Computing. Only 11%, 6% and 5%, respectively, reported extensive or high utilisation of these capabilities.

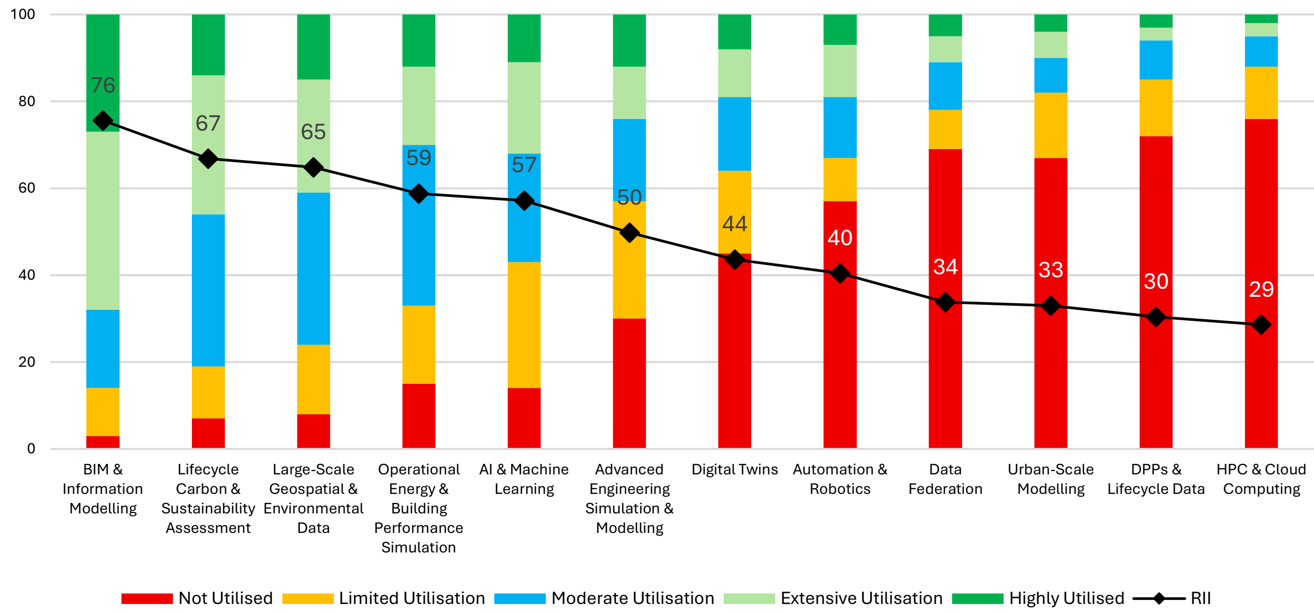

Figure 4. Organisational adoption of digital and compute-intensive technologies and workflows

Comparison with the familiarity results in Section 3.2.1 indicates that awareness has not consistently translated into operational implementation, particularly for infrastructure-dependent technologies such as Data Federation, HPC/Cloud Computing and DPPs. This suggests that, beyond improving infrastructure availability, future NFCS development will also require implementation support that helps organisations convert emerging awareness into routine operational practice.

3.2.3 Organisational Readiness

Technology familiarity and adoption provide important indicators of digital maturity but do not necessarily reflect organisational preparedness to implement sustainability-aware federation. The survey therefore assessed organisations' readiness to adopt national carbon-aware compute governance recommendations. As shown in Figure 5, the results reveal a substantial readiness deficit.

Sixty-five per cent of organisations reported that they were Not Ready, with a further 19% only Slightly Ready. Therefore, 84% of the organisational sample demonstrated low readiness, compared with only 8% reporting that they were Ready or Highly Ready. The remaining 8% considered themselves Moderately Ready. This distribution indicates that preparedness for carbon-aware governance remains at an early stage across much of the organisational landscape.

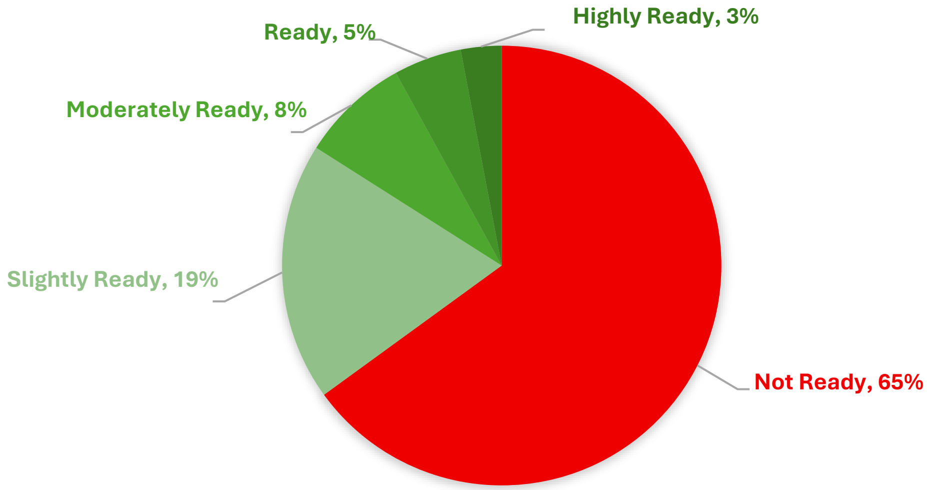

Figure 5. Organisational readiness for carbon-aware compute governance

Considered alongside the familiarity and adoption findings, the readiness results indicate that technological maturity alone is insufficient to support sustainable federation. Although many organisations have adopted established digital practices, organisational preparedness for carbon-aware compute governance remains limited.

The readiness deficit is therefore not simply a consequence of low technology adoption. Rather, it indicates a broader socio-technical capability gap involving governance structures, sustainability and carbon-aware computing literacy, digital infrastructure capability, organisational processes and implementation guidance.

These findings indicate that many organisations are progressing with digitalisation at the application level while remaining less prepared for the governance, organisational and infrastructure changes required for sustainable federation. For NFCS, this highlights the importance of complementing infrastructure investment with governance frameworks, capability development and practical implementation support.

Key Evidence

- A clear application-infrastructure maturity gap emerged: BIM showed the highest familiarity and adoption (RII = 78% and 76%), compared with Data Federation (45% and 34%) and HPC/Cloud Computing (38% and 29%).

- Adoption declined markedly for emerging and infrastructure-dependent capabilities, with 69% reporting no use of Data Federation, 72% no use of DPPs and Lifecycle Data, and 76% no use of HPC/Cloud Computing.
- Organisational readiness remained particularly limited: 65% were Not Ready and 19% Slightly Ready to adopt national carbon-aware compute governance, meaning 84% demonstrated low readiness.
- The findings demonstrate that improving federated infrastructure alone will be insufficient without parallel investment in organisational capability, governance and implementation support.

3.3 Sustainability Measurement and KPI Priorities

Effective sustainable federated computing requires consistent, measurable and decision-useful performance indicators. The NETZERO survey therefore examined organisational sustainability measurement across four complementary dimensions: current KPI use, decision-usefulness, future NFCS measurement priorities and measurement feasibility. Together with stakeholder co-creation and Rapid Delphi validation, these findings provide the evidence base for identifying measurement gaps and developing a harmonised National Sustainability KPI Framework for NFCS.

3.3.1 Current Use and Integration of Sustainability KPIs

The survey examined the extent to which organisations currently use and integrate sustainability KPIs across digital and compute-intensive workflows. Twenty indicators spanning energy and carbon, data and interoperability, governance and security, resource efficiency, circularity and infrastructure impacts were assessed on a five-level scale from Not Used to Fully Integrated and Optimised. As shown in Figure 6, the results reveal substantial variation in KPI maturity, with established energy and carbon measures considerably more embedded than indicators relating to federation, governance, dynamic compute optimisation and infrastructure resource impacts.

Renewable Energy Use was the most mature KPI (RII = 79%), with 70% of organisations reporting widespread or fully integrated use. This was followed by Compute Energy Consumption (RII = 73%; 62% widespread/fully integrated) and Operational Energy Use (RII = 71%; 56%). Carbon assessment also showed comparatively established use, although at lower levels: Embodied Carbon achieved an RII of 67%, Whole-Life Carbon 64%, and Net-Zero Progress 63%. Collectively, these findings indicate that organisational sustainability measurement remains strongest where established energy, carbon and net-zero reporting practices already exist.

A middle tier of indicators reflects emerging attempts to connect sustainability measurement with digital infrastructure and data management. Data Storage Energy/Carbon Intensity (RII = 61%), Data Quality Score (60%) and Compute Carbon Intensity (59%) showed moderate levels of integration. However, Data Integration and Interoperability Score (55%) and Open Data Standards Adoption (54%) were less established, indicating that organisations are beginning to measure digital sustainability impacts but have yet to embed equivalent measures of data readiness and interoperability consistently.

Governance, resource efficiency and circularity indicators showed a more pronounced maturity gap. Data Governance and Secure Information Exchange (RII = 49%), Cybersecurity Maturity (47%), Compute Resource Utilisation/Efficiency (46%) and Material Circularity/Recovery (45%) all achieved RII values below 50%, indicating comparatively limited organisational integration.

This is significant because these indicators address conditions required for secure, resource-efficient and interoperable federation rather than conventional project-level environmental performance alone.

The least mature measures were those associated with dynamic and infrastructure-level sustainability management. Carbon-Aware Workload Scheduling achieved an RII of only 40%, while Real-Time Data Monitoring Coverage scored 39%. Computing Infrastructure Water Consumption/Intensity was the least established KPI (RII = 31%), with 71% of organisations reporting no current use and only 7% reporting widespread or fully integrated use. Carbon-aware workload scheduling was similarly immature, with 47% reporting no use and only 12% indicating widespread or fully integrated application.

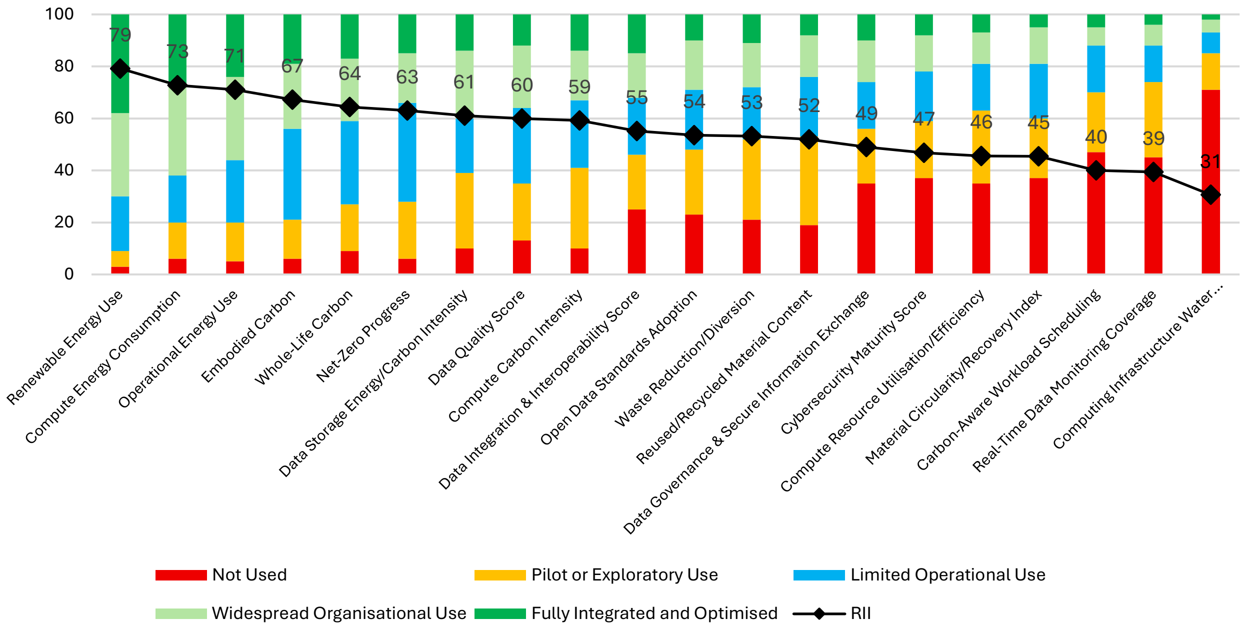

Figure 6. Current organisational use and integration of sustainability KPIs

Taken together, the findings demonstrate that organisational sustainability measurement remains strongest for established energy and carbon indicators, while measures relating to digital infrastructure, interoperability and compute-level sustainability are considerably less embedded. This provides an important baseline for assessing whether the indicators currently used by organisations are also sufficiently clear and useful to support decision-making, which is examined in the following section.

3.3.2 Sustainability KPIs Effectiveness and Decision-Usefulness

While current KPI use indicates the maturity of organisational measurement practices, it does not necessarily reflect whether those indicators support effective decision-making. The survey therefore assessed the clarity and decision-usefulness of the same twenty sustainability KPIs using a five-point scale ranging from Very Unclear and Difficult to Use to Very Clear and Highly Usable. As shown in Figure 7, the results reveal substantial variation between established sustainability measures and emerging indicators associated with digital infrastructure and federated computing.

Established energy indicators demonstrated the greatest decision-readiness. Renewable Energy Use achieved the highest RII (82%), with 78% of organisations rating it Clear/Very Clear and usable. This was followed by Compute Energy Consumption (RII = 77%; 69% Clear/Very Clear) and Operational Energy Use (RII = 75%; 65%). Established carbon indicators were also comparatively well understood, including Embodied Carbon (RII = 69%), Whole-Life Carbon (66%) and Net-Zero Progress (64%). These findings suggest that organisations can more readily interpret indicators supported by established measurement methodologies, reporting conventions and sustainability practice.

Clarity declined for indicators connecting sustainability with data and computing infrastructure. Data Storage Energy/Carbon Intensity (RII = 63%), Data Quality Score (62%) and Compute Carbon Intensity (61%) occupied an intermediate position. Measures of Data Integration and Interoperability (58%) and Open Data Standards Adoption (57%) were less decision-ready, indicating greater uncertainty in translating data and federation characteristics into consistent performance measures.

A more substantial usability gap emerged for governance, resource-efficiency and circularity indicators. Data Governance and Secure Information Exchange achieved an RII of 54%, while Cybersecurity Maturity and Compute Resource Utilisation/Efficiency both scored 52%, and Material Circularity/Recovery scored 51%. These results suggest that organisations recognise these dimensions but lack equally mature or standardised approaches for interpreting them within sustainability-related digital infrastructure decisions.

The lowest clarity was associated with emerging infrastructure-level sustainability indicators. Carbon-Aware Workload Scheduling and Real-Time Data Monitoring Coverage both achieved an RII of 46%. For carbon-aware scheduling, 62% rated the indicator unclear or very unclear, while only 20% considered it clear or very clear. Computing Infrastructure Water Consumption/Intensity was the least decision-ready indicator (RII = 36%), with 76% reporting low or very low clarity and only 12% considering it clear or highly usable.

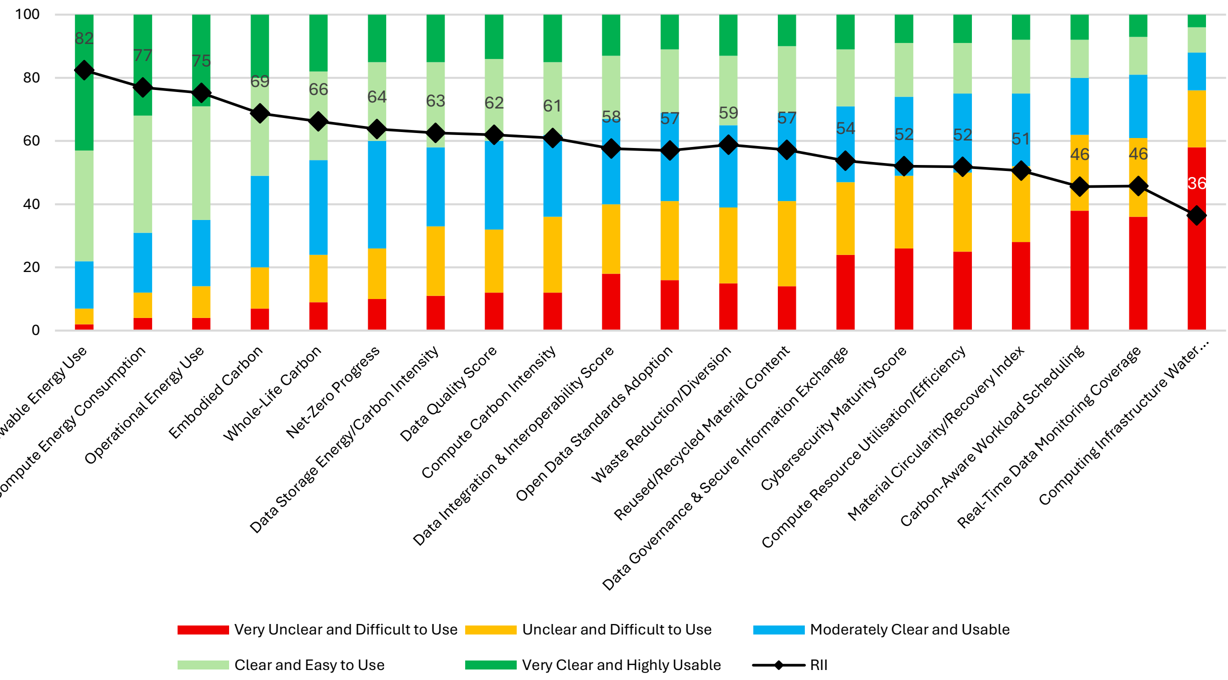

Figure 7. Clarity and decision-usefulness of sustainability KPIs for digital and compute-intensive workflows

Comparison with the current KPI utilisation results indicates that indicators already embedded in organisational practice are generally those organisations also find easiest to interpret and apply. In contrast, emerging compute-level and infrastructure-related measures remain both less widely used and less decision-ready, highlighting the need for clearer definitions, standardised methodologies and implementation guidance before they can consistently support operational decision-making.

3.3.3 Sustainability KPI Priorities for NFCS

Having examined current measurement practice and the decision-usefulness of existing indicators, the survey next explored which sustainability KPIs organisations believe should be prioritised within a future NFCS performance framework. Organisations rated eleven KPIs across operational performance, resource and carbon efficiency, interoperability, governance, policy readiness and inclusion. As shown in Figure 8, the results demonstrate strong support for a multidimensional performance framework extending beyond conventional environmental metrics.

Operational performance indicators received the highest priority. Average Job Turnaround Time achieved the highest RII (90%), with 91% of organisations rating it High or Very High importance. Resource Utilisation Rate and Infrastructure Uptime both achieved an RII of 88%, with 89% and 87%, respectively, rated High or Very High. This indicates that organisations view sustainability within the context of efficient, reliable and responsive infrastructure, rather than as an environmental objective isolated from service performance.

Interoperability and environmental efficiency formed a second group of high-priority indicators. Federated Data Interoperability Score achieved an RII of 86%, with 85% rating it High or Very High, demonstrating the importance of effective data exchange across federated environments. Power Usage Effectiveness (RII = 85%), Renewable Energy Utilisation Ratio (85%), Low-Carbon Incentive Adoption Rate (84%), and Carbon Intensity per Federated Compute Job (82%) also received strong support. Collectively, these findings show that organisations expect NFCS sustainability measurement to capture both infrastructure efficiency and the carbon implications of compute operations.

Governance and implementation readiness were also considered important. Data Governance Alignment Rate achieved an RII of 79%, while the Policy Implementation Readiness Index achieved 78%. Their inclusion among highly rated indicators reinforces the wider project finding that sustainable federation depends not only on technical performance but also on organisations' ability to operate within consistent governance and policy arrangements.

Inclusive Participation Rate was the only indicator receiving substantially lower support (RII = 55%), with 26% rating it High or Very High compared with 42% rating it Low or Very Low. This does not necessarily imply that inclusion is unimportant; rather, organisations appear to assign greater immediate measurement priority to operational efficiency, interoperability, carbon performance and governance readiness within an NFCS sustainability framework.

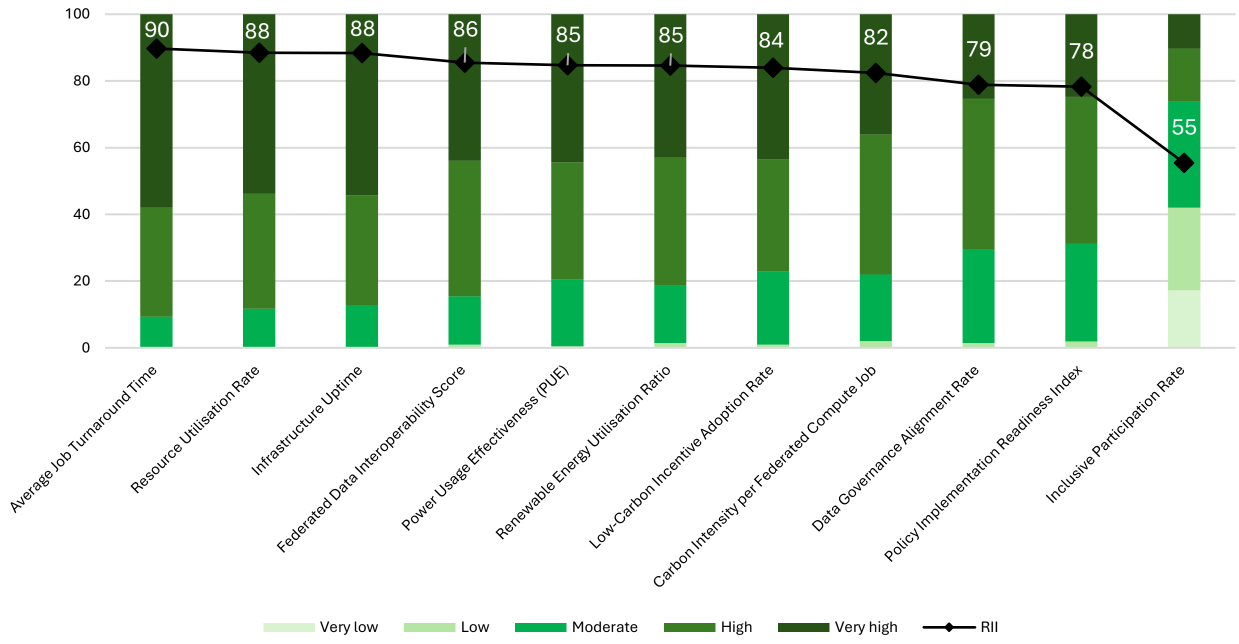

Figure 8. Importance of sustainability KPIs for NFCS

Collectively, the findings indicate that organisations view sustainable federation as a multidimensional challenge encompassing operational performance, interoperability, environmental efficiency and governance, rather than carbon reduction alone. These priorities provide the basis for assessing which indicators are both strategically important and practically measurable.

3.3.4 Feasibility of KPI Measurement

Identifying priority KPIs is insufficient unless they can be measured reliably and consistently across federated environments. Organisations therefore assessed the feasibility of measuring the eleven proposed NFCS sustainability KPIs. As shown in Figure 9, most indicators were considered practically measurable, although feasibility declined for more complex carbon, governance, policy and inclusion measures.

Operational performance indicators demonstrated the highest measurement feasibility. Average Job Turnaround Time achieved the highest RII (90%), with 91% of organisations rating it Feasible or Highly Feasible. Resource Utilisation Rate and Infrastructure Uptime both achieved an RII of 88%, with 87% and 86%, respectively, considering them Feasible or Highly Feasible. These results indicate that indicators derived from established infrastructure monitoring and operational data could be implemented relatively readily within NFCS.

Environmental and interoperability indicators also demonstrated strong feasibility. Power Usage Effectiveness (RII = 82%) was considered Feasible or Highly Feasible by 77% of organisations, while Federated Data Interoperability Score and Renewable Energy Utilisation Ratio both achieved an RII of 80%, with 75% and 73%, respectively, reporting high feasibility. Low-Carbon Incentive Adoption Rate (RII = 78%) also showed relatively strong measurement potential.

Feasibility declined for indicators requiring more complex data integration or organisational assessment. Carbon Intensity per Federated Compute Job achieved an RII of 73%, with 61% considering it Feasible or Highly Feasible, while Data Governance Alignment Rate and Policy

Implementation Readiness Index both achieved an RII of 70%. These indicators remain measurable but are likely to require greater methodological standardisation, consistent data availability and agreed assessment procedures across federated organisations.

Inclusive Participation Rate showed the lowest feasibility (RII = 59%), with only 35% rating it Feasible or Highly Feasible and 36% considering it Difficult or Very Difficult to measure. This suggests that community and inclusion outcomes may require clearer definitions, consistent participation data and agreed reporting approaches before federation-wide implementation.

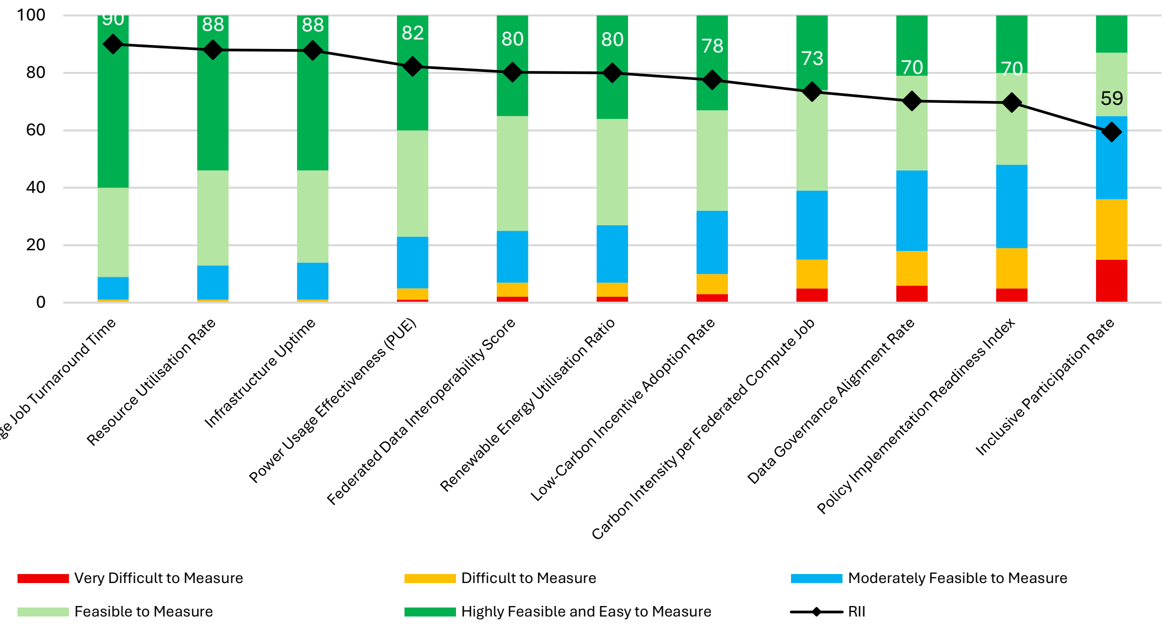

Figure 9. Feasibility of sustainability KPI measurement across NFCS

Overall, the findings demonstrate strong alignment between stakeholder priorities and measurement feasibility, particularly for operational and infrastructure indicators. More complex governance, carbon and inclusion measures remain feasible but are likely to require greater methodological standardisation and organisational capability before widespread implementation. These findings provide the evidence base for developing a phased National Sustainability KPI Framework.

3.3.5 Evidence for a Harmonised National KPI Framework

The evidence presented across Sections 3.3.1–3.3.4 demonstrates a consistent need for a coordinated national approach to sustainability measurement within NFCS. Standardised KPI definitions across organisations achieved an RII of 94%, while explicit linkage between KPIs and net-zero targets also achieved an RII of 94%, indicating strong stakeholder consensus on both measurement consistency and strategic alignment.

Collectively, the findings demonstrate that organisations require sustainability measurement extending beyond conventional energy and carbon reporting to encompass compute-level performance, interoperability, governance and operational readiness. While stakeholder priorities were generally considered measurable, implementation maturity varies, supporting a phased approach to KPI adoption.

Triangulation of these survey findings with stakeholder co-creation and Rapid Delphi validation resulted in five evidence-derived sustainability domains:

- Domain A: Carbon & Resource-Aware Federated Computing
- Domain B: Data Interoperability & Federation Readiness
- Domain C: Governance, Policy & Regulatory Alignment
- Domain D: Community, Equity & Capacity Building
- Domain E: Operational Performance & Infrastructure Efficiency

Together, these domains respond to the identified gap between current measurement practice and the broader performance requirements of sustainable federation. They extend sustainability assessment beyond conventional environmental reporting to incorporate the carbon and resource impacts of computing, data interoperability, governance, organisational capability and infrastructure performance.

The evidence therefore supports a harmonised framework combining common terminology, standardised indicators and consistent measurement approaches, while recognising differences in current measurement feasibility. This provides a basis for phased implementation, with mature and readily measurable indicators introduced early and more complex measures progressively enabled through improved data availability, methodological standardisation and organisational capability.

These five domains were subsequently operationalised through the 124-KPI National Sustainability KPI Framework presented in Section 4, where the framework architecture, KPI categories and validation results are discussed in detail.

Key Evidence

- Current measurement remains strongest for established indicators, particularly Renewable Energy Use (RII = 79%), Compute Energy Consumption (73%) and Operational Energy Use (71%), while Carbon-Aware Workload Scheduling (40%) and Computing Infrastructure Water Consumption/Intensity (31%) remain weakly integrated.
- KPI decision-usefulness follows a similar pattern, ranging from Renewable Energy Use (RII = 82%) to Carbon-Aware Workload Scheduling (46%) and Computing Infrastructure Water Consumption/Intensity (36%), demonstrating lower measurement maturity for emerging infrastructure-level sustainability indicators.
- NFCS priorities extend beyond carbon: Average Job Turnaround Time (RII = 90%), Resource Utilisation and Infrastructure Uptime (both 88%), Federated Data Interoperability (86%), and Carbon Intensity per Federated Compute Job (82%) received strong support.
- Priority KPIs were generally considered measurable, particularly operational indicators (RII = 88-90%); however, feasibility was lower for Carbon Intensity per Federated Compute Job (73%), governance and policy indicators (70%), and Inclusive Participation (59%), supporting phased KPI implementation.
- Strong support for standardised KPI definitions and explicit alignment with net-zero targets (RII = 94% each) provides clear evidence for nationally harmonised sustainability measurement.

- Triangulation of survey, co-creation and Rapid Delphi evidence informed the five sustainability domains underpinning the 124-KPI National Sustainability KPI Framework presented in Section 4.

3.4 Challenges and Enablers of Sustainable Federation

The successful transition to sustainable federated computing depends not only on technological capability but also on organisations' ability to overcome economic, governance, data and organisational barriers. The NETZERO survey therefore examined both the principal implementation challenges and the factors organisations consider most important for overcoming them. Together, these findings identify the conditions required to support effective and scalable adoption across NFCS.

3.4.1 Key Challenges and Barriers

The survey assessed eight challenges that may constrain the transition towards sustainability-aware federated computing. As shown in Figure 10, the results reveal a clear hierarchy of barriers, with economic uncertainty, governance and policy limitations emerging as the most significant constraints, followed by data and interoperability challenges. Skills and KPI harmonisation were perceived as comparatively less severe, although they remain relevant implementation barriers.

Economic considerations represented the strongest challenges. Uncertainty about the cost implications of carbon-aware scheduling achieved the highest RII (86%), with 83% of organisations rating it High or Very High. Similarly, the high cost of sustainable compute achieved an RII of 84%, with 80% assigning it High or Very High importance. The close ranking of these factors indicates that the challenge is not limited to the absolute cost of sustainable computing; organisations also lack sufficient evidence and predictability regarding the financial consequences of changing workload allocation or scheduling according to carbon and energy conditions.

Governance and policy barriers were almost equally significant. Unclear governance responsibilities achieved an RII of 83%, with 78% rating it High or Very High, while limited policy guidance achieved an RII of 82%, with 75% reporting High or Very High significance. This demonstrates that uncertainty around accountability, institutional responsibilities and policy expectations represents a substantial constraint on organisational participation in sustainable federation. Importantly, these barriers closely follow cost-related concerns, indicating that institutional clarity is a central implementation requirement rather than a secondary governance consideration.

Data availability and interoperability formed a second tier of challenges. Incompatible data standards achieved an RII of 76%, with 62% rating the challenge High or Very High, while limited carbon data for compute jobs achieved an RII of 73%, with 54% assigning High or Very High significance. These findings indicate that organisations face practical difficulties in exchanging comparable information across systems and obtaining sufficiently granular carbon data to support workload-level sustainability assessment. Such limitations can constrain benchmarking, interoperability and evidence-based carbon-aware compute decisions across federated services.

Capability and measurement barriers received lower, but still meaningful, ratings. The skills gap in carbon-aware computing achieved an RII of 58%, while lack of harmonised KPIs achieved 56%. In both cases, responses were more dispersed, with 30% and 27%, respectively, rating these challenges High or Very High. This suggests greater variation in organisational capability and existing measurement practice than for the more consistently recognised economic, governance and policy barriers.

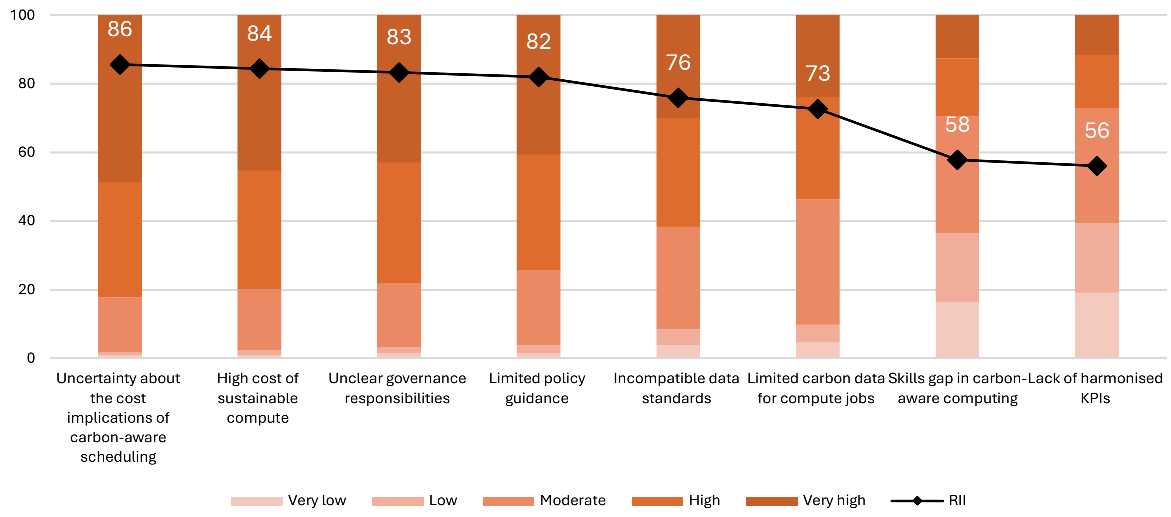

Figure 10. Key challenges and barriers to sustainable federated computing

Overall, the findings indicate that the principal barriers extend beyond technology itself, with economic uncertainty, governance and policy limitations emerging as the most significant constraints on sustainable federation. These findings provide the context for examining which interventions organisations believe would be most effective in reducing these barriers.

3.4.2 Factors Enabling Barrier Reduction

Having identified the principal implementation barriers, the survey next examined the interventions organisations considered most important for overcoming them. As shown in Figure 11, all fifteen enabling factors received strong support (RII = 81–91%), indicating broad consensus that successful sustainable federation requires coordinated action across governance, interoperability, measurement, capability and infrastructure.

Data interoperability and governance emerged as the strongest enabling conditions. Improved data interoperability and common data standards achieved the highest RII (91%), with 92% of organisations rating it Important or Very Important. This was closely followed by clear data governance, ownership and security frameworks (RII = 90%; 91% Important/Very Important) and standardised KPI definitions across organisations (RII = 90%; 91%). These findings demonstrate strong demand for common technical and institutional foundations that enable organisations to exchange, govern and assess data consistently across federated environments.

Economic evidence and strategic alignment were similarly important. Demonstrated cost and carbon reduction benefits achieved an RII of 89%, with 90% rating it Important or Very Important, while clear linkage between KPIs and net-zero/carbon-reduction targets also achieved an RII of 89%, with 89% assigning high importance. Clear business cases for investment in sustainable computing (RII = 87%) further reinforce the importance of demonstrating both environmental and economic value. These results directly complement the barriers identified in Section 3.4.1, where cost uncertainty and the high cost of sustainable compute were the two highest-ranked challenges.

Organisational capability and collaborative infrastructure also received consistently strong support. Improved digital and sustainability skills, shared and secure federated data environments, and training and capacity-building programmes each achieved an RII of 88%. In each case, approximately 87-88% of organisations rated the factor Important or Very Important. Automated data validation and quality-assurance processes (RII = 87%) were similarly prioritised, demonstrating that effective federation requires not only technical access but also trusted data, organisational capability and mechanisms for maintaining information quality.

Technology integration and infrastructure access remained important, although they ranked below interoperability, governance and capability factors. Integration with BIM and Digital Twin platforms achieved an RII of 84%, followed by better access to shared computing infrastructure (82%), policy and regulatory alignment across the sector (82%), accessible low-carbon computing and HPC resources (81%), and alignment of incentives across the project and asset lifecycle (81%). Their consistently high scores nevertheless demonstrate that organisations view existing digital platforms, shared computing capacity, regulatory coordination and aligned incentives as important components of an enabling ecosystem.

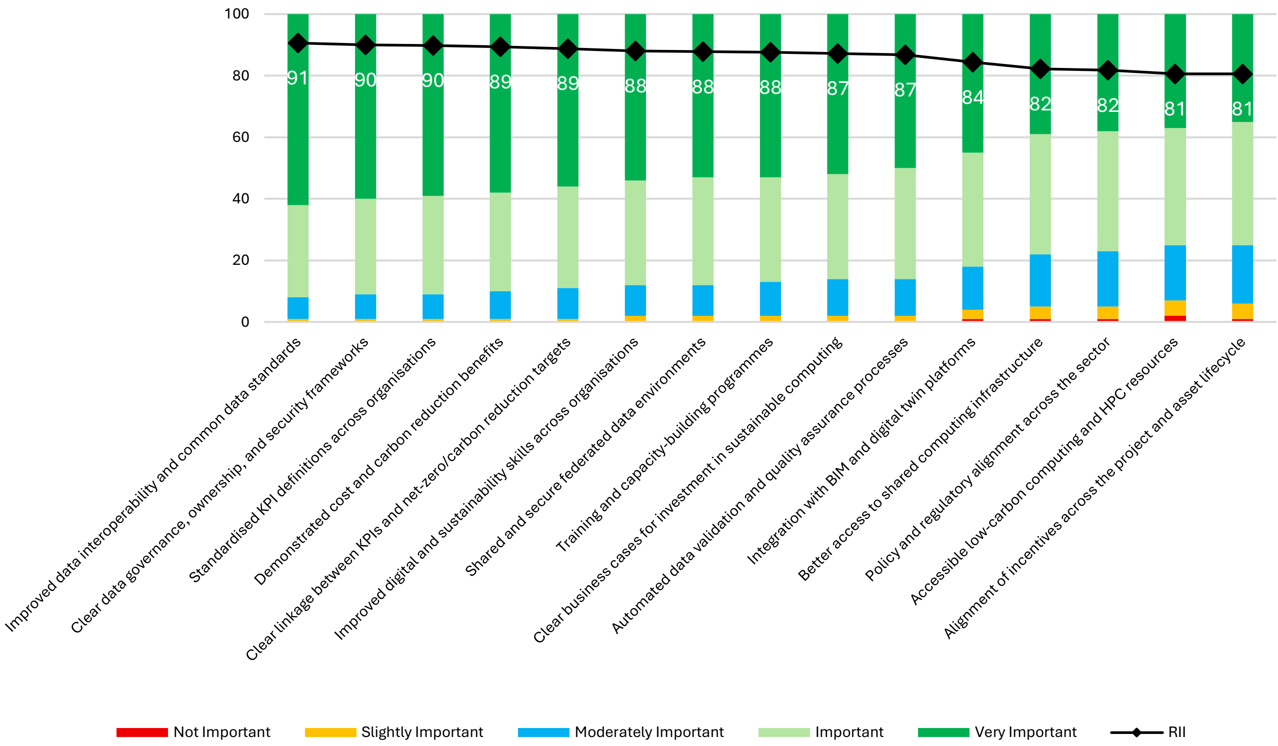

Figure 11. Factors enabling the reduction of barriers to sustainable federated computing

Collectively, these findings demonstrate that organisations favour coordinated interventions spanning governance, interoperability, economic evidence, workforce capability and infrastructure rather than isolated technical solutions. The relationship between the identified barriers and proposed enabling factors is synthesised in the following section.

3.4.3 Integrated Barrier-Enabler Assessment

The evidence demonstrates that sustainable federation is primarily a socio-technical and institutional challenge rather than an infrastructure issue alone. While organisations identified economic uncertainty, governance ambiguity and data interoperability as the principal barriers, they consistently prioritised improved interoperability, trusted governance, standardised measurement and stronger economic evidence as the most effective mechanisms for overcoming them.

The close alignment between identified barriers and proposed enabling factors increases confidence that the recommended interventions respond directly to organisational implementation needs rather than isolated stakeholder preferences. Notably, although KPI harmonisation was not viewed as the most immediate barrier, organisations nevertheless regarded standardised KPI definitions as an essential foundation for future federation.

No single intervention is sufficient. Instead, the findings support a coordinated implementation approach integrating governance, interoperability, measurement, organisational capability, economic justification and infrastructure development. These priorities provide the foundation for the future NFCS capability requirements presented in Section 3.5.

Key Evidence

- Economic and institutional barriers dominated, led by uncertainty over carbon-aware scheduling costs (RII = 86%), high sustainable compute costs (84%), unclear governance responsibilities (83%) and limited policy guidance (82%).
- Data and interoperability constraints remained substantial, particularly incompatible data standards (RII = 76%) and limited carbon data for compute jobs (73%), restricting consistent federation and carbon-aware decision-making.
- Organisations strongly prioritised interoperability and common data standards (RII = 91%), clear governance, ownership and security frameworks (90%), and standardised KPI definitions (90%) as the leading conditions for reducing barriers.
- Economic evidence was critical to adoption, with demonstrated cost and carbon reduction benefits (RII = 89%) and clear investment business cases (87%) strongly supported.
- The consistently high ratings across all enabling factors (RII ≥ 81%) demonstrate that successful sustainable federation requires coordinated organisational, technical and governance interventions rather than isolated infrastructure improvements.

3.5 Future Requirements and Priorities

The evidence presented in Sections 3.2–3.4 converges on five strategic capability requirements for advancing sustainable federated computing: trusted governance, harmonised sustainability measurement, workforce capability, decision-support and interoperability. Together, these priorities provide an evidence-based roadmap for strengthening organisational readiness and supporting the wider adoption of sustainability-aware federation across NFCS. Their implementation is underpinned by a cross-cutting requirement to demonstrate economic viability and cost-carbon benefits, reflecting the prominence of economic uncertainty throughout the evidence base.

3.5.1 Strengthening Governance and Trusted Collaboration

Trusted governance should be a foundational priority for future NFCS development. The evidence indicates that uncertainty around governance responsibilities remains a significant implementation constraint (RII = 83%), while clear data governance, ownership and security frameworks are regarded as essential enabling conditions (RII = 90%). Future NFCS should therefore establish consistent governance arrangements covering accountability, data stewardship, security, regulatory compliance and trusted cross-organisational collaboration.

3.5.2 Harmonising Sustainability Measurement and Standards

Harmonised sustainability measurement is essential for enabling consistent performance assessment across federated environments. Strong stakeholder support for standardised KPI definitions and explicit alignment with net-zero targets (RII = 94%) demonstrates the need for common terminology, KPIs and reporting approaches that support benchmarking, comparison and transparent sustainability assessment across NFCS.

3.5.3 Building Workforce Capability and Community Capacity

Building organisational capability should accompany future infrastructure development. Given the limited familiarity and adoption of Data Federation and HPC/Cloud Computing identified in Section 3.2, together with strong support for skills development and capacity-building (RII = 88%), NFCS should provide targeted training, implementation guidance, onboarding resources and communities of practice to strengthen organisational capability and participation.

3.5.4 Supporting Sustainability Assessment and Decision-Support

Sustainable federation will require decision-support capabilities that help organisations interpret increasingly complex sustainability, governance and infrastructure information. The evidence shows that while established sustainability indicators are generally well understood, emerging compute-level indicators remain considerably less decision-ready. NFCS should therefore support integrated sustainability assessment and decision-support tools capable of evaluating alternative computing and federation options using harmonised evidence.

3.5.5 Improving Interoperability Across Federated Services

Interoperability emerged consistently across the evidence as both a barrier and a strategic priority. Incompatible data standards achieved an RII of 76%, while the Federated Data Interoperability Score was strongly prioritised (RII = 86%). Most importantly, improved data interoperability and common data standards was the highest-rated barrier-reduction factor (RII = 91%). Future NFCS development should therefore strengthen technical, semantic and organisational interoperability through common standards, metadata practices, shared terminology, FAIR data principles and interoperable reporting.

Figure 12. Evidence-based priorities for sustainable federated computing

These five priorities are mutually reinforcing. Harmonised measurement and interoperability establish the technical and information foundations; governance provides trust and accountability; workforce capability enables organisational adoption; and decision-support translates these capabilities into informed operational decisions. Collectively, they define the strategic capability requirements for transitioning from fragmented organisational practices to coordinated, sustainability-aware federated computing across NFCS.

Key Evidence

- Governance: unclear governance responsibilities were a major barrier (RII = 83%), while clear governance, ownership and security frameworks were strongly supported (90%).
- Measurement: standardised KPI definitions and alignment with net-zero targets received exceptionally strong support (RII = 94% each).
- Capability: improved digital and sustainability skills and training/capacity building were strongly prioritised (RII = 88% each).
- Interoperability: incompatible standards remained a substantial barrier (RII = 76%), while improved interoperability/common standards was the highest-rated enabling factor (91%).
- Decision-support: Variation in the usability of emerging compute-level sustainability indicators highlights the need for practical tools that translate harmonised sustainability evidence into operational decision-making.

3.6 Evidence Synthesis

The organisational evidence generated through the NETZERO project consistently demonstrates that sustainable federated computing is not solely a technological challenge but a broader socio-technical transformation requiring coordinated advances in organisational capability, sustainability measurement, governance, interoperability, workforce development and decision-support. Rather than representing independent findings, the evidence converges on a common conclusion: sustainable federation depends on the simultaneous development of technical, organisational and governance capabilities across the NFCS ecosystem.

The evidence further demonstrates that these requirements are highly interdependent. Progress in one area is unlikely to achieve sustainable federation without complementary advances in the others. For example, improvements in infrastructure capability require trusted governance and interoperable data; harmonised sustainability measurement depends on common standards and organisational capability; and carbon-aware decision-making relies on robust evidence, practical implementation guidance and organisational readiness. Triangulation of survey findings with stakeholder engagement, co-creation, Rapid Delphi validation and SustainFed evaluation translated these interconnected findings into a coherent set of project outputs, strategic recommendations and implementation priorities.

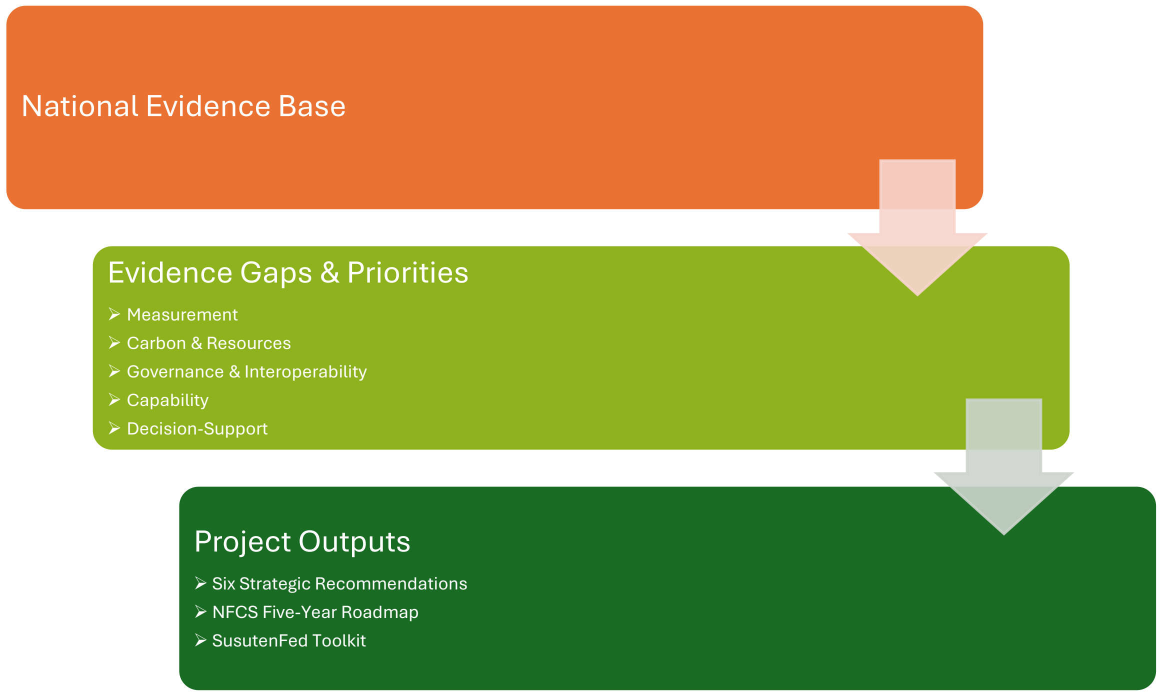

Figure 13. Evidence-to-Action Pathway for Sustainable Federated Computing

Table 4. Evidence synthesis and project response

Evidence Theme	Principal Evidence / Finding	Project Response
Stakeholder Landscape	Evidence from 214 organisations across ten sectors, complemented by workshops, co-creation, Rapid Delphi and platform validation, provided multidisciplinary perspectives across the NFCS Community, Technology and Governance dimensions.	Organisational evidence base informing the development, validation and prioritisation of all project outputs and recommendations.
Technology Maturity & Organisational Readiness	BIM showed the highest familiarity/adoption (RII = 78%/76%), while Data Federation (45%/34%) and HPC/Cloud Computing (38%/29%) remained substantially less mature. 84% of organisations were Not Ready or only Slightly Ready for national carbon-aware compute governance.	Evidence-informed capacity-building strategy and Recommendation 5: Build Capacity and Inclusive Participation.
Sustainability Measurement	Current measurement and usability were strongest for established energy indicators but substantially weaker for emerging compute-level measures. Stakeholders strongly supported standardised KPI definitions and linkage to net-zero targets (RII = 94% each).	Harmonised Sustainability Vocabulary, 124-KPI National Sustainability KPI Framework and Recommendations 1–2.
NFCS Performance Priorities	Stakeholders prioritised Job Turnaround Time (RII = 90%), Resource Utilisation and Infrastructure Uptime (88%), Federated Data Interoperability (86%) and Carbon Intensity per Federated Compute Job (82%).	Five evidence-derived sustainability domains and National Sustainability KPI Framework.

	Most priority indicators also demonstrated relatively high measurement feasibility.	
Carbon & Resource-Aware Operations	Carbon Intensity per Federated Compute Job was strongly prioritised (RII = 82%), while carbon-aware scheduling cost uncertainty (86%) and sustainable compute costs (84%) were the highest-ranked barriers.	Carbon- and resource-aware assessment logic and Recommendation 3: Embed Carbon- and Resource-Aware Decision-Making.
Governance & Interoperability	Unclear governance responsibilities (RII = 83%) and incompatible data standards (76%) constrained federation. Conversely, common data standards (91%) and clear governance, ownership and security frameworks (90%) were the highest-ranked enabling conditions.	Governance and Federation Readiness Frameworks and Recommendation 4: Trusted Governance, Interoperability and AI-Ready Data Framework.
Capability & Implementation	Low organisational readiness was accompanied by strong support for improved digital and sustainability skills and training/capacity building (RII = 88% each).	Capacity-building resources, engagement toolkit and Recommendation 5.
Decision-Support	Emerging compute-level indicators remained less clear and decision-useful, including Carbon-Aware Workload Scheduling (RII = 46%) and Computing Infrastructure Water Consumption/Intensity (36%), demonstrating difficulty translating emerging sustainability considerations into operational decisions.	SustainFed sustainability assessment and decision-support platform and Recommendation 6.
Future NFCS Priorities	Evidence converged around five mutually reinforcing capability requirements, trusted governance, harmonised measurement, workforce capability, decision-support and interoperability, underpinned by the cross-cutting need for demonstrable economic and carbon benefits.	Evidence-based strategic recommendations and phased Five-Year NFCS Roadmap.

Collectively, the organisational evidence demonstrates that sustainable federation cannot be achieved through infrastructure expansion or isolated environmental interventions alone. Instead, it requires an integrated ecosystem combining harmonised sustainability measurement, trusted governance, interoperable data, carbon- and resource-aware operations, organisational capability and practical decision-support. Importantly, each of the project outputs presented in Section 4 and the strategic recommendations developed in subsequent sections can be directly traced to the organisational evidence synthesised in this chapter, demonstrating a clear and transparent evidence-to-action pathway for future NFCS development.

4. Project Outputs

Building on the organisational evidence presented in Section 3, the NETZERO project developed five integrated outputs: a Harmonised Sustainability Vocabulary, a National Sustainability KPI Framework, evidence-based governance and policy recommendations, the SustainFed sustainability assessment and decision-support platform, and a Transferable Engagement and Co-Creation Toolkit. Together, these outputs provide the common language, measurement architecture, strategic direction, practical decision-support and reusable engagement methods required to advance sustainable, interoperable and governance-aware federated compute and data services across NFCS.

All five outputs were developed through a shared evidence-to-action process combining evidence review, the 214-response organisational survey, stakeholder workshops, structured consultations, co-creation and Rapid Delphi validation. Where relevant, this process was supplemented by prototype development, scenario testing and user evaluation. Section 3 established the underlying organisational evidence; this section focuses on the resulting outputs, their structure, validation and potential application.

Table 5. Overview of NETZERO Project Outputs

Output	Primary contribution	Detailed resource
Harmonised Vocabulary	Common terminology	Appendix C
KPI Framework	Measurement architecture	Appendix D
Strategic Recommendations	Governance and implementation direction	Section 5
SustainFed	Adaptive assessment and decision-support	Section 4.4
Engagement Toolkit	Reusable engagement and validation methods	Appendix B

4.1 Output 1: Harmonised Sustainability Vocabulary

The Harmonised Sustainability Vocabulary establishes a common language for sustainability-aware federated computing across the NFCS ecosystem. It addresses semantic fragmentation arising from the convergence of computing, data infrastructure, sustainability, built environment, governance and policy communities, where related concepts may be defined or interpreted differently.

Rather than providing an exhaustive technical glossary, the vocabulary defines priority concepts required for consistent communication, sustainability assessment, interoperability, governance and operational decision-making across the Community, Technology and Governance dimensions of NFCS. It provides the semantic foundation for the National Sustainability KPI Framework presented in Output 2.

Development

Candidate terms were identified across sustainability, federated computing, digital infrastructure, interoperability and governance. They were then consolidated to remove duplication, reconcile disciplinary differences and retain concepts directly relevant to NFCS assessment, implementation and decision-making.

Development was guided by six principles: clarity, cross-sector relevance, actionability, transferability, future readiness and proportionality. These principles ensured that definitions were sufficiently precise for technical and policy use while remaining accessible across different organisational and disciplinary communities.

Core Structure

The vocabulary is organised into five thematic groups aligned with the multidimensional requirements of sustainable federated computing.

Table 6. Thematic Structure of the Harmonised Sustainability Vocabulary

Thematic Group	Scope
Carbon, Resource & Sustainability Performance	Carbon intensity, compute carbon, operational and embodied impacts, energy, renewables, water, resource efficiency, circularity and lifecycle performance
Data Federation, Interoperability & Digital Infrastructure	Data and compute federation, technical and semantic interoperability, metadata, provenance, FAIR data, data quality, access and digital infrastructure
Governance, Policy & Trust	Governance, accountability, policy and regulatory alignment, standards, transparency, auditability, cybersecurity, ethics and responsible AI
Community, Inclusion & Capacity Building	Inclusion, equity, accessibility, engagement, co-creation, capacity building, digital readiness, cross-disciplinary participation and societal value
Operational Performance, Resilience & Value	Performance, capacity, reliability, resilience, service quality, federation operability, scalability, automation, cost efficiency and value creation

The five thematic groups provide conceptual alignment with the five sustainability domains subsequently operationalised through the KPI framework. The complete vocabulary, including the harmonised definition and strategic relevance of each term, is provided in Appendix C.

Evidence and Validation

The vocabulary responds directly to the semantic and interoperability gaps identified in Section 3, including strong organisational demand for common data standards and standardised KPI definitions. It was refined through workshops, structured consultations, co-creation and Rapid Delphi validation, with terms assessed for conceptual clarity, technical relevance, cross-sector applicability and consistency with the emerging KPI architecture.

The vocabulary was progressively refined through two hybrid expert workshops, five structured consultations, stakeholder co-creation and Rapid Delphi validation. Terms and definitions were reviewed for conceptual clarity, technical relevance, cross-sector applicability and consistency with the emerging KPI architecture. This process resulted in five thematic groups aligned with the evidence-derived sustainability domains, establishing consistency between terminology and subsequent performance measurement.

Applications

The vocabulary provides a reusable semantic resource for NFCS strategy, sustainability assessment, KPI specification and reporting, metadata and data interoperability, governance and policy development, procurement, training and onboarding, infrastructure benchmarking and decision-support. It can support consistent interpretation of sustainability concepts across research organisations, infrastructure providers, industry, government and professional communities. The vocabulary also provides the terminology layer underpinning SustainFed and the National Sustainability KPI Framework.

4.2 Output 2: National Sustainability KPI Framework

The National Sustainability KPI Framework provides a structured measurement architecture for assessing sustainability across federated compute and data services. Building on the common terminology established through the Harmonised Sustainability Vocabulary, it translates sustainability concepts into measurable indicators spanning environmental, technical, governance, social and operational performance.

The framework is designed for application at programme, infrastructure, organisational and workflow levels and supports progressive adoption according to organisational maturity, priorities and data availability. Rather than reducing sustainability to a single environmental measure, it enables multidimensional assessment of the conditions and performance required for sustainable federation.

Development

The framework comprises 124 KPIs, developed through evidence review, organisational survey findings, stakeholder workshops, co-creation and expert validation. Candidate indicators were progressively consolidated and refined to improve their relevance, measurability and practical applicability to federated compute and data services.

Each KPI is supported by a consistent 14-field metadata specification covering its category, code, title, definition, purpose, unit, measurement basis, data source, calculation rule, maturity level, KPI type, reporting frequency, owner and priority. Together, these fields define what is measured, how it should be assessed, who is responsible and how implementation can be sequenced according to organisational maturity.

KPIs are classified as quantitative, composite or qualitative/survey-based and assigned a Core, Advanced or Optional priority. This enables organisations to establish an initial baseline using Core KPIs and progressively introduce more advanced measures as their data, governance and monitoring capabilities mature. The complete framework and metadata specifications are provided in Appendix D.

Core Structure

The 124 KPIs are organised across five interconnected sustainability domains.

Table 7. Sustainability Domains of the National Sustainability KPI Framework

Domain	Strategic Focus
A. Carbon & Resource-Aware Federated Computing	Carbon, energy, water and resource impacts; carbon-aware scheduling; infrastructure and lifecycle burdens; sustainability impacts of digital workflows.
B. Data Interoperability, Quality & Federation Readiness	Technical and semantic interoperability; data quality; metadata; provenance; FAIR principles; access, reuse and readiness for federation.
C. Governance, Policy & Regulatory Alignment	Governance maturity; policy and regulatory compliance; accountability; cybersecurity; ethics; auditability and responsible AI readiness.
D. Community, Equity & Capacity Building	Inclusive participation; equitable access; stakeholder engagement; trust; skills; organisational capability and societal value.
E. Operational Performance & Infrastructure Efficiency	Compute utilisation; capacity; energy efficiency; reliability; resilience; federation operability; scalability and lifecycle cost efficiency.

The domain architecture reflects the project evidence that sustainability within federated infrastructure extends beyond carbon and energy to include operational performance, interoperability, governance and organisational capability. It therefore enables environmental outcomes to be assessed alongside the technical and institutional conditions required for effective federation.

Evidence and Validation

The framework directly addresses the organisational demand for harmonised KPI definitions, alignment with net-zero objectives and broader measurement of compute, data, governance and infrastructure performance identified in Section 3.

Candidate KPIs were assessed through stakeholder co-creation and Rapid Delphi validation for strategic relevance, clarity, measurability, data requirements and implementation feasibility before consolidation into the five-domain architecture. The resulting framework combines readily implementable Core KPIs with Advanced and Optional indicators that can be introduced progressively as organisational and infrastructure maturity develops.

Applications

The framework provides NFCS and participating organisations with a common basis for baseline assessment, performance monitoring, benchmarking, sustainability reporting, governance oversight and evidence-based decision-making. Its metadata structure also enables responsibilities, measurement frequency and implementation priorities to be defined consistently across participating organisations.

Implementation can progress through three stages: Foundation, using Core KPIs to establish baseline performance; Integrated Management, introducing Advanced KPIs as data and governance capabilities mature; and Optimisation and Innovation, extending measurement towards benchmarking, automation, predictive analytics and strategic scenario assessment.

KPIs are intended to be interpreted collectively across the five domains rather than aggregated into a single sustainability score. This systems-based approach enables potential trade-offs, for example between compute performance, energy and carbon impacts, data accessibility, governance requirements and lifecycle costs, to remain visible within decision-making.

The framework therefore provides the measurement and assessment foundation for sustainability-aware federated computing and the quantitative basis subsequently operationalised through SustainFed.

4.3 Output 3: Evidence-Based Governance and Policy Recommendations

The Evidence-Based Governance and Policy Recommendations translate the organisational evidence into six coordinated actions for integrating sustainability into the future development and operation of NFCS. They address the governance, operational, organisational and implementation conditions required alongside technical infrastructure and provide the strategic foundation for the five-year roadmap presented in Section 5.

Development

Quantitative evidence on organisational maturity, barriers and enabling conditions was combined with stakeholder and expert perspectives on governance, policy and implementation requirements. This evidence was synthesised through a structured pathway linking identified needs and constraints to strategic requirements, recommendations and implementation actions. This process maintained traceability between the evidence and proposed interventions and enabled the six recommendations to operate as an integrated package rather than independent policy measures.

Core Structure

The evidence was synthesised into six mutually reinforcing strategic recommendations.

Table 8. Strategic Recommendations for Sustainable Federated Computing

Recommendation	Strategic Focus
R1. Establish a Harmonised Sustainability Vocabulary	Create a common sustainability language across NFCS communities to improve consistency, interoperability and cross-sector communication.
R2. Implement a National Sustainability KPI Framework	Establish consistent, measurable and progressively implementable sustainability performance indicators across federated services.
R3. Embed Carbon- and Resource-Aware Decision-Making	Integrate carbon, energy, water, resource utilisation and cost considerations into compute allocation, scheduling and infrastructure decisions.
R4. Establish Trusted Governance, Interoperability and AI-Ready Data Practices	Strengthen accountability, data governance, security, interoperability, standards and responsible use of data and AI across federated environments.
R5. Build Capacity and Inclusive Participation	Strengthen organisational capability through training, guidance, communities of practice and inclusive participation across NFCS stakeholder groups.
R6. Deploy SustainFed as a National Sustainability Assessment and Decision-Support Capability	Operationalise project evidence, KPIs and governance principles through practical sustainability and federation-readiness assessment and decision-support.

The recommendations form a progressive and interconnected architecture. R1-R2 establish common terminology and measurement; R3-R4 embed sustainability within operational and governance practices; R5 strengthens the capability required for adoption; and R6 supports practical application through integrated assessment and decision-support.

Evidence and Validation

The recommendations respond directly to the principal economic, governance, interoperability and capability constraints identified in Section 3. Stakeholder co-creation and Rapid Delphi validation were used to refine their strategic relevance, practical applicability and interdependencies. Their development also considered the wider UK policy and standards environment, including net-zero policy, information management, cybersecurity, interoperability, responsible AI and relevant ISO standards. Detailed evidence and alignment for each recommendation are presented in Section 5.

Applications

The recommendation package provides NFCS with a structured basis for strategic planning, governance and policy development, sustainability requirements, infrastructure decision-making, organisational capability development and implementation planning. It also provides the organising structure for the project's five-year roadmap, enabling interventions to be sequenced according to dependencies, organisational maturity and implementation priorities.

Detailed recommendation rationale, supporting evidence, proposed actions, responsible actors, policy and standards alignment, expected outputs and outcomes, and implementation sequencing are presented in Section 5: Strategic Recommendations and Five-Year Roadmap. This maintains a clear distinction between Output 3 as the evidence-derived strategic package and Section 5 as its detailed implementation pathway.

4.4 Output 4: SustainFed Sustainability Assessment and Decision-Support Platform

SustainFed is a web-based adaptive sustainability assessment and decision-support platform developed to translate the NETZERO evidence base into practical guidance for federated compute and data decisions. It addresses the gap between the growing use of compute-intensive digital workflows and organisations' limited capability to assess their sustainability, governance, interoperability and federation requirements.

Rather than functioning as a conventional sustainability calculator, SustainFed integrates workflow context, computing requirements, sustainability priorities, governance and risk, federation suitability, data interoperability and relevant KPIs within a single adaptive environment. It is designed particularly to support users with limited specialist knowledge of HPC, data federation or sustainable digital infrastructure, while maintaining human judgement and accountability in final decisions.

Architecture

SustainFed uses a layered architecture that progressively translates user and workflow requirements into context-sensitive assessment and recommendations. The architecture comprises six interconnected layers:

1. Context Acquisition, captures workflow, compute, collaboration, sustainability, governance and interoperability requirements.
2. Adaptive Conditional Orchestration activates relevant questions and assessment pathways based on user context.
3. Continuous Validation Intelligence, identifies incomplete, inconsistent or conflicting inputs.
4. Multi-Domain Intelligence evaluates relevant conditions and activates KPIs from the five sustainability domains.
5. Explainable AI and Decision Reasoning, interprets dependencies and trade-offs and generates contextual guidance.
6. Recommendation and Reporting, produces prioritised recommendations, KPI guidance and phased actions.

Governance, interoperability, security, privacy, sustainability and human oversight operate as cross-cutting requirements throughout the architecture rather than as separate post-assessment checks.

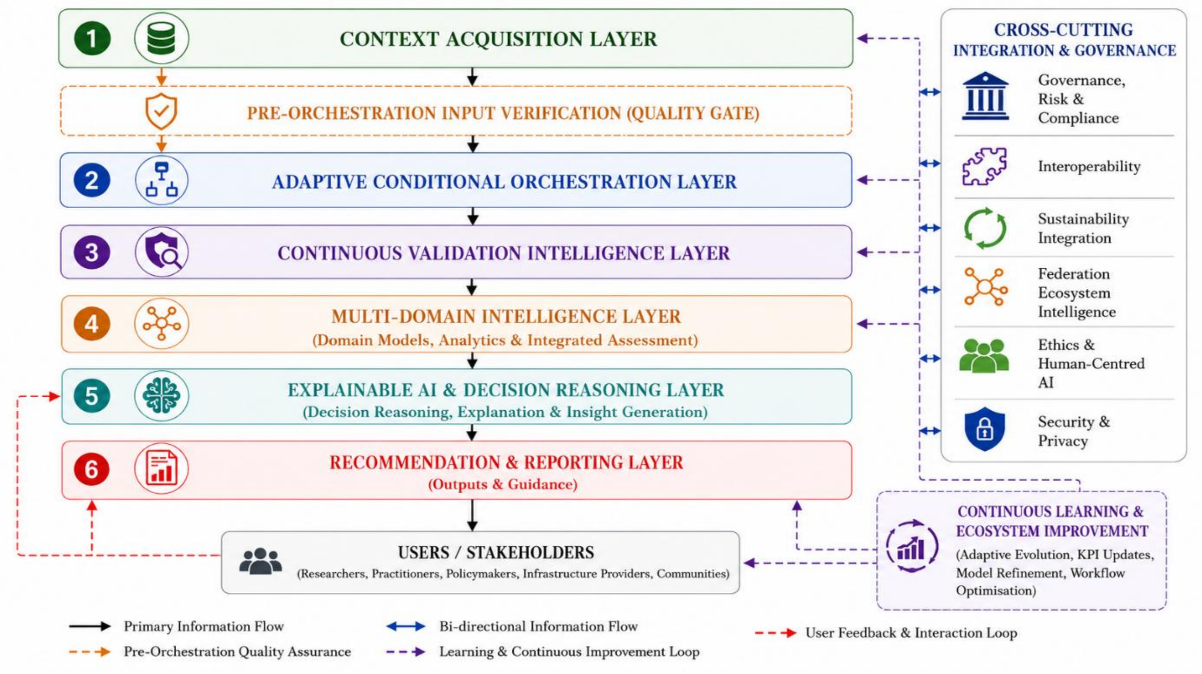

Figure 14. SustainFed adaptive sustainability assessment and decision-support architecture

Assessment and Recommendation Engines

The assessment engine uses conditional logic to adapt questions and KPI pathways according to workflow type, computational intensity, data characteristics, collaboration requirements, governance sensitivity and federation conditions. It therefore avoids applying a fixed questionnaire or assessing all 124 KPIs uniformly. Rule-based and contextual checks identify potentially incomplete or inconsistent responses before recommendations are generated.

The recommendation engine combines deterministic workflow and KPI logic with AI-assisted contextual reasoning to interpret dependencies and potential trade-offs. AI supports interpretation and communication rather than autonomously selecting infrastructure; recommendations remain grounded in the assessment logic, activated KPIs and human oversight.

The platform generates five principal decision-support outputs.

Table 9. SustainFed Decision-Support Outputs

Output	Decision-Support Function
Indicative Compute Configuration	Identifies potentially suitable HPC, cloud, federated or hybrid configurations based on workflow requirements.
Sustainability Priority	Identifies priority carbon, energy, resource and wider sustainability considerations.
Governance & Risk	Highlights relevant governance, compliance, data-management and operational risks.
Federation Suitability	Assesses the suitability and readiness of the workflow for federated infrastructure and collaborative deployment.
Data Interoperability & Readiness	Identifies data accessibility, compatibility, interoperability and information-management requirements.

These outputs are complemented by context-relevant KPI recommendations and phased actions, enabling users to distinguish immediate priorities from medium-term improvements and more advanced optimisation opportunities.

Evidence and Validation

SustainFed was progressively evaluated and refined through multidisciplinary expert engagement, focus-group review, two iterative testing rounds and scenario-based assessment. Evaluation examined workflow coherence, contextual responsiveness, recommendation relevance, explainability, sustainability integration, governance alignment, interoperability and usability.

Representative scenarios covered different levels of computational intensity, data scale, collaboration, governance sensitivity and interoperability. Testing indicated that the platform could adapt its assessment pathways, KPI activation and recommendation priorities to different operational contexts. Feedback informed refinement of the conditional logic, validation prompts, KPI-action mapping, recommendation wording and reporting outputs.

The resulting prototype therefore provides a validated proof of concept for adaptive sustainability and federation-readiness assessment, while further technical testing and deployment evaluation would be required before implementation at national scale.

4.5 Output 5: Transferable Engagement and Co-Creation Toolkit

The Transferable Engagement and Co-Creation Toolkit packages the stakeholder engagement, evidence-generation, co-creation and validation approaches developed through NETZERO into a reusable resource for NFCS and other compute- and data-intensive research communities. It provides a structured approach for incorporating organisational, technical, sustainability, governance and user perspectives into the development of federated digital infrastructure.

Rather than prescribing a single engagement method, the toolkit provides a modular evidence-to-action pathway that can be adapted to different sectors, stakeholder communities and levels of organisational and federation maturity.

Development

The toolkit consolidates the engagement and validation methods applied throughout NETZERO into reusable templates and guidance. It supports the progression from stakeholder mapping and organisational baseline assessment through evidence interpretation, co-creation, expert validation and identification of implementation priorities.

Its modular design retains common methodological elements for consistency and cross-sector comparison while allowing sector-specific technologies, terminology, workflows and stakeholder requirements to be adapted.

Core Structure

The toolkit comprises seven complementary components.

Table 10. Components of the Transferable Engagement and Co-Creation Toolkit

Toolkit Component	Primary Function

Organisational Survey Template	Establish baseline technology maturity, organisational readiness, current practices, priorities, barriers and enabling conditions.
Stakeholder Mapping Template	Identify relevant organisational groups, expertise, roles and representation requirements.
Workshop Planning & Facilitation Template	Structure evidence review, stakeholder discussion, prioritisation and collaborative interpretation.
Co-Creation Template	Translate evidence and stakeholder needs into requirements, frameworks, actions and implementation priorities.
Rapid Delphi Template	Support structured expert assessment, convergence, feedback and iterative refinement.
Validation Template	Assess relevance, clarity, feasibility, applicability and implementation readiness of emerging outputs.
Evidence Synthesis Template	Triangulate quantitative, qualitative and expert evidence and maintain traceability from identified needs to project outputs.

Together, the components support a staged pathway from stakeholder mapping and baseline assessment through co-creation, validation and evidence synthesis. The templates and supporting materials are provided in Appendix B.

Evidence and Validation

The toolkit is grounded in methods applied and refined during NETZERO rather than being developed as a standalone methodological resource. Its components supported the generation, interpretation and validation of evidence underpinning the vocabulary, KPI framework, strategic recommendations and SustainFed platform.

This practical application demonstrated how quantitative organisational evidence, contextual stakeholder perspectives and expert judgement can be triangulated while maintaining traceability from identified needs to resulting outputs and implementation actions.

Applications and Reuse

The toolkit is methodologically transferable rather than built-environment specific. Its core areas, organisational maturity, sustainability priorities, interoperability, governance, capability, performance measurement, barriers and implementation readiness are relevant across federated research infrastructure communities. NFCS can therefore apply the common engagement structure in other compute- and data-intensive domains while adapting sector-specific technologies, terminology, workflows and stakeholder groups. This supports cross-sector comparison, cumulative evidence generation and more consistent roadmap development.

The toolkit therefore provides a practical mechanism for replicating and scaling the NETZERO evidence-to-action approach across future NFCS communities.

5. National Recommendations

Building on the evidence presented in Section 3 and the project outputs developed in Section 4, NETZERO proposes six national recommendations to support the transition towards sustainable, interoperable and governance-aware federated computing. The recommendations translate the project's empirical evidence, stakeholder co-creation and validation findings into strategic priorities for future NFCS development and implementation.

The recommendations form a coordinated package spanning the Community, Technology and Governance dimensions of NFCS. Recommendations 1-4 establish the core terminology, measurement, operational and governance foundations required for sustainable federation, while Recommendations 5-6 strengthen organisational capability and provide practical mechanisms for implementation. The complete recommendation profiles, including rationale, evidence base, policy and standards alignment, expected outcomes, resource requirements, dependencies and roadmap actions, are provided in Appendix E.

Recommendation 1: Adopt a Harmonised Sustainability Vocabulary for Federated Computing

NFCS should adopt, maintain and periodically review the Harmonised Sustainability Vocabulary developed through NETZERO as a common reference across sustainability assessment, governance, reporting, interoperability, onboarding and stakeholder engagement.

This is a Must Have, High-Priority recommendation with high expected impact but relatively low implementation complexity and resource requirements. It provides the semantic foundation upon which subsequent measurement, governance and implementation activities depend.

Recommendation 2: Establish a National Sustainability KPI Framework for Federated Computing

NFCS should adopt and progressively implement the 124-KPI National Sustainability KPI Framework as a common mechanism for assessing, benchmarking, monitoring and reporting sustainability performance across federated compute and data services.

This Must Have, High-Priority recommendation establishes the measurement foundation for the roadmap. Progressive implementation should enable organisations to move from Core indicators towards more advanced measurement as their data, governance and monitoring capabilities mature.

Recommendation 3: Embed Carbon- and Resource-Aware Decision-Making into Federated Computing

NFCS should progressively integrate carbon, energy, water, resource utilisation and cost considerations into workload scheduling, infrastructure selection, storage management and resource allocation alongside conventional performance and availability requirements.

This Must Have, High-Priority recommendation provides the strongest pathway towards direct environmental improvement by moving NFCS from sustainability measurement towards active optimisation of federated infrastructure operations.

Recommendation 4: Develop a Trusted Governance, Interoperability and AI-Ready Data Framework for Sustainable Federation

NFCS should establish an integrated framework for trusted federation encompassing governance accountability, data stewardship, interoperability, metadata, secure access, FAIR data practices, cybersecurity, AI readiness and lifecycle information management.

This Must Have, High-Priority recommendation provides the institutional and information foundation required for secure and scalable federation. Its implementation should progress alongside sustainability measurement and carbon-aware operational capabilities.

Recommendation 5: Build Capacity and Inclusive Participation for Sustainable Federated Computing

NFCS should establish a coordinated programme of training, onboarding, guidance, knowledge exchange and community development covering carbon-aware computing, federation readiness, sustainability assessment, governance, interoperability, FAIR data and responsible AI.

This Should Have, High-Priority recommendation addresses the human and organisational capabilities required to translate technical and governance developments into sustained adoption across research, industry, government and infrastructure communities.

Recommendation 6: Deploy SustainFed as a National Sustainability Assessment and Decision-Support Capability

NFCS should further develop and progressively deploy SustainFed as a national capability for sustainability assessment, federation-readiness evaluation, infrastructure planning, KPI selection, governance assessment and evidence-based decision-support.

This Should Have; High-Priority recommendation provides an operational mechanism for applying the project's terminology, measurement, governance and sustainability principles. Deployment should progress through further validation and integration with NFCS services before wider scaling.

5.1 Integrated Recommendation Architecture

The six recommendations are mutually reinforcing and should be implemented as an integrated architecture rather than as independent interventions. Recommendations 1-2 establish common language and measurement; Recommendations 3-4 embed sustainability within operational and governance practices; Recommendation 5 develops the organisational capability required for adoption; and Recommendation 6 provides an integrated mechanism for applying these capabilities in practice.

Implementation should therefore be phased according to dependencies and maturity. Foundational terminology, measurement and governance activities should commence early, while more advanced operational optimisation, capacity development and decision-support capabilities are progressively expanded as data availability, organisational readiness and federation capability mature. This integrated sequencing provides the basis for the Five-Year NFCS Implementation Roadmap presented in Section 6.

6. Five-Year NFCS Implementation Roadmap

The Five-Year Roadmap translates the six national recommendations into a phased implementation pathway for sustainability-aware federated computing across NFCS. The sequencing reflects dependencies between the recommendations and recognises that implementation should progress from common foundations and baseline capability, through integration and operationalisation, towards scaling, optimisation and continuous improvement. Detailed actions, responsible actors, resource requirements and dependencies for individual recommendations are provided in Appendix E.

The roadmap is intentionally progressive rather than prescriptive. Organisations and infrastructure providers may enter at different levels of maturity; however, national coordination is required to maintain consistency in terminology, measurement, governance and interoperability while allowing implementation to adapt to different services and communities.

Year 1: Establish Foundations and Baselines

Year 1 should establish the common foundations required for coordinated implementation. Priority should be given to adopting the Harmonised Sustainability Vocabulary (R1), establishing governance and ownership arrangements for the National Sustainability KPI Framework (R2), and defining the initial governance and interoperability requirements (R4).

Initial implementation should focus on a manageable set of Core KPIs and baseline assessments across participating services. Carbon-, energy- and resource-related data requirements should be defined to prepare for subsequent operational optimisation under R3. In parallel, an NFCS-wide capability and skills assessment should establish the baseline for targeted capacity development under R5, while SustainFed should undergo further technical refinement and broader user validation before national deployment.

Year 1 outcome: common terminology, baseline sustainability measurement, initial governance arrangements, capability baseline and validated foundations for subsequent implementation.

Year 2: Pilot and Integrate

Year 2 should move from framework establishment to controlled implementation and integration. Core KPIs should be piloted across selected NFCS services, supported by common reporting and data-quality requirements. Governance, interoperability, metadata and secure information-exchange practices should be tested in representative federated environments.

Carbon- and resource-aware decision-making should begin through targeted pilots examining workload carbon intensity, resource utilisation, renewable-energy availability and associated cost implications. Capacity-building activities should move from needs assessment to targeted training, onboarding and communities of practice. SustainFed should be piloted with selected NFCS services and user communities to evaluate integration with real operational and organisational contexts.

Year 2 outcome: tested measurement, governance and interoperability mechanisms; initial carbon-aware operational pilots; targeted workforce development; and SustainFed deployment in representative NFCS contexts.

Year 3: Scale and Operationalise

Year 3 should focus on scaling validated approaches across a wider proportion of the NFCS ecosystem. The KPI framework should expand beyond Core indicators towards relevant Advanced KPIs, supported by improved monitoring, data availability and reporting capability. Governance and interoperability requirements should increasingly become embedded within service management, procurement and federation arrangements.

Carbon- and resource-aware practices should move from pilots towards operational workload and infrastructure decisions, including scheduling, infrastructure selection, storage and resource allocation where appropriate. Training and communities of practice should be expanded across participating organisations, while SustainFed should be integrated with a broader range of NFCS workflows and services.

Year 3 outcome: wider adoption of harmonised sustainability assessment, operational carbon- and resource-aware practices, embedded governance and interoperability, and scaled organisational decision-support.

Year 4: Optimise and Automate

Year 4 should shift the emphasis from implementation towards optimisation, automation and cross-service coordination. Increasing availability of harmonised performance data should enable benchmarking across services and identification of opportunities for improved resource allocation, carbon reduction and infrastructure efficiency.

Where technically and operationally appropriate, carbon- and resource-aware decision-making can progress towards greater automation using workload, energy, carbon, utilisation and renewable-energy data. Governance and interoperability arrangements should mature to support more dynamic cross-organisational federation, while SustainFed can incorporate richer data integration, scenario analysis and predictive decision-support. Capacity development should increasingly address advanced competencies in AI-enabled infrastructure management, automated sustainability monitoring and federated optimisation.

Year 4 outcome: increasingly automated sustainability management, cross-service benchmarking, mature federation practices and advanced decision-support capability.

Year 5: Consolidate, Evaluate and Future-Proof

Year 5 should consolidate the national approach and evaluate its contribution to NFCS sustainability, operational performance and organisational capability. The vocabulary, KPI framework, governance arrangements and implementation guidance should undergo formal review to incorporate lessons from deployment, technological development and changes in policy and standards.

Longitudinal KPI evidence should be used to assess progress in carbon and resource performance, infrastructure efficiency, interoperability, governance maturity and community capability. SustainFed should be evaluated for continued national operation and potential extension to additional research domains. The engagement toolkit can support renewed stakeholder consultation and roadmap co-creation, ensuring that the next implementation cycle reflects emerging requirements.

Future-proofing should consider developments in AI-enabled infrastructure orchestration, increasingly automated carbon-aware scheduling, advanced federation, lifecycle data management and evolving sustainability and regulatory requirements.

Year 5 outcome: evaluated and institutionalised sustainability capability, updated national frameworks, evidence of benefits realisation and a refreshed roadmap for the next phase of NFCS development.

6.1 Integrated Five-Year Roadmap

The five-year pathway can be summarised through five progressive implementation stages.

Table 11. Five-Year Implementation Roadmap for the NETZERO Recommendations

Year	Implementation Stage	Principal Focus	Main Recommendations
1	Foundation & Baseline	Vocabulary, Core KPIs, governance foundations, baseline assessment, capability mapping and platform refinement	R1, R2, R4, R5, R6
2	Pilot & Integration	KPI pilots, governance/interoperability testing, carbon-aware pilots, training and SustainFed pilots	R2-R6
3	Scale & Operationalise	Wider KPI adoption, operational carbon/resource management, embedded governance and scaled decision-support	R2-R6
4	Optimise & Automate	Benchmarking, automation, advanced federation and AI-enabled decision-support	R2-R6
5	Consolidate & Future-Proof	Benefits evaluation, framework review, institutionalisation, wider transfer and roadmap renewal	R1-R6

Figure 15. Five-Year NFCS Roadmap for Sustainability-Aware Federated Computing

Underneath these stages, show the six recommendations as horizontal implementation streams. This will make an important point visually: R1-R6 do not simply occur in individual years; several begin early and mature progressively across the roadmap.

6.2 Implementation Dependencies

The roadmap contains important dependencies that should inform sequencing. R1 provides the semantic foundation for R2, R4 and R5, while R2 establishes the measurement capability required to monitor R3 and wider sustainability performance. Effective implementation of R3 depends on access to reliable workload, energy, carbon and resource data, together with the governance and interoperability arrangements established through R4.

R5 is cross-cutting, because workforce and organisational capability influence implementation of all other recommendations. R6 is similarly integrative: SustainFed draws on the terminology, KPI architecture, governance requirements and organisational capability established through R1-R5 and should therefore scale progressively as these foundations mature.

The principal implementation logic begins with the establishment of a common terminology (R1), which provides the foundation for consistent measurement practices (R2). Consistent measurement, in turn, supports the development of trusted data and effective governance structures (R4). Building on this foundation, organisations can adopt carbon- and resource-aware operational practices (R3), which subsequently enable integrated decision-support capabilities (R6). Throughout this progression, capacity building and inclusive participation (R5) play a cross-cutting role, ensuring that all stages are supported by the necessary skills, engagement, and stakeholder involvement.

These dependencies reinforce the need for phased implementation. More advanced capabilities, particularly automated carbon-aware scheduling, cross-service optimisation and AI-enabled orchestration, should not be scaled ahead of reliable measurement, interoperable data, appropriate governance and sufficient organisational capability. The roadmap therefore provides a maturity-based pathway through which NFCS can progress from foundational harmonisation to increasingly integrated, optimised and sustainable federation.

7. Project Impact

NETZERO has generated impact beyond the production of individual research outputs by establishing an integrated evidence base, measurement architecture, governance direction and operational decision-support capability for sustainability-aware federated computing. Its principal contribution is to position sustainability as a system-level requirement for federated digital infrastructure, encompassing carbon and resource performance, interoperability, governance, organisational capability and operational efficiency. The project creates impact across six interconnected dimensions: research, community, policy, infrastructure, environmental performance and longer-term legacy.

7.1 Research Impact

NETZERO advances research on sustainable digital infrastructure by connecting fields that have largely developed independently, including sustainable computing, federated infrastructure, built environment digitalisation, data interoperability, governance and organisational readiness. The project moves the research agenda beyond conventional assessment of data-centre energy efficiency towards a multidimensional understanding of sustainability across the lifecycle of compute- and data-intensive workflows.

The project provides several reusable research assets: a Harmonised Sustainability Vocabulary, a 124-KPI National Sustainability KPI Framework across five domains, an evidence-based recommendation architecture, the SustainFed decision-support platform, and a transferable engagement and co-creation methodology. Together, these provide conceptual, measurement and methodological foundations for subsequent research into carbon-aware computing, sustainable federation and digital infrastructure governance.

The built environment also provides a strategically valuable pilot context because its increasing adoption of BIM, digital twins, AI, simulation and lifecycle data creates growing dependence on compute, storage and interoperable data services. The resulting framework therefore establishes a basis for comparative research and validation across other compute- and data-intensive NFCS communities.

7.2 Community Impact

The project has strengthened connections between communities that influence sustainable digital infrastructure but do not routinely work within a common sustainability framework. The evidence base incorporated 214 organisational responses alongside workshops, structured consultations, co-creation, Rapid Delphi validation and platform evaluation, bringing together perspectives spanning research, industry, government, infrastructure providers and professional communities.

This engagement created value in two directions. It enabled organisational needs and implementation constraints to directly influence the project outputs, while also increasing dialogue around less mature areas such as data federation, carbon-aware computing, interoperability and infrastructure-level sustainability. This is particularly relevant given that 84% of surveyed organisations were Not Ready or only Slightly Ready to adopt national carbon-aware compute governance, demonstrating that future NFCS development requires capability building alongside technological investment.

The Transferable Engagement and Co-Creation Toolkit extends this impact beyond the project by enabling other NFCS communities to undertake comparable stakeholder mapping, baseline assessment, co-creation and validation. This provides a mechanism for continued community participation as federated services evolve.

7.3 Policy Impact

NETZERO provides an evidence-informed basis for integrating sustainability into future NFCS governance, policy and implementation decisions. The six national recommendations translate organisational evidence and stakeholder priorities into coordinated interventions covering terminology, performance measurement, carbon- and resource-aware operations, governance and interoperability, capacity development and decision-support.

The policy relevance is supported by clear implementation evidence. Unclear governance responsibilities (RII = 83%) and limited policy guidance (82%) were major barriers, while organisations strongly prioritised clear governance, ownership and security frameworks (90%) and improved interoperability and common standards (91%). The project therefore demonstrates that sustainable federation cannot be addressed through environmental policy alone; it requires alignment between sustainability objectives, data governance, technical standards and institutional responsibilities.

The recommendations have been mapped to relevant UK strategies, policies and standards and translated into a five-year implementation pathway, providing NFCS with a structured basis for moving from evidence and recommendations towards coordinated national action.

7.4 Infrastructure Impact

NETZERO introduces sustainability as a decision variable in the planning and operation of federated compute and data infrastructure. This is important because conventional infrastructure decisions are frequently dominated by performance, availability and cost, while carbon, resource consumption, data interoperability and governance implications receive less systematic consideration.

The project provides mechanisms for changing this practice. The KPI framework enables comparable assessment across environmental, interoperability, governance, community and operational dimensions, while SustainFed translates these requirements into context-sensitive guidance on compute-system selection, sustainability priorities, governance and risk, federation suitability, and data interoperability and readiness.

The evidence demonstrates the relevance of this integrated approach: organisations rated Average Job Turnaround Time (RII = 90%), Resource Utilisation Rate and Infrastructure Uptime

(88% each), Federated Data Interoperability (86%) and Carbon Intensity per Federated Compute Job (82%) as important future NFCS indicators. This demonstrates that sustainable infrastructure should simultaneously address computational performance, resource efficiency, interoperability and environmental impacts rather than optimise these dimensions independently.

7.5 Environmental Impact

The project's environmental impact lies principally in establishing the measurement and decision infrastructure required to enable future reductions in the environmental footprint of federated computing. NETZERO does not claim direct national carbon savings at the current stage; instead, it creates the capability to identify, measure and progressively reduce carbon, energy, water and resource impacts associated with compute-intensive workflows.

This contribution is particularly important because current organisational measurement remains uneven. While established indicators such as Renewable Energy Use (RII = 79%) and Compute Energy Consumption (73%) were comparatively well integrated, emerging practices such as Carbon-Aware Workload Scheduling (40%) and Computing Infrastructure Water Consumption/Intensity (31%) remained substantially less mature. At the same time, uncertainty regarding the cost implications of carbon-aware scheduling was the highest-rated implementation barrier (86%).

NETZERO addresses this gap by introducing workload-level carbon KPIs, resource-efficiency metrics, carbon-aware decision-making principles, and SustainFed guidance. Through progressive implementation, NFCS could gain the capability to compare infrastructure options, identify inefficient resource use, take advantage of lower-carbon computing opportunities, and assess trade-offs across carbon emissions, energy consumption, water use, performance, cost, and resilience. In this way, the environmental contribution of NETZERO lies in its ability to strengthen measurement and transparency, support more informed resource allocation, enable continuous optimisation, and ultimately facilitate demonstrable reductions in environmental impact.

7.6 Legacy

The principal legacy of NETZERO is an integrated and reusable capability for embedding sustainability within federated computing, rather than a set of outputs that conclude with the project. The Harmonised Sustainability Vocabulary provides a common language; the National Sustainability KPI Framework establishes consistent measurement; the recommendations and roadmap provide strategic direction; SustainFed translates these foundations into practical decision-support; and the Engagement and Co-Creation Toolkit enables the approach to be adapted and extended to other communities.

This creates three complementary legacy pathways. First, institutionalisation can embed common terminology, KPIs and governance principles within NFCS strategy and operations. Second, scaling can extend SustainFed, capacity-building and sustainability assessment across additional services and research domains. Third, continuous improvement can allow the vocabulary, KPIs and decision logic to evolve alongside emerging technologies, evidence, standards and regulatory requirements.

The longer-term value of NETZERO will therefore depend not simply on continued use of individual outputs, but on their integration into NFCS governance, infrastructure planning and operational practice. If progressively adopted through the Five-Year Roadmap, the project provides a foundation for moving from fragmented sustainability practices towards a measurable, interoperable, trusted and progressively optimised national federated computing ecosystem.

8. Conclusions

The NETZERO project demonstrates that achieving sustainability across federated compute and data services requires more than improving infrastructure energy efficiency. It requires a systems-oriented approach in which environmental performance, operational efficiency, data interoperability, governance and organisational capability are considered together. Evidence from the built environment pilot indicates that digital adoption is advancing faster than the organisational and infrastructure capabilities required to manage its sustainability implications, creating an important implementation challenge for the future development of NFCS.

8.1 Key Achievements

NETZERO has progressed from evidence generation to the development of an integrated set of practical and reusable outputs. The project established an organisational evidence base identifying current maturity, measurement practices, implementation barriers and future priorities, and translated these findings through stakeholder co-creation and expert validation into five complementary outputs.

The principal achievements are the development of a Harmonised Sustainability Vocabulary, a 124-KPI National Sustainability KPI Framework, six evidence-based governance and policy recommendations, the SustainFed sustainability assessment and decision-support platform, and a Transferable Engagement and Co-Creation Toolkit. Together, these outputs address different stages of the implementation pathway, from establishing shared meaning and consistent measurement to supporting governance, organisational adoption and operational decision-making.

A further achievement is the establishment of a clear evidence-to-action pathway. Rather than treating sustainability as an additional reporting requirement, the project provides mechanisms through which sustainability considerations can progressively inform infrastructure assessment, workload and resource decisions, governance arrangements and federation readiness.

8.2 Contribution to NFCS

The principal contribution of NETZERO to NFCS is a structured foundation for embedding sustainability within the design, governance and operation of federated services. The project demonstrates that future sustainability assessment should extend beyond conventional carbon and energy metrics to consider the wider conditions that determine whether federation can operate efficiently, responsibly and at scale.

The built environment pilot also provides an applied test case for NFCS. Its combination of heterogeneous organisations, compute-intensive workflows, distributed data, lifecycle information requirements and differing levels of digital maturity reflects many of the challenges likely to arise across other research communities. The resulting approaches are therefore designed to be transferable, while recognising that further sector-specific validation will be required before wider application.

Importantly, NETZERO provides NFCS with both foundational resources and an implementation pathway. The recommendations and Five-Year Roadmap establish how common terminology, sustainability measurement, trusted governance, carbon- and resource-aware operations, capacity development and decision-support can be progressively integrated rather than pursued as disconnected initiatives.

8.3 Future Work

Future work should prioritise implementation, longitudinal validation and cross-sector transfer. The immediate requirement is to test the proposed vocabulary, Core KPIs and governance principles across a broader range of NFCS services and organisational contexts, generating longitudinal evidence on feasibility, consistency and decision value.

Further development of SustainFed should focus on wider real-world validation, integration with relevant infrastructure and monitoring data, refinement of its assessment and recommendation logic, and evaluation of user and organisational outcomes. As reliable operational data become available, future research should also examine opportunities for more automated carbon- and resource-aware workload allocation while maintaining appropriate governance, transparency and human oversight.

The KPI framework should remain a living measurement architecture, evolving with changes in infrastructure, AI-enabled computing, data federation, sustainability science, standards and regulation. Cross-sector application of the engagement toolkit can provide further evidence on which elements are universally applicable and which require domain-specific adaptation.

Ultimately, the next phase should move from demonstrating what sustainable federation requires towards establishing what works in practice, under which conditions, and with what measurable benefits. This transition from framework development to implementation and longitudinal evaluation will be critical to determining the longer-term contribution of NETZERO to a sustainable, interoperable and resilient NFCS ecosystem.

Appendices

Appendix A. stakeholder engagement, co-creation, validation and dissemination activities

Date	Location	Format	Primary Purpose	Key Outputs	Participants	Principal Stakeholder Groups	Research Council Representation
26 & 27/02/2026	Bristol (M Shed)	In-person	Stakeholder engagement, requirements gathering and sustainability priorities	Sustainability priorities and user requirements	5	Academia, infrastructure providers, industry, sustainability experts	EPSRC, ESRC, NERC, STFC, Innovate UK
11-Mar-26	Virtual	Online	Stakeholder mapping, KPI development and vocabulary harmonisation	Draft vocabulary and KPI categories	7	Researchers, NFCS stakeholders, digital infrastructure specialists	EPSRC, ESRC, NERC
27-Apr-26	London (LSBU)	Hybrid	KPI co-creation and sustainability metric prioritisation	Prioritised sustainability KPIs	9	Professional institutions, researchers, industry, policymakers	EPSRC, ESRC, STFC, Innovate UK
28-Apr-26	London (CIOB)	Hybrid	KPI validation, federation readiness and governance	Validated KPI framework and readiness criteria	7	Academia, built environment professionals, infrastructure providers, local authorities	EPSRC, ESRC, NERC, AHRC, Innovate UK
08-May-26	London (Kingston University)	Hybrid	Governance co-creation, recommendations and SustainFed review	Draft governance recommendations	6	Researchers, policymakers, industry, infrastructure providers	EPSRC, ESRC, Innovate UK
28-May-26	Oxford (DAFNI)	Hybrid	Expert review of SustainFed and governance recommendations	SustainFed refinement and expert feedback	7	Digital infrastructure experts, sustainability specialists, researchers	EPSRC, NERC
04-Jun-26	Bristol (UWE Bristol)	Hybrid	Scenario testing and platform validation	Platform validation results	13	Researchers, industry practitioners, infrastructure providers	EPSRC, ESRC
16-Jun-26	Bristol (UWE Bristol)	Hybrid	SustainFed validation and recommendation refinement	Refined recommendations and	4	Academia, infrastructure providers, sustainability experts	EPSRC, ESRC, NERC

				platform improvements			
24-Jun-26	Birmingham (VINCI)	Hybrid	Stakeholder validation and implementation review	Implementation priorities	4	Industry, academia, professional bodies	EPSRC, Innovate UK
01-Jul-26	London (Imperial College London)	Hybrid	Final validation and roadmap discussion	Roadmap refinement	4	Researchers, policymakers, NFCS stakeholders, industry	EPSRC, ESRC, NERC, Innovate UK
06-Jul-26	Cardiff (Cardiff University)	Hybrid	Validation of recommendations, governance and KPI mapping	Final KPI-governance alignment	4	Researchers, public-sector stakeholders, infrastructure specialists	EPSRC, ESRC
27-Jul-26	Cambridge (Anglia Ruskin University)	Hybrid	Project dissemination	Research dissemination and stakeholder feedback	12	Academic researchers, infrastructure and sustainability communities	AHRC, ESRC, EPSRC, NERC, Innovate UK
28-Jul-26	Oxford (Oxford Brookes University)	Hybrid	Project dissemination	Research dissemination and stakeholder feedback	8	Academic and professional communities	AHRC, ESRC, EPSRC, Innovate UK

Appendix B. Transferable Engagement and Co-Creation Toolkit

B1. Organisational Survey Instrument

National Federated Compute Service

Net-Zero and Circular Economy Federation: Evidence-based Policy Roadmap for Carbon-Aware Compute in the Built Environment This survey explores how digital tools, data, and computing are used in the built environment and how a future UK National Federated Compute Service (NFCS) could support net-zero and circular economy goals. You are invited to share your views on:

- Your use of digital and computing workflows
- Sustainability priorities and metrics (KPIs)
- Governance, policy, and incentive mechanisms
- Preferred ways to engage with national initiatives such as NFCS

The survey should take about 20 minutes. Your responses will be anonymised and analysed in aggregate.

Before completing this survey, please read the Participant Information Sheet, Privacy Notice, and Consent Form. By continuing, you confirm that you have read the participant information, understand the purpose of the study, and voluntarily consent to take part. You may withdraw at any time before submission.

- Proceed
- Leave the survey

Section A – Background & Role

Q1. What is your primary role?

Local / regional government (e.g. planning, housing, infrastructure)
National government / regulator
Designer / Architect
Engineer (structural / M&E / civil)
Contractor / Main contractor
Developer / Client / Asset owner
Consultant (sustainability / carbon / digital)
Data provider / platform operator
HPC / research computing provider
Academic / researcher
NGO / civil society organisation
Other (please specify): -----------------

Q2. Which part(s) of the built environment do you mainly work with?

Housing / residential
Non-residential buildings (commercial, public, education, health)

Infrastructure (transport, energy, water, digital)
Urban planning / regeneration
Materials, components, products
Policy / standards / regulation
Other (please specify): ------------

Q3. How familiar are you with High-Performance Computing (HPC) or large-scale cloud computing for built environment projects?

Very familiar – I use / manage HPC or similar regularly
Somewhat familiar – I have used or interacted with these systems
Aware but not a user
Not familiar

Q4. Have you or your organisation used any of the following digital / compute-intensive workflows in the last 3 years?

Net-Zero Emissions
Whole-life carbon assessment (WLCA)
Operational energy / building performance simulations
Digital Twins (asset- or district-scale)
Urban-scale models (e.g. transport, energy, climate risk)
Digital Product Passports (DPPs) or Materials Banks
Large-scale geospatial / environmental datasets
Machine learning / AI for built environment applications
HPC / cloud computing for sustainability or infrastructure analytics
None of the above
Other (please specify): -------

Q5. Which region are you mainly based in?

England – North
England – Midlands
England – South
Scotland
Wales
Northern Ireland
Outside the UK (please specify country): -----

Q6. How many years of experience do you have in the built environment / related fields?

Less than 5 years
6–10 years
11–20 years
More than 20 years

Section B – Sustainability Priorities & Challenges

Q7. How important are the following priorities for digital and compute workflows in the built environment?

	Very Important	Important	Moderately important	Slightly important	Not important
Reducing carbon intensity per compute job					

Reducing energy intensity per compute job					
Using renewable energy for computing					
Carbon-aware job scheduling					
Long-term lifecycle data retention with low carbon burden					
Transparency of compute-related emissions					
Cross-organisation data interoperability					
Equitable access to compute resources					
Managing the financial cost of low-carbon computing					
Lifecycle carbon burden of data storage					
Carbon transparency of scheduling decisions					
Others --------					

Q8. How critical are the following barriers to using digital and compute-intensive tools in ways that support net-zero and circular economy goals?

	Very critical	Critical	Moderately critical	Slightly critical	Not critical
Limited carbon data for compute jobs					
Incompatible data standards					
Lack of harmonised KPIs					
Limited policy guidance					
Skills gap in carbon-aware computing					
Unclear governance responsibilities					
High cost of sustainable compute					
Uncertainty about the cost implications of carbon-aware scheduling					
Others -------					

Q9. What change would most improve sustainable use of digital tools and compute in your work? ----------

Section C – Vocabulary, Metrics & KPIs

Q10. Which sustainability-related terms do you use most often in your work? (Select all that apply)

Carbon intensity per compute job

Carbon-aware scheduling
Federated data interoperability
Circular data processing
Power Usage Effectiveness (PUE)
Data provenance
Low-carbon compute incentives
Governance maturity
Inclusive participation
Net-Zero Emissions
Scope 1-3 carbon
Whole-life carbon / Whole-life carbon assessment (WLCA)
Embodied carbon
Operational carbon
Circular economy
Resource efficiency / resource productivity
Material passports / Digital Product Passports
Materials banks
Urban Mine
Net-zero (operational)
Net-zero (whole life)
Climate resilience / adaptation
ESG reporting
Other (please specify): -------

Q11. Are sustainability and compute-related terms interpreted consistently across your collaborators?

Yes
Sometimes
Rarely
No
Not sure
If not consistent, please explain: --------

Q12. Which sustainability KPIs or metrics does your organisation currently use for projects involving digital / compute-intensive workflows?

Whole-life carbon ($kgCO_2e$ per m^2 or per asset)
Embodied carbon benchmarks (per m^2, per component)
Operational energy use ($kWh/m^2/year$)
Carbon intensity of energy supply (gCO_2e/kWh)
Proportion of reused / recycled materials (%)
Waste reduction / diversion from landfill (%)
Circularity indicators (e.g., material recovery potential)
Net-zero emissions progress (% reduction vs baseline)
None of the above
Other (please specify): --------

Q13. Please rate the importance of the following KPIs for NFCS

	Very Low	Low	Moderate	High	Very High
Carbon Intensity per Federated Compute Job					

Renewable Energy Utilisation Ratio					
Federated Data Interoperability Score					
Policy Implementation Readiness Index					
Inclusive Participation Rate					
Infrastructure Uptime					
Data Governance Alignment Rate					
Low-Carbon Incentive Adoption Rate					
Infrastructure Uptime					
Power Usage Effectiveness (PUE)					

Q14. How feasible is it for your organisation to measure these KPIs?

	Not feasible	Slightly Feasible	Moderately Feasible	Mostly Feasible	Fully feasible
Carbon Intensity per Federated Compute Job					
Renewable Energy Utilisation Ratio					
Federated Data Interoperability Score					
Policy Implementation Readiness Index					
Inclusive Participation Rate					
Infrastructure Uptime					
Data Governance Alignment Rate					
Low-Carbon Incentive Adoption Rate					
Infrastructure Uptime					
Power Usage Effectiveness (PUE)					

Q15. How clear and usable are your current KPIs for guiding decisions on digital tools and computing?

Not clear or usable
Slightly clear and usable
Somewhat clear but limited in practice
Clear and generally usable
Very clear and useful for decision-making

Q16. Which of the following data does your organisation currently have access to? (Select all that apply)

Energy consumption of compute jobs
Carbon intensity of electricity supply
CPU/GPU utilisation logs

Data storage volumes and retention periods
Renewable energy sourcing information
Scheduling and queue metadata
Data provenance and metadata records
None of the above
Not sure

Q17. Which of the following would most improve sustainability metrics for compute-intensive workflows in your project?

Standardised KPI definitions across organisations
Sector-specific guidance (for housing, infrastructure, etc.)
Better integration with existing reporting frameworks (e.g. GHG Protocol, ESG)
Tools or templates for consistent data collection
Example use cases / case studies
Alignment with national / international initiatives (e.g. NetDRIVE, NFCS, DAFNI, UKCRIC)
Training or capacity building
Automated data validation and quality checks
Clear linkage between KPIs and net-zero targets
Benchmark datasets for comparison across projects
Integration with BIM and digital twin platforms
Real-time dashboards for monitoring sustainability performance
Guidance on accounting for embodied emissions in computing infrastructure
Other (please specify): -------

Section D – Governance, Incentives & NFCS

Q18. How important are the following governance features for a future national federated compute service (NFCS)?

	Very Important	Important	Moderately important	Slightly important	Not important
Transparent information on the carbon / energy intensity of jobs					
Fair allocation of resources between sectors and organisations					
Carbon-aware scheduling rules					
Clear rules for prioritising jobs (e.g. based on societal value / urgency)					
Support for long-term lifecycle data stewardship					
Alignment with UK Net Zero Strategy and other policies					
Clear responsibilities for data security and privacy					
Simple, understandable access policies and terms of use					
Cross-facility agreements					

Others -----					

Q19. Who should be primarily responsible for reporting sustainability KPIs for federated compute?

Individual users / project teams
HPC / compute facility operators
NFCS central coordination body
Data providers / platform operators
Joint/shared responsibility
Unsure

Q20. How ready is your organisation to adopt national carbon-aware compute governance recommendations?

Not ready
Slightly ready
Moderately ready
Mostly ready
Fully ready

Q21. Which types of incentive mechanisms would you support for encouraging more sustainable use of compute?

Lower-cost access for low-carbon job scheduling
Priority access for jobs supporting net-zero / circularity outcomes
Recognition schemes (e.g. "low-carbon compute" labels / badges)
Quotas or limits for high-intensity jobs
Usage caps on high-carbon jobs
Informational nudges (e.g. "this job is X times more carbon intensive than alternative")
No incentives – neutral access only
Other (please specify): -------

Q22. What concerns, if any, would you have about introducing sustainability-related incentives or constraints on compute access? -------

Q23. In your view, how should a national NFCS coordinate with other initiatives such as NetDRIVE, DAFNI, and UKCRIC?

Share data and methodological standards
Share data infrastructure
Align KPIs and reporting frameworks
Joint governance frameworks
Joint stakeholder engagement
Maintain separate remits with interoperability
I am not familiar with these initiatives
Other (please specify): ----

Q24. Would your organisation be willing to share anonymised compute and sustainability data within a national federated service (NFCS)?

Yes, without restriction
Yes, with contractual safeguards
Yes, only aggregated data
No, due to commercial / security concerns

Unsure
If "No / Unsure", please briefly explain: ---------

SECTION E — COMMUNITY, EDI & CAPACITY

Q25. How inclusive should NFCS engagement be for the following groups?

Group	Essential	Important	Optional	Not needed
SMEs				
Local authorities				
Researchers & ECRs				
NGOs				
Devolved regions				
Asset owners				

Q26. How well do current national digital or sustainability initiatives represent your community?

Very well
Well
Adequately
Poorly
Very poorly
Not applicable

Q27. Which capacity gaps are most critical?

Carbon-aware computing literacy
Data governance skills
Policy translation skills
Interdisciplinary collaboration
Digital infrastructure readiness
Other: _______

Q28. Is there any specific policy, governance, or data-sharing change you believe NFCS should prioritise first to enable sustainable computing in the built environment?

Having now completed the questionnaire and reviewed the questions, do you confirm that you consent to your anonymised responses being used for the purposes of this research?
☐ **Yes**, I consent to my anonymised responses being used
☐ **No**, I do not consent to my anonymised responses being used (**your responses will be deleted immediately**)

B1. Workshop Protocol

NFCS HYBRID WORKSHOPS PROTOCOL

Workshops: 2–3 (Housing & Buildings, Infrastructure & Local Government, Computing / Data /National Facilities)

Workshop programme

Item	Activity Description	Expected Outputs	Time
Welcome & Project Introduction	Facilitators introduce the NFCS project, workshop aims, deliverables (vocabulary, KPIs, governance), and provide consent reminders.	Shared understanding of workshop goals Confirmed participant consent	5 mins
Focus Group Diagnostic Discussion (Icebreaker)	Facilitated round-table discussion on current sustainability challenges in digital/compute workflows, carbon burdens in modelling, and practical needs for a fair NFCS.	Priority sustainability themes Surface lived challenges Context for vocabulary & KPI co-design	20 mins
Vocabulary Harmonisation & Concept Mapping	Participants review and refine definitions of NFCS key terms, identify inconsistencies, propose missing terms, and cluster concepts for harmonised vocabulary.	Revised vocabulary definitions Concepts requiring standardisation Missing or conflicting terminology	45 mins
KPI Co-Design, Clustering & Prioritisation	Collaborative evaluation of KPI relevance, feasibility, and sector alignment using KPI cards. Participants cluster KPIs (Essential / Useful / Low priority), add missing KPIs, and refine definitions.	Prioritised KPI list per domain Identified feasibility barriers Recommendations for KPI refinement	60 mins
Governance & Policy Co-Creation	Structured small-group scenario exercises to design governance mechanisms, incentives, accountability structures, and risk mitigations for carbon-aware federated compute.	8–10 community-generated governance & policy recommendations Incentives matrix Risks + mitigation strategies	45 mins
Summary& Closing Reflection	Participants reflect on key insights and validate KPI relevance, vocabulary clarity, and governance proposals.	Final notes Top recommendations Unresolved issues flagged for Delphi	10 mins

Focus group discussion prompt questions

Surface real-world challenges, establish shared starting point, warm up participants for co-design.

- Where in built environment projects do you encounter the highest computational or data demands?
- What sustainability challenges arise when you use digital or compute-intensive tools in built environment projects?
- What are the biggest barriers that limit sustainable use of digital tools or computing in built environment?
- Are there opportunities where better computing infrastructure or governance could support the net-zero or circular economy goals in built environment?

- What principles should guide responsible and fair allocation of computing resources in built environment?

Vocabulary Harmonisation & Concept Mapping

Participants will review a set of pre-defined vocabulary cards, identify inconsistencies, clarify meanings, add missing terms, and map relationships between concepts.

Vocabulary Cards

- Carbon and Energy Intensity per Federated Compute Job
- Carbon Intensity per Core-Hour
- Renewable Energy Utilisation Ratio
- Carbon-Aware Scheduling
- Job Re-Routing for Carbon Reduction
- WLCA and Digital Twin Compute Carbon
- DPP Update Energy
- Circular Data Processing Carbon
- Data Retention Carbon Burden
- Data Provenance
- Semantic Interoperability
- Metadata Completeness
- Version Control
- Federated Interoperability
- Data Access Success
- API Federation Compatibility
- Machine-Readable Data
- Governance Maturity
- Cybersecurity Compliance
- Accountability Coverage
- Policy Implementation Readiness
- Decision Transparency
- Data Rights Management
- Inclusive Participation
- Procedural Fairness
- Community Trust
- Digital Readiness
- Power Usage Effectiveness (PUE)
- Uptime
- Mean Time to Recovery (MTTR)
- Scalability
- Queue Wait Time
- Waste Heat Recovery

Workflow

1: Individual Review of Vocabulary Cards

Participants review a set of 8–10 cards.

- Read each term and definition
- Mark: Clear, Unclear, Misleading or Inconsistent
- Add missing terms on blank cards

2: Group Harmonisation Discussion

Small groups (5 participants) discuss differences and propose edits.

Prompt questions

- Do you all agree on what this term means? If not, what differs?
- Is this definition usable across planning, design, HPC, and policy contexts?
- Could this definition be easily used in guidelines or regulation?
- Would non-technical stakeholders understand it?
- What misunderstandings cause delays or misalignment in projects?
- What terms should NFCS add to ensure complete coverage?

3: Concept Mapping
Groups map relationships between terms.
Prompt questions

- Which terms directly influence KPI measurement?
- Which terms belong together conceptually?
- Where do misunderstandings affect governance or policy?
- Which terms are essential for cross-sector interoperability?

Potential Concept Clusters

- Carbon & Compute
- Data & Interoperability
- Governance & Policy
- EDI & Capacity
- Infrastructure Performance

KPI Co-Design, Clustering & Prioritisation

This activity enables workshop participants to collaboratively refine and interpret the draft KPI catalogue, validate the clarity and usability of KPI definitions and vocabulary and cluster KPIs into meaningful logical groupings.
Workflow
1: Individual KPI Reflection
Participants receive 10–15 KPI Cards. Ask participants to sort cards into three piles:

- Green: Clear and relevant
- Yellow: Possibly relevant but unclear or complex
- Red: Not relevant / not feasible / not understandable

Prompt questions

- What does this KPI mean to you in practice?
- Could your organisation realistically measure this KPI?
- Would this KPI influence decisions in built environment sector?
- Which terms or concepts are unclear or confusing?
- Is any KPI missing for your practice?

2: Group KPI Clustering
Participants work in small groups (4–6). Groups place KPI cards into clusters based on how *they* logically relate KPIs.
Possible emergent clusters:

- Compute carbon & energy footprint
- Data quality & interoperability
- Governance and policy alignment
- Social equity, participation & capacity
- Operational performance
- Risk & resilience

Prompt questions

- Which KPIs naturally belong together in your workflow?
- Which KPIs represent similar sustainability ideas?

- Do any KPIs overlap or repeat each other?
- Which KPIs might be merged or simplified?
- Are any KPIs missing for your sector?

3: Feasibility & Impact Assessment
Groups evaluate each KPI cluster using two criteria:
Criterion A: Feasibility
Prompt: How feasible is it for your organisation or sector to measure this KPI?
Participants mark each KPI with 3 colour coding: Green = Feasible, Yellow = Somewhat feasible, Red = Not feasible / unrealistic.
Criterion B: Sustainability Impact
Prompt: How strongly does this KPI influence net-zero and circular economy outcomes?
Participants tag each KPI: High Impact (should be prioritised nationally), Medium Impact, Low Impact
Guided Discussion Questions

- What makes this KPI easy or difficult to measure?
- What data sources exist today to support this KPI?
- Would your organisation adopt this KPI if NFCS mandated or recommended it?
- Does this KPI meaningfully influence decisions?
- Which KPIs require new standards, governance, or digital infrastructure?
- Which KPIs raise concerns or unintended consequences?

4: KPI Prioritisation
Participants use priority voting to rank KPIs.
Prompt: Choose the KPIs that you believe should form the Core National KPI Set for sustainable, carbon-aware federated computing.
Prioritisation Questions

- Which KPIs are absolutely essential for NFCS success?
- Which KPIs should be recommended but optional?
- Which KPIs should be simplified, merged, or removed?
- Which KPIs are only relevant to niche users?

5: Whole-Group Validation
Participants reconvene to compare results.
Prompt questions

- Are there clear top-priority KPIs across all tables?
- Were there disagreements between groups? Why?
- Which KPIs need further clarification or redefinition?
- Should any KPIs be removed altogether?
- Does the combined set feel usable for practice?

Closing Questions

- *What three KPIs should NFCS implement first?*
- *Are there governance or policy barriers preventing KPI adoption?*
- *What must NFCS provide (tools/data/standards) to make KPI tracking possible?*

Governance & Policy Co-Creation

Participants will co-develop governance and policy recommendations needed for the design of a NFCS
Governance Themes

- Transparency & Accountability

- Access, Fairnss & Equity
- Incentives & Behavioural Mechanisms
- Data Governance & Ethics
- Federation Rules & Interoperability
- Policy Alignment

Workflow
1: Governance Mechanism Co-Design (15 minutes)
Participants work in small groups using Governance Canvas.
Governance Canvas:

- Carbon transparency requirements
- Job prioritisation rules
- Access policies
- Incentives & pricing
- Standardised reporting
- Data rights & privacy
- Lifecycle data stewardship
- Interoperability standards
- Risk management & audit
- Governance structure options
- Appeal & dispute processes
- Accountability mechanisms

Prompt questions

- What governance rules are required for carbon-aware scheduling?
- What access rules ensure fairness, especially for SMEs and local authorities?
- What incentives are appropriate to encourage sustainable compute?
- How should NFCS enforce lifecycle data stewardship?
- What governance mechanisms ensure data security and privacy?
- How should interoperability standards be set and maintained?
- Where should NFCS sit within UK policy frameworks?

2: Policy Scenario Testing
Participants test their proposed governance mechanisms using realistic policy scenarios.
Sample Scenarios

Scenario A – High-Carbon Simulation Request
Scenario B – SME With Limited Budget
Scenario C – Conflicting Priorities Between Sectors
Scenario D – Missing Metadata in DPP or WLCA

3: Policy Prioritisation & Validation
Participants use priority to identify the top 10–12 governance recommendations that NFCS must adopt.
Prompt questions

- Which governance rules are absolutely essential for NFCS?
- Which policies would drive the greatest sustainability impact?
- Which rules may be too burdensome or unrealistic?
- Which policies raise ethical or equity concerns?
- Which governance mechanisms require legislation or national-level guidance?

B3. Stakeholder Workshop Protocol

B2. Rapid Delphi Validation Protocol

Formal Expert Validation & Prioritisation of KPIs, Policy and Toolkit for NFCS
Purpose of the Delphi: To conduct structured expert consensus-building and formal validation of:

1. The Harmonised NFCS Vocabulary & KPI Catalogue
2. Policy & governance recommendations for carbon-aware federated computing
3. Usability, transferability, and practicality of the NFCS Engagement Toolkit

DELPHI ROUND 1: INITIAL EXPERT SCORING & ASSESSMENT

Duration: 15–20 minutes
Objective: Capture independent expert judgement on importance, feasibility, and clarity without peer influence.

Part A: Validation of NFCS Vocabulary (All Domains)

Experts score each vocabulary derived from co-design workshops:
For each vocabulary:
Carbon Intensity per Federated Compute Job (gCO_2e/job): Average lifecycle carbon emissions generated per individual compute job executed across the NFCS federation.

Vocabulary	1 (Very Low)	2	3	4	5 (Very High)
Definition is clear and unambiguous	☐	☐	☐	☐	☐
Definition is technically accurate	☐	☐	☐	☐	☐
Definition is suitable for national standardisation	☐	☐	☐	☐	☐

Open comment: *Please suggest any refinement if needed.*

Part B: KPI PRIORITISATION & IMPLEMENTABILITY

Experts score each KPI, which are organized by domain, with embedded vocabulary definitions derived from co-design workshops.
For each KPI:

KPI	1 (Very Low)	2	3	4	5 (Very High)
Strategic importance for NFCS	☐	☐	☐	☐	☐
Practical feasibility within 2 years	☐	☐	☐	☐	☐
Data availability today	☐	☐	☐	☐	☐
Policy relevance	☐	☐	☐	☐	☐

Open questions: *Is this KPI essential, desirable, or optional for NFCS launch?*

Part C: POLICY & GOVERNANCE RECOMMENDATION SCORING

Experts score each draft recommendation derived from co-design workshops.
For each policy or governance recommendation

Policy	1 (Very Low)	2	3	4	5 (Very High)
Policy relevance	☐	☐	☐	☐	☐
Institutional feasibility	☐	☐	☐	☐	☐
Alignment with UK regulation & NFCS remit	☐	☐	☐	☐	☐

Open question: *What legal, operational, or political risks do you foresee?*

Part D: ENGAGEMENT TOOLKIT USABILITY ASSESSMENT

For each toolkit component:

Tool	Usability (1–5)	Practicality (1–5)	Transferability (1–5)
KPI Worksheet	☐☐☐☐☐	☐☐☐☐☐	☐☐☐☐☐
Policy Co-Design Sheet	☐☐☐☐☐	☐☐☐☐☐	☐☐☐☐☐
Rapid Delphi Template	☐☐☐☐☐	☐☐☐☐☐	☐☐☐☐☐
Stakeholder Mapping Tool	☐☐☐☐☐	☐☐☐☐☐	☐☐☐☐☐

Open question: *Which tools should be core to all future NFCS sector engagements?*

DELPHI ROUND 2

CONSENSUS CONFIRMATION & FINAL RANKING

Objective: Resolve disagreements and lock final prioritised lists.

FEEDBACK

Each expert receives:

- Median scores for all vocabularies, KPIs, policies & tools
- Distribution graphs
- Anonymous summary of expert comments

Experts are asked:

- Do you confirm or revise your previous scores?
- Do you agree with the top-tier KPIs?
- Are any lower-ranked items strategically essential despite feasibility limits?

Appendix C. Complete harmonised vocabulary as a practical reference resource.

Group 1: Carbon, Resource & Sustainability Performance

Term	Harmonised Definition	Strategic Relevance
Carbon Intensity	Greenhouse gas emissions generated per unit of activity, energy use, service, or compute workload.	Core metric for benchmarking environmental performance and decarbonisation progress.
Compute Carbon	Total greenhouse gas emissions associated with digital workloads, data processing, storage, and computational services.	Makes hidden emissions from digital systems visible.
Embodied Carbon	Emissions arising from extraction, manufacture, transport, maintenance, and end-of-life of physical infrastructure or hardware.	Important for assessing server and equipment lifecycle impacts.
Operational Carbon	Emissions resulting from energy consumed during operation of compute, storage, and cooling systems.	Distinguishes use-phase impacts from embodied impacts.
Energy Intensity	Amount of energy consumed per unit of delivered service, output, or workload.	Key measure of efficiency and resource performance.
Renewable Energy Utilisation	Share of total energy demand supplied from certified renewable sources.	Tracks transition toward lower-carbon operations.
Carbon-Aware Optimisation	Use of scheduling, routing, or operational decisions to minimise carbon emissions while maintaining required performance.	Enables smarter and lower-impact federated computing.
Resource Efficiency	Delivery of required outcomes while minimising energy, water, materials, time, and waste.	Central principle of sustainable infrastructure management.
Water Intensity	Volume of water consumed per unit of compute activity, service output, or facility operation.	Important where cooling demand or water stress is significant.
Circularity	Keeping resources, components, and materials in productive use through reuse, repair, refurbishment, remanufacture, and recycling.	Reduces waste and lowers embodied impacts.
Lifecycle Burden	Total environmental impact accumulated across the full life cycle of an asset, service, infrastructure, or dataset.	Supports whole-life decision-making rather than short-term optimisation.

Sustainability Performance	Combined environmental, resource, and long-term operational outcomes of a system or service.	Provides a holistic sustainability view beyond single indicators.

Group 2: Data Federation, Interoperability & Digital Infrastructure

Term	Harmonised Definition	Strategic Relevance
Data Federation	Coordinated connection of distributed data sources, services, and systems so they can operate as one wider environment while remaining locally governed.	Core concept underpinning NFCS and cross-institutional collaboration.
Federated Computing	Coordinated use of distributed compute resources across multiple organisations or facilities through shared access, scheduling, and governance.	Enables efficient national compute capability.
Interoperability	Ability of systems, platforms, datasets, and organisations to exchange information and use it effectively.	Essential for collaboration, scaling, and avoiding silos.
Technical Interoperability	Compatibility of hardware, software, networks, APIs, and interfaces that allows systems to connect and function together.	Supports reliable technical integration across providers.
Semantic Interoperability	Shared meaning of data through common definitions, schemas, ontologies, and vocabularies.	Prevents misinterpretation across sectors and disciplines.
API Compatibility	Ability of application programming interfaces to exchange data and services using agreed protocols and standards.	Enables automation and machine-to-machine integration.
Data Quality	Degree to which data is accurate, complete, consistent, timely, and fit for intended use.	Poor data quality undermines trust and decision-making.
Metadata	Structured descriptive information explaining the content, source, format, ownership, and conditions of a dataset.	Improves discovery, governance, and reuse.
Data Provenance	Documented history of where data originated, how it changed, and who handled it over time.	Essential for trust, auditability, and reproducibility.

Version Control	Formal management of changes to datasets, models, or code through traceable revision history.	Prevents confusion, loss, and conflicting versions.
FAIR Data	Data managed so it is Findable, Accessible, Interoperable, and Reusable according to recognised good practice principles.	Widely accepted benchmark for modern data stewardship.
Data Access	Authorised ability of users or systems to retrieve and use data when required.	Fundamental to usability, productivity, and collaboration.
Identity and Access Management (IAM)	Systems and processes used to verify identities and control secure access to data, services, and infrastructure.	Critical for trusted multi-organisation federation.
Digital Infrastructure	Combined compute, storage, network, software, and enabling systems that support digital services, analytics, and data use.	Foundation of NFCS capability and future digital transformation.

Group 3: Governance, Policy & Trust

Term	**Harmonised Definition**	**Strategic Relevance**
Governance	Structures, rules, decision processes, and accountability mechanisms used to direct and oversee systems or organisations.	Foundation for credible and coordinated NFCS delivery.
Governance Maturity	Degree to which governance arrangements are formalised, effective, transparent, and continuously improved.	Indicates readiness for sustainable long-term operation.
Policy Alignment	Extent to which activities, services, and decisions support relevant public policy goals and strategic priorities.	Ensures NFCS contributes to national objectives.
Regulatory Compliance	Adherence to applicable laws, regulations, codes, and mandatory requirements.	Essential for lawful and low-risk operation.
Standards Conformance	Alignment with recognised technical, management, or reporting standards.	Improves consistency, interoperability, and assurance.
Governance Coordination	Effective collaboration between institutional, regional, national, and cross-sector decision-makers.	Supports coherent action across the federation.

Accountability	Clear assignment of responsibility for decisions, actions, performance, and outcomes.	Prevents governance gaps and improves delivery.
Decision Transparency	Degree to which decisions, criteria, and governance processes are documented, explainable, and open to scrutiny.	Builds trust and legitimacy.
Auditability	Ability for actions, data, calculations, or decisions to be independently reviewed and verified.	Critical for assurance and reporting credibility.
Ethics	Principles and practices ensuring actions are fair, responsible, and respectful of rights, wellbeing, and public interest.	Essential for trusted innovation and public confidence.
Data Rights Management	Protection of rights relating to personal data, consent, privacy, access, and lawful processing.	Central to responsible data governance.
Cybersecurity	Protection of systems, networks, and data from unauthorised access, attack, disruption, or misuse.	Essential for resilient national infrastructure.
Responsible AI Governance	Governance arrangements ensuring AI systems are lawful, transparent, fair, safe, accountable, and subject to human oversight.	Increasingly important for AI-enabled NFCS services.
Trust	Stakeholder confidence that systems, institutions, and decisions are competent, fair, secure, and reliable.	Core condition for adoption, collaboration, and legitimacy.

Group 4: Community, Inclusion & Capacity Building

Term	**Harmonised Definition**	**Strategic Relevance**
Community	Network of users, organisations, stakeholders, and partners who engage with, benefit from, or help shape NFCS.	Recognises NFCS as a socio-technical ecosystem, not only infrastructure.
Inclusion	Active removal of barriers so diverse individuals and organisations can participate meaningfully and benefit fairly.	Essential for equitable national impact.
Equity	Fair distribution of opportunities, resources, influence, and benefits	Goes beyond equal access to address structural imbalance.

	according to differing needs and starting positions.	
Representation	Extent to which participating groups reflect the diversity of relevant sectors, regions, and communities.	Prevents narrow decision-making and concentration of benefits.
Accessibility	Degree to which systems, events, tools, and opportunities are usable by people with diverse needs and abilities.	Ensures practical inclusion, not only nominal access.
Stakeholder Engagement	Structured interaction with relevant groups to inform design, decisions, delivery, and improvement.	Strengthens relevance, legitimacy, and adoption.
Co-Creation	Collaborative development of solutions, frameworks, tools, or policies with stakeholders rather than for them.	Improves ownership and quality of outcomes.
Knowledge Co-Production	Joint creation of knowledge by combining academic, technical, professional, policy, and lived experience perspectives.	Produces more robust and usable outcomes.
Community Trust	Stakeholder confidence in the fairness, competence, and value of NFCS processes and institutions.	Critical for long-term participation and uptake.
Capacity Building	Activities that strengthen skills, resources, systems, and confidence to participate effectively.	Enables broader and more capable user communities.
Digital Readiness	Preparedness of individuals or organisations to use digital tools, data systems, and federated services effectively.	Identifies capability gaps and support needs.
Cross-Disciplinary Integration	Effective collaboration between different professional or academic disciplines.	Essential for complex built environment challenges.
Procedural Fairness	Perception that processes are transparent, respectful, unbiased, and provide genuine opportunity to contribute.	Strengthens trust and legitimacy.
Societal Value	Positive social, environmental, economic, or public-interest outcomes created through NFCS activities.	Demonstrates wider return on investment.

Group 5: Operational Performance, Resilience & Value

Term	Harmonised Definition	Strategic Relevance
Operational Performance	Effectiveness and efficiency with which services, infrastructure, and processes deliver required outcomes.	Core measure of whether NFCS works in practice.
Capacity Management	Planning, allocating, and balancing compute, storage, network, and user demand against available resources.	Prevents shortages, waste, and poor service performance.
Reliability	Ability of systems or services to operate consistently without failure over time.	Fundamental for trusted national infrastructure.
Resilience	Ability to prepare for, absorb, adapt to, and recover from disruption while maintaining essential functions.	Critical for digital infrastructure continuity.
Disaster Recovery	Preparedness of systems, processes, backups, and recovery plans to restore operations after major incidents.	Reduces downtime and business continuity risk.
Climate Resilience of Infrastructure	Preparedness of facilities and systems for climate-related risks such as heat, flooding, storms, or grid instability.	Important for long-term infrastructure security.
Predictive Maintenance	Use of monitoring data and analytics to anticipate failures and optimise maintenance before breakdown occurs.	Improves uptime and reduces reactive maintenance cost.
Service Quality	User-facing quality of performance, responsiveness, reliability, accessibility, and support.	Determines satisfaction and continued adoption.
User Satisfaction	User perception of the usefulness, reliability, and quality of services received.	Essential feedback for continuous improvement.
Federation Operability	Ability of multiple facilities or providers to function together as one coordinated service environment.	Central to NFCS success as a federation.
Scalability	Ability to increase capacity, users, or workload demand without unacceptable loss of performance.	Essential for future growth.
Operational Automation	Use of automated processes for monitoring, provisioning, optimisation, or management tasks.	Improves efficiency, speed, and consistency.

Cost Efficiency	Ability to deliver required outcomes with optimal use of financial resources across the lifecycle.	Important for long-term sustainability and public value.
Value Creation	Combined operational, economic, environmental, and societal benefits generated by NFCS activities.	Captures outcomes beyond narrow cost measures.

Appendix D. National Sustainability KPI Framework and Implementation Metadata

Domain A: Carbon & Resource-Aware Federated Computing (Built Environment)

Category	Code	KPI	KPI Definition	Unit	Measurement Basis	Purpose	Data Source	Calculation Rule / Formula	Maturity	KPI Type	Frequency	Owner	Priority
Environmental Footprint Intensity	A1	Carbon Intensity per Federated Compute Job	Total greenhouse gas emissions generated by executing one compute job across the federation, accounting for energy source and location.	gCO_2e/job	Job-level energy × location-based carbon factor	Benchmark job-level carbon impact	Scheduler logs, energy meters, grid carbon data	Total compute CO_2e ÷ Total compute jobs	M4 - Federated	Quantitative	Monthly	Sustainability Lead	Core
	A2	Energy Intensity per Federated Compute Job	Total electrical energy consumed to complete one federated compute job.	kWh/job	Metered energy ÷ completed jobs	Quantify workload energy demand	Facility energy meters, job logs	Total compute electricity ÷ Total compute jobs	M4 - Federated	Quantitative	Monthly	Infrastructure Ops	Core
	A3	Carbon Intensity per Core-Hour	Carbon emissions associated with one CPU/GPU core-hour across participating facilities.	gCO_2e/core-hr	Total emissions ÷ total core-hours	Cross-facility benchmarking	Scheduler logs, carbon factors	Total compute CO_2e ÷ Total core-hours	M4 - Federated	Quantitative	Monthly	Sustainability Lead	Core
	A4	Renewable Energy Utilisation Ratio	Proportion of compute electricity demand met through certified renewable sources.	%	Renewable electricity ÷ total electricity	Track clean energy penetration	Energy procurement records, utility data	(Renewable kWh ÷ Total kWh) × 100	M3 - Operational	Quantitative	Quarterly	Facilities Manager	Core
	A5	Time-of-Use Carbon Differential	Relative difference in workload carbon intensity between high-carbon and low-carbon operating periods.	%	Peak CI vs off-peak CI	Identify benefits of temporal load shifting	Time-stamped carbon intensity data	((Peak CI − Off-peak CI) ÷ Off-peak CI) × 100	M3 - Operational	Quantitative	Monthly	Infrastructure Ops	Advanced
	A6	Water Intensity per Federated Compute Job	Water consumed directly or indirectly to execute one compute job, including cooling-related water where applicable.	L/job	Water attributable to compute operations ÷ jobs	Assess water footprint of digital workloads	Water meters, cooling logs, allocation models	Total compute-related water use ÷ Total jobs	M2 - Pilot	Quantitative	Quarterly	Facilities Manager	Advanced
	A7	Carbon Data Confidence Level	Reliability score of carbon calculations based on completeness, accuracy, granularity, timeliness, and traceability of source data.	Score (1-5)	Weighted quality assessment	Improve trust and auditability of carbon reporting	Carbon datasets, logs, metadata, audits	Weighted quality score normalised to 1-5	M2 - Pilot	Composite	Quarterly	Data Governance Lead	Advanced

Carbon-Aware Scheduling & Resource Optimisation	A8	Carbon-Aware Scheduling Adoption Rate	Proportion of jobs scheduled using real-time or forecast carbon signals.	%	Carbon-aware jobs ÷ total jobs	Track adoption of greener scheduling	Scheduler logs	(Carbon-aware jobs ÷ Total jobs) × 100	M2 - Pilot	Quantitative	Monthly	Platform Ops Lead	Core
	A9	Carbon-Optimised Job Allocation Ratio	Share of workloads allocated to the lowest-carbon feasible compute location while meeting service constraints.	%	Optimised jobs ÷ total jobs	Measure federation-wide optimisation	Orchestration data, scheduler logs	(Optimised jobs ÷ Total jobs) × 100	M2 - Pilot	Quantitative	Monthly	Federation Ops Lead	Core
	A10	Carbon Mitigation per Re-Scheduled Job	Average emissions reduction achieved when jobs are rescheduled or relocated for carbon optimisation.	gCO_2e/job	Baseline job emissions − optimised emissions	Quantify realised mitigation benefit	Scheduler logs, carbon dataset	Total avoided CO_2e ÷ Re-scheduled jobs	M2 - Pilot	Quantitative	Monthly	Sustainability Lead	Advanced
	A11	Scheduling Efficiency Gain	Improvement in operational efficiency achieved through carbon- and resource-aware scheduling.	%	Baseline vs optimised performance	Demonstrate multi-objective optimisation value	Performance analytics, scheduler logs	((Optimised performance − Baseline) ÷ Baseline) × 100	M2 - Pilot	Quantitative	Quarterly	Performance Lead	Advanced
	A12	Cross-Facility Workload Redistribution Rate	Share of jobs executed at a different facility than originally submitted to optimise performance, cost, or sustainability.	%	Cross-site jobs ÷ total jobs	Measure practical federation use	Federation orchestration logs	(Cross-site jobs ÷ Total jobs) × 100	M3 - Operational	Quantitative	Monthly	Federation Ops Lead	Advanced
Built Environment Workflow Impacts	A13	Compute Carbon per WLCA Assessment	Carbon emissions attributable to performing one whole-life carbon assessment.	gCO_2e/WLCA	Energy × carbon factor ÷ WLCA runs	Reveal digital carbon cost of WLCA workflows	WLCA platforms, NFCS logs	Total WLCA compute CO_2e ÷ WLCA runs	M3 - Operational	Quantitative	Quarterly	Built Environment Applications Lead	Core
	A14	Compute Carbon per Digital Twin Simulation	Carbon emissions attributable to running one digital twin simulation.	gCO_2e/run	Simulation energy × carbon factor	Measure digital twin compute impact	DT platform logs, facility energy data	Total DT compute CO_2e ÷ DT runs	M3 - Operational	Quantitative	Quarterly	Digital Twin Lead	Core
	A15	Compute Energy per DPP Lifecycle Update	Energy required to process one Digital Product Passport lifecycle update.	kWh/update	Measured update workload energy	Quantify DPP digital burden	DPP platform logs	Total DPP compute energy ÷ Updates	M2 - Pilot	Quantitative	Quarterly	DPP Lead	Advanced

	A16	Compute Load for Material Bank Processing	Average compute demand required for one material bank or reuse-cycle processing event.	CPU-h/event	CPU time per processing event	Quantify circular data workload intensity	Material bank systems	Total CPU-hours ÷ Processing events	M2 - Pilot	Quantitative	Quarterly	Circular Systems Lead	Advanced
	A17	Carbon Impact of Circular Data Processing	Carbon emissions from digital processes that enable reuse, recovery, matching, or circular asset decisions.	gCO_2e/event	Processing energy × carbon factor	Expose hidden carbon of circular workflows	Circular platforms, compute logs	Total circular data CO_2e ÷ Events	M2 - Pilot	Quantitative	Quarterly	Sustainability Lead	Advanced
Storage, Infrastructure & Lifecycle Burden	A18	Carbon Intensity of Federated Data Storage	Annual carbon emissions associated with storing 1 TB of federated data.	gCO_2e/TB/year	Storage energy × carbon factor	Monitor storage sustainability	Storage metrics, energy data	Annual storage CO_2e ÷ Total TB stored	M3 - Operational	Quantitative	Quarterly	Storage Lead	Core
	A19	Lifecycle Data Storage Carbon Burden per Asset	Total storage-related carbon emissions associated with retaining all digital records for one asset across its lifecycle.	gCO_2e/asset lifecycle	Annual storage burden across retention years	Support whole-life digital carbon accounting	Asset repositories, retention records	Total storage CO_2e linked to asset records	M2 - Pilot	Quantitative	Annual	Asset Information Manager	Advanced
	A20	Energy Intensity of Long-Term Data Retention	Annual energy required to preserve 1 TB of archived data over long durations.	kWh/TB/year	Storage power × uptime	Improve archival energy strategies	Archive systems, meters	Annual archive energy ÷ Total TB archived	M3 - Operational	Quantitative	Annual	Storage Lead	Advanced
	A21	Embodied Carbon per Compute Capacity Unit	Allocated embodied carbon of servers, GPUs, storage, and supporting infrastructure per unit of installed compute capacity.	$kgCO_2e$/core (or GPU)	Embodied carbon inventory ÷ installed capacity	Capture lifecycle infrastructure impacts beyond operational energy	Asset registers, EPDs, procurement records	Total embodied CO_2e ÷ Installed cores/GPUs	M1 - Conceptual	Quantitative	Annual	Procurement Lead	Advanced
	A22	Embodied Circularity of Compute Assets Ratio	Proportion of retired or renewed compute assets managed through reuse, refurbishment, remanufacture, recovery, or certified secondary deployment.	%	Circularly managed assets ÷ retired/renewed assets	Reduce e-waste and embodied carbon	Asset registers, ITAD records, supplier take-back logs	(Circularly managed assets ÷ Total retired or renewed assets) × 100	M2 - Pilot	Quantitative	Annual	Asset Manager	Advanced

Domain B: Data Interoperability, Quality & Federation Readiness

Category	Code	KPI	KPI Definition	Unit	Measurement Basis	Purpose	Data Source	Calculation Rule / Formula	Maturity	KPI Type	Frequency	Owner	Priority
Interoperability & Technical Integration	B1	Federated Data Interoperability Score	Composite measure of the technical, semantic, and operational ability of datasets and services to interoperate across NFCS environments.	0-5 Index	Audit scoring + standards assessment	Assess federation interoperability maturity	Technical audits, partner assessments	Weighted expert score (0-5)	M4 - Federated	Composite	Quarterly	Data Architecture Lead	Core
	B2	API Federation Compatibility Rate	Proportion of services and datasets accessible through NFCS-compliant APIs.	%	API-enabled assets / total assets	Measure machine-to-machine readiness	API registry	(Compliant APIs ÷ Total APIs) × 100	M4 - Federated	Quantitative	Quarterly	API Lead	Core
	B3	Cross-Platform Data Exchange Success Rate	Percentage of attempted cross-platform or cross-institution data transfers completed successfully.	%	Successful transfers / attempts	Evaluate robustness of data exchange	Transfer logs	(Successful transfers ÷ Total attempts) × 100	M4 - Federated	Quantitative	Monthly	Integration Lead	Core
	B4	Standards Compliance Level	Share of datasets compliant with recognised national or international standards.	%	Standards-compliant datasets / total datasets	Ensure conformity and interoperability	Metadata audits, repositories	(Compliant datasets ÷ Total datasets) × 100	M5 - Policy-Embedded	Quantitative	Annual	Data Governance Lead	Core
	B5	Semantic Interoperability Maturity Index	Degree to which shared vocabularies, ontologies, and schemas are aligned across federation partners.	0-5 Index	Ontology/schema assessment	Enable meaningful cross-domain integration	Schema registries, vocabularies	Weighted semantic maturity score	M3 - Operational	Composite	Quarterly	Data Standards Lead	Advanced
Data Quality, Trust & Assurance	B6	Data Quality Compliance Rate	Proportion of datasets meeting agreed thresholds for accuracy, completeness, consistency, and timeliness.	%	Quality-compliant datasets / total datasets	Improve reliability of analytics and decisions	QA tools, validation systems	(Compliant datasets ÷ Total datasets) × 100	M4 - Federated	Quantitative	Monthly	Data Quality Lead	Core

	B7	Metadata Completeness Rate	Percentage of datasets containing all mandatory descriptive, technical, and governance metadata fields.	%	Complete metadata records / total datasets	Improve discoverability and reuse	Metadata catalogues	(Complete records ÷ Total datasets) × 100	M4 - Federated	Quantitative	Monthly	Metadata Manager	Core
	B8	Data Provenance Traceability Score	Degree to which dataset origin, transformations, ownership, and handling history are auditable.	0-5 Index	Provenance audit scoring	Strengthen trust and reproducibility	Provenance logs, audit records	Weighted traceability score	M4 - Federated	Composite	Quarterly	Data Governance Lead	Core
	B9	Version Control Adoption Rate	Share of datasets managed under formal version control and change tracking systems.	%	Version-controlled datasets / total datasets	Prevent ambiguity and loss of historical records	Repositories, pipelines	(Versioned datasets ÷ Total datasets) × 100	M4 - Federated	Quantitative	Monthly	Data Platform Lead	Advanced
	B10	Error & Anomaly Detection Coverage	Proportion of datasets monitored through automated quality, anomaly, or integrity checks.	%	Monitored datasets / total datasets	Detect issues early	Monitoring pipelines	(Monitored datasets ÷ Total datasets) × 100	M3 - Operational	Quantitative	Monthly	Data Quality Lead	Advanced
Data Access, Reuse, Availability & Readiness	B11	Federated Data Access Success Rate	Percentage of authorised requests successfully accessing required data on first attempt.	%	Successful first-time requests / total requests	Assess federation usability	Access logs	(Successful first access ÷ Total requests) × 100	M4 - Federated	Quantitative	Monthly	Service Operations Lead	Core
	B12	Average Federated Data Access Time	Mean time between validated request and successful data retrieval.	Seconds	Time-stamped request logs	Measure responsiveness	Monitoring tools	Mean(retrieval time)	M4 - Federated	Quantitative	Monthly	Platform Performance Lead	Core
	B13	Cross-Federation Data Reuse Rate	Proportion of datasets reused across multiple institutions, projects, or workflows.	%	Reused datasets / total datasets	Measure value creation	Usage analytics	(Reused datasets ÷ Total datasets) × 100	M3 - Operational	Quantitative	Quarterly	Collaboration Lead	Advanced
	B14	Machine-Readable Data Availability Ratio	Proportion of datasets available in structured machine-readable formats suitable for automated processing.	%	Machine-readable datasets / total datasets	Enable automation and analytics	Data catalogues	(Machine-readable datasets ÷ Total datasets) × 100	M5 - Policy-Embedded	Quantitative	Quarterly	Data Platform Lead	Core

	B15	Long-Term Data Retention Readiness Index	Capability of NFCS systems to preserve and serve data reliably over long built-asset lifecycles.	0-5 Index	Storage resilience + governance audit	Support lifecycle data continuity	Archive audits	Weighted readiness score	M3 - Operational	Composite	Annual	Records Manager	Advanced
	B16	FAIR Discoverability Score	Extent to which datasets are searchable, indexed, uniquely identifiable, and easily discoverable across federated catalogues.	0-5 Index	FAIR assessment + catalogue audit	Improve findability and reuse	Catalogues, repositories	Weighted FAIR score	M3 - Operational	Composite	Quarterly	Metadata Lead	Advanced
	B17	Data Licensing Clarity Rate	Proportion of datasets with explicit, valid, and machine-readable licences defining reuse conditions.	%	Properly licensed datasets / total datasets	Reduce legal uncertainty	Repository records, licence metadata	(Licensed datasets ÷ Total datasets) × 100	M4 - Federated	Quantitative	Quarterly	Governance + Legal Lead	Core
	B18	Privacy-Preserving Access Readiness Index	Capability of federation systems to enable secure access using anonymisation, secure environments, federated analytics, or privacy-by-design controls.	0-5 Index	Security + governance audit	Enable compliant access to sensitive data	Security audits, access controls	Weighted readiness score	M3 - Operational	Composite	Quarterly	Information Security Lead	Core
	B19	AI-Ready Data Availability Ratio	Proportion of datasets suitable for AI use through sufficient quality, structure, labels, governance, and machine readability.	%	AI-ready datasets / total datasets	Support AI innovation	Metadata audits, AI pipeline reviews	(AI-ready datasets ÷ Total datasets) × 100	M3 - Operational	Quantitative	Quarterly	AI/Data Lead	Advanced
Federation Governance & Operational Readiness	B20	Federation Onboarding Readiness Score	Organisational readiness to join the NFCS federation technically, legally, and operationally.	0-5 Index	Onboarding assessment	Accelerate expansion	Onboarding reviews	Weighted readiness score	M3 - Operational	Composite	Quarterly	Federation Programme Manager	Core
	B21	IAM Federation Compatibility Rate	Proportion of partners compatible with federated identity and access management standards.	%	IAM-compliant partners / total partners	Enable secure cross-partner access	IAM records	(Compatible partners ÷ Total partners) × 100	M4 - Federated	Quantitative	Quarterly	IAM Lead	Core

	B22	Data Governance Alignment Rate	Proportion of participating organisations whose local data policies align with NFCS governance requirements.	%	Aligned organisations / reviewed organisations	Reduce fragmentation	Governance audits	(Aligned organisations ÷ Reviewed organisations) × 100	M3 - Operational	Quantitative	Annual	Data Governance Board	Core
	B23	Federated Data Service Uptime	Operational availability of federated data services across participating infrastructures.	%	Service uptime / scheduled time	Measure reliability	Service monitoring systems	(Operational time ÷ Scheduled time) × 100	M4 - Federated	Quantitative	Monthly	Service Operations Lead	Core
	B24	Incident Resolution Time for Federated Data Services	Average time required to resolve federated data access, interoperability, or service incidents.	Hours	Mean time to resolution	Assess resilience and support quality	Incident logs	Mean(time to resolution)	M3 - Operational	Quantitative	Monthly	Incident Manager	Core

Domain C: Governance, Policy & Regulatory Alignment

Category	Code	KPI	KPI Definition	Unit	Measurement Basis	Purpose	Data Source	Calculation Rule / Formula	Maturity	Validation Status	KPI Type	Measurement Frequency	Owner	Priority
Policy Alignment & Regulatory Conformance	C1	National Net-Zero Policy Alignment Index	Degree to which NFCS operational policies, services, investments, and governance mechanisms align with national net-zero strategies, carbon budgets, and decarbonisation pathways.	0-5 Index	Structured policy mapping against defined criteria	Ensure NFCS supports national climate objectives	NFCS policy documents, strategy papers, national climate policy documents	Mean expert score across alignment criteria (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Annual	Sustainability Governance Board	Core
	C2	Digital and Data Regulation Compliance Rate	Proportion of federated services, platforms, and processes compliant with applicable digital, data protection, privacy, and cybersecurity regulations.	%	Compliant services / total assessed services	Reduce legal exposure and ensure lawful operation	Compliance audits, legal reviews, assurance reports	(Compliant services ÷ Total assessed services) × 100	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Quarterly	Compliance Officer + Legal Lead	Core

	C3	International Standards Conformance Ratio	Share of federated processes, services, or datasets aligned with recognised international technical, management, or reporting standards.	%	Standards-conforming items / total assessed items	Enable interoperability, assurance, and external credibility	Standards audits, certification records, internal reviews	(Conforming items ÷ Total assessed items) × 100	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Annual	Standards & Compliance Lead	Core
	C4	Built Environment Regulatory Alignment Score	Degree to which federated computing governance and services align with built environment regulatory requirements relating to construction, planning, infrastructure, asset management, and sustainability reporting.	0-5 Index	Regulatory mapping and expert scoring	Ensure lawful sector integration and relevance	Built environment regulations, planning frameworks, policy reviews	Mean expert score across sector criteria (0-5)	M3 - Operational (Local)	Drafted - Pending Expert Validation	Composite	Annual	Built Environment Governance Lead	Core
	C5	Cross-Sector Policy Harmonisation Index	Level of coherence between NFCS governance and related policies across energy, infrastructure, innovation, research, and digital sectors.	0-5 Index	Comparative policy assessment	Reduce fragmentation and conflicting requirements	Cross-sector policy documents, strategic frameworks	Mean harmonisation score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Annual	Policy Lead / Strategy Board	Advanced
	C6	Green Public Procurement Alignment Rate	Proportion of procurement activities incorporating sustainability, low-carbon, circular economy, ethical sourcing, and social value criteria.	%	Sustainable procurements / total procurements	Embed sustainability through purchasing decisions	Procurement records, tender documents, supplier evaluations	(Aligned procurements ÷ Total procurements) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Annual	Procurement Lead	Advanced
	C7	Regulatory Horizon Scanning Readiness Index	Capability of governance systems to identify, assess, and prepare for emerging regulations, standards, and policy changes affecting federated computing.	0-5 Index	Maturity assessment of scanning processes	Improve future readiness and reduce disruption risk	Governance plans, monitoring reports, compliance reviews	Mean readiness score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Quarterly	Regulatory Affairs Lead	Core

Governance Maturity & Institutional Coordination	C8	Federation Governance Maturity Index	Overall maturity of NFCS governance structures, decision rights, escalation processes, assurance mechanisms, and accountability arrangements.	0-5 Index	Governance maturity framework assessment	Strengthen institutional robustness	Governance framework documents, board reviews	Mean maturity score (0-5)	M3 - Operational (Local)	Drafted - Pending Expert Validation	Composite	Annual	Governance Board Chair	Core
	C9	Multi-Level Governance Coordination Score	Effectiveness of coordination between organisational, regional, national, and cross-sector governance levels.	0-5 Index	Expert coordination assessment	Improve vertical and horizontal alignment	Coordination records, stakeholder feedback	Mean coordination score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Quarterly	Programme Director + Partner Board	Core
	C10	Partner Governance Compliance Rate	Proportion of participating organisations compliant with agreed federation governance requirements, operating rules, and reporting obligations.	%	Compliant partners / total partners	Ensure consistent governance across partners	Partner audits, compliance reviews	(Compliant partners ÷ Total partners) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Quarterly	Partner Assurance Manager	Core
	C11	Decision Transparency Level	Degree to which governance decisions, criteria, records, and rationales are documented, traceable, and appropriately accessible.	0-5 Index	Transparency audit and document review	Build trust and accountability	Governance minutes, repositories, decision logs	Mean transparency score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Quarterly	Governance Secretariat	Core
	C12	Policy Update Responsiveness Time	Average time required to revise governance policies or procedures following regulatory, strategic, or operational change triggers.	Months	Trigger date to approved update date	Measure adaptive governance capacity	Policy registers, change logs	Mean(Date approved update – Trigger date)	M2 - Pilot	Drafted - Pending Expert Validation	Quantitative	Quarterly	Policy Lead	Advanced
	C13	Inter-Partner Dispute Resolution Effectiveness Index	Effectiveness of formal mechanisms used to prevent, manage, and resolve governance, operational, or data-sharing disputes between partners.	0-5 Index	Case outcome and framework assessment	Maintain collaboration stability	Agreements, governance records, dispute logs	Mean effectiveness score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Annual / As Needed	Governance Board + Legal Lead	Advanced
Data Governance, Ethics & Assurance	C14	Ethics Compliance Certification Rate	Share of participating organisations holding valid ethics, research governance, or equivalent institutional approvals relevant to federation activities.	%	Certified partners / total partners	Ensure ethical legitimacy	Ethics boards, governance registers	(Certified partners ÷ Total partners) × 100	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Annual	Ethics & Governance Lead	Core

	C15	Consent and Data Rights Management Compliance	Proportion of relevant data processes compliant with consent, lawful basis, subject rights, retention, and privacy obligations.	%	Compliant processes / total assessed processes	Protect stakeholder and user rights	GDPR audits, privacy documentation, process reviews	(Compliant processes ÷ Total assessed processes) × 100	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Quarterly	Data Protection Officer	Core
	C16	Cybersecurity and Resilience Compliance Level	Degree to which infrastructure, systems, and operational controls align with recognised cybersecurity and digital resilience frameworks.	0-5 Index	Security maturity assessment	Safeguard critical infrastructure	Security audits, penetration tests, resilience reviews	Mean compliance score (0-5)	M4 - Federated	Drafted - Pending Expert Validation	Composite	Quarterly	CISO / Security Lead	Core
	C17	Auditability of Carbon and Compute Data	Degree to which carbon accounting, energy use, utilisation, and compute performance data can be independently verified and traced to source evidence.	0-5 Index	Audit readiness assessment	Support credible reporting and assurance	Carbon logs, metering data, audit trails	Mean auditability score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Quarterly	Audit Lead + Sustainability Lead	Core
	C18	Breach Management Effectiveness Index	Effectiveness of mechanisms for detecting, reporting, containing, responding to, and recovering from cybersecurity or data breaches.	0-5 Index	Incident lifecycle performance assessment	Strengthen resilience and trust	Incident registers, response reports	Mean effectiveness score (0-5)	M3 - Operational (Local)	Drafted - Pending Expert Validation	Composite	Quarterly	Security Lead + Incident Manager	Core
Incentives, Accountability & Delivery Readiness	C19	Low-Carbon Compute Incentive Adoption Rate	Share of participating organisations formally implementing incentives that encourage carbon-aware scheduling or low-carbon digital practices.	%	Incentive-adopting partners / total partners	Encourage behavioural change	Partner submissions, policy reviews	(Adopting partners ÷ Total partners) × 100	M1 - Conceptual	Drafted - Pending Expert Validation	Quantitative	Annual	Sustainability Lead + HR / Policy Lead	Advanced
	C20	Policy Implementation Readiness Index	Organisational readiness to operationalise federation governance requirements, policies, and recommended practices.	0-5 Index	Capability and readiness assessment	Improve likelihood of successful implementation	Self-assessments, audits, readiness reviews	Mean readiness score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Annual	Change Manager / Programme Office	Core

	C21	Compliance Enforcement Strength Index	Strength of governance enforcement mechanisms used to monitor compliance, apply corrective action, and address non-conformance.	0-5 Index	Enforcement framework assessment	Ensure policy credibility	Compliance procedures, governance controls	Mean enforcement score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Annual	Compliance Board	Core
	C22	Stakeholder Accountability Coverage	Proportion of governance roles with clearly assigned accountability, responsibility, and decision ownership.	%	Defined accountable roles / total governance roles	Improve governance clarity	Role registers, governance charts	(Roles with assigned accountability ÷ Total roles) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Annual	Governance Board Secretariat	Core
	C23	Cross-Federation Agreement Formalisation Rate	Share of required data-sharing, service, or governance agreements formally established across federation partners.	%	Formal agreements / total required agreements	Strengthen legal and operational stability	Contracts, MoUs, data-sharing agreements	(Formal agreements ÷ Total required agreements) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Annual	Legal Lead + Partnership Manager	Core
	C24	Responsible AI Governance Readiness Index	Degree to which governance systems are prepared to oversee AI through fairness, transparency, explainability, accountability, human oversight, and risk controls.	0-5 Index	AI governance maturity assessment	Ensure trustworthy AI deployment	AI policies, governance audits, model assurance records	Mean readiness score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Quarterly	AI Governance Lead	Core

Domain D: Community, Equity & Capacity Building (EDI)

Category	Code	KPI	KPI Definition	Unit	Measurement Basis	Purpose	Data Source	Calculation Rule / Formula	Maturity	Validation Status	KPI Type	Measurement Frequency	Owner	Priority

Representation, Access & Equity	D1	Inclusive Participation Rate	Proportion of participants from SMEs, local authorities, public sector bodies, and underrepresented groups engaged in NFCS activities.	%	Participants from target groups / total participants	Ensure representative and equitable engagement	Attendance logs, registration records, demographic surveys	(Participants from target groups ÷ Total participants) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Per Event / Quarterly	Community Engagement Lead	Core
	D2	Geographical Equity Index	Degree to which NFCS participation and engagement activities are distributed across regions, including devolved nations, rural areas, and underserved locations.	0-5 Index	Regional coverage mapping and scoring	Avoid spatial concentration of benefits	Event locations, participant postcodes, regional participation data	Mean expert score across regional coverage criteria (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Quarterly	Community Engagement Lead + EDI Lead	Core
	D3	Gender Balance Ratio	Distribution of participation across gender identities relative to agreed diversity or parity targets.	%	Representation by gender category / total participants	Promote inclusive and balanced participation	Equality monitoring forms, registration data	(Participants meeting diversity target criteria ÷ Total participants) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Quarterly	EDI Lead	Core
	D4	Early-Career Researcher (ECR) Inclusion Rate	Share of participants who are doctoral researchers, postdoctoral researchers, or early-career professionals within defined career-stage criteria.	%	ECR participants / total participants	Build future talent pipelines and next-generation capacity	Registration profiles, participant records	(ECR participants ÷ Total participants) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Quarterly	Research Culture / Training Lead	Core
	D5	SME Engagement Penetration	Percentage of participating organisations that are SMEs or micro-enterprises.	%	SME organisations / total participating organisations	Strengthen SME inclusion and innovation diffusion	Partner registers, organisational records	(SME organisations ÷ Total participating organisations) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Quarterly	Industry Engagement Lead	Core

	D6	Socio-Economic Inclusion Rate	Proportion of participants from low-resource institutions, underfunded organisations, deprived regions, or financially constrained groups engaged in NFCS activities.	%	Eligible participants / total participants	Reduce structural inequalities and widen opportunity	Registration data, institutional profiles, postcode indices, surveys	(Participants from target socio-economic groups ÷ Total participants) × 100	M2 - Pilot	Drafted - Pending Expert Validation	Quantitative	Quarterly	EDI Lead + Community Lead	Advanced
Engagement, Trust & Co-Creation Quality	D7	Stakeholder Retention Rate	Proportion of stakeholders who continue participating across multiple NFCS activities over time.	%	Repeat participants / total participants	Measure sustained community engagement	Attendance tracking, CRM systems	(Repeat participants ÷ Total participants) × 100	M2 - Pilot	Drafted - Pending Expert Validation	Quantitative	Quarterly	Community Engagement Lead	Core
	D8	Co-Creation Participation Intensity	Depth and quality of stakeholder involvement in co-creation activities such as workshops, Delphi studies, consultations, and design sessions.	0-5 Index	Facilitator assessment and participation scoring	Assess quality of participatory processes	Facilitator scoring sheets, workshop records	Mean participation intensity score (0-5)	M1 - Conceptual	Drafted - Pending Expert Validation	Composite	Per Workshop / Quarterly	Participation Lead / Facilitator Lead	Advanced
	D9	Community Trust Index	Stakeholder-reported level of trust in NFCS governance, methods, fairness, and neutrality.	0-5 Index	Post-engagement trust survey	Strengthen legitimacy and long-term participation	Stakeholder surveys, feedback forms	Mean trust score (0-5)	M1 - Conceptual	Drafted - Pending Expert Validation	Composite	Per Event / Biannual	Community Lead	Core
	D10	Knowledge Co-Production Index	Extent to which stakeholders actively shape KPIs, policies, recommendations, tools, and strategic outputs.	0-5 Index	Expert and participant scoring	Ensure genuine co-production	Workshop outputs, consultation records, Delphi data	Mean co-production score (0-5)	M1 - Conceptual	Drafted - Pending Expert Validation	Composite	Per Workshop / Quarterly	Co-Creation Lead	Core
	D11	Public Sector Engagement Rate	Participation level of municipalities, planners, regulators, government agencies, and public bodies in NFCS activities.	%	Public sector participants / total participants	Embed outcomes into public policy and planning	Registration records, attendee data	(Public sector participants ÷ Total participants) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Quarterly	Public Sector Partnerships Lead	Core

Skills, Capacity & Digital Readiness	D12	Carbon-Aware Computing Literacy Rate	Share of assessed participants demonstrating baseline understanding of carbon-aware computing principles and sustainable digital practices.	%	Correct responses in literacy assessment	Build a carbon-literate user community	Pre/post quizzes, learning assessments	(Literate respondents ÷ Total assessed respondents) × 100	M2 - Pilot	Drafted - Pending Expert Validation	Quantitative	Pre/Post Programme / Biannual	Training Lead	Core
	D13	Training Uptake Rate	Proportion of invited or eligible participants attending NFCS training, learning, or capability-building activities.	%	Training participants / total invited participants	Measure reach of capacity-building programmes	Training attendance records	(Training participants ÷ Total invited participants) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Quarterly	Training Lead	Core
	D14	Digital Infrastructure Readiness Index	Capacity of participating organisations to access and use federated digital infrastructure effectively.	0-5 Index	Self-assessment plus technical screening	Identify digital capability gaps	Organisation surveys, readiness assessments	Mean readiness score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Annual	Digital Capability Lead	Advanced
	D15	Cross-Disciplinary Skills Integration Score	Degree of collaboration and skills integration between computing, engineering, planning, policy, and sustainability participants.	0-5 Index	Collaboration pattern analysis and expert scoring	Foster socio-technical integration	Workshop interaction logs, programme reviews	Mean integration score (0-5)	M1 - Conceptual	Drafted - Pending Expert Validation	Composite	Per Programme / Annual	Skills & Innovation Lead	Advanced
	D16	Post-Engagement Capability Growth	Improvement in participant knowledge, confidence, or practical capability following engagement or training activities.	%	Pre/post capability assessment	Measure learning and development impact	Questionnaires, capability surveys	((Post score − Pre score) ÷ Pre score) × 100	M2 - Pilot	Drafted - Pending Expert Validation	Quantitative	Pre/Post Programme	Training Lead + Evaluation Lead	Core
	D17	Behaviour Change Adoption Score	Extent to which participants apply carbon-aware computing, sustainable data practices, or governance improvements after training or engagement.	0-5 Index	Follow-up survey and behavioural evidence scoring	Measure real-world impact beyond awareness	Follow-up surveys, case studies, practice logs	Mean adoption score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	6-Month Follow-up / Annual	Evaluation Lead	Advanced
Fairness, Inclusion & Societal Impact	D18	Procedural Fairness Index	Perceived fairness, transparency, respect, and opportunity to influence within NFCS participation processes.	0-5 Index	Fairness perception survey	Ensure ethical and inclusive engagement	Feedback forms, participant surveys	Mean fairness score (0-5)	M1 - Conceptual	Drafted - Pending Expert Validation	Composite	Per Event / Annual Review	EDI Lead	Core

	D19	Barrier Reduction Effectiveness Score	Effectiveness of measures designed to reduce digital, financial, geographic, institutional, or cultural participation barriers.	0-5 Index	Before/after barrier assessment	Improve access for disadvantaged groups	Access audits, surveys, feedback reports	Mean effectiveness score (0-5)	M1 - Conceptual	Drafted - Pending Expert Validation	Composite	Annual	Inclusion Lead + Programme Manager	Advanced
	D20	Policy Influence Inclusivity Index	Degree to which diverse stakeholder voices are reflected in governance outputs, recommendations, and policy proposals.	0-5 Index	Diversity analysis of contributors and outputs	Ensure equitable policy shaping	Drafting records, consultation evidence	Mean inclusivity score (0-5)	M1 - Conceptual	Drafted - Pending Expert Validation	Composite	Annual	Governance Lead + Community Lead	Core
	D21	Societal Value Creation Index	Stakeholder-perceived social, environmental, economic, and public-interest value generated through NFCS activities.	0-5 Index	Post-project value perception survey	Capture wider public benefit	Impact surveys, evaluation reports	Mean value score (0-5)	M1 - Conceptual	Drafted - Pending Expert Validation	Composite	Annual	Impact Lead	Core
	D22	Long-Term Community Sustainability Score	Likelihood that NFCS networks, partnerships, and engagement communities remain active and valuable beyond initial funding.	0-5 Index	Longitudinal engagement intention survey	Assess durability of community outcomes	Follow-up surveys, network analytics	Mean stakeholder score on continued engagement likelihood (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Annual	Community Lead + Programme Director	Advanced
	D23	Accessibility Inclusion Score	Degree to which NFCS events, tools, digital platforms, communications, and engagement processes are accessible to people with disabilities and diverse access needs.	0-5 Index	Accessibility audit and participant feedback scoring	Ensure equitable participation and inclusive design	Accessibility audits, participant surveys, event evaluations	Mean accessibility score (0-5)	M2 - Pilot	Drafted - Pending Expert Validation	Composite	Per Event / Annual Review	Accessibility Lead + EDI Lead	Core
	D24	Stakeholder Satisfaction with Engagement Outcomes	Stakeholder satisfaction with the usefulness, relevance, quality, and practical value of NFCS engagement outputs, tools, and recommendations.	0-5 Index	Post-engagement satisfaction survey	Improve quality of engagement processes and outputs	Feedback forms, evaluation surveys, workshop reviews	Mean participant satisfaction score (0-5)	M3 - Operational (Local)	Drafted - Pending Expert Validation	Composite	Per Event / Quarterly	Community Lead + Evaluation Lead	Core

Domain E: Operational Performance & Infrastructure Efficiency

Category	Code	KPI	KPI Definition	Unit	Measurement Basis	Purpose	Data Source	Calculation Rule / Formula	Maturity	Validation Status	KPI Type	Measurement Frequency	Owner	Priority
Compute Utilisation & Capacity Efficiency	E1	Average Compute Utilisation Rate	Proportion of total available federated compute capacity actively used over a defined period.	%	Used core-hours / total available core-hours	Assess efficiency of resource utilisation	HPC monitoring systems, scheduler logs	(Used core-hours ÷ Total available core-hours) × 100	M5 - Policy-Embedded	Drafted - Pending Expert Validation	Quantitative	Real-time / Monthly	Infrastructure Ops Lead	Core
	E2	Idle Capacity Ratio	Share of available compute resources remaining unused during operational periods.	%	Unused core-hours / total available core-hours	Identify underutilisation and optimisation opportunities	Scheduler logs	(Unused core-hours ÷ Total available core-hours) × 100	M5 - Policy-Embedded	Drafted - Pending Expert Validation	Quantitative	Real-time / Monthly	Infrastructure Ops Lead	Core
	E3	Job Throughput Rate	Number of compute jobs successfully completed within a defined time period across the federation.	Jobs/day	Total completed jobs per day	Measure operational productivity	Job scheduler records	Total completed jobs ÷ Number of days	M5 - Policy-Embedded	Drafted - Pending Expert Validation	Quantitative	Daily / Monthly	Scheduler Operations Lead	Core
	E4	Queue Wait Time	Average time between job submission and execution across the federation.	Hours	Mean waiting time from submission to execution	Evaluate service responsiveness	Scheduler timestamps	Mean(Execution start time − Submission time)	M5 - Policy-Embedded	Drafted - Pending Expert Validation	Quantitative	Real-time / Monthly	Scheduler Operations Lead	Core
	E5	Peak Load Management Efficiency	Effectiveness of maintaining acceptable service performance during periods of peak demand.	%	Peak demand successfully served / total peak demand	Assess load-balancing capability	Infrastructure performance logs	(Peak demand served within SLA ÷ Total peak demand) × 100	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Real-time / Monthly	Platform Performance Lead	Core

	E6	Capacity Forecast Accuracy	Accuracy of projected compute, storage, or user demand compared with actual observed demand.	%	Forecast variance vs actual demand	Improve planning and reduce over/under-provisioning	Capacity planning reports, dashboards, usage logs	(1 − ABS(Forecast − Actual) ÷ Actual) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Quarterly	Capacity Planning Lead	Advanced
Energy, Cooling & Environmental Efficiency	E7	Power Usage Effectiveness (PUE)	Ratio of total facility energy use to IT equipment energy use.	Ratio	Total facility energy / IT energy	Benchmark data-centre energy efficiency	Energy meters, BMS systems	Total facility energy ÷ IT equipment energy	M5 - Policy-Embedded	Drafted - Pending Expert Validation	Quantitative	Monthly	Facilities Manager	Core
	E8	Cooling Energy Intensity	Energy consumed for cooling per unit of data-centre floor area over a defined period.	$kWh/m^2/year$	Cooling energy / floor area	Evaluate cooling efficiency	Facility energy records	Annual cooling energy ÷ Data hall floor area	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Monthly / Annual	Facilities Manager	Core
	E9	Waste Heat Recovery Rate	Proportion of rejected heat recovered for productive secondary use.	%	Recovered heat / total rejected heat	Promote circular energy use	Facility energy systems	(Recovered heat ÷ Total rejected heat) × 100	M3 - Operational (Local)	Drafted - Pending Expert Validation	Quantitative	Quarterly	Sustainability Lead + Facilities Manager	Advanced
	E10	Dynamic Cooling Optimisation Index	Maturity of adaptive cooling systems that respond to real-time workload and environmental conditions.	0-5 Index	Expert audit of cooling controls	Improve energy-responsive operations	Facility audits, BMS data	Mean expert score (0-5)	M3 - Operational (Local)	Drafted - Pending Expert Validation	Composite	Quarterly	Facilities Manager + Controls Engineer	Advanced
	E11	Facility Energy Efficiency Improvement Rate	Year-on-year improvement in facility-wide energy performance.	%/year	Annual change in energy intensity or consumption	Track long-term efficiency progress	Utility and facility energy records	((Previous year − Current year) ÷ Previous year) × 100	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Annual	Sustainability Lead + Facilities Manager	Core
	E12	Renewable Operational Energy Ratio	Proportion of operational electricity consumed by NFCS infrastructure sourced from certified renewable energy.	%	Renewable electricity / total electricity	Track clean energy transition	Utility bills, procurement records, smart meters	(Renewable electricity ÷ Total electricity consumed) × 100	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Quarterly	Energy Manager + Procurement Lead	Core

Reliability, Resilience & Service Quality	E13	Infrastructure Uptime	Percentage of time federated compute nodes and services remain available and operational.	%	Operational time / scheduled time	Measure system reliability	Infrastructure monitoring systems	(Operational time ÷ Scheduled time) × 100	M5 - Policy-Embedded	Drafted - Pending Expert Validation	Quantitative	Real-time / Monthly	Service Operations Lead	Core
	E14	Mean Time Between Failures (MTBF)	Average operating time between unplanned failures.	Hours	Total uptime / number of failures	Assess infrastructure robustness	Incident logs	Total uptime hours ÷ Failure events	M5 - Policy-Embedded	Drafted - Pending Expert Validation	Quantitative	Monthly	Reliability Engineer	Core
	E15	Mean Time to Recovery (MTTR)	Average time required to restore service after failure or disruption.	Hours	Total recovery time / incidents	Measure resilience and recovery capability	Incident response logs	Total recovery time ÷ Number of incidents	M5 - Policy-Embedded	Drafted - Pending Expert Validation	Quantitative	Monthly	Incident Manager	Core
	E16	Service Disruption Frequency	Number of unplanned outages or major service interruptions over a defined period.	Events/year	Count of outages	Monitor reliability risk	Service management records	Count(service outage events)	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Monthly / Annual	Service Operations Lead	Core
	E17	Disaster Recovery Readiness Score	Level of preparedness for cyber, power, climate, or infrastructure disruptions.	0-5 Index	Audit of DR plans, redundancy, backups, testing	Strengthen federation resilience	Business continuity audits	Mean readiness score (0-5)	M4 - Federated	Drafted - Pending Expert Validation	Composite	Annual	Risk & Resilience Lead	Core
	E18	User Satisfaction with Service Performance	Degree of user satisfaction with responsiveness, reliability, usability, and overall quality of NFCS services.	0-5 Index	Post-service user survey	Capture user experience and service quality	User feedback surveys, helpdesk reviews	Mean user satisfaction score (0-5)	M3 - Operational (Local)	Drafted - Pending Expert Validation	Composite	Quarterly	Service Manager + User Support Lead	Advanced
	E19	Predictive Maintenance Readiness Index	Maturity of systems and processes using monitoring data and analytics to predict failures and optimise maintenance.	0-5 Index	Capability assessment	Improve uptime and reduce reactive maintenance	CMMS systems, IoT sensors, audits	Mean readiness score (0-5)	M3 - Operational (Local)	Drafted - Pending Expert Validation	Composite	Quarterly	Maintenance Lead + Asset Manager	Advanced

	E20	Climate Resilience of Infrastructure Index	Degree to which NFCS facilities and infrastructure can withstand, adapt to, and recover from climate-related disruptions.	0-5 Index	Climate risk audit and resilience assessment	Reduce long-term climate risk	Climate risk reports, audits, continuity plans	Mean resilience score (0-5)	M3 - Operational (Local)	Drafted - Pending Expert Validation	Composite	Annual	Risk & Resilience Lead + Facilities Manager	Advanced
Federation Operability & System Integration	E21	Cross-Facility Scheduling Success Rate	Share of cross-facility jobs successfully scheduled and completed across NFCS sites.	%	Successful cross-site jobs / total cross-site jobs	Measure federation operability	Scheduler federation logs	(Successful cross-site jobs ÷ Total cross-site jobs) × 100	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Monthly	Federation Ops Lead	Core
	E22	System Interoperability Performance Index	Effectiveness of middleware, APIs, orchestration layers, and service integration across the federation.	0-5 Index	Technical testing and audit scoring	Support seamless federation integration	Middleware tests, integration logs	Mean interoperability score (0-5)	M4 - Federated	Drafted - Pending Expert Validation	Composite	Quarterly	Integration Architect	Core
	E23	Data Transfer Latency	Average delay for inter-facility data movement.	ms	Mean transfer latency	Assess network performance	Network monitoring tools	Mean(inter-facility transfer latency)	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Real-time / Monthly	Network Operations Lead	Core
	E24	Platform Scalability Index	Ability to expand compute, storage, users, and workload demand without unacceptable performance loss.	0-5 Index	Stress testing and expert audit	Support future federation growth	Infrastructure scaling tests	Mean scalability score (0-5)	M3 - Operational (Local)	Drafted - Pending Expert Validation	Composite	Annual	CTO / Infrastructure Strategy Lead	Advanced
	E25	Operational Automation Level	Proportion of infrastructure management processes that are automated.	%	Automated processes / total processes	Improve operational efficiency and consistency	IT operations records	(Automated processes ÷ Total management processes) × 100	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Quarterly	IT Operations Lead	Advanced

Cost Efficiency & Operational Sustainability	E26	Cost per Compute Job	Average direct operational cost of executing one compute job.	£/job	Total compute OPEX / total jobs	Monitor economic efficiency	Finance and operations records	Total compute operational cost (£) ÷ Total compute jobs	M5 - Policy-Embedded	Drafted - Pending Expert Validation	Quantitative	Quarterly	Finance Lead + Ops Lead	Core
	E27	Energy Cost per Core-Hour	Electricity cost associated with one compute core-hour.	£/core-hr	Energy cost / total core-hours	Track energy-cost efficiency	Utility bills, scheduler logs	Total energy cost ÷ Total core-hours	M5 - Policy-Embedded	Drafted - Pending Expert Validation	Quantitative	Monthly	Finance Lead + Energy Manager	Core
	E28	Maintenance Cost Efficiency Ratio	Share of maintenance cost as a proportion of total operational expenditure.	Ratio	Maintenance cost / total OPEX	Benchmark asset management efficiency	Finance records	Maintenance cost ÷ Total operational expenditure	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Quarterly	Finance Lead + Asset Manager	Advanced
	E29	Carbon Cost Exposure	Financial exposure associated with carbon pricing, emissions charges, or internal carbon valuation.	£/tCO_2e	Carbon-related cost / emissions	Inform carbon-aware investment decisions	Carbon accounts, finance records	Total carbon-related charges (£) ÷ Total tCO_2e	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Quarterly	Sustainability Lead + Finance Lead	Advanced
	E30	Total Cost of Ownership (TCO) Reduction Rate	Annual improvement in lifecycle infrastructure cost efficiency compared with baseline.	%/year	Change in lifecycle cost over time	Support long-term financial sustainability	Lifecycle costing models, finance data	((Baseline TCO − Current TCO) ÷ Baseline TCO) × 100	M4 - Federated	Drafted - Pending Expert Validation	Quantitative	Annual	Finance Director + Programme Board	Core

Appendix E. Detailed Profiles of the NETZERO National Recommendations

NETZERO-1: Adopt a Harmonised Sustainability Vocabulary for Federated Computing

Recommendation Classification	
Category	Must Have
Priority	High
Expected Impact	High
Implementation Complexity	Low
Resource Requirement	Low
NFCS Pillar	Primary: Governance Secondary: Community, Technology
Recommendation Profile	
Recommendation	NFCS should establish, maintain and periodically review a Harmonised Sustainability Vocabulary for Federated Computing that provides standardised definitions, terminology and conceptual mappings across sustainability, carbon management, resource efficiency, interoperability, governance, digital infrastructure and built environment applications. The vocabulary should be adopted as a common reference across NFCS activities and embedded within governance frameworks, sustainability reporting, KPI implementation, onboarding, training, stakeholder engagement and future federation services.
Rationale	The NETZERO project identified significant inconsistency in the interpretation of sustainability and compute-related terminology across stakeholder groups, creating barriers to collaboration, interoperability, benchmarking, governance implementation, and decision-making. Survey findings, workshops, co-creation activities, and expert consultations consistently highlighted the need for a common language capable of bridging technical and non-technical communities. To address this challenge, the project developed a Harmonised Sustainability Vocabulary aligned with UK policies, built environment frameworks, international standards, and sustainability-focused computing practices. The vocabulary provides a foundation for consistent KPI implementation, sustainability assessment, stakeholder onboarding, and roadmap delivery across federated computing environments.
Evidence Base	
Survey Findings	Only 23% agreement that sustainability and compute-related terminology is interpreted consistently across projects. Standardised KPI definitions across organisations were identified as a priority improvement area (RII = 94%). Current KPI clarity and usability for decision-making was low (RII = 24%).
Requirements Gathering and Needs Analysis	Stakeholder mapping identified terminology inconsistency as a recurring barrier to collaboration across technical, policy, and built environment communities.
Community Engagement and Co-Creation Activities	Participants prioritised a common sustainability language to improve communication, reporting, and interoperability.
Rapid Delphi Validation	Experts consolidated and validated key sustainability, governance, interoperability, and federation terminology for inclusion in the final vocabulary.

SustainFed Validation Activities	Scenario-based testing demonstrated that standardised terminology improved assessment consistency and recommendation transparency.
Alignment with Standards, Policies and Initiatives	
UK Policies and Initiatives	UK Net Zero Strategy; Climate Change Act; Construction Playbook; Government Workplace Design Guide
Built Environment Frameworks	UK BIM Framework; Information Management Framework; RICS Whole Life Carbon Assessment; UKGBC Net Zero Carbon Framework
International Standards	ISO 19650, 14040-14044, 50001, 55000, 27001; EN 15978
European Frameworks	European Green Deal; Circular Economy Action Plan; Ecodesign for Sustainable Products Regulation (ESPR); Construction Products Regulation; Energy Performance of Buildings Directive (EPBD); Level(s)
National Infrastructure Initiatives	NFCS; NetDRIVE; DAFNI; UKCRIC; National Digital Twin Programme
Research and Knowledge Sources	Sustainability terminology harmonisation; federated computing governance; digital infrastructure sustainability; carbon accounting and lifecycle assessment literature.
Contribution, Outputs and Outcomes	
Sustainability and Carbon Contribution	Direct carbon savings cannot be quantified because this is an enabling recommendation. However, it supports consistent carbon accounting, lifecycle assessment, sustainability KPI implementation, benchmarking, and reporting across federated environments.
Supporting Project Outputs	Harmonised Sustainability Vocabulary; survey findings; stakeholder engagement and co-creation activities; policy and standards mapping; SustainFed Assessment Platform.
Relevant KPI Domains	Domain A: Medium; Domain B: High; Domain C: High; Domain D: High; Domain E: Medium.
Expected Outcome	A shared sustainability language that improves interoperability, governance consistency, stakeholder communication, KPI implementation, sustainability reporting and decision-making across federated computing ecosystems.
Roadmap Implementation	
Start Timing	Year 1
Duration	Initial development and adoption during Years 1-2, followed by ongoing review and updates.
Short-Term Activities	Establish a vocabulary governance/review group; publish Version 1.0; integrate terminology into NFCS documentation, onboarding materials and stakeholder engagement resources.
Medium-Term Activities	Align the vocabulary with the KPI framework, governance activities, training resources, SustainFed and future federation services.
Long-Term Activities	Maintain the vocabulary as a living resource and update it to reflect emerging standards, technologies, regulations and federation requirements.
Dependencies	NFCS governance structures; stakeholder participation; expert review; alignment with UK and international standards; integration with KPI framework and governance development activities.
Resource Implications	*Personnel:* 0.2-0.5 FTE sustainability/governance specialist. *Cost:* Low. *Expertise:* sustainability, governance, federated computing, and digital

	infrastructure. *External alignment:* NFCS, NetDRIVE, DAFNI, UKCRIC, National Digital Twin Programme, and UK BIM Framework.
Contribution to the NFCS Roadmap	Establishes the common terminology required to support governance, KPI implementation, sustainability assessment, interoperability, onboarding, and stakeholder engagement across the NFCS roadmap.

NETZERO-2: Establish a National Sustainability KPI Framework for Federated Computing

Recommendation Classification	
Category	Must Have
Priority	High
Expected Impact	High
Implementation Complexity	Medium
Resource Requirement	Medium
NFCS Pillar	Primary: Governance Secondary: Technology, Community
Recommendation Profile	
Recommendation	NFCS should establish and maintain a National Sustainability KPI Framework for Federated Computing that provides a standardised approach for assessing, benchmarking, monitoring and reporting sustainability performance across federated digital research infrastructures. The framework should be adopted as the primary mechanism for sustainability assessment, performance benchmarking, governance monitoring, roadmap evaluation and continuous improvement across NFCS services and participating organisations.
Rationale	The NETZERO project identified significant inconsistency in sustainability measurement and reporting across computing environments. Stakeholders reported difficulties in assessing carbon impacts, comparing infrastructure performance, evaluating governance maturity, and demonstrating sustainability improvements. Existing approaches were often fragmented, organisation-specific, and unsuitable for federation-wide benchmarking. To address this challenge, the project developed and validated a National Sustainability KPI Framework comprising 124 KPIs organised across five domains covering carbon and resource efficiency, interoperability and federation readiness, governance and policy alignment, community and capacity building, and operational performance. The framework provides a consistent and evidence-based foundation for sustainability assessment across federated computing ecosystems.
Evidence Base	
Survey Findings	Lack of harmonised KPIs was identified as a significant barrier (RII = 56%). Standardised KPI definitions achieved very high support (RII = 94%). Clear linkage between KPIs and net-zero targets achieved strong support (RII = 94%).

Requirements Gathering and Needs Analysis	Stakeholders identified the need for a common KPI structure capable of supporting benchmarking, reporting, and federation performance assessment.
Community Engagement and Co-Creation Activities	KPI co-creation workshops prioritised measurable, auditable, and transferable indicators across environmental, governance, operational, and social dimensions.
Rapid Delphi Validation	Experts refined, clustered, and validated the final 124-KPI framework across five domains.
SustainFed Validation Activities	Platform testing confirmed the practical applicability of KPI-driven assessments across diverse federation scenarios.
Alignment with Standards, Policies and Initiatives	
UK Policies and Initiatives	UK Net Zero Strategy; Climate Change Act; Construction Playbook; Government Workplace Design Guide
Built Environment Frameworks	UK BIM Framework; Information Management Framework; RICS Whole Life Carbon Assessment; UKGBC Net Zero Carbon Framework
International Standards	ISO 19650, 14040-14044, 50001, 55000, 27001, 37301; EN 15978
European Frameworks	European Green Deal; Circular Economy Action Plan; ESPR; Construction Products Regulation; EPBD; Level(s)
National Infrastructure Initiatives	NFCS; NetDRIVE; DAFNI; UKCRIC; National Digital Twin Programme
Research and Knowledge Sources	HPC sustainability frameworks; Green Software Foundation principles; Cloud Carbon Footprint methodologies; sustainability performance measurement and federated computing assessment literature.
Contribution, Outputs and Outcomes	
Sustainability and Carbon Contribution	Supports the measurement and management of sustainability performance across NFCS infrastructures by enabling carbon accounting, resource-efficiency assessment, lifecycle sustainability evaluation, governance monitoring, interoperability assessment, and organisational capability tracking. The framework provides the basis for quantifying future carbon reductions and sustainability improvements using recognised metrics, including tCO_2e.
Supporting Project Outputs	National Sustainability KPI Framework; SustainFed Assessment and Recommendation Engines; stakeholder survey findings; community engagement activities; policy and standards mapping; governance and federation readiness framework.
Relevant KPI Domains	Domain A: High; Domain B: High; Domain C: High; Domain D: High; Domain E: High.
Expected Outcome	A nationally consistent sustainability assessment and benchmarking framework that enables evidence-based decision-making, transparent reporting, performance comparison and continuous improvement across federated computing infrastructures.
Roadmap Implementation	
Start Timing	Year 1
Duration	Initial adoption during Years 1-2, followed by integration and refinement through Years 3-5.
Short-Term Activities	Adopt KPI framework baseline; establish governance arrangements; publish Version 1.0; undertake pilot assessments; develop reporting templates and benchmarking procedures.

Medium-Term Activities	Integrate KPIs into NFCS services, SustainFed, dashboards, onboarding processes, governance reviews, federation readiness assessments and infrastructure evaluations.
Long-Term Activities	Establish national sustainability benchmarking capability; implement reporting mechanisms; align framework with emerging technologies, policies and federation requirements; periodically review and update indicators.
Dependencies	Harmonised Sustainability Vocabulary (NETZERO-1); NFCS governance and reporting structures; stakeholder validation; availability of sustainability and operational data; integration with federation monitoring platforms; alignment with evolving standards and regulations.
Resource Implications	*Personnel:* 1-2 FTE sustainability, data and federation specialists.. *Cost:* Medium. *Expertise:* sustainability assessment, federated computing, governance, interoperability, data analytics and built environment. *External alignment:* NFCS, DAFNI, NetDRIVE, UKCRIC, National Digital Twin Programme and UK BIM Framework.
Contribution to the NFCS Roadmap	Establishes the measurement and benchmarking foundation of the NFCS roadmap, enabling consistent performance evaluation, sustainability reporting, governance monitoring, and progress tracking towards net-zero and federation objectives.

NETZERO-3: Embed Carbon- and Resource-Aware Decision-Making into Federated

Recommendation Classification	
Category	Must Have
Priority	High
Expected Impact	High
Implementation Complexity	Medium-High
Resource Requirement	Medium-High
NFCS Pillar	Primary: Technology Secondary: Governance
Recommendation Profile	
Recommendation	NFCS should embed carbon- and resource-aware decision-making mechanisms into federated infrastructure operations to optimise workload scheduling, resource allocation, storage management and infrastructure utilisation using sustainability criteria alongside performance, availability and cost.
Rationale	The NETZERO project identified strong stakeholder support for reducing the environmental impact of compute-intensive activities and improving transparency around carbon emissions, energy consumption and resource use. Current infrastructure management practices often prioritise performance, availability and cost, while sustainability is rarely embedded into operational decisions. As demand grows for digital twins, AI, simulation, lifecycle assessment and Digital Product Passport workflows, NFCS should integrate carbon-aware scheduling, renewable-energy-aware workload placement, resource optimisation, workload consolidation and storage-efficiency management to ensure

	future services actively optimise both operational and sustainability outcomes.
Evidence Base	
Survey Findings	Uncertainty regarding carbon-aware scheduling costs was the highest-ranked barrier (RII = 86%). High cost of sustainable computing was identified as a critical barrier (RII = 84%). Carbon Intensity per Federated Compute Job was identified as a priority KPI (RII = 82%).
Requirements Gathering and Needs Analysis	Stakeholders prioritised carbon reduction, energy efficiency, and resource optimisation as core sustainability objectives for federated computing.
Community Engagement and Co-Creation Activities	Participants emphasised the need to translate sustainability goals into operational decisions such as workload scheduling and infrastructure selection.
Rapid Delphi Validation	Experts prioritised carbon-aware scheduling, renewable energy utilisation, and resource-efficiency indicators as high-value intervention areas.
SustainFed Validation Activities	Digital twin, AI, and lifecycle assessment scenarios demonstrated the value of sustainability-aware infrastructure recommendations.
Alignment with Standards, Policies and Initiatives	
UK Policies and Initiatives	UK Net Zero Strategy; Climate Change Act; Construction Playbook
Built Environment Frameworks	RICS Whole Life Carbon Assessment; UKGBC Net Zero Carbon Framework
International Standards	ISO 14040-14044, 50001; EN 15978
European Frameworks	European Green Deal; Circular Economy Action Plan; Level(s)
National Infrastructure Initiatives	NFCS; NetDRIVE; DAFNI; UKCRIC
Research and Knowledge Sources	Green Software Foundation principles; Carbon-aware scheduling research; Cloud Carbon Footprint methodologies; HPC sustainability assessment frameworks; Energy-efficient computing literature; Sustainable digital infrastructure research
Contribution, Outputs and Outcomes	
Sustainability and Carbon Contribution	This recommendation has the most direct carbon reduction potential among the NETZERO recommendations. It supports reduced operational emissions, improved energy efficiency, increased renewable energy use, lower idle resource consumption and better workload efficiency. Impacts should be monitored through indicators such as carbon intensity per compute job, renewable energy utilisation, carbon-aware scheduling adoption and resource utilisation efficiency, with reductions quantified in tCO_2e where operational data is available.
Supporting Project Outputs	SustainFed Assessment Platform; SustainFed Recommendation Engine; Carbon-Aware Infrastructure Assessment Logic; Sustainability Prioritisation Framework; National Sustainability KPI Framework; survey findings; stakeholder engagement activities.
Relevant KPI Domains	Domain A: High; Domain B: Medium; Domain C: Medium; Domain D: Low; Domain E: High.

Expected Outcome	A federated computing ecosystem that actively optimises workloads, infrastructure utilisation and resource allocation based on sustainability objectives, resulting in measurable reductions in carbon emissions, improved energy efficiency and enhanced resource utilisation without compromising operational performance.
Roadmap Implementation	
Start Timing	Year 1
Duration	Initial guidance development and pilot implementation during Years 1-2, followed by progressive integration and optimisation through Years 3-5.
Short-Term Activities	Develop carbon-aware operational guidance; establish baseline measurements; identify priority sustainability metrics; initiate pilot implementations of sustainability-aware workload scheduling and infrastructure assessment.
Medium-Term Activities	Integrate sustainability-aware scheduling, monitoring, optimisation mechanisms and decision-support tools into federated infrastructure operations and SustainFed services.
Long-Term Activities	Deploy advanced dynamic optimisation capabilities, federation-wide sustainability orchestration, automated carbon-aware workload management and continuous sustainability performance monitoring.
Dependencies	Harmonised Sustainability Vocabulary (NETZERO-1); National Sustainability KPI Framework (NETZERO-2); operational infrastructure data; federation monitoring systems; governance mechanisms for sustainability reporting; collaboration between infrastructure providers and NFCS governance groups.
Resource Implications	*Personnel:* 1-3 FTE infrastructure, sustainability and software specialists during implementation. *Cost:* Medium-High. *Expertise:* HPC operations, cloud computing, sustainability assessment, energy management, workload scheduling and data analytics. *External alignment:* NFCS, DAFNI, NetDRIVE, UKCRIC, Green Software Foundation and national net-zero initiatives.
Contribution to the NFCS Roadmap	Operationalises sustainability within the NFCS roadmap by moving from measurement and reporting towards active optimisation of federated infrastructure operations.

NETZERO-4: Develop a Trusted Governance, Interoperability, and AI-Ready Data Framework for Sustainable Federation

Recommendation Classification	
Category	Must Have
Priority	High
Expected Impact	High
Implementation Complexity	Medium-High
Resource Requirement	Medium-High
NFCS Pillar	Primary: Governance Secondary: Technology, Community
Recommendation Profile	

Recommendation	NFCS should establish a Trusted Governance, Interoperability and AI-Ready Data Framework that enables secure, interoperable, machine-readable and reusable data ecosystems across federated computing infrastructures. The framework should integrate governance principles, FAIR data practices, interoperability standards, metadata requirements, secure access mechanisms, data stewardship responsibilities, AI-readiness criteria and lifecycle data management principles.
Rationale	The NETZERO project identified governance uncertainty, data-sharing concerns, interoperability limitations, fragmented information structures and inconsistent data standards as major barriers to federation adoption. Stakeholders highlighted the need for trusted mechanisms that enable organisations to share, access and manage data while maintaining security, compliance, ownership and accountability. The project also identified growing demand for AI-enabled workflows, digital twins, Digital Product Passports, lifecycle assessment platforms and data-driven decision-support systems, all of which depend on high-quality, interoperable and machine-readable data. A trusted governance and interoperability framework would improve federation adoption, collaboration, AI innovation and sustainability assessment across NFCS infrastructures.
Evidence Base	
Survey Findings	Unclear governance responsibilities identified as a major barrier (RII = 83%). Incompatible data standards identified as a major barrier (RII = 76%). Federated Data Interoperability Score identified as a priority KPI (RII = 86%). Data Governance Alignment Rate identified as a priority KPI (RII = 79%).
Requirements Gathering and Needs Analysis	Stakeholders consistently identified governance clarity, trusted data sharing, and interoperability as prerequisites for federation adoption.
Community Engagement and Co-Creation Activities	Governance and interoperability emerged as recurring priority themes across stakeholder workshops and consultations.
Rapid Delphi Validation	Experts prioritised governance maturity, interoperability readiness, and AI-ready data capabilities within the final framework.
SustainFed Validation Activities	Scenario testing confirmed the importance of governance and data-readiness assessments in supporting infrastructure decision-making.
Alignment with Standards, Policies and Initiatives	
UK Policies and Initiatives	Construction Playbook; National Digital Twin Programme; Government Workplace Design Guide
Built Environment Frameworks	UK BIM Framework; Information Management Framework
International Standards	ISO 19650, 8000, 27001, 37301; IFC/buildingSMART Standards
European Frameworks	ESPR; Construction Products Regulation; EPBD; Level(s)
National Infrastructure Initiatives	NFCS; NetDRIVE; DAFNI; UKCRIC; National Digital Twin Programme
Research and Knowledge Sources	FAIR Data Principles; Federated computing governance literature; Data interoperability research; AI-ready data infrastructure studies; Digital twin information management research

Contribution, Outputs and Outcomes	
Sustainability and Carbon Contribution	While this recommendation does not directly reduce carbon emissions, it provides essential enabling infrastructure for sustainability assessment and carbon-aware decision-making. The framework supports whole-life carbon assessment, Digital Product Passports, lifecycle data stewardship, sustainability KPI reporting, resource optimisation and AI-assisted sustainability analysis. Improved data quality and interoperability enable more accurate sustainability reporting and implementation of carbon reduction strategies.
Supporting Project Outputs	Harmonised Sustainability Vocabulary; Governance Framework; Federation Readiness Framework; SustainFed Assessment Platform; Data Interoperability and Readiness Engine; National Sustainability KPI Framework; survey findings; stakeholder engagement activities.
Relevant KPI Domains	Domain A: Medium; Domain B: High; Domain C: High; Domain D: Medium; Domain E: Medium.
Expected Outcome	A trusted, secure, interoperable and AI-ready data ecosystem that enables efficient federation, improved collaboration, enhanced sustainability assessment, stronger governance and greater adoption of advanced digital technologies across NFCS infrastructures.
Roadmap Implementation	
Start Timing	Year 1
Duration	Initial framework development during Years 1-2, followed by progressive implementation and maturation through Years 3-5.
Short-Term Activities	Establish governance principles, interoperability requirements, metadata standards, AI-readiness criteria and baseline framework requirements; develop implementation guidance and governance models.
Medium-Term Activities	Implement interoperability standards, metadata requirements, secure federated access mechanisms, data stewardship processes and federation governance arrangements across NFCS environments.
Long-Term Activities	Mature trusted data ecosystems, AI-ready infrastructure capabilities, interoperability assessment and continuous governance improvement.
Dependencies	Harmonised Sustainability Vocabulary (NETZERO-1); National Sustainability KPI Framework (NETZERO-2); NFCS governance structures; coordination with DAFNI, NetDRIVE, UKCRIC and National Digital Twin initiatives; stakeholder participation; secure federated identity and access management.
Resource Implications	*Personnel:* 2-4 FTE governance, interoperability, cybersecurity and data specialists. *Cost:* Medium-High. *Expertise:* data governance, interoperability, information management, cybersecurity, AI, digital infrastructure and policy development. *External alignment:* NFCS, DAFNI, NetDRIVE, UKCRIC, National Digital Twin Programme, UK BIM Framework and buildingSMART.
Contribution to the NFCS Roadmap	Provides the governance and interoperability foundation required for federation at scale by enabling trusted data sharing, AI readiness, interoperability and governance maturity across NFCS services.

NETZERO-5: Build Capacity and Inclusive Participation for Sustainable Federated Computing

Recommendation Classification	
Category	Should Have
Priority	High
Expected Impact	High
Implementation Complexity	Medium
Resource Requirement	Medium
NFCS Pillar	Primary: Community Secondary: Technology, Governance
Recommendation Profile	
Recommendation	NFCS should establish a coordinated programme for capacity building, skills development and inclusive participation to support the adoption of sustainable federated computing across research, industry, government and infrastructure communities. The programme should include carbon-aware computing literacy, federation readiness training, data governance, interoperability and FAIR data practices, responsible AI awareness, onboarding activities and knowledge-sharing networks.
Rationale	The NETZERO project identified significant capability gaps relating to sustainability assessment, carbon-aware computing, federation readiness, governance, data stewardship and interoperability. Although stakeholders recognised the benefits of federated computing, limited awareness, insufficient training and uncertainty regarding implementation pathways were identified as major barriers to adoption. These challenges were particularly evident among SMEs, local authorities, infrastructure operators, built environment practitioners and interdisciplinary communities. The project therefore concludes that successful federation requires investment not only in technology and governance, but also in people, organisational readiness and community development.
Evidence Base	
Survey Findings	Carbon-aware computing literacy was identified as the most significant capability gap (64%). Digital infrastructure readiness was identified as a major capability gap (57%). Training and capacity building achieved strong support (RII = 87%). SME participation was identified as a priority for future NFCS engagement (RII = 95%).
Requirements Gathering and Needs Analysis	Stakeholders highlighted limited sustainability and federation-related skills.
Community Engagement and Co-Creation Activities	Participants requested practical training, onboarding resources, and implementation guidance.
Rapid Delphi Validation	Experts emphasised capacity building as a prerequisite for long-term adoption.
SustainFed Validation Activities	Users highlighted the value of guided assessment and learning through the platform.
Alignment with Standards, Policies and Initiatives	
UK Policies and Initiatives	NFCS Principles; UK Net Zero Strategy; Climate Change Act; Construction Playbook

Built Environment Frameworks	UK BIM Framework; Information Management Framework; RICS Whole Life Carbon Assessment; UKGBC Net Zero Carbon Framework
International Standards	ISO 19650, 14040-14044, 50001, 27001; EN 15978
European Frameworks	ESPR; Construction Products Regulation; EPBD; Level(s)
National Infrastructure Initiatives	DAFNI; NetDRIVE; UKCRIC; National Digital Twin Programme
Research and Knowledge Sources	FAIR Data Principles; Sustainable digital infrastructure research; Federated computing governance literature; Sustainability assessment frameworks; Capacity-building and digital skills literature; Carbon-aware computing literature.
Contribution, Outputs and Outcomes	
Sustainability and Carbon Contribution	This recommendation indirectly supports sustainability and carbon reduction by strengthening the skills and organisational capabilities needed to implement carbon-aware computing, sustainability assessment, lifecycle thinking and resource-efficiency practices. Improved awareness and capability are expected to accelerate adoption of sustainable federation practices and improve implementation of carbon reduction measures.
Supporting Project Outputs	Community engagement activities; stakeholder survey findings; Harmonised Sustainability Vocabulary; National Sustainability KPI Framework; SustainFed Assessment Platform; Governance Framework; Federation Readiness Framework.
Relevant KPI Domains	Domain A: Low; Domain B: Medium; Domain C: Medium; Domain D: High; Domain E: Low.
Expected Outcome	A more capable, inclusive and sustainability-aware federation community with the skills, confidence and organisational readiness required to adopt, implement and scale sustainable federated computing practices across diverse sectors and disciplines.
Roadmap Implementation	
Start Timing	Year 1
Duration	Initial programme development during Years 1-2, followed by progressive expansion and embedding through Years 3-5.
Short-Term Activities	Develop training resources, onboarding materials, guidance documents, engagement programmes and community networks; identify priority user groups and capability gaps.
Medium-Term Activities	Deliver training activities, establish communities of practice, expand participation across sectors and disciplines, and provide ongoing support through knowledge-sharing and demonstration activities.
Long-Term Activities	Embed capacity-building activities within NFCS operations and maintain long-term knowledge-sharing and onboarding programmes.
Dependencies	Harmonised Sustainability Vocabulary (NETZERO-1); National Sustainability KPI Framework (NETZERO-2); Governance and Interoperability Framework (NETZERO-4); stakeholder participation; collaboration with training initiatives; availability of demonstration projects and use cases.
Resource Implications	*Personnel:* 1-2 FTE community engagement, training and knowledge exchange specialists. *Cost:* Medium.

	Expertise: sustainability, education and training, community engagement, digital infrastructure, governance, built environment and knowledge exchange. *External alignment:* UKRI, NFCS, DAFNI, NetDRIVE, UKCRIC, professional bodies, universities and industry networks.
Contribution to the NFCS Roadmap	Strengthens the human dimension of the NFCS roadmap by improving skills, organisational readiness, inclusive participation and long-term adoption of sustainable federated computing practices.

NETZERO-6: Deploy SustainFed as a National Sustainability Assessment and Decision-Support Capability for Federated Computing

Recommendation Classification	
Category	Should Have
Priority	High
Expected Impact	High
Implementation Complexity	Medium-High
Resource Requirement	Medium-High
NFCS Pillar	Primary: Technology Secondary: Governance, Community
Recommendation Profile	
Recommendation	NFCS should adopt and further develop SustainFed as a national sustainability assessment and decision-support capability to support federation readiness assessment, infrastructure planning, sustainability benchmarking, governance implementation and continuous improvement across federated computing environments.
Rationale	The NETZERO project identified that organisations often struggle to determine the most appropriate computing infrastructure for their workflows, assess federation readiness, prioritise sustainability requirements, and understand governance, interoperability and data-readiness obligations. To address these challenges, the project developed SustainFed as an integrated assessment and decision-support platform that combines sustainability objectives, governance requirements, interoperability needs and infrastructure characteristics within a single assessment environment. Wider adoption of SustainFed would provide NFCS with a consistent mechanism for supporting federation planning, benchmarking and continuous improvement.
Evidence Base	
Survey Findings	Joint governance frameworks achieved the highest level of support (RII = 100%). Alignment of KPIs and reporting frameworks achieved very high support (RII = 98%). Sharing methodological standards achieved very high support (RII = 98%). Real-time sustainability dashboards and monitoring capabilities achieved very high support (RII = 96%). 65% of organisations reported they were not ready to adopt national carbon-aware governance recommendations.

Requirements Gathering and Needs Analysis	Stakeholders requested coordinated governance and sustainability leadership across national initiatives.
Community Engagement and Co-Creation Activities	Workshops highlighted the need for stronger coordination between NFCS, DAFNI, NetDRIVE, and UKCRIC.
Rapid Delphi Validation	Experts supported a national governance mechanism to oversee sustainability implementation.
SustainFed Validation Activities	Participants identified governance coordination and roadmap alignment as key platform benefits.
Alignment with Standards, Policies and Initiatives	
UK Policies and Initiatives	UKRI Community Engagement Principles; UK Net Zero Strategy; Construction Playbook
Built Environment Frameworks	UK BIM Framework; Information Management Framework
International Standards	ISO 19650; ISO 37301
European Frameworks	European Green Deal; Level(s)
National Infrastructure Initiatives	NFCS; DAFNI; NetDRIVE; UKCRIC
Research and Knowledge Sources	Sustainability assessment frameworks; Decision-support systems research; Federated computing governance literature; Digital twin and infrastructure assessment research; Carbon-aware computing literature; Sustainable digital infrastructure research.
Contribution, Outputs and Outcomes	
Sustainability and Carbon Contribution	SustainFed supports sustainability and carbon reduction by enabling evidence-based infrastructure planning, carbon-aware infrastructure selection, KPI implementation, governance assessment and sustainability performance monitoring. While it does not directly reduce emissions, it provides a practical mechanism for implementing and tracking sustainability improvements across federated environments.
Supporting Project Outputs	SustainFed Assessment Platform; Assessment and Recommendation Engines; Harmonised Sustainability Vocabulary; National Sustainability KPI Framework; Governance Framework; Federation Readiness Framework; stakeholder survey and engagement outputs.
Relevant KPI Domains	Domain A: High; Domain B: High; Domain C: High; Domain D: High; Domain E: High.
Expected Outcome	A nationally accessible sustainability assessment and decision-support capability that enables organisations to evaluate federation readiness, identify sustainability opportunities, benchmark performance, improve governance practices and make evidence-based infrastructure decisions.
Roadmap Implementation	
Start Timing	Year 1
Duration	Initial refinement and validation during Years 1-2, followed by progressive deployment, integration and expansion through Years 3-5.
Short-Term Activities	Refine SustainFed prototype; validate with additional stakeholders; establish governance arrangements; enhance assessment logic; develop onboarding and user guidance resources.
Medium-Term Activities	Integrate SustainFed into NFCS onboarding, assessment, sustainability benchmarking, federation planning and governance activities; expand adoption across stakeholder groups and sectors.

Long-Term Activities	Develop SustainFed into a federation-wide decision-support capability with advanced analytics, benchmarking and sustainability performance monitoring.
Dependencies	Harmonised Sustainability Vocabulary (NETZERO-1); National Sustainability KPI Framework (NETZERO-2); Governance and Interoperability Framework (NETZERO-4); stakeholder participation; availability of operational and sustainability data; ongoing platform validation.
Resource Implications	*Personnel:* 2-4 FTE software developers, sustainability specialists, governance experts and user engagement leads. *Cost:* Medium-High. *Expertise:* software development, federated computing, sustainability assessment, governance, interoperability, user experience design and data analytics. *External alignment:* NFCS, DAFNI, NetDRIVE, UKCRIC, National Digital Twin Programme and UK BIM Framework.
Contribution to the NFCS Roadmap	Provides the practical implementation mechanism for the NETZERO roadmap by operationalising vocabulary, KPI, governance and interoperability recommendations within a single decision-support environment.