GreenDIGIT Key Exploitable Results – Turning Innovation into Impact

*Welcome to the 3rd edition of the GreenDIGIT Newsletter! This issue highlights the seven **Key Exploitable Results (KERs)** — the tangible outcomes of our collective work that shape the sustainability transformation of Digital Research Infrastructures (RIs) across Europe. Each KER represents a concrete step from research and design to implementation and impact, covering all dimensions of the project. Together, these results demonstrate how GreenDIGIT is moving from conceptual frameworks to operational solutions that will enable RIs to monitor, manage, and reduce their environmental footprint across their entire lifecycle.*

Introduction

The goal of the GreenDIGIT project is to advance the environmental sustainability of Research Infrastructures (RIs) through a set of technical innovations and policy-level solutions. The project is midway, has recently completed its first period, and is now entering its second phase. During the first period, GreenDIGIT carried out a comprehensive landscape analysis, developed key architectural components, released practical software tools, and proposed initial policy recommendations and guidelines. These efforts collectively support the adoption of more sustainable practices and operations across digital RIs.

In this newsletter, we present the project's achievements from the first period in the form of Key Exploitable Results (KERs) as summarised in Table 1, and highlight several of them with high-impact, that are ready for broader adoption by targeted audience and the wider community.

1. KER1 – State of the Art and Technology Recommendations

This KER has established a comprehensive and harmonized baseline on sustainability in digital research infrastructures, consolidating the technical, operational, and policy foundations for several subsequent GreenDIGIT activities. The work, presented in Deliverable 4.1, reviewed and assessed the current landscape of sustainable computing technologies and practices across areas such as cloud, HPC systems, networking, and data management. It identified the most relevant indicators, international and EU standards, tools, and techniques to measure energy and environmental performance - such as power use efficiency (PUE), water use effectiveness (WUE), and energy reuse factor (ERF) and evaluated their applicability to RI. The analysis also examined emerging methodologies in carbon-aware and energy-aware scheduling, as well as techniques for software optimisation and sustainable data life-cycle management.

The resulting report provides actionable recommendations for improving energy efficiency, adopting renewable energy sources, reducing data redundancy, and enabling reproducible research. These findings served as the reference for the project's architecture (KER2) design and sustainability-by-design approach, ensuring that future tools and prototypes developed in GreenDIGIT are grounded in a shared understanding of the current technological capabilities and environmental impact drivers within the digital RI ecosystem.

Key outcome: A reference catalogue of sustainable computing technologies and actionable recommendations. *Target audience:* RI designers and operators.

2. KER2 – Architecture Framework for Sustainability by Design

KER	Title	Associated Material
1	**State of the Art (SotA) and Technology Recommendations**	D4.1
2	**Architecture Framework for Digital RI Sustainability by Design**	D4.2
3	**Research Infrastructure Lifecycle Model (RILM)**	RILM White Paper
4	**User Tools for Lowering the Environmental Impact**	D5.1, D5.2, D5.3,
5	**Environmental Impact Architecture and RI Prototypes**	WP6
6	**Environmental Impact Assessment Methodology and Self-Assessment Toolkit**	D3.2, D8.1
7	**Training Modules and Competence Framework**	D10.2, WP11

Table 1: GreenDIGIT Key Exploitable Results (KERs)

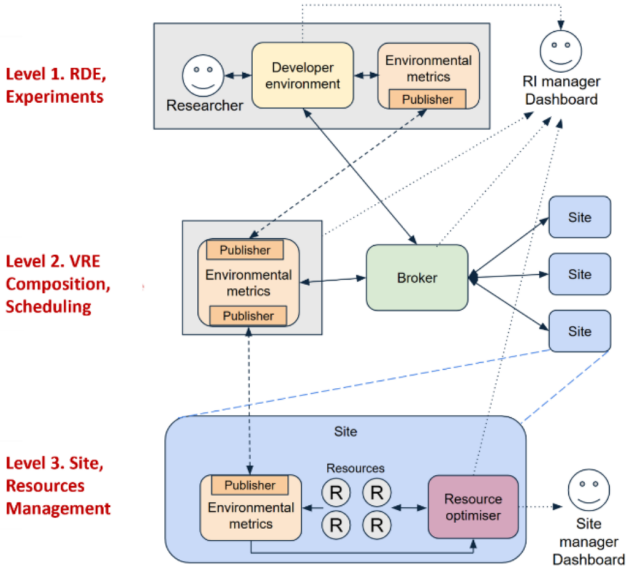

Figure 1: GreenDIGIT Software Solutions for Environmental Impact Monitoring

This KER establishes the GreenDIGIT modular architecture framework as depicted in Figure 1, a unifying structure that embeds sustainability principles throughout the life-cycle of digital research infrastructures. The consortium efforts produced a layered modular design separating, infrastructure, platform, and application components, allowing energy efficiency, interoperability, and life-cycle management to be addressed concisely yet independently. It operates under the concept of "Sustainability by Design" by providing clear interfaces, shared data models, and integration points for the tools and services developed across WPs 4–7.

The architecture also introduced the Shared Responsibility Model for Sustainability (SRM4S), aligning technical components with governance and user practices to ensure measurable environmental impact reduction. By linking architectural layers to sustainability metrics and life-cycle checkpoints, it provided a flexible reference for deploying and operating environmentally conscious RIs across Europe.

Key outcome: A reusable, open reference architecture supporting green design principles in digital RIs. *Target audience:* RI operators, researchers, RI software developers.

3. KER3 – Research Infrastructure Lifecycle Model (RILM)

The work conducted for this KER included a substantial effort to develop a common understanding of how sustainability can be embedded throughout the life-cycle of digital RIs. Building on cross-WP analysis and consultation with RI representatives, the project defined the stages as presented at Figure 2, processes, and governance principles that form the basis of the RI Life-cycle Model (RILM). There the existing life-cycle and assessment methodologies were carefully examined, such as those from ISO 14040/14044, and mapped them to the operational and management realities of digital infrastructures.

This work was consolidated into a structured framework (RILM White Paper) that links sustainability requirements with European regulatory developments, including the Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS). It introduced different life-cycle phases from concept and design to development, operation, and termination. Each of them is accompanied by sustainability checkpoints, performance indicators, and reporting mechanisms. By harmonising these elements, the RILM produced a practical reference model for aligning technological evolution, governance, and sustainability performance in RIs.

Key outcome: Lifecycle methodology and template supporting continuous environmental optimisation of RIs. *Target audience:* RI engineers and operators, policy makers.

4. KER4 – User Tools for Lowering the Environmental Impact

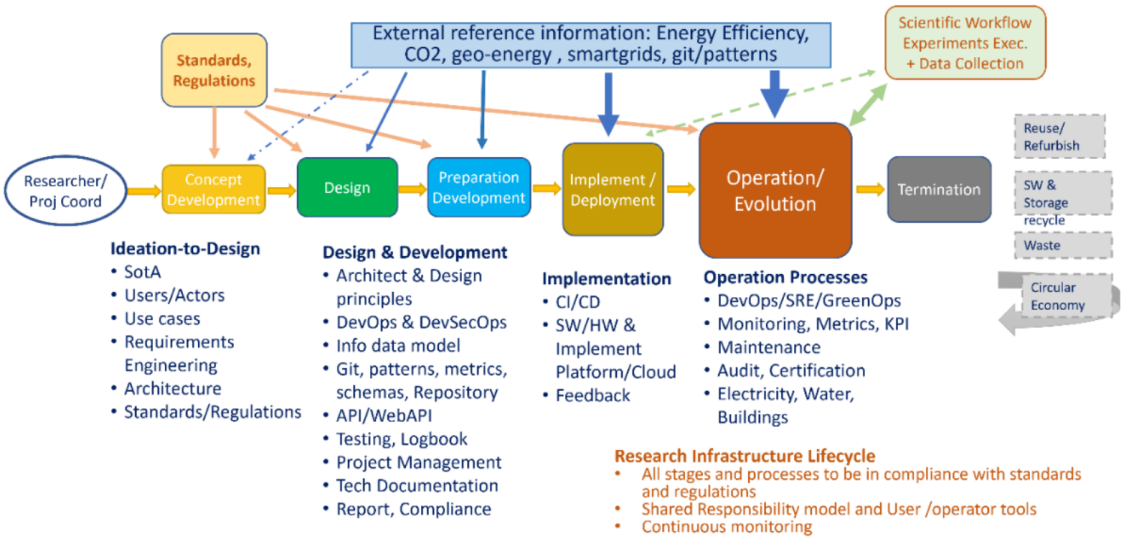

Figure 2: RI Life-cycle Stages and Activities

This KER delivers a suite of software solutions that embed sustainability and reproducibility directly into the digital research process. During the first 18 months, GreenDIGIT developed an integrated Virtual Research Environment (VRE) based on the Jupyter platform, forming the foundation for reproducible and environmentally responsible scientific work. Guided by the project's 4-Pillar Conceptual Reproducibility Framework, the VRE enables researchers to define, execute, and preserve experiments with full transparency, reducing redundant computation and unnecessary energy use.

Central to this work is EcoJupyter, a JupyterLab plugin providing real-time tracking of energy consumption and carbon footprint through metrics such as Software Carbon Intensity (SCI). The tool also includes predictive capabilities, allowing users to estimate the environmental cost of different experimental configurations before running large-scale workloads. All outputs are packaged following the RO-Crate standard, ensuring FAIR compliance and the inclusion of sustainability metadata. These enriched research objects are now shareable through the operational Federated Data Management Infrastructure (FDMI), offering a federated catalogue for publishing and discovering experiments across the GreenDIGIT ecosystem.

Key outcome: A set of open tools empowering RI users to make informed, sustainable computing choices. *Target audience:* RI users, researchers, RI software developers.

5. KER5 – Environmental Impact Architecture and RI Prototypes

Building on the architecture and design work conducted in the first project period, this KER focuses on translating sustainability-by-design principles into practical, deployable prototypes. The activity entered its implementation phase at M13 and is now progressing toward the development and integration of demonstrators within selected RIs.

The work aims to demonstrate how environmental performance indicators such as energy consumption, carbon footprint, and resource efficiency can be continuously monitored and reported across heterogeneous infrastructures including EGI, SLICES, SoBigData, and EBRAINS. The results of these efforts, including functional pilot deployments and cross-RI demonstrations, will be detailed in upcoming newsletters as the prototypes reach maturity in the next project phase.

Key outcome: Proof-of-concept systems demonstrating measurable sustainability gains in RI operations. *Target audience:* RI operators, RI software developers.

6. KER6 – Environmental Impact Assessment Methodology and Toolkit

During the first reporting period for this KER, GreenDIGIT developed a harmonised methodology and supporting toolkit to assess and improve the environmental sustainability of digital RIs. Detailed in Deliverable 3.2, the methodology evaluates environmental performance across four key categories carbon emissions, energy consumption, waste, and water use indicators such as Global Warming Potential (GWP), Cumulative Energy Demand (CED), Waste of Electrical and Electronic Equipment (WEEE), and Resource Depletion: Water (RDW). It introduces three guiding parameters, impact magnitude, likelihood, and effort, to prioritise improvement actions effectively and resource-efficiently.

Complementing this, Deliverable 8.1 presented the Self-Assessment Questionnaire (SAQ), a practical online tool that benchmarks RI practices against core sustain-

ability dimensions, including climate change mitigation, energy efficiency, circular economy, pollution reduction, and biodiversity protection. The SAQ integrates European regulatory frameworks such as the CSRD, ESRS, ESPR, and EED, helping RIs align their strategies with evolving compliance and reporting requirements. Together, the methodology and questionnaire provide a coherent assessment and planning system, offering actionable insights to enhance sustainability maturity, transparency, and continuous improvement.

Key outcome: Environmental Impact Assessment, Practical toolkit for self-assessment and benchmarking of RI environmental sustainability. *Target audience:* RI operators, policy makers.

7. KER7 – Training Modules and Competence Framework

This KER focuses on building capacity across the RIs community by defining the competences, skills, and training needed to support environmentally sustainable digital operations. Based on Deliverable 10.2, GreenDIGIT has defined an initial framework green competences and training modules tailored to key RI roles researchers, developers, operators, and managers.

The framework builds on existing European initiatives such as GreenComp and the Education for Sustainable Development (ESD) programme, extending them with technical competences aligned with the GreenDIGIT architecture and Sustainable Design Principles. Using the EDISON Data Science Framework, the work identifies gaps in current training provision and maps competence needs across the RI life-cycle from system design and monitoring to energy efficiency and life-cycle management.

A first set of learning units and training modules has been outlined, providing the foundation for GreenDIGIT's education and awareness programme. These materials will evolve into structured courses, workshops, and summer school content to strengthen the human dimension of sustainable RI management. Work on the training implementation and digital delivery mechanisms has just started under WP11.

Key outcome: Comprehensive competence framework and open training materials for sustainable digital RIs. *Target audience:* RI operators, users, students, and the general public.

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