GreenDIGIT

Greener Future Digital Research Infrastructures

Whitepaper: Digital Research Infrastructure Lifecycle Model

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Abbreviation	Description
LCA	Lifecycle Analysis
CSRD	Corporate Sustainability Reporting Directive
ESPR	Ecodesign for Sustainable Products Regulation
EED	Energy Efficiency Directive
DRI	Digital Research Infrastructure
ISO	The International Organization for Standardization
ITU-T	International Telecommunication Union
CI/CD	Continuous Integration/ Continuous Delivery
TRLs	Technology Readiness Level
ESFRI	The European Strategy Forum on Research Infrastructures
PUE	Power Usage Effectiveness
CUE	Carbon Usage Effectiveness
WUE	Water Usage Effectiveness
WEEE	Waste Electrical and Electronic Equipment
GPU	Graphics processing unit
ML	Machine Learning
GHG	Greenhouse gas

1 Introduction

The advancement of scientific innovation and discovery throughout Europe and beyond depends heavily on the creation, management, and expansion of research infrastructures (RIs). It has become strategically necessary to manage these infrastructures' whole lifecycle as they become more digital, sophisticated, and interdependent. This whitepaper offers a thorough framework for comprehending and utilising the Digital Research Infrastructure Lifecycle Model (RILM), considering the requirements for consistent procedures, coherent governance, and adherence to changing European laws.

The first section of the paper outlines the important phases of the lifecycle of digital research infrastructures, including concept development and design, development, operation, and eventual termination. There are unique opportunities and problems at each step, especially when considering new technologies and sustainability requirements.

The whitepaper identifies and clarifies the wide range of stakeholders, including policymakers and administration of RI, users/researchers, technical operators, and reseearchers on infrastrcuture, building on the strategic insights from the European Strategy Forum on Research Infrastructures (ESFRI). By defining and clarifying these actors' roles and duties, it offers a useful framework for cooperation and decision-making throughout the lifecycle.

Analysing lifecycle assessment methodologies—examining best practices, instruments, and indicators currently used to measure RI sustainability, performance, and impact—is a crucial part of the whitepaper. Stricter rules and guidelines like the Corporate Sustainability Reporting Directive (CSRD) and the European Sustainability Reporting Standards (ESRS), which affect how infrastructures must plan, measure, and report their operations and societal contributions, are increasingly influencing these assessments.

For policymakers/infrastructure administration and technical operators, the whitepaper provides proposals to enable successful lifecycle governance. Guidelines for strengthening interoperability, ensuring regulatory alignment, promoting long-term sustainability, and boosting strategic planning are among them.

In order to match technological development with policy objectives and stakeholder needs, a unified lifecycle strategy is essential, as the study concludes. The annexe of the whitepaper, which supports transparency and future-readiness, contains a public guide to the ESFRI Roadmap 2026 and reporting requirements under ESRS and CSRD. These tools are crucial for organisations working on ongoing and planned research infrastructure initiatives.

2 Lifecycle stages of research infrastructure

The core for defining the RI LCA methodology is the well-defined RI lifecycle model together with the corresponding activities, roles and expected outcomes.

Figure 1 provides an illustration of the RI lifecycle stages and corresponding activities at each stage. Details about organisational roles and their activities are provided in Section 4, and Table 1. The figure shows the importance of addressing environmental sustainability aspects defined in relevant standards and regulations. The figure also shows that the RI lifecycle stages require and use a wide spectrum of information important for RI design, development, implementation and operation, which must be provided by power and environmental management systems, organised into (supported by) a federated data management infrastructure.

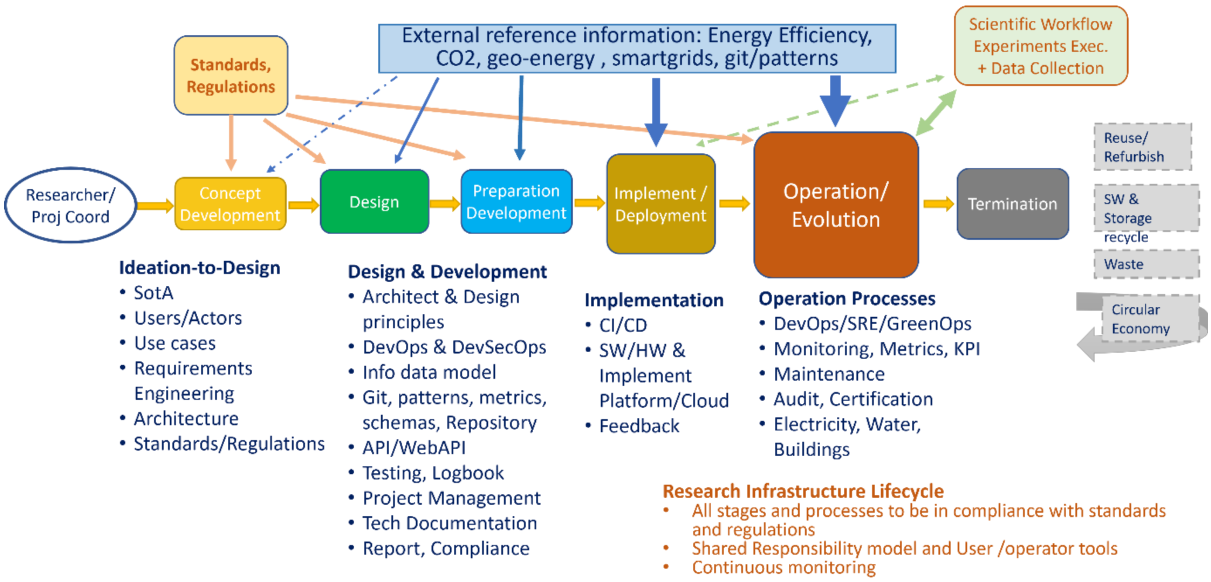

Figure 1. RI Lifecycle stages and activities

1. Concept development (Feasibility & Vision):
   The initial stage entails determining the necessity of research infrastructure through stakeholder discussion, exploration of use cases, and full comprehension of regulations and guidelines for sustainable research infrastructure. This process necessitates interacting with policymakers, industry professionals, and the scientific community to evaluate existing gaps and future demands. Additionally, it involves evaluating technological feasibility, long-term sustainability, and potential socio-economic impacts. A well-defined needs assessment at this stage ensures that the research infrastructure is aligned with emerging scientific trends, regulatory requirements, and environmental sustainability goals, paving the way for an efficient and future-proof implementation.

2. Design (Planning):
   During this stage, the development of the system architecture and thorough planning occur. The task of this stage is to create a robust and scalable infrastructure that aligns with research objectives and operational requirements. Key considerations include regulatory compliance,

estimation of costs (ESFRI guidelines for cost estimation of RIs), sustainable strategies, and the overall architectural design. Risk assessments, feasibility studies, and stakeholder consultations are conducted to ensure the infrastructure meets long-term sustainability and performance standards. This stage also incorporates technological evaluations, resource optimization strategies, and interoperability planning to enhance efficiency and future adaptability. A well-structured approach at this stage lays the foundation for a resilient and innovative research infrastructure.

3. Preparation & Development (Construction & Assembly):
   Following the completion of the hardware and software procurement, the technical team starts developing and deploying the critical services in accordance with the architectural framework and project requirements. This includes implementing API/Web API integrations, establishing CI/CD (Continuous Integration/Continuous Deployment) pipelines, implementing energy-efficient code practices, conducting rigorous system testing, and ensuring seamless interoperability between different components.
   To facilitate future scalability, troubleshooting, and knowledge transfer, the technical team also develops extensive technical documentation that covers the architecture, service functionalities, integration workflows, and maintenance protocols. Security considerations, regulatory compliance, and performance optimisations are also incorporated into the development process to improve system sustainability and reliability. A well-organised approach in this stage guarantees a seamless transition from infrastructure setup to operational readiness.

4. Implementation & Deployment (Testing and Validation):
   The research infrastructure goes through a rigorous testing, calibration, and validation process before going into full operation to ensure all components function optimally and meet predefined performance, safety, and sustainability standards. Before deployment, this procedure identifies and fixes any possible problems through functional testing, stress testing, and system-wide integration evaluations.
   Pilot tests are also carried out to assess practicality, improve operational procedures, and get input from early users. At this point of the lifecycle, user training programs are also implemented to guarantee that technical personnel, researchers, and other stakeholders can interact with the infrastructure and its services in an efficient manner.
   During this phase, the technical team assesses the Technology Readiness Levels (TRLs) of the provided services, determining their maturity and readiness for deployment. This evaluation helps in identifying areas for further development and ensuring that the infrastructure is resilient, scalable, and consistent with long-term research goals. Through comprehensive system validation, this phase reduces risks and guarantees a seamless transition to full operational capability.

5. Operation & Evolution (Utilization & Optimization):
   At this stage, the research infrastructure becomes fully operational, providing essential services to support a wide range of research activities. Researchers actively utilize the infrastructure for data collection, analysis, and experimentation, while technical operators oversee its performance to ensure seamless functionality.

To maintain long-term efficiency, security, and sustainability, this phase involves continuous monitoring, proactive maintenance, periodic upgrades, and robust data management strategies. Performance metrics are regularly assessed to identify potential bottlenecks, optimize resource allocation, and enhance system reliability. Cybersecurity measures are enforced to safeguard sensitive data and maintain compliance with regulatory standards.
The operation stage also includes the regular activities by the target research community, what entail providing and managing the Research Development Environment, supporting the researcher with tools for energy and environmental impact aware scientific workflow placement.

Furthermore, infrastructure adaptability and scalability are key factors, that enable future growth and integration of emerging technologies. For services to be improved and put into place, stakeholder interaction and user feedback loops are essential. By ensuring operational resilience and technological evolution, this stage supports sustained scientific innovation and long-term research success.

6. Termination (End of Life & Transitioning):
When the research infrastructure reaches the end of its lifecycle, a structured phase-out process is initiated to ensure a responsible and efficient transition. In this stage, materials are environmentally-responsibly dismantled, repurposed, or disposed of, with a focus on reducing the negative effects on the environment and following legal requirements.
As for the software part, VMs will be shut down and after will be deleted, and any subscription-based services will be cancelled.
A top goal is the implementation of sustainable decommissioning strategies, such as recycling components, repurposing facilities for alternative research or industrial applications, and integrating circular economy principles to reduce waste. Additionally, site restoration efforts are undertaken to return the location to its original state or prepare it for new developments.
A thorough data archiving strategy is implemented to preserve scientific contributions, guaranteeing that important research outputs are still available for future investigations and policymaking. Stakeholder engagement, including researchers, policymakers, and environmental experts, plays a crucial role in guiding the phase-out process to align with best practices in sustainability, knowledge preservation, and resource optimization. This stage guarantees an innovative legacy while reducing the negative effects on the environment and society by emphasising responsible decommissioning.

3 European (ESFRI) Research Infrastructures Stakeholders

3.1 Policymakers/Administrative part:

- International standardization
- Governmental entities
- Internal administration/management of research infrastructure

At the international level, organisations like ISO (International Organization for Standardization) and ITU-T (International Telecommunication Union, (based in Switzerland) are examples of standardisation policymakers. They create and implement international standards for data management, sustainability, and quality assurance in research infrastructures. Their impact guarantees that research infrastructures in many nations and fields are consistent and compatible.

In the case of Europe, the primary governmental entity is the European Commission, which provides relevant guidelines and regulations for research infrastructures. These policies shape the legal, ethical, and operational frameworks within which research infrastructure functions.

At the level of research infrastructure, administrative departments or management boards make decisions about RI's future and daily issues. This group develops policies within the RIs for internal usage, based on guidelines provided by the European Commission.

3.2 Technical Operators of RIs

Project managers and technical operators are in charge of the upkeep, operation and long-term viability of research infrastructure. These experts make sure that research facilities continue to be secure, operational, and technologically advanced. IT managers are in charge of digital infrastructure, guaranteeing high-performance computing, cybersecurity, and effective data storage. Project managers ensure regulatory compliance, organise interdisciplinary cooperation, and plan the distribution of resources. Additionally, sustainability consultants are essential in providing guidance on how these infrastructures should develop in order to become more sustainable, with an emphasis on energy efficiency, lowering carbon emissions, and utilising eco-friendly materials and technology. Their knowledge helps research infrastructures align with global sustainability goals and reduce operational costs.

3.3 Experimental Researchers conducting research on infrastructure

This group consists of researchers studying the research infrastructure itself, either from a sustainability perspective or with the aim of introducing innovative improvements. These individuals focus on optimizing the efficiency, resilience, and adaptability of research infrastructures, ensuring they meet future technological and environmental demands. Their work may involve developing new materials, automation systems, or AI-driven solutions to enhance infrastructure performance. Additionally, they may study the environmental and societal impact of research infrastructures, aiming to create more sustainable, inclusive, and cost-effective models for future facilities. Their findings support ongoing advancements in the planning, administration, and use of research infrastructures around the world.

3.4 RI applications and service users

This target group consists of the primary users of research infrastructures and recipients of scientific research services. It includes universities, individual researchers, research groups, and scientific advisory boards that rely on these infrastructures for conducting experiments, data collection, and scientific advancements. Their work stimulates innovation in a variety of fields, including engineering, environmental research, physics, and life sciences. This group also contributes significantly to the development of research infrastructure policy by offering input on operational effectiveness, data accessibility, and usability. Their insight can be used to enhance research facilities' usefulness, sustainability, and design to better serve the changing demands of the scientific community.

Businesses (such as SMEs) and industry leaders can be included in this group in addition to academia, as they increasingly depend on advanced research infrastructures for product development, technological innovation, and market-driven solutions. Their participation strengthens the partnership between academic institutions and the private sector, which promotes economic growth, enhanced knowledge transfer and commercialisation opportunities.

4 Roles and Actors in RI Lifecycle Management

Table 1 provides mapping of the main organisational roles and their activities or functions to the RI Lifecycle stages. The suggested mapping can be used for RI capacity planning and building defining the necessary competences and skills for specific job positions. This also may provide a basis for developing necessary training modules for RI staff.

Table 1. Roles and Actors in RI Lifecycle Management

Target audience\LCA stages	Policymakers /Admin	Technical Operators of RI	Researchers on Infrastructure	Researchers/ Users
Concept Development	Stakeholders' collaboration &Define sustainable goals	Stakeholders' collaboration	Stakeholders' collaboration	Stakeholders' collaboration &Provide insights on research needs
Design	Lifecycle cost analysis & Risk management	Designing of the architecture and shared responsibility model & Evaluation of the technical feasibility of green infra from an operational perspective	Review and comments on design solutions	
Development	Workforce training &Environmentally conscious hardware procurement	- Hardware procurement -Software procurement or open-source software -CI/CD pipelines - API/ Web API -Testing, Logbooks	Providing suggestions, infrastructure configuration and metrics availability	Pilot testing of RI
Deployment /Pre-op	Transparent reporting on sustainable goals and expected operational impacts	Implementation early corrective actions to optimize sustainability before full operation & TRLs of services and infrastructure	Participation in pre-operation	Finish the trainings &Finish onboarding documentations
Operation & Evolution	Implementing policies to reduce	-Monitoring the hardware &software - Auditing the system for possible inefficiencies	Providing suggestions about metrics availability and	Providing continuous feedback

	energy usage, waste	- Receiving the feedback from users and possible fixing issues -Following the policies to minimize waste through repairs, repurposing and recycling components	collections, necessary infrastructure configuration for experiments	
Termination	Implementation policies of recycling of hardware &Implementation policies of data storage	Following the policies of recycling Hardware	Ensure data preservation efforts to avoid research duplication	Support data preservation efforts to avoid research duplication

5 Lifecycle Assessment Methodologies and Practices – Analysis

Lifecycle Analysis (LCA), also known as Lifecycle Assessment, is a systematic approach to assessing the environmental impact of a product, service, or system throughout its entire lifecycle, from raw material extraction to end-of-life disposal [1]. The ISO 14040 and ISO 14044 standards provide an important framework for LCA. LCA is widely used to measure and reduce environmental footprints and is a core principle in EU sustainability regulations (e.g., CSRD, ESPR, and EED). Practical aspects of LCA use are supported by multiple guidelines both EC Green Business Initiatives [2] and other initiatives [3], a comprehensive guide is also available on Wikipedia [4].

Although LCA and ISO 14040/ISO 14044 are not directly oriented on ICT and digital RIs their systematic methodology can be used for evaluating the environmental aspects and impacts associated with different RILM stages. For Digital Research Infrastructures (DRIs), LCA helps evaluate the sustainability of IT equipment, networking infrastructure, AI workloads, and data centers.

5.1 Lifecycle Assessment Methodology according to ISO 14040/ISO 14044

The ISO 14040 (Principles and Frameworks)/ISO 14044 (Requirements and Guidelines) standards address environmental sustainability through Life Cycle Assessment (LCA), which is a structured methodological approach that evaluates the environmental impacts associated with all stages of a product or service lifecycle from raw material extraction through production, distribution, use, recycling, and disposal (end-of-life).

Although LCA and ISO 14040/ISO 14044 are not directly oriented on ICT and digital RIs their systematic methodology can be used for evaluating the environmental aspects and impacts associated with different RILM stages.

Figure 2 Illustrates the structure of the LCA methodology, containing four main phases described in ISO 14040, while ISO 14044 provides valuable guidelines for Impact Assessment (LCIA) phase together with identified impact factors and recommended metrics.

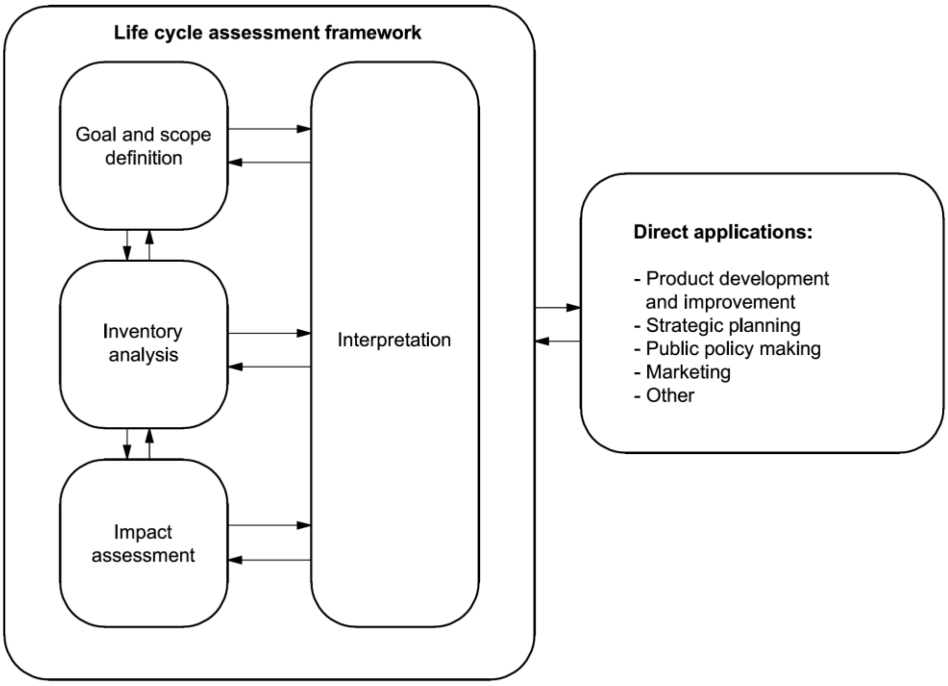

Figure 2. LCA Phases according to ISO 14040/ISO 14044

The ISO 14040/ISO 14044 standards define the LCA framework with four main phases:

Phase 1: Goal & Scope Definition

Objective: Define what the LCA aims to measure. Key aspects for DRIs:

- Assess environmental impacts of HPC, AI clusters, 5G testbeds, and networking infrastructure.
- Define system boundaries (e.g., individual servers, full data centers, IoT sensors).
- Identify environmental categories: carbon footprint, energy efficiency, e-waste generation, water use.

Phase 2: Lifecycle Inventory (LCI)

Objective: Collect data on resource inputs and environmental outputs throughout the lifecycle. Key data points for DRIs:

- Raw materials & production – Rare earth metals in processors, server chassis materials.
- Operation & energy use – Power consumption, cooling requirements (PUE, CUE, WUE).
- Networking infrastructure – Bandwidth and data transmission energy consumption.
- End-of-life disposal – E-waste generation, refurbishment, or recycling rates (WEEE compliance).

Example: Federated AI research testbed LCA would track GPU power usage, cooling energy, carbon emissions, and disposal of outdated AI accelerators.

Phase 3: Lifecycle Impact Assessment (LCIA)

Objective: Evaluate the environmental impact categories using collected data. Key environmental indicators for DRIs that GreenDIGIT selected to use:

Environmental impact category	Environmental impact indicator
Global Warming Potential **(GWP)** / Climate Change **(CC)**	Kg CO_2 eq
Cumulative Energy Demand **(CED)**	Joule [J] of primary energy demand
Waste of Electrical and Electronic Equipment **(WEEE)**	Total electrical and electronic waste (kg)

Example: A 5G testbed LCA would measure energy efficiency of radio units, fiber optics carbon footprint, and lifecycle emissions of 5G equipment.

Phase 4: Interpretation & Sustainability Optimisation

Objective: Identify improvements and sustainability strategies. Key improvement areas for DRIs:

- Optimise ML model training energy efficiency to reduce CO_2 footprint.
- Use modular servers & upgradable networking devices to extend hardware lifespan.
- Implement circular economy by refurbishing and reusing testbed hardware.
- Reduce cooling energy demand with liquid cooling and free cooling systems.
- Shift to renewable energy sources for research computing clusters.

Example: After analysing an IoT testbed's LCA, researchers might reduce emissions by deploying low-power edge computing nodes instead of cloud-heavy architectures.

5.2 Challenges of Using LCA for RI Sustainability Assessment

While Life Cycle Assessment (LCA) is a well-established method for evaluating environmental impacts, applying it to digital Research Infrastructures (RIs)—like data centers and networked platforms—presents unique challenges.

LCA was originally designed for physical products, not complex, service-based infrastructures. As a result, it struggles to fully capture the environmental footprint of distributed, evolving systems like RIs. One major issue is data availability and quality; infrastructure-wide data is often incomplete, inconsistent, or fragmented, leading to unreliable results. Regional differences in regulations, energy mixes, and practices further complicate comparisons across sites.

LCAs are also resource- and time-intensive, often requiring months of expert effort—yet still may miss key lifecycle aspects. The selection of impact categories (e.g., carbon, water, toxicity) is often subjective, and traditional LCA methods tend to overlook social and economic dimensions, such as labour conditions or regional benefits.

Other limitations include difficulties in defining a consistent functional unit for digital services, a lack of temporal and spatial sensitivity (e.g., seasonal energy variations), and high uncertainty in the end-of-life phase, especially given the fast pace of technological obsolescence.

In short, while LCA remains a valuable tool, using it effectively for Research Infrastructures requires adaptation. The unique characteristics of digital RIs demand new approaches, better data models, and frameworks that reflect the service-based, distributed, and dynamic nature of these systems—while still adhering to the core principles of environmental responsibility and transparency.

6 Regulations and Standards Compliance for RILM Stages

Digital RIs, including datacenters and networking infrastructure, are required to comply with the energy and environmental impact management regulations and standards (refer to the Milestone MS4 document for regulations analysis [5]):

- European Sustainability Reporting Standards (ESRS) and the linked Corporate Sustainability Reporting Directive (CSRD)
- Eco-design for Sustainable Products Regulation (ESPR)
- Energy Efficiency Directive (EED)
- Waste Electrical and Electronic Equipment (WEEE) Directive
- Lifecycle Analysis framework (LCA)
- ISO 14040/ISO 14044 standards defining LCA methodology
- Energy and environmental management systems and metrics ISO 50001/EN50600, ISO 30134, ISO 14001

Error! Reference source not found. below provides a summary of how these regulations and s tandards are mapped to the RILM stages.

Table 2. Mapping European regulations to RILM stages

Regulation	Link to RILM stage
General Environmental Impact Management Regulations	
CSRD & ESRS (Reporting and Disclosure Regulations	**Design stage:** planning for robust sustainability reporting systems. **Preparation, Implementation, Operation, Termination stages:** ongoing sustainability reporting and performance disclosure.
Energy Efficiency Directive (EED)	**Design stage:** setting energy efficiency objectives. **Preparation and Development, Implementation and Deployment, Operation stages:** achieving and demonstrating compliance with energy efficiency targets. Typically, not directly applicable at **Termination**, as energy consumption ceases.
Eco-design for Sustainable Products Regulation (ESPR)	Starts from the **Design stage**: embedding eco-design principles. Relevant throughout all following stages, including **Termination**, as it addresses design for reuse, repair, recycling, or sustainable disposal.
WEEE Directive	Applies predominantly at the **Operation and Termination** stages: addresses responsible management, disposal, recycling, or reuse of electronic and electrical equipment waste.
Energy Efficiency and Environment Monitoring Systems - -Standards and Best Practices	

JRC CoC DC EE	Required for **Operation**, expected to address at **Design, Development, Deployment** energy efficiency and use in datacenters
ISO 50001/EN50600	Required for **Operation**, expected to address at **Design, Development** energy efficiency and metrics in datacenters
ISO 30134	Required for **Operation**, expected to address at **Design, Development** energy efficiency and metrics in datacenters
ISO 140001	Required for **Operation**, expected to address at **Design, Development, Deployment** of Environment Monitoring Systems

Error! Reference source not found. provides an integrated view of how the LCA methodology, r elevant European environmental regulations, internationally recognised standards, and associated energy and environmental metrics align with and support the sustainability of RIs throughout their lifecycle. The figure is structured around the six RI lifecycle stages defined by the ESFRI framework. The four phases of LCA are linked to specific RI lifecycle stages. These links indicate where each LCA phase is most relevant or actively applied. For example, the goal and scope definition are typically aligned with the Concept and Design stages, while impact assessment and interpretation are most critical during Operation.

Similarly, key regulatory frameworks are linked to relevant RI lifecycle stages. These connections highlight when specific legal or policy obligations come into effect (e.g., ESPR during Design and Operation/Procurement; CSRD/ESRS during Operation and Reporting; WEEE during Operation and Termination).

The figure also integrates a set of technical and management standards (ISO and EN group) that support environmental and energy performance across the RI lifecycle. Each standard is linked to the stages where it is typically implemented or referenced, supporting activities such as environmental performance monitoring, energy optimisation, and data-driven operational decision-making.

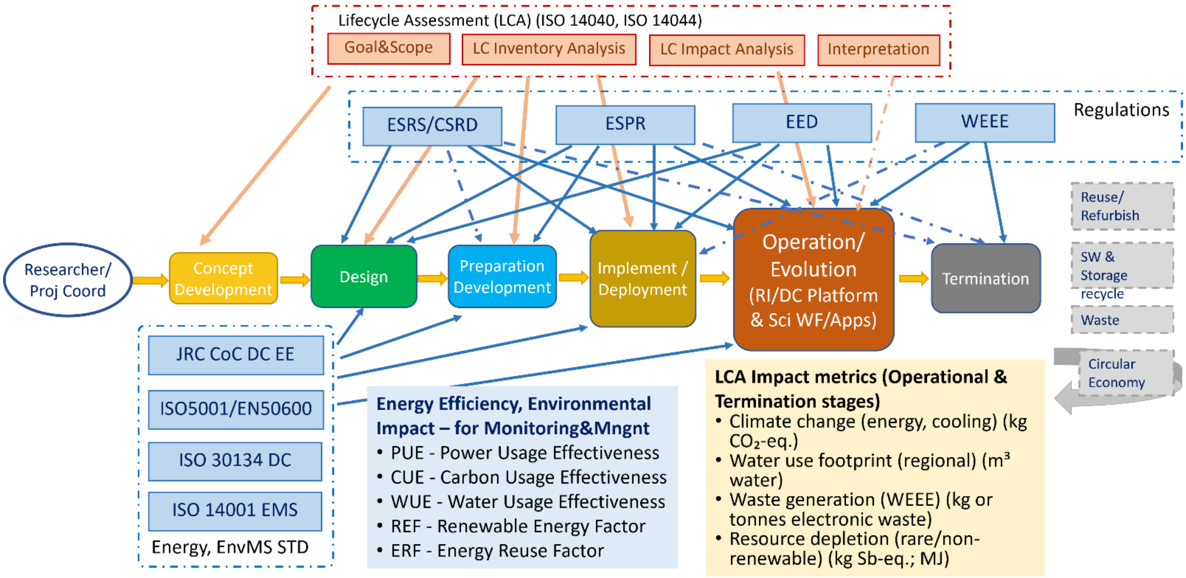

Figure 3. Linking LCA Phases, Environmental Regulations, Standards, and Metrics across the Research Infrastructure Lifecycle Stages

The presented figure demonstrates how a lifecycle-based sustainability approach can be operationalised in digital and distributed RIs by aligning the phases of LCA with infrastructure development and operation, embedding regulatory compliance at appropriate stages, and applying relevant standards, and operational and environmental impact metrics. It intends to serve as a conceptual tool for integrating sustainability into RI planning, governance, monitoring, and continuous improvement.

7 Key recommendations for the Research Infrastructures

In order to give a clear understanding, key recommendations are divided to 3 categories: technical recommendation, policy/admin recommendations, overall link between LCA and EU regulations.

Technical recommendations

The sustainability of digital RIs such as data centers, experimental testbeds, and federated ICT services, requires proactive, lifecycle-based planning that integrates environmental, regulatory, and operational considerations from concept to decommissioning. The following key recommendations are proposed:

1. Adopt Lifecycle Thinking as a Strategic Approach
RIs should incorporate environmental sustainability from the earliest stages of concept development through to decommissioning. Lifecycle thinking supports strategic alignment with ESFRI and EU sustainability goals and enables long-term planning for compliance, efficiency, and resilience.

2. Integrate LCA Methodology Across RI Lifecycle Stages
Although not originally designed for digital infrastructures, the LCA methodology (as defined in ISO 14040/14044) should be adapted and applied across all RI lifecycle stages. This can inform planning, procurement, operations, and decommissioning decisions.

3. Build Compliance into Design and Development
Design and development stages should embed compliance with ESRS/CSRD, ESPR, EED, and WEEE regulations. This includes selecting ESPR-compliant hardware, planning for energy efficiency (EN50600, ISO 50001), and establishing monitoring mechanisms for sustainability metrics such as PUE, WUE, GHG emissions, and e-waste.

4. Strengthen Environmental and Energy Monitoring Infrastructure
RIs should implement integrated monitoring systems (aligned with ISO 30134 and ISO 14001) to track energy, water, material use, and emissions in real time.

5. Adopt Circular Economy Principles and Sustainable Decommissioning
Operational and end-of-life stages should incorporate circular economy strategies, including refurbishment, hardware reuse, and component recycling, in line with WEEE and ESPR requirements.

6. Develop RI-Specific LCA Guidelines and Competences
Given the limitations of general-purpose LCA methods for digital RIs, dedicated guidelines should be developed.

7. Align Environmental Strategy with ESFRI Roadmap 2026 Guidelines
Each RI should develop an environmental sustainability strategy as outlined in the ESFRI Roadmap 2026.

8. Foster Collaboration Across Stakeholder Groups
Collaboration between RI managers, researchers, policymakers, and sustainability experts is essential to ensure that the sustainability strategy reflects both operational realities and scientific needs.

Policymakers and admin recommendations

1. Require Lifecycle-Based Environmental Planning: Encourage RIs to integrate lifecycle thinking from concept to decommissioning into project planning and funding requirements. This ensures the environmental impact is addressed systematically and early.

2. Promote Adoption of LCA for Digital Infrastructures: Support the development and use of adapted LCA frameworks for digital and ICT-based RIs, aligned with ISO 14040/14044.

3. Align RI Strategy with EU Sustainability Regulations: CSRD, ESRS, ESPR, EED, and WEEE directives.

4. Support Standards-Based Environmental Monitoring based on recognised standards such as ISO 50001, ISO 14001, EN 50600, ISO 30134

6. Incentivise Circular Economy principles and Practices such as reuse, refurbishment, and recycling in RI procurement, operation, and decommissioning.

7. Support capacity building and training for RI operators, administrators, and researchers on LCA, environmental impact assessment, and sustainability reporting.

Relation of LCA to Environmental Sustainability of Digital RIs

LCA is directly linked to the sustainability of DRIs by providing a data-driven approach to:

Sustainability Goal	How LCA Supports It	Relevant EU Regulation
Reduce Carbon Footprint	Tracks emissions from data centers, ML/AI workloads, 5G testbeds	CSRD/ESRS (mandatory reporting of carbon emissions)
Improve Energy Efficiency	Assesses power use of ML training, IoT sensors, HPC workloads	EED (energy efficiency targets for IT infrastructure)
Optimise IT Procurement	Encourages use of recyclable, repairable, ESPR-compliant hardware	ESPR (Ecodesign for IT products, Digital Product Passport)
Minimize E-Waste	Tracks lifecycle of networking, computing, storage equipment	WEEE (mandatory recycling & refurbishment of IT assets)
Enhance Circular Economy	Supports refurbishment & material recovery	ESPR/ESRS & WEEE (circular economy principles)

The following are summary considerations for applying LCA methodology for RI LCA:

- The early lifecycle stage (Concept Development) is primarily strategic and visionary, often not directly regulated but shapes strategic alignment for future compliance.
- Compliance infrastructure (systems, data collection, processes) is set primarily during the Design and Preparation stages.
- Continuous performance monitoring and optimisation are important during the Operation stage.

- Waste management compliance and procurement for hardware/software upgrade/replacement are essential at the Termination stage; however, ESPR ensures anticipatory actions are embedded much earlier.

The described mapping defines how each key regulation relates directly to each lifecycle stage, facilitating strategic alignment and operational compliance management for RIs within ESFRI guidelines on environmental sustainability.

8 Conclusion

The growth of European and international scientific capacities is largely dependent on the effective creation and administration of Digital Research Infrastructures (DRIs). As this whitepaper has outlined, a lifecycle-oriented approach to research infrastructures (concept development, design, preparation/development, operation/evolution and termination) is essential for guaranteeing long-term value, sustainability, and alignment with changing scientific and social demands.

Key insights from the analysis highlight the need for rigorous and flexible integrated lifecycle assessment approaches, as well as the need of clearly defined roles and responsibilities throughout the infrastructure lifespan. Expectations for accountability, sustainability, and transparency are shaped by European regulatory frameworks, especially the CSRD, ESRS, and ESFRI Roadmap.

A wide range of stakeholders, including policymakers/admin, technical operators, researchers on infrastructure and users should work closely together to manage RIs effectively. Additionally, it demands a forward-thinking governance architecture that preserves strong performance and scientific relevance while anticipating changes in technology and policy.

A systematic model and useful suggestions for improving lifecycle governance and strategic planning across research infrastructures have been offered in this whitepaper. Stakeholders may improve the scientific impact, societal value, and sustainability of Europe's research ecosystem by implementing these findings, guaranteeing that digital research infrastructures continue to be vibrant, innovation-enabling platforms for years to come.

Annex A. ESFRI Roadmap 2026 Public Guide and required ESRS/CSRD Reporting

Environmental Sustainability Recommendations, included in the ESFRI Roadmap 2026, outline minimal key requirements for environmental sustainability across different RI lifecycle phases:

- Design Phase: Outline an environmental strategy at a headline level, referencing applicable elements from the ESRS nomenclature.
- Preparation Phase: Identify and address significant environmental issues within the environmental strategy.
- Implementation Phase: Develop a detailed environmental strategy and action plan, including the identification of responsibilities and necessary resources.
- Operation Phase: Implement and monitor the environmental strategy and action plan using Key Performance Indicators (KPIs).
- Termination Phase: Execute decommissioning according to high environmental standards.

These guidelines ensure that environmental considerations are embedded throughout the RI's lifecycle, promoting sustainability from inception to decommissioning.

The ESFRI Roadmap 2026 Public Guide aligns its environmental strategies with the ESRS nomenclature, ensuring consistency in sustainability reporting. The ESRS provides a framework for organizations to report on environmental, social, and governance (ESG) factors, facilitating transparency and accountability. By referencing ESRS, RIs can standardize their reporting practices, making them comparable and aligned with broader European sustainability goals.

Incorporating ESRS elements into the environmental strategy of an RI ensures that sustainability efforts are systematically planned, executed, and reported, contributing to the overarching objectives of the European Green Deal and sustainable development.

Linking to reporting regulations CSRD and ESRS

Required Environmental Sustainability reporting is based on two connected regulations: Corporate Sustainability Reporting Directive (CSRD) [6] and European Sustainability Reporting Standards (ESRS) [7] [8].

1. CSRD as the Legal Framework

The Corporate Sustainability Reporting Directive (CSRD) is the EU legislative framework that mandates sustainability reporting requirements for companies. It defines who must report, what information must be disclosed, and how the reporting integrates with financial disclosures. CSRD applies to large companies, listed SMEs, and non-EU companies with significant EU operations.

However, CSRD itself does not specify detailed reporting metrics - instead, it delegates the standardization of reporting requirements to the European Sustainability Reporting Standards (ESRS).

2. ESRS as the Detailed Reporting Standards

The European Sustainability Reporting Standards (ESRS) are the technical standards that define the content, structure, and methodology for CSRD compliance. These standards provide specific disclosure requirements on Environmental, Social, and Governance (ESG) topics.

- ESRS is developed by the European Financial Reporting Advisory Group (EFRAG).
- ESRS ensures uniformity and comparability across corporate sustainability reports.
- It aligns with international ESG frameworks, such as Global Reporting Initiative (GRI), Task Force on Climate-related Financial Disclosures (TCFD), and the EU Green Taxonomy.

3. Structure of ESRS as mapped to ESG (Environment, Social, Governance) GRI (Global Reporting Initiative)

ESRS is structured into sector-agnostic, sector-specific, and entity-specific standards:

1. General Standards
    - ESRS 1: General principles (materiality, reporting boundary, etc.).
    - ESRS 2: General disclosures (governance, business model, strategy).
2. Environmental Standards
    - ESRS E1: Climate change
    - ESRS E2: Pollution
    - ESRS E3: Water and marine resources
    - ESRS E4: Biodiversity and ecosystems
    - ESRS E5: Resource use and circular economy
3. Social Standards
    - ESRS S1: Own workforce
    - ESRS S2: Workers in the value chain
    - ESRS S3: Affected communities
    - ESRS S4: Consumers and end-users
4. Governance Standards
    - ESRS G1: Business conduct
5. Sector-Specific Standards (Future Development)
    - Additional industry-specific ESG disclosures for data centres, finance, manufacturing, etc.

Environmental group E1-E5 create a basis for ESFRI Checklist for Dimension "Environmental Considerations" that provide a guidance for developing Environmental Sustainability Strategy by RIs.