Architecture and KPIs for Green IT Networked Systems and Cloud

Standards and Regulations for Environmental Impact Monitoring and Reporting

GreenDIGIT

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27 June 2025

SLICES/CONVERGE Summer School 2025, Porto

Outline

- GreenDIGIT project scope and goals for RI/ESFRI community
  - Founding EU ESFRI Research Infrastructures: SoBigData, EBRAINS, SLICES, EGI
- Shared Responsibility Model for Sustainability
  - Sustainability aspects in Digital Infrastructure: From researcher/experimenter to developer to operator
- Sustainability by Design: Architecture Framework and Energy/Impact Monitoring Infrastructure
- Monitoring and metrics for Energy Efficiency optimisation and Environmental Impact
- Research Infrastructure Lifecycle Model (RILM) and EU Regulations Compliance
- Additional: Standardisation on Environmental Sustainability and technical requirements

GreenDIGIT tutorials reference codes: LU-GRIU02 - LU-GRIU0207, LU-RIOS05 - LU-RIOS06

Funded by the European Union.
Grant ID: 101131207

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What is this Tutorial about?

- Modern digital RI are highly distributed and evolving at many layers:
  - Physical, Virtual, Scientific applications and AI/LLM integration, Scientific workflow, Data (management)
- **Multiple aspects** of environmental sustainability and energy efficiency
- **KPI and metrics** to monitor energy efficiency and environmental impact of operating digital infrastructure and scientific applications
- What **standards and regulations** need to know to ensure compliance and required reporting?
- How operational and compliance **requirements to** be transferred to infrastructure **design and monitoring** infrastructure?

Sustainability Aspects: Energy Efficiency – Decarbonisation – Environmental Impact

- **Energy Efficiency of Digital Infrastructures**:
  - **Definition**: This refers to optimizing digital infrastructures to consume as little energy as possible for a given workload or service. It's about achieving more computational or storage results with less energy input.
- **Decarbonization of Digital Infrastructures**:
  - **Definition**: This specifically targets the reduction of carbon emissions associated with the operation and maintenance of digital infrastructures.
- **Reducing Environmental Impact of Digital Infrastructures**:
  - **Definition**: This is a more comprehensive consideration of the various ways digital infrastructures might affect the environment, going beyond just energy consumption and carbon emissions.

Architecture, Design, Recommendations

Operation, Monitoring, KPI

Lifecycle, Policy, Training

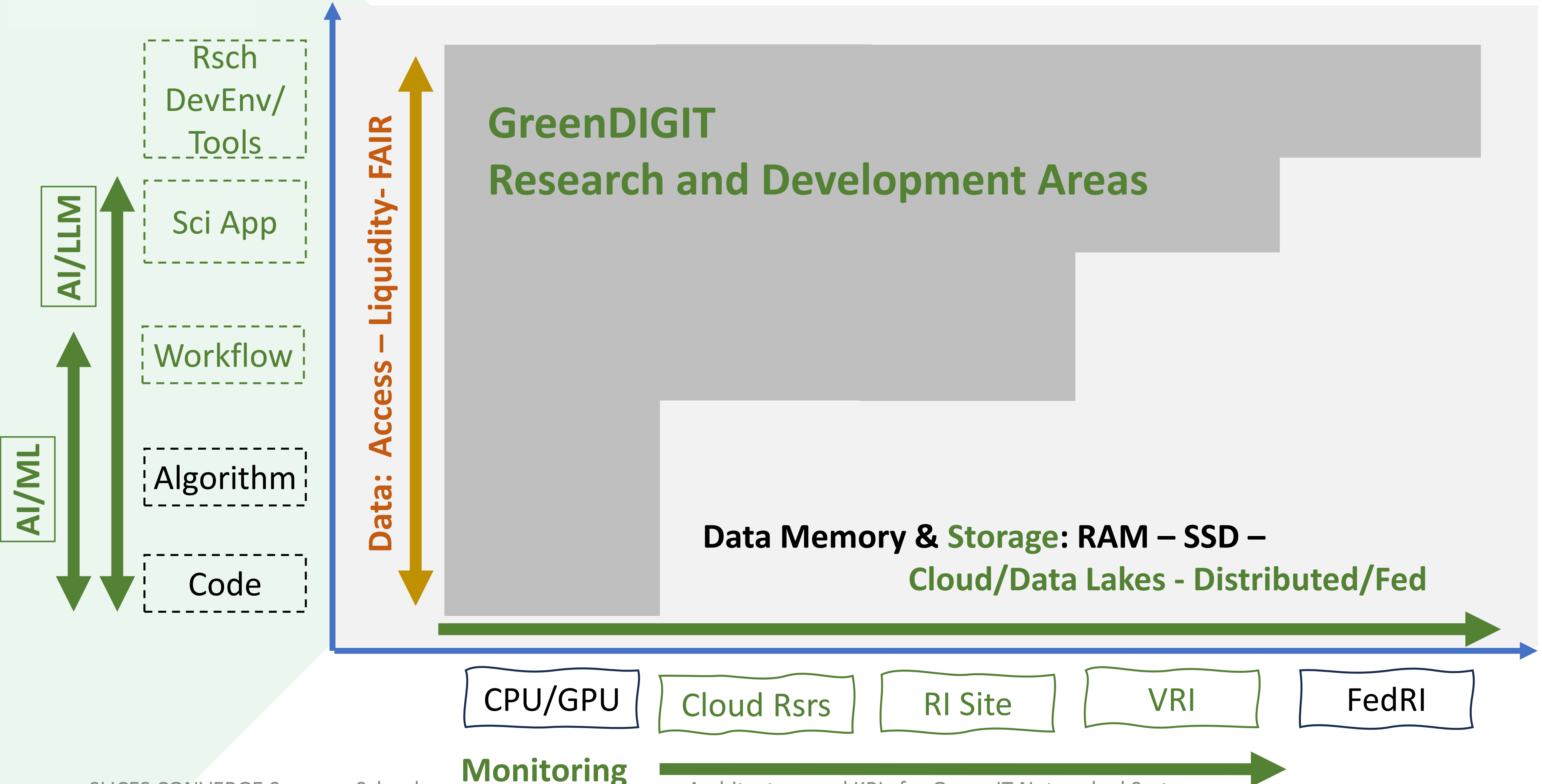
AI/ML/LLM and Research Practices/Use

Energy Efficiency and Environmental Impact

- Algorithms and workflow optimisation
- Effective data management through the whole ML lifecycle
  - Extended data model enriched with semantics, metadata, vocabularies
- **Infrastructure monitoring and metrics optimisation**
  - **Smart energy sources management**
- User side: LLM input and output caching and embedding

- **Research on ML/Data Analytics**
  - Common algorithms and models for different scientific domains and data –> require algorithms profiling and efficient management (data liquidity)
  - Access to developer controlled computation platforms
- **AI/ML enabled research environment** to assist in domain-specific research and hypothesis testing
  - Expected growing role of LLM –> LLM infrastructure to be optimised for operation/inference and the creation of domain specific knowledge base(s)
    - Instrument for *conversation research* methodology
- AI4EOSC Flagship project: Focusing on AI/ML tools and EOSC targeted services
  - Software stack, composite serverless AI platform (cross-discipline)
  - Data and models repository and management –> extending FAIR data principles for actionable data management (beyond data storage and sharing)
    - Rich data models (beyond textual and relational) including semantics, ontology, metadata, vocabulary

GreenDIGIT Scope Areas: RI & Sustainability AI/ML Aspects



Multiple RI dimensions

- Code – Algorithms – Workflow
- CPU/GPU – Cloud – Site – VRI/VRE

Data dimensions

- Memory – Storage – Distributed
- Access – Liquidity (Data & Model) - FAIR

GreenDIGIT Approach: Architecture as Consolidation Concept and Instrument

- **Architecture** is a way to coordinate and synchronise/unite
  - Developers of Infrastructure and Applications
  - Operators
  - Users/Researchers
  - Policy and decision makers
  - Refer to TOGAF architecture principles (as an approach accepted by the majority of businesses)
- A basis for linking standards and regulations to architecture functional components
  - Ensure compliance of the designed/developed RI and services (including for audit)

GreenDIGIT implementation and current outcomes

- Landscape analysis (2024)
- Overview European policies, regulations and standards
- Architecture Framework for Sustainability by Design
- **Shared Responsibility Model for Sustainability**
- Metrics and Monitoring Architecture
  - Researcher Tools for Energy and Environmental Impact Awareness
- RI Lifecycle Model and Impact Assessment Framework
- Green Competences Framework and Thematic Tutorial Groups

GreenDIGIT Architecture Definition Methodology – General aspects and dimensions

- General aspects/dimensions of architecture definition for RI ecosystem optimisation and Green IT
  - Horizontal, vertical, lifecycle
  - RI continuum: (Research Object) – Sensor - (RAN) – Edge – Cloud – Workflow - Researcher
  - Target groups: RI Developers, RI Operators, Researchers/Scientific applications developers

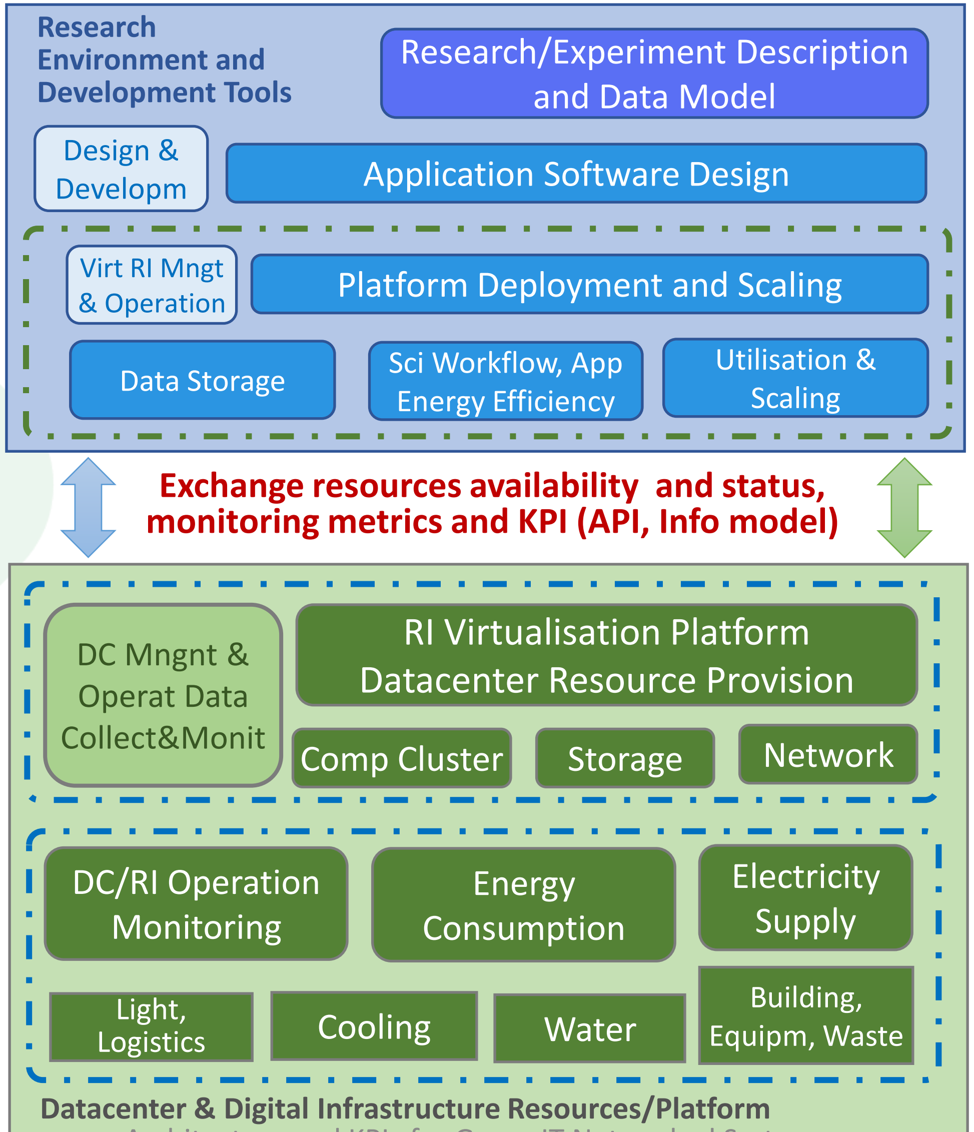
GreenDIGIT Architecture Definition Methodology – System Engineering Approach

- Sustainable architecture design principles
  - As a basis for modelling and metrics for RI infrastructure operation and optimisation
  - **Shared Responsibility Model**: RI provider/operator and Researchers/Projects
  - **Sustainability by design** – A novel concept to be introduced to address different aspects and stages
- Linkage with existing Standards and Regulations to ensure Sustainable Architecture Design principles support compliance with the standards, regulations and audit
  - To provide the opportunity for RI/datacenter operation (and design) optimisation (through the whole lifecycle)
- System Engineering and Design (thinking) approach in Green research and technologies
  - **Sustainable (Durable) Architecture Design Principles**
  - **Challenge: How to ensure regulations and standard compliant design and operation?**

Shared Responsibility in Sustainability – Reflecting Operational and Management Aspects

Users responsible for sustainability ***on*** the RI

Providers responsible for the sustainability ***of*** the RI



- **Researcher tools**
- **Scientific applications/** workflow development environment
- **Virtual Research Infrastructure** operation and Management
- Monitoring and metrics exchange and APIs
- **RI virtualisation platform**: data center resources management & cloud platform
- **Data center** operation and physical/HW resources management
  - **Facilities and buildings** environment monitoring

Shared Responsibility in Sustainability – Reflecting Operational and Management Aspects and Roles

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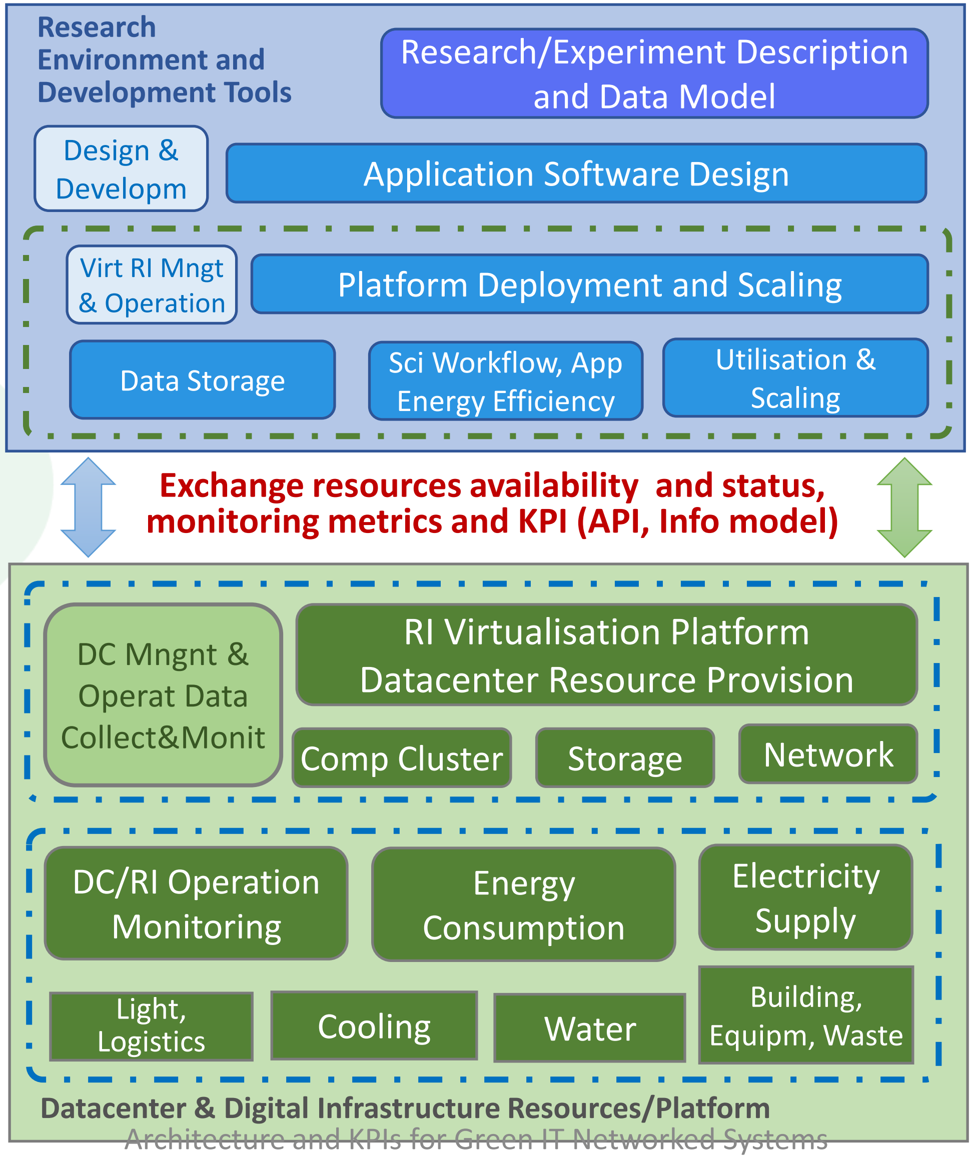


Project/Researcher Responsibility:
- Applications Development,
- Deployment, Jobs submission & Energy Efficiency optimisation
- Operation, Workflow execution
- Energy usage and KPI monitoring

Experimenter/Researcher Demand:
- Access to datacenter (internal) monitoring data and custom configuration
- Energy usage and KPI & metrics monitoring

Provider/Operator Responsibility:
- Operation of Research Infrastructure or Datacenter,
- Monitoring Energy: environmental impact metrics and KPI
- Waste
- Lifecycle and evolution

RI Sustainability by Design Components/Aspects:
Motivated by the Shared Responsibility Model

Users responsible for sustainability ***on*** the RI

Researcher/ Project Responsibility:
Applications Development, Energy usage and KPI monitoring

Sustainability by Design Pillars/Challenges

RI/Datacenter Provider/Operator Responsibility:
Monitoring Energy and environmental impact, metrics and KPI

Providers responsible for the sustainability ***of*** the RI

Pillar 1 – Layered and Modular Architecture for Sustainable Digital Infrastructur
- Functional components, Layers, API, Requirements

Pillar 2 - Software and Scientific Applications Design Patterns for Energy Efficiency and Environmental Impact Reduction
- Green aware API including necessary energy, performance, environment information

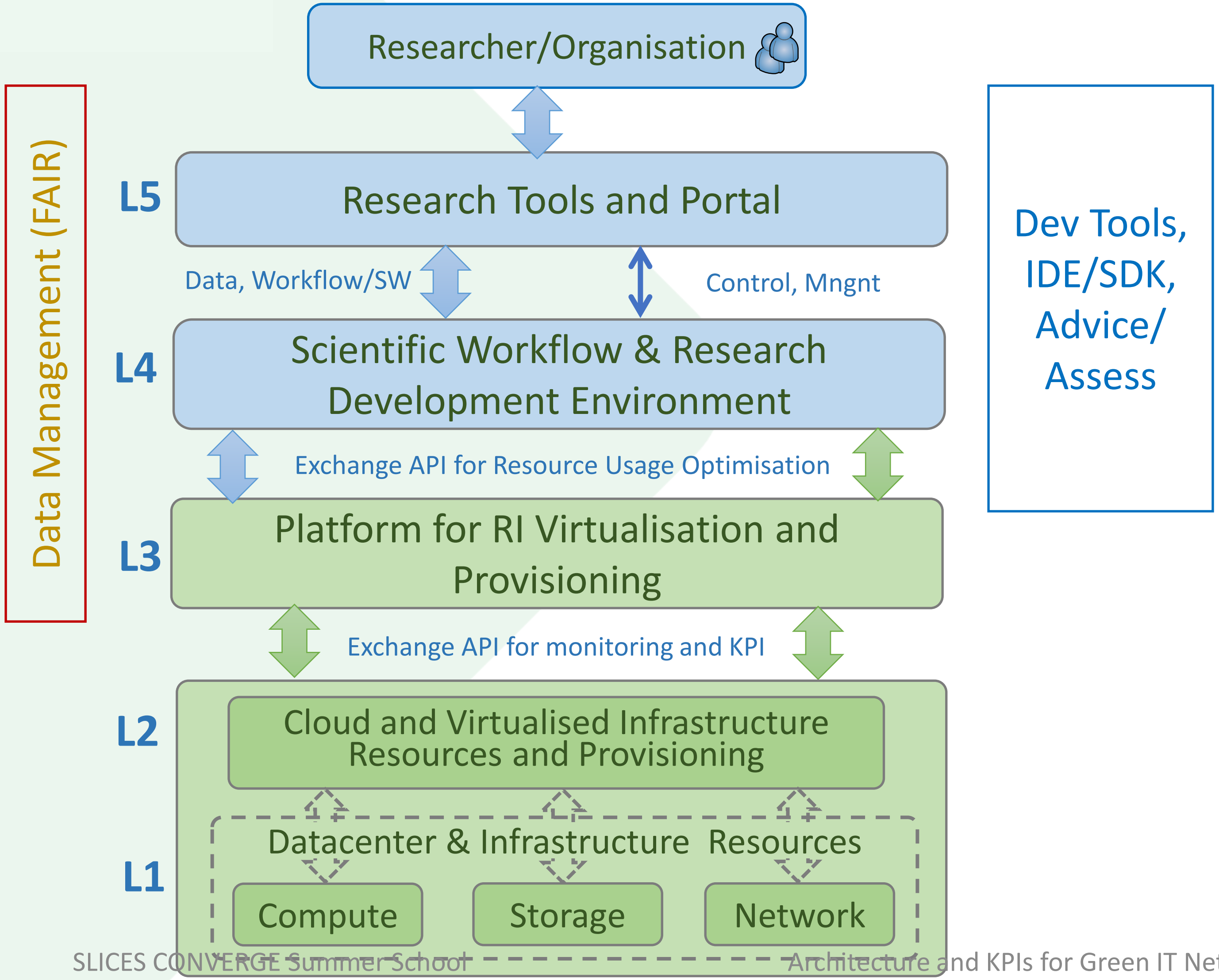
Pillar 3 - Lifecycle-Oriented Sustainability Management of Research Infrastructures and Scientific Applications
- RI lifecycle stages (concept, design, development, deployment, operation, decommissioning) and scientific workflow and research data

(!) Pillar 4 – Interoperable/common Information Models for **Sustainability Metrics and Monitoring**
- Including **Requirements, KPI, Metrics**
  + FAIR for Sustainability

Pillar 5 - Sustainable Data Management and Energy-Efficient Storage Systems

RI Sustainability by Design Components/Aspects:

5 Pillars Architecture Framework for Sustainability by Design



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5 Pillars Architecture Framework for Sustainability by Design - Technical

- Pillar 1 – Layered and Modular Architecture for Sustainable Digital Infrastructure
- Pillar 2 - Software and Scientific Applications Design Patterns for Energy Efficiency and Environmental Impact Reduction
- Pillar 3 - Lifecycle-Oriented Sustainability Management of Research Infrastructures and Scientific Applications
- Pillar 4 – Interoperable/common Information Models for Sustainability Metrics and Monitoring
- Pillar 5 - Sustainable Data Management and Energy-Efficient Storage Systems

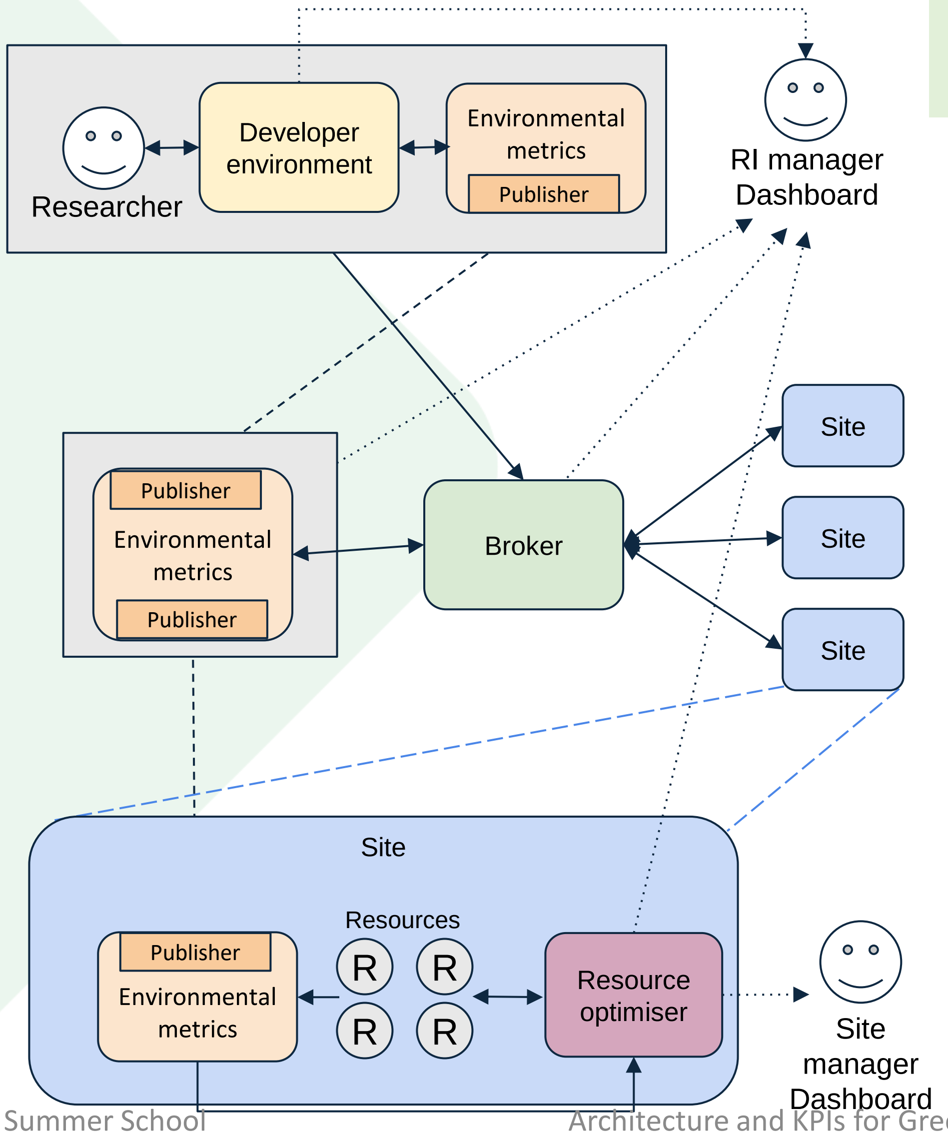
Architecture for Metrics and Optimisation – Stage 1 Distributed Computing and Cloud

To be adopted and piloted on the EGI federated computing infrastructure

Level 1: RDE, Experiment

Level 2: Infrastructure Composition/ Scheduling

Level 3: Site, Resources Management



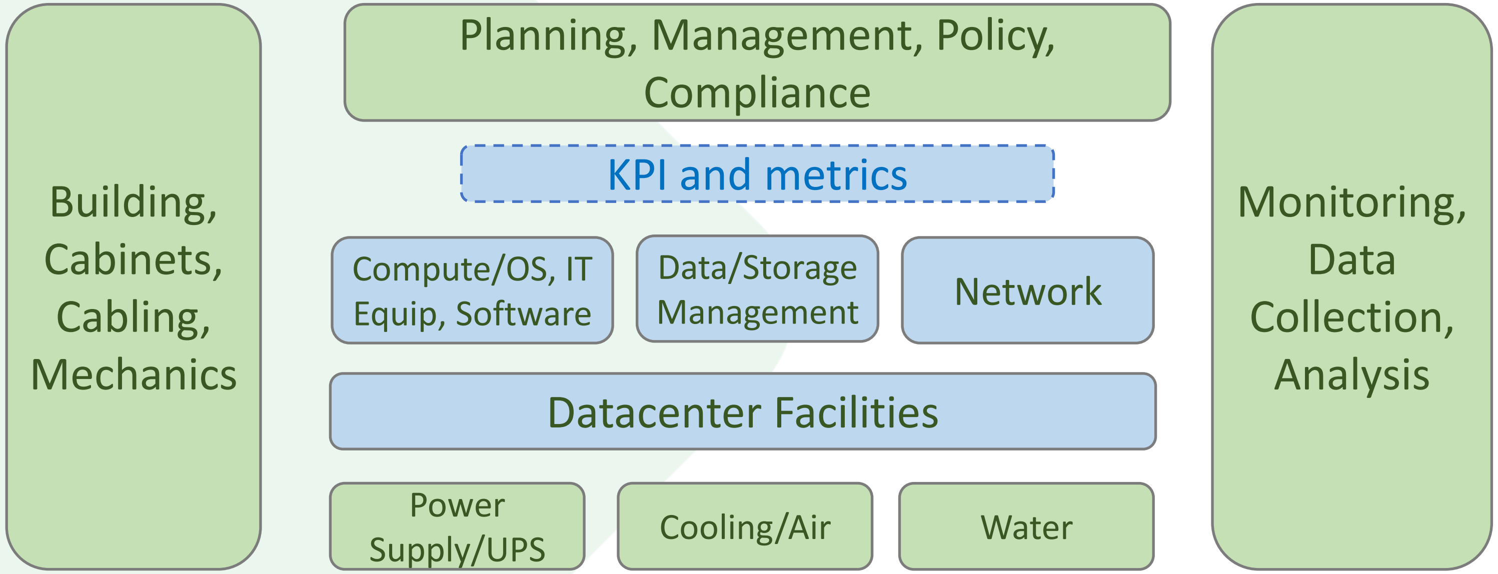
- **Level 1 – Developer tools for energy efficient software design**
  - Optimised code; Prevent re-execution of already conducted experiments
- **Level 2 – Energy efficiency aware schedulers**
  - Reshuffle jobs based on site carbon intensity attributes
- **Level 3 – Energy efficiency aware resources manager**
  - Delay execution based on electricity cost, regulations, carbon intensity, resources turning on-off
- **Metrics Infrastructure**
  - Gather relevant environmental impact metrics
  - Serve metrics to decision making systems (schedulers, researcher tools, VREs)
  - Present statistics and monitoring in dashboards

KPI and Metrics: Definition and Design Aspects

- KPI and metrics are defined by standards and regulations
  - Standards: ISO, IEEE, ITU-T, CEN, RFC, Industry BCP
- Challenge: Translation of legal and audit/certification language of regulation documents to technical requirements
- Semantics and metadata interoperability for metrics sharing -> Common Information Model
  - Multiple groups of standards and regulations
- Metrics and KPI GreenDIGIT stages
  - Stage 1: Data centers, cloud, researcher tools
  - Stage 2: Network, 5G/6G and IoT
  - Stage 3: Datacenter facilities, water, pollution, waste

Best Practice for the EU CoC on Data Centre Energy Efficiency: Main Infrastructure components – RI/Datacenter Operator Perspective

Also supported in the EC Delegated Regulation (EU) 2024/1364 of 14 March 2024



Areas of responsibility/ management

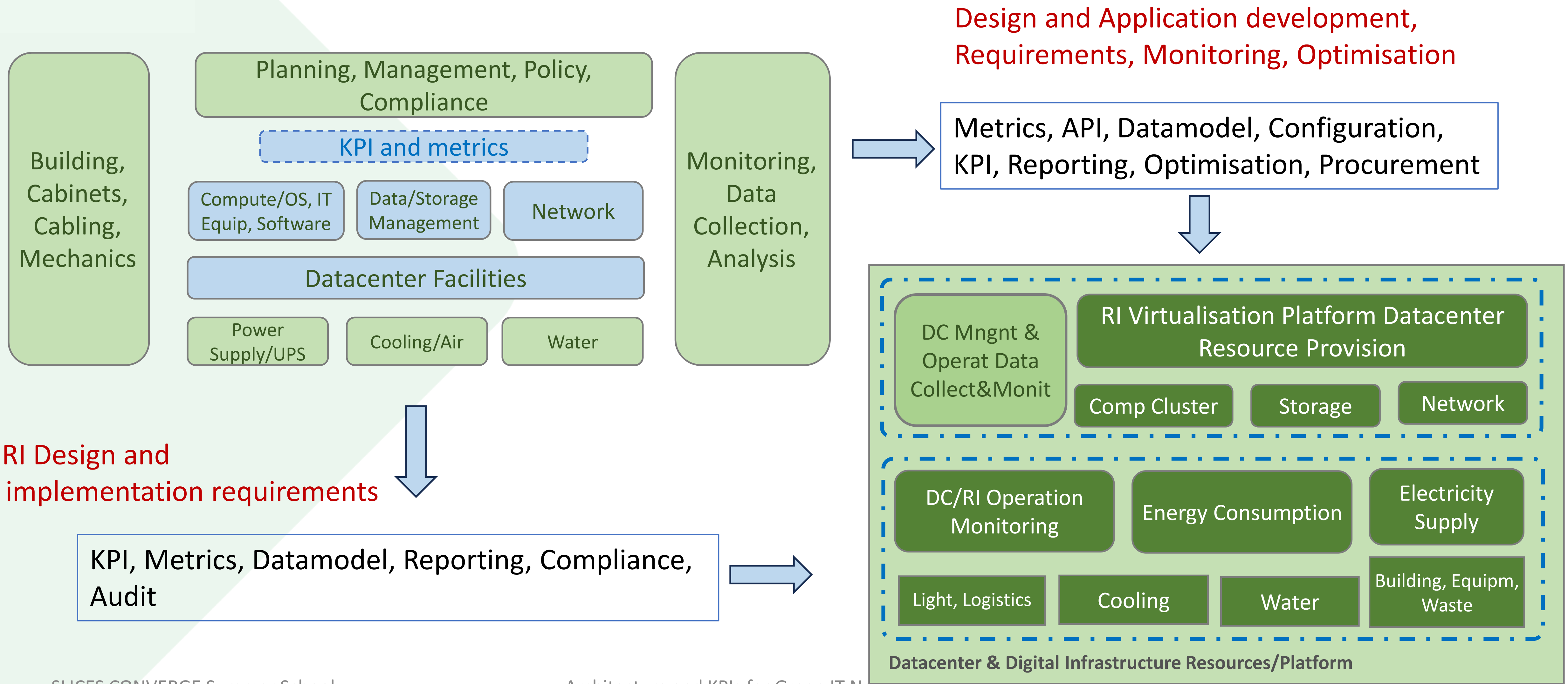
- Physical building
- Mechanical and electrical plant
- Data floor and air floor
- Cabinets and cabinets airflow
- Metrics and operation measurement points
- **IT equipment**
- **Operating systems and virtualisation**
- **Software**
- Business Practices

Different roles of participants/ stakeholders

- Operator
- Collocation provider
- Colocation customer
- Managed services provider
- Managed services provider in the collocation space

[ref] https://e3p.jrc.ec.europa.eu/sites/default/files/documents/publications/jrc136986_2024_best_practice_guidelines.pdf

Mapping KPI and Metrics to Functional Infrastructure components and Applications/Workflow – To do in consultation with Data centers



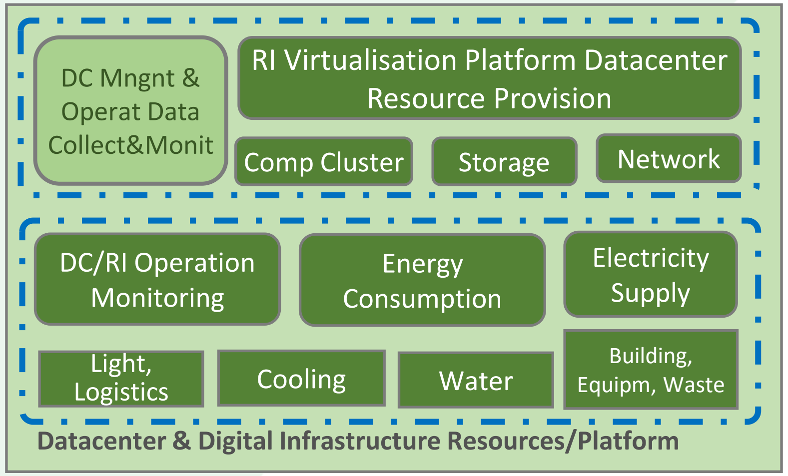
Linking KPI, Metrics and Design Patterns – To be clarified and extended – In a progress

KPI (Key Performance Indicators)

- Energy consumption (kWh).
- PUE (Power Usage Effectiveness): Ratio total energy used to energy consumed by IT
- Carbon footprint: Amount of CO_2 emissions associated with energy usage.
- Water Usage Efficiency (WUE)
- Uptime or reliability: How well the infrastructure maintains consistent service
- Resource utilisation efficiency: Resources (servers, storage, etc.) usage w/o wasting energy.

Metrics

- CPU usage and load: The utilization levels of computing resources
- Energy draw per server
- IT equipment energy consumption
- Temperature: The internal temperature of servers or cooling systems
- Cooling system efficiency
- Water use



Design Solutions/Patterns

Under RI provider control/management

- Energy-efficient hardware
- Green energy sources
- Monitoring and energy efficiency analytics and optimisation at the level of RI provider
- Advanced cooling systems
- Smart grid integration

Under user/developer control

- Energy and environment aware applications development
- Modelling, simulation and testing as part of the development process
- Green software practices and templates
- Virtualisation and containerization

Datacenter - Example KPI

KPI	Example Value	Context / Source
Power Usage Effectiveness (PUE)	**1.45**	EU CoC recommends ≤ 1.5; best-in-class data centers achieve ≤ 1.2 (ISO 30134-2)
Carbon Usage Effectiveness (CUE)	**0.20 kg CO_2e/kWh IT**	Calculated based on energy source mix; lower with renewable procurement (ISO 30134-8)
Water Usage Effectiveness (WUE)	**1.6 L/kWh IT**	EU Regulation (2024/1364) suggests this as a good benchmark
Energy Reuse Factor (ERF)	**0.25**	25% of energy reused (e.g., waste heat recovery); encouraged by ESPR and EED (ISO 30134-6)
Renewable Energy Factor (REF)	**0.80**	80% of total energy from renewable sources; aligned with ESPR and Climate Neutral Data Centre Pact
IT Equipment Utilization (ITEUsv)	**65%**	Indicates efficient server usage; virtualization & orchestration help reach >60%
Facility Energy Consumption	**1.5 million kWh/year**	Typical for a medium-scale research data center (~500–1000 kW IT load)
Carbon Footprint (Scope 2)	**450 metric tons CO_2e/year**	Based on 0.3 kg CO_2e/kWh for non-renewable grid power
Uptime (Reliability)	**99.982%**	Tier III compliance (~1.6 hours/year downtime)
Cooling Efficiency Ratio (CER)	**4.0**	Common in modern data centers using efficient liquid cooling
Achieved Free Cooling Hours	**5,500 hours/year**	Applicable in temperate zones using air economization

Datacenter – Supporting Metrics

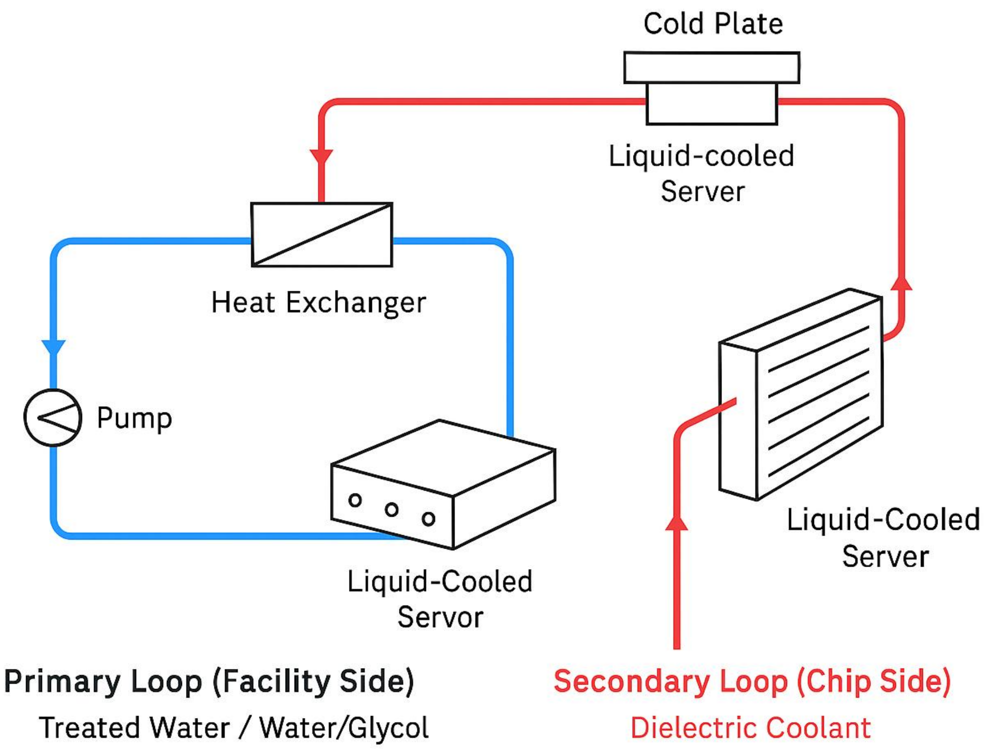
Metric	Example Value	Relevance
Average CPU Utilization	**65%**	Optimized through virtualization, cloud bursting, or energy-aware scheduling
Energy Draw per Server	**600W (active), 250W (idle)**	Focus on minimizing idle power via power management or VM consolidation
IT Equipment Energy Consumption	**1,034,000 kWh/year**	Used to calculate PUE and carbon footprint
Cooling System Energy Use	**350,000 kWh/year**	Represents ~25% of total energy if PUE is 1.45
Temperature (Server Inlet)	**22–27°C**	ASHRAE A1–A3 guidelines; higher ranges allow better cooling efficiency (American Society of Heating, Refrigerating, and Air Conditioning Engineers)
Water Consumption	**2,400 m³/year**	For data centers using evaporative or liquid cooling with ~1.6 WUE
Waste Heat Recovery (Volume)	**300 MWh/year**	Captured for heating adjacent buildings or district heating grids
Data Volume Stored (cold tier)	**1 PB (Petabyte)**	Using low-energy archival storage to reduce active power demand

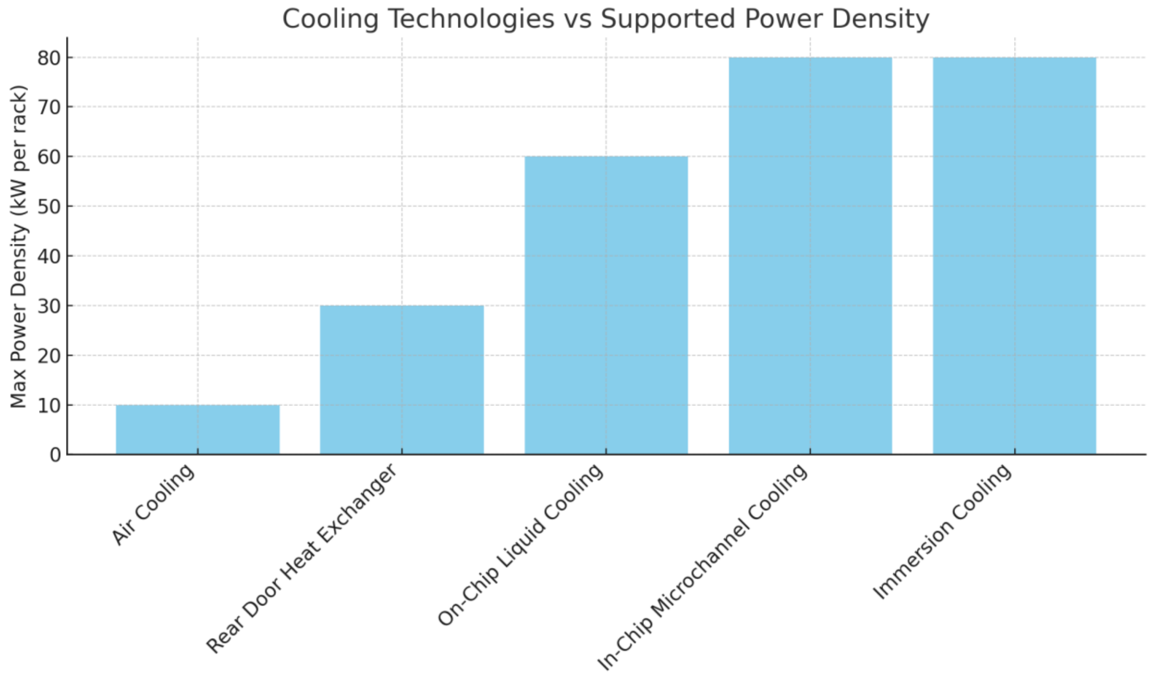
Example KPI Profile for a Mid-Size Research Data Center (aligned with EU 2024/1364 regulation)

Indicator	Value	Regulatory Status
Installed IT power	750 kW	Must report under EU 2024/1364
Total energy (site)	1.5 GWh/year	Required under CSRD/ESRS
PUE	1.45	Aligned with EU CoC, ISO 30134-2
CUE	0.15 kg CO_2e/kWh	Acceptable if renewables >50%
REF (renewable energy factor)	0.75	Strong performance if using on-site PV + district heating
WUE	1.6 L/kWh	Within EU benchmark
Server utilization	65%	Best practices encourage >60%
Renewable energy share	80%	Meets ESPR target for 2030

- The presented KPI and metric values are **regulator-approved targets** or **realistic benchmarks** from top-performing EU-aligned data centers
  - Can serve as references when building sustainability policies or energy optimisation frameworks for digital research

Two-loop Liquid/Water cooling setup and comparison chart of cooling technologies





Cooling Technologies vs Supported Power Density

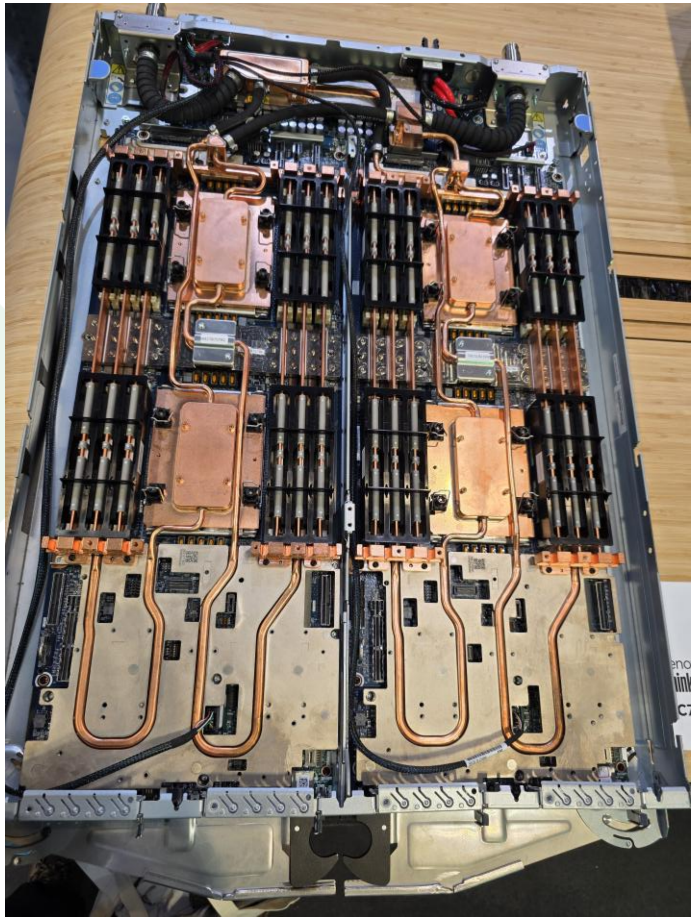
- Air cooling
- Rear door heat exchanger
- On-chip liquid cooling
- In-chip microchannel cooling
- Immersive cooling

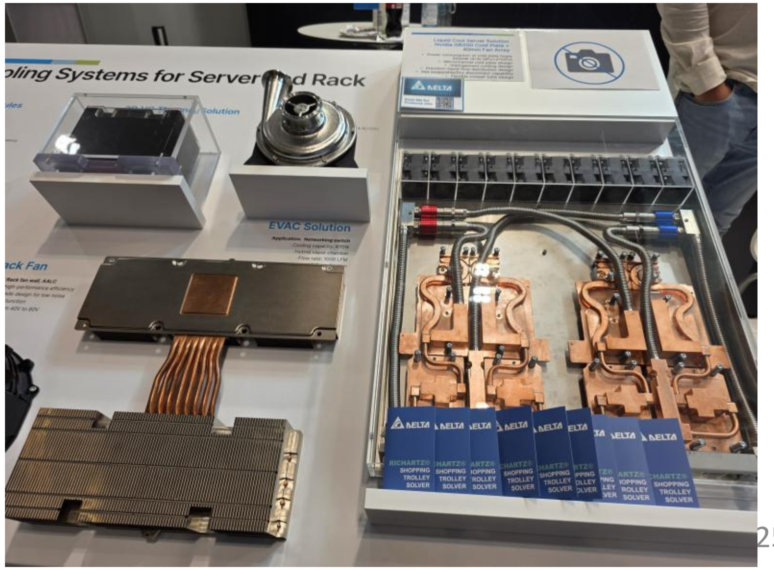
Water/Liquid cooling – Liquid use, Flow rates and Benefits

Component	Cooling Medium	Flow Rate	Volume per Rack	Notes
In-chip cooling	Dielectric coolant	1–5 L/min per server	~20–30 L total per rack	Used in custom loops; very small internal volume
On-chip cold plate	Water/glycol	3–6 L/min per server	~50–80 L total per rack	Higher flow required to maintain delta-T
Facility loop (per rack)	Water	20–40 L/min per rack	Hundreds of liters across loops	Handles many racks through shared infrastructure

Benefit	How It Works
Higher heat reuse	Outlet temperatures of 60–70°C can be used for district heating or reabsorption chillers.
Lower PUE	Systems often reduce PUE to ~1.1–1.2 (vs. 1.4–1.6 for air-cooled systems).
Lower WUE	Closed-loop designs drastically cut water consumption compared to air+evaporative cooling. Some in-chip systems are **fully waterless**.

ISC HPC2025 Conference and Exhibition – Liquid Cooling (1)





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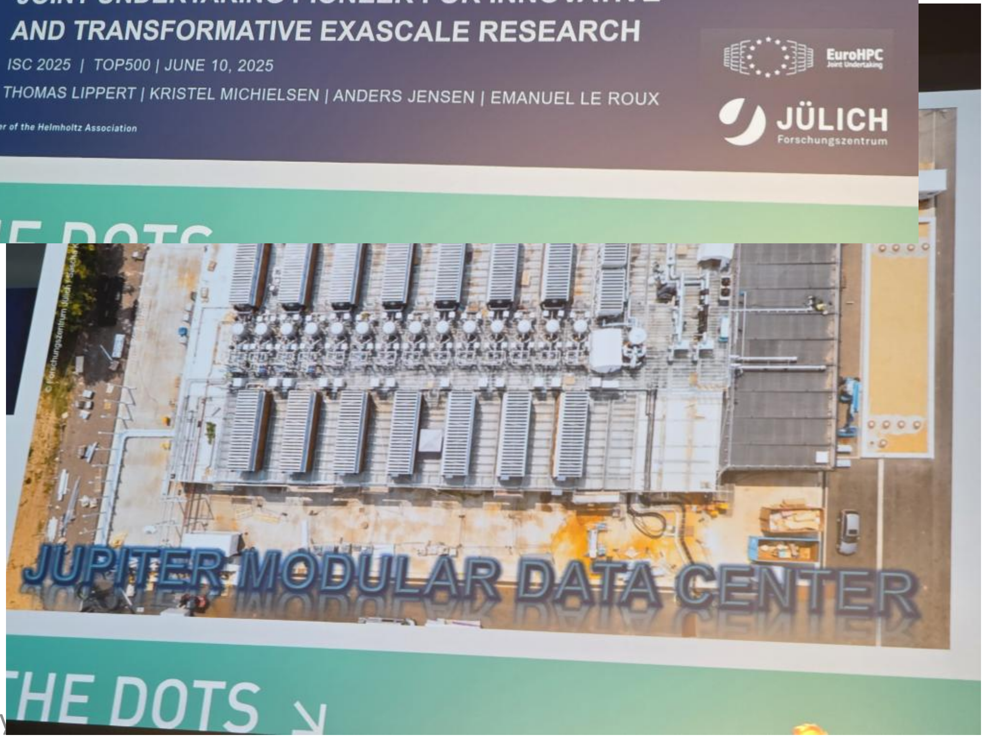


KPIs and Metrics for Network Infrastructure

KPI	Unit	Description
Network Energy Efficiency (NEE)	Gbps/kWh or bits/Joule	Throughput delivered per unit of energy consumed
Carbon Intensity of Network Traffic	g CO_2e/GB	Emissions generated per GB transmitted
Idle-to-Peak Power Ratio	Ratio (0–1)	Ratio of power consumed in idle state to power at full load; lower is better
Uptime / Network Availability	% (e.g., 99.999%)	Measure of service reliability (aka “five nines” availability)
Equipment Utilization	%	Utilization of switch/router capacity over time

Metric	Example Value	Purpose
Router power draw	100–800 W per device	To assess total network load
Traffic per port	e.g., 10 Gbps	Measures link efficiency
Latency	1–10 ms (core), 20–40 ms (edge)	High latency can cause retransmits (waste energy)
Power consumption per switch	200–400 W	Basis for site-level energy tracking
Link uptime	99.995%	For SLAs and energy-waste diagnostics

KPIs and Metrics for 5G and Radio Networks

KPI	Unit	Description
Energy Consumption per Bit	J/Mb or kWh/TB	Total energy used per unit of data transmitted
Energy Efficiency of RAN	bits/Joule	Throughput per unit of energy in the radio access network
Spectral Efficiency	bits/s/Hz	How efficiently frequency spectrum is used
Base Station Energy Savings	%	Power reduction through sleep modes, AI-based management
RAN Availability	%	Operational uptime of radio equipment
Energy Consumption per Cell Site	kWh/day	Site-level tracking to enable savings from hardware upgrades or AI-based controls

Metric	Example Value	Purpose
Base station idle power	800 W–1.5 kW	Can account for over 60% of energy waste
Active power draw (full load)	2–5 kW per macro cell	Critical for provisioning and sustainability planning
Sleep mode duration	% of time	Used to evaluate energy-saving effectiveness
Cell load factor	20–80%	Higher load = better energy efficiency per bit
Temperature of radio units	40–70°C	Affects cooling needs and reliability

Digital RI Lifecycle Stages

and European Environmental Regulations Compliance (based on ESFRI Roadmap 2026 Guidelines)

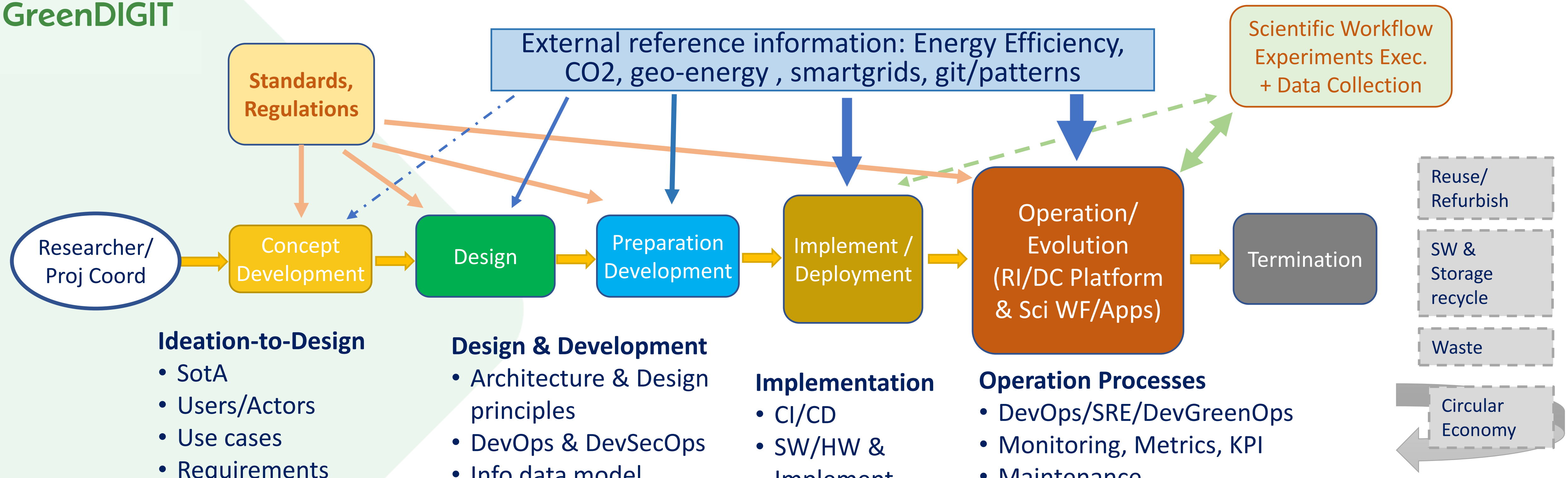
RI Lifecycle stages (ESFRI compliant)

- Concept Development
- Design
- Development
- Deployment and Pre-operation
- Operation & Evolution
- Termination/Decommissioning

Set of EU Regulations on Environmental Compliance

- ESRS/CSRD (European Sustainability Reporting Standard)
  - Required by ESFRI Roadmap 2026
- Ecodesign for Sustainable Products Regulation (ESPR)
- Energy Efficiency Directive (EED)
- Waste Electrical and Electronic Equipment (WEEE) Directive
- Lifecycle Analysis (LCA and ISO 14040/ISO 14044)

GreenDIGIT: RI Lifecycle Stages, Activities and Factors



Ideation-to-Design

- SotA
- Users/Actors
- Use cases
- Requirements Engineering
- Architecture
- Standards/Regulations

Design & Development

- Architecture & Design principles
- DevOps & DevSecOps
- Info data model
- Git, patterns, metrics, schemas, Repository
- API/WebAPI
- Testing, Logbook
- Project Management
- Tech Documentation
- Report, Compliance

Implementation

- CI/CD
- SW/HW & Implement Platform/Cloud
- Feedback to Dev

Operation Processes

- DevOps/SRE/DevGreenOps
- Monitoring, Metrics, KPI
- Maintenance
- Update/Upgrade/Procurement
- Audit, Certification
- Electricity, Water, Buildings

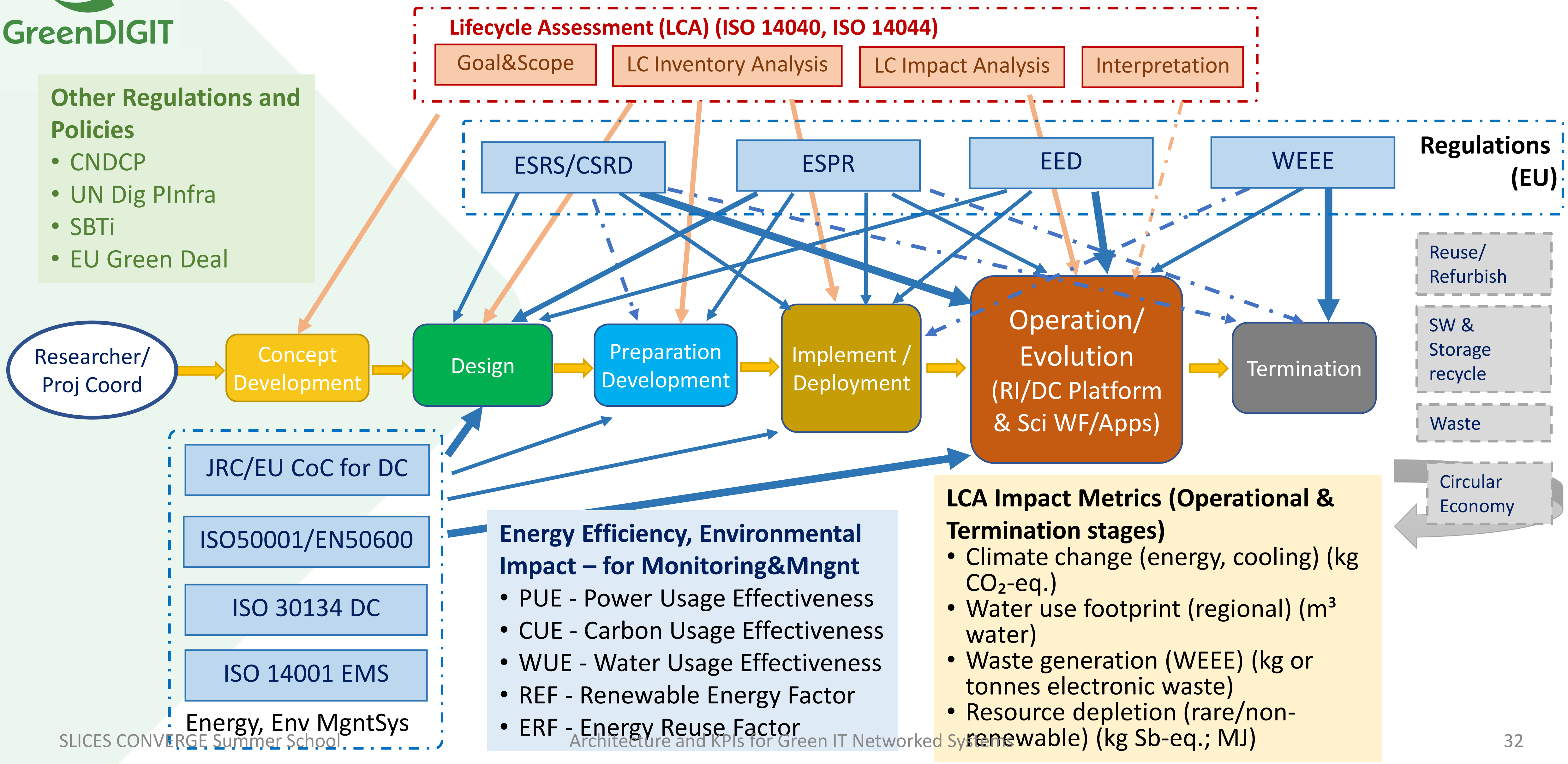
Research Infrastructure Lifecycle

- All stages and processes to be in compliance with standards and regulations
- Shared Responsibility model and User /operator tools
- Continuous monitoring

RI Lifecycle Model: Stages, Actors, Activities

RI Lifecycle Stage	Involved Actors	Activities
RI Concept development	Researchers (target RI users) Infrastructure and System Engineering team (professional, experienced)	**Concept development** (Ideation- for-Design) • SotA analysis • Users/Actors, Use cases analysis, Requirements Engineering • Architecture, Standards/Regulations analysis
Design and Development (preparation)	Researchers (consulting of domain related research facilities) Infrastructure and System Engineering team (professional, experienced) Application and service developers Project management	**Design & Development** • Architecture & Design principles • DevOps & DevSecOps, Project Management • Info data model, API/WebAPI • Git, patterns, metrics, schemas, Repository, Testing, Logbook • Tech Documentation, Reporting, Compliance
Implementation, Deployment (pre-operation)	Researchers (for pre-op testing) Infrastructure and System Engineering team Project management	**Implementation** • CI/CD • SW/HW & Implement Platform/Cloud
Operation	RI Management (including staffing and financial aspects) Operation team (Potentially, sustainability officer)	**Operation Processes** • Monitoring, Metrics, KPI, DevOps/SRE • Maintenance, Audit, Certification • Electricity, Water, Buildings
Termination	Management Operator team	**Termination procedure** • Termination/Decommission plan and procedure, including recycle and circular economy procedures, Waste utilisation • Data archiving or migrating, secure storage recycling

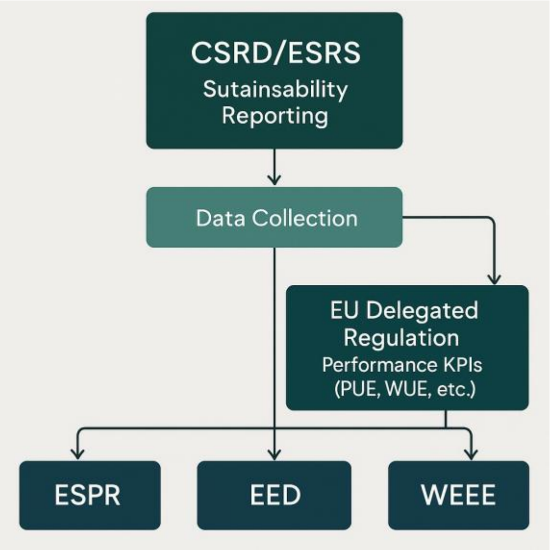
GreenDIGIT: RI Lifecycle Stages, Regulations, Impact Factors



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.
Ecodesign 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 EnergEffic EC Delegated Regulation	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
ISO 140040/ISO14044	Lifecyle Analysis methodology and stages: Goal&Scope; Inventory Analysis (LCI); Impact Assessment (LCIA); Interpretation

Example: Environmental Metrics Reporting for a Digital Research Data Center

Metric / Indicator	Unit / Format	Regulatory Link	Example Value
Scope 2 CO_2 emissions	tCO_2e/year	ESRS E1	450 tCO_2e/year
Reused/refurbished servers	% of total deployed hardware	ESRS E5, WEEE	25%
Recycled e-waste	kg/year, % of total	WEEE	1,200 kg/year, 85%
Water usage (cooling)	m^3/year	ESRS E3	2,400 m^3/year
Refrigerant leakage	kg/year + GWP impact	ESRS E2, ISO 14064	12 kg/year (R134a) = ~17 tCO_2e
Presence of hazardous substances in IT equipment	Qualitative (Y/N + % mass)	ESPR, DPP	Yes (1.8% PCB mass contains brominated flame retardants)
Average hardware lifespan	Years	ESPR, ESRS E5	6 years
Circularity rate (material recovery)	%	ESRS E5, ESPR	70%



Additional Information

- Standards related to energy management and environmental impact monitoring

RI/Systems Sustainability by Design Components/Aspects

- Architecture for Sustainability by Design
  - Functional components, layers, API, Requirements **<= Sustainable Architecture Design Principles (SADP)** + Energy efficiency tactics (VU)
  - **RI continuum: (Research Object) – Sensor - (RAN) – Edge – Cloud – Workflow - Researcher**
- Software and application components that can be optimised during design and controlled during operation
  - Corresponding optimisation model to be proposed
  - Supported with VRE and IDE with sustainability awareness
  - Sustainability design patterns (software, application, middleware, infrastructure) **<= Architecture styles**
- Link and interaction between components via APIs
  - **Green aware API** including necessary energy, performance, environment information
  - Based on well defined Information Model
- Common information/data model and metadata (naming)
  - Including Requirements, KPI, Metrics
  - Verified with existing standards
  - Compliant with PUE and other KPI
- Relations between the system/RI and software sustainability aspects to be defined
  - System related aspects: Lifecycle, Operation and Governance, metrics on energy and GHG
- RI and applications lifecycle
  - Scientific workflow and research data lifecycle to be aligned with sustainability policy and monitoring

Architecture Framework Pillars – Technical – Pillars 1-5 - Details

Pillar 1 –Layered and Modular Architecture for Sustainable Digital Infrastructure

Benefits of layers definition:

- Benefit of layered architecture: Makes easier to support dynamic energy-aware orchestration across layers (actually using the same API/infomodel)

Pillar 2 - Software and Scientific Applications Design Patterns for Energy Efficiency and Environmental Impact Reduction

Goal and benefits:

- Primarily focus on scientific workflows and user-driven applications for energy efficiency awareness.
- Allows to benefit from (general) green software engineering and (research focused) reproducible (experimental) science.
- Links application design to infrastructure energy-aware execution.

Pillar 3 - Lifecycle-Oriented Sustainability Management of Research Infrastructures and Scientific Applications

Goal and benefits:

- Lifecycle stages define different actors and requirements to RI components and services
- Incorporate **LCA methodologies** to evaluate and mitigate environmental impacts throughout the RI's operational life

Pillar 4 – Interoperable/common Information Models for Sustainability Metrics and Monitoring

Goal and benefit:

- Ensures semantic interoperability for API definition and machine-actionability.
- Simplifies infrastructure metrics telemetry with regulatory reporting needs.
- Cross-infrastructure benchmarking and optimization

Pillar 5 - Sustainable Data Management and Energy-Efficient Storage Systems

Goal and benefits:

- Efficient data management practices contribute to the overall sustainability of RIs
- Implement tiered storage architectures and data compression techniques to reduce energy consumption associated with data storage and retrieval
- Linking FAIR data principles for sustainability metadata: Important for RI/EOSC liaison but needs some additional definitions

Architecture Framework Pillars (Additional) – Pillars 6-7 – To address ESFRI RM2026 Environmental Sustainability Requirements

Additional pillars to extend the sustainability architecture of future DRIs and scientific applications and address critical gaps and emerging needs in areas such as governance and policy integration, which are essential to achieving environmental sustainability goals through the DRI lifecycle (ensuring alignment with ESFRI Roadmap 2026):

Pillar 6 – Governance, Policy Integration, and Compliance Framework

- Establish clear governance models that incorporate sustainability objectives, ensuring accountability and continuous alignment with ESFRI's evolving requirements.
- Provide a basis for interoperability and energy-aware infrastructure federation, adopt interoperable standards for data exchange across federated infrastructures.

Pillar 7 – User Awareness, Behavior, and training for Sustainability by Design

- Develop training programs and user interfaces that encourage energy-efficient behaviors and provide feedback on the environmental impact of user activities

Policies and Regulations for Energy Efficiency and Environmental Sustainability (GreenDIGIT Milestone Report MS4/MS8.1 – 40 pp.)

- Policies related to environmental sustainability and energy efficiency UN Sustainable development goals (SDG)
  - UN Digital Public Infrastructure for Environmental Sustainability
  - SBTi: The Science Based Targets Initiative
  - The European Green Deal
  - ESFRI Roadmap 2026 Public Guide
  - Climate Neutral Data Centre Pact (CNDCP)
- Regulations and Directive (to be checked)
  - JRC Data Center Code of Conduct
  - EU Delegated Regulation (EU) 2024/1364 of 14 March 2024
  - Corporate Sustainability Reporting Directive (CSRD) and European Sustainability Reporting Standards (ESRS)
  - Ecodesign for Sustainable Products Regulation (ESPR)
  - Energy Efficiency Directive (EED)
  - Waste Electrical and Electronic Equipment (WEEE) Directive
  - Lifecycle Analysis (LCA)
  - Environmental Management Standards (EMS)
    - Energy Management Systems ISO 50001, ISO 50002, ISO 14001, ISO 30134
    - European standards series EN 50600: EN 50600-4-1 and EN 50600-4-2 Datacenter and supporting infrastructure

Standards and Regulation – Overview and Analysis

- Architecture Requirements based on Standards, BCP and Regulations
  - Mapping standards requirements to infrastructure functional components
- EU Code of Conduct for data centers - Best Practices published annually by JRC
- European standards series EN 50600
- International group of standards ISO 50001, ISO 50002, ISO 14001, ISO 30134

- Full summary of the standards and regulations analysis is provided in a form of Whitepaper – To be open for the research community
  - Currently available as the project Milestone MS4 “Analysis of Policies and Regulations”

RI/App Dev and Ops – Greening Aspects

- Requirements engineering
  - To ensure future compliance and assessment and auditing/certification
- Software components
  - Design
  - Development: Software patterns
  - Development: Quality assessment
- Deployment
- Operation & Energy/Sustainability monitoring
  - Metrics
- Governance
- Procurement and IT equipment selection

ISO Standards (Providing a basis)

- ISO14062 Product design and development
- ISO25010 Software Quality
- ISO 14001 Environment Management System
- ISO30105 Sustainable Business with IT
- ISO 20400 Procurement
- EN 50600 Data center Design and Operation
- ISO/IEC 30134: Data centres – Key Performance indicators

Regulations and recommendations

JRC Datacenter Code of Conduct

Operational Stage – Green Monitoring Aspects

- Metrics and/or KPI
  - Ensuring compatibility with existing standards and models
- Data model and reporting
  - Compliance and extension of the existing data model (software and system operation)
- Monitoring and measurement
  - Energy and workload optimisation
  - Workload relocation to green energy time
- Data collection and analysis
- Maintenance
  - Planning
- Green energy and smart grids

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Regulations and recommendations

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