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Advancing Energy System Research With the FAIR+S Framework

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Abstract. The FAIR principles (Findable, Accessible, Interoperable, and Reusable) have transformed research data management. Yet, they overlook sustainability aspects such as energy consumption, carbon footprint, and life cycle impact made be creating and using research software and data – critical factors for energy-intensive disciplines. This work reframes FAIR+S, an extension of FAIR and FAIR4RS, as a cornerstone for advancing Energy System Research and the NFDI4Energy initiative.

Keywords: FAIR, FAIR4RS, Energy System Research, NFDI4Energy, Sustainability, Green Software

1. Introduction

The FAIR principles[1] revolutionized how research data are shared and reused. Their extension to software through FAIR4RS[2] enhanced reproducibility and interoperability across computational disciplines. Together, FAIR and FAIR4RS underpin Europe's open science infrastructure, influencing major initiatives such as the European Open Science Cloud (EOSC) and the National Research Data Infrastructure (NFDI) in Germany.

Yet, FAIR and FAIR4RS remain largely silent on sustainability – an increasingly critical concern for energy-intensive research domains. Scientific computing contributes significantly to global energy demand, from AI training to large-scale simulations[3], [4]. While frameworks like the Software Carbon Intensity (SCI)[5] and tools such as CodeCarbon[6] and the Green Software Foundation's methodologies[7] enable energy and carbon tracking, these are rarely integrated into mainstream research workflows.

Energy System Research – the data-driven study of energy systems, sits at the intersection of digitalization and sustainability[8]. It relies on high-performance computing, simulation, and large-scale data integration, all of which have environmental costs. As the NFDI4Energy initiative[9] seeks to build a national infrastructure for interoperable, FAIR energy research data[10], the challenge becomes clear: FAIRness alone is not enough[11]. The next generation of research infrastructures must also be sustainable.

This work introduces the FAIR+S framework as a pathway to bridge this gap. FAIR+S extends FAIR and FAIR4RS by adding an explicit sustainability dimension, aligning data and software stewardship with the focus of Energy System Research and the NFDI4Energy goals.

2. Energy System Research and the NFDI4Energy

Energy System Research encompasses data, models, and software that describe, simulate, and optimize energy systems ranging from grid stability and renewable integration to energy markets and building efficiency[8], [12]. The field depends on open, interoperable datasets and tools, yet it also faces high computational costs and fragmented sustainability practices[13].

The NFDI4Energy consortium, part of Germany's NFDI, aims to address this fragmentation by developing new research infrastructures and services to enable FAIR-compliant workflows across the energy domain *"for a sustainable energy future"*[9], [10]. This includes extending registries of software, models, and data with tailored metadata schemas and providing Simulation-as-a-Service with different co-simulation frameworks to facilitate operative energy system analysis. However, ensuring that these infrastructures are also environmentally sustainable, meaning minimization of their computational and storage footprint, requires extending FAIR principles beyond reproducibility to include environmental accountability.

FAIR+S principles directly support NFDI4Energy's objectives by embedding sustainability metadata, tools, and standards into existing FAIR-based frameworks. Interoperable sustainability descriptors that connect with standardized reporting formats (e.g., SCI, GHG protocol, ISO 14044) and energy-aware metadata schemas support recording and comparing computational resource use and carbon footprint of energy research artefacts, which allows reuse without perpetuating unsustainable computing practices.

3. The FAIR+S Framework

FAIR+S (for details, see also [11]) extends the FAIR and FAIR4RS principles by adding five sustainability-oriented dimensions that are well designed for integration into metadata, repository, and workflow standards used in Energy System Research.

S1 – Energy Efficiency Attributes

Research artefacts should be described with accurate and relevant energy efficiency attributes, including measurements of resource use and carbon footprint.

Tools such as CodeCarbon[6], CarbonTracker[14], and MLCO2[15] streamline this process by automatically monitoring or estimating carbon emissions in computational workflows, while GreenAI[16] integrates energy consumption metrics directly into model development to promote sustainable practices. Embedding such energy-related metadata within research artefacts allows both researchers and infrastructure providers to assess the sustainability impact of their workflows and to make informed choices toward more energy-efficient alternatives.

S2 – Sustainability Benchmarks

Research artefacts and evaluation should be supplemented with community-accepted sustainability benchmarks.

Community initiatives such as NFDI4Energy are expected to play a key role in developing structured frameworks for evaluating the energy efficiency of computational workflows and data management processes, thereby fostering reproducible and comparable sustainability assessments. Similar to established corporate-level[17] or domain-oriented benchmarks, such as MLPerf[18] for machine learning workloads and SPECpower[19] for system-level energy efficiency, these community-driven efforts, aligned with the FAIR+S principles, could support the creation of shared reference models to promote environmental accountability.

S3 – Alignment with Sustainability Frameworks

Research artefacts, their development, and evaluation processes should, where possible, align with existing sustainability frameworks or community standards.

Aligning research practices with recognized sustainability frameworks and standards, such as ISO/IEC 21031:2024[7], the Greenhouse Gas (GHG) Protocol[20], and ISO 14044 for life cycle assessment, enhances credibility, transparency, and interoperability between academic and industrial energy research ecosystems.

This alignment is particularly relevant for NFDI4Energy, where compliance with interoperable and domain-specific standards is essential to ensure the comparability of sustainability metrics across institutions, datasets, and computational infrastructures within the broader energy research community.

S4 – Carbon Transparency and Accountability

Carbon-related metadata and estimates must include transparency and accountability, disclosing uncertainty ranges, methodological assumptions, tools used, and responsible parties.

This principle mandates the disclosure of critical metadata, such as hardware specifications, energy source mix, and measurement methodologies, in accordance with open science best practices. In practice, this principle can be operationalized through digitalized frameworks such as digital Measuring, Reporting, and Verification (dMRV)[21].

S5 – Life Cycle Sustainability

Research artefacts should, where possible, include information about their long-term life cycle sustainability, including expected maintenance, update frequency, and cumulative resource needs across development, deployment, and preservation.

FAIR+S expands sustainability assessment beyond runtime metrics to include maintenance, storage, and reuse over the full research artefact life cycle. This life cycle perspective aligns with ISO 14044 and Life Cycle Assessment (LCA) methodologies[22], [23], encouraging sustainable long-term curation of energy-related datasets and software.

4. Enabling Sustainable Energy System Research

Minimizing carbon emissions through increasingly efficient computational methods is widely regarded as an essential response to climate change. The computer science community, the field of Energy Informatics and Energy System Research, and the NFDI4Energy initiative can all play a central role in reducing carbon emissions across the economy by designing and implementing more energy-efficient algorithms, models, and datasets.

Integrating FAIR+S into Energy System Research workflows aims supporting NFDI4-Energy's long-term goals:

- Metadata integration: FAIR+S aligned descriptors can be added to metadata schemas used and developed by NFDI4Energy repositories.
- Sustainability-aware workflows: FAIR+S implies that cloud and orchestration systems (e.g., Kubernetes, Snakemake, CWL) optimize job placement based on energy intensity or renewable availability.
- Monitoring and reporting: FAIR+S aims to structure the provenance of tools and dashboards for continuous sustainability assessment of research pipelines.

For Energy System Research and initiatives like NFDI4Energy, FAIR+S provides the conceptual and technical foundation for sustainable digital research infrastructures advancing open, reproducible, and energy-aware science.

Data availability statement

Not applicable.

Author contributions

Danila Valko: Writing – original draft, Writing – review & editing, Methodology, Conceptualization. Jan Sören Schwarz: Writing – original draft, Writing – review & editing. Ralf Isenmann: Writing – review & editing, Supervision, Conceptualization. Jorge Marx Gómez: Supervision, Conceptualization.

Competing interests

The authors declare that they have no competing interests.

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