Towards a Multidimensional Impact Evaluation Framework for AI Applications in the Energy Sector

Emily Bringmann, Bianca Weber, Celina Kacperski and **Florian Kutzner** *Seeburg Castle University*
{emily.bringmann,bianca.weber,celina.kacperski,florian.kutzner}@uni-seeburg.at

Abstract

Artificial Intelligence (AI) is increasingly deployed to enhance energy efficiency, for example by predicting energy demand, enabling demand-side management, or supporting predictive maintenance of renewable energy infrastructure. While these applications offer substantial potential to reduce energy consumption and greenhouse gas emissions, their actual impacts often remain unclear. Especially unintended consequences are rarely assessed. This lack of systematic impact evaluation hampers responsible deployment and risks undermining the contribution of AI to a just energy transition. This contribution addresses this gap by developing a multidimensional impact evaluation framework tailored to AI applications in the energy sector. Based on a systematic literature review and expert interviews, the framework integrates environmental, social, economic, and technical impact dimensions and embeds energy justice considerations. It provides a modular structure of outcomes and associated indicators that practitioners can select according to their specific use case. The framework aims to support evidence-based evaluation of AI-based energy solutions, ensuring their effectiveness, efficiency, and fairness.
Keywords: Multidimensional Impact Evaluation, Energy Efficiency, AI Governance, Energy Justice, Environmental and Socioeconomic Impacts

1 Introduction

AI technologies are increasingly used to improve the energy performance of systems and infrastructures. Examples include demand-side management, predictive maintenance for solar and wind farms, and AI-supported optimization of energy-intensive industrial processes (Shahverdi et al. [2025]). These approaches promise to enhance energy efficiency, reduce operational costs, and lower greenhouse gas emissions, thereby contributing to climate neutrality targets.

However, while the potential benefits of AI in the energy sector are widely emphasized, its actual impacts are rarely systematically assessed (Gröger et al. [2025], Huber et al. [2025]). Especially when AI systems are scaled up without prior evaluation, they may produce unintended negative effects, such as high energy consumption during model training and operation, higher cost than anticipated, or a reinforcement of socio-economic inequalities. This raises concerns about their contribution to Energy Justice (Carley and Konisky [2020], Chen et al. [2024], Noorman et al. [2023]). Chen et al. [2024], for example, identify biases in data selection and algorithm design that can disadvantage less affluent consumers, while Noorman et al. [2023] highlight inequities in the allocation of smart grid pilots.

To ensure that AI-based solutions genuinely support a just energy transition, it is essential to systematically evaluate both their intended and unintended consequences. This requires frameworks that cover not only environmental impacts but also social, economic, and technical aspects.

2 Background and Research Gap

Several frameworks for assessing the impacts of AI in general have been proposed (Bogucka et al. [2024], Sætra [2021], Slattery et al. [2024]). However, most of these focus on single dimensions (typically environmental) and are not tailored to the specific context of energy-sector AI. Stahl et al. [2023] show that existing approaches often rely on generic checklists or questionnaires but lack domain-specific indicators. Moreover, justice-related aspects such as algorithmic bias, unequal access, or consumer empowerment are rarely considered as central evaluation criteria.

At the same time, a growing body of work highlights the importance of energy justice in the context of digitalization and AI (Carley and Konisky [2020], Chen et al. [2024], Noorman et al. [2023]). Without explicit consideration of these issues, AI deployment risks exacerbating existing social inequalities and undermining public acceptance.

Research gap: Currently, there is no multidimensional, modular, and practical framework for evaluating the impacts of AI used to optimize energy-intensive processes (including demand-side management, predictive maintenance, and energy consumption simulation). Such a framework is needed to support practitioners and policymakers in ensuring that AI contributes positively to sustainability and fairness.

3 Objectives and Research Design

This study aims to develop a multidimensional impact evaluation framework for AI applications in the energy sector. The framework is designed to integrate environmental, social, economic, and technical impact dimensions, embed energy justice as a cross-cutting principle, and provide a modular structure that allows practitioners to select relevant indicators for their specific use cases. The research design consists of three steps:

1. **Systematic literature review:** Identification and synthesis of existing AI impact assessment frameworks and relevant indicators from energy and sustainability research.

2. **Expert interviews:** Interviews with experts from energy companies, AI solution providers, regulatory agencies, and civil society to capture current practices, perceived barriers, and user needs for impact assessment.

3. **Framework development:** Integration of findings into a modular framework structure consisting of dimensions, subdimensions, outcomes, and example indicators.

The requested submission, in the form of a poster, will report on preliminary results from steps 1 and 2 and showcases the structure of the developing framework.

4 Preliminary Framework Overview

The emerging framework organizes impacts across four main dimensions – economic, social, technical, and environmental – each with associated subdimensions and example indicators. It is designed as a modular toolkit from which practitioners can select relevant outcomes and indicators. As part of the framework, a focus will also be to help identify methodologies to assess the indicators. This is based on work carried out within the Horizon Europe project COSMIC – AI powered energy optimization (COSMIC Consortium [2024]).

Table 1: Preliminary impact evaluation framework (excerpt).

Dimension	**Subdimension**	**Example indicators**
Economic outcomes	Project / micro level	% costs saved; hours of working time saved; years to return on investment
Social outcomes	End-user level	Perceived usability; % satisfied users; engagement rate
Technical outcomes	Accuracy / precision	Error reduction; MAE/RMSE; share of predictions within $\pm 1\%$
Environmental outcomes	Green Deal alignment	GHG reduction (tCO_2e/yr); carbon intensity ($kgCO_2$/kWh)

5 Current Status

Using PRISMA methodology (Page et al. [2021]), we have collected N=180 relevant articles that we are currently filtering for relevance in the literature review. In parallel, we have finalized N=9 expert interviews, with experts representing AI engineers, researchers, energy and technology providers, municipalities, and citizen initiatives – all working at the intersection of AI and energy-intensive processes. Current findings indicate that there is no standardized way evaluations of AI in energy-intensive processes are conducted. Especially strong are differences across the mentioned stakeholders; while technical indicators are highly important for AI engineers and technology providers, economic indicators are especially important for energy providers. Environmental indicators seem to be assessed and considered relevant only when externally mandated.

6 Expected Contributions

The framework will support industry stakeholders by providing a practical tool to evaluate the environmental, social, economic, and technical impacts of AI-based energy solutions early in their development, helping them to identify risks and make evidence-based design decisions. At the same time, it will enable policymakers to set informed requirements and regulations for responsible AI deployment in the energy sector, ensuring that efficiency gains do not come at the expense of social equity and sustainability.

7 Next Steps

The ongoing work will focus on finalizing the analysis of the expert interviews to refine the structure and content of the framework. Building on these results, the framework will be iteratively tested and further developed in collaboration with industry and policy partners through workshops and pilot applications to real-world AI use cases. The resulting validated version will then be published as an open-access guidance toolkit, enabling practitioners to systematically assess the impacts of AI-based energy solutions in future projects.

References

E. Bogucka, M. Constantinides, S. Ščepanović, and D. Quercia. Co-designing an AI impact assessment report template with AI practitioners and AI compliance experts, 2024. URL `https://arxiv.org/abs/2407.17374`.

S. Carley and D. M. Konisky. The justice and equity implications of the clean energy transition. *Nature Energy*, 5(8):569–577, 2020. doi: 10.1038/s41560-020-0641-6.

C. Chen, R. Napolitano, Y. Hu, B. Kar, and B. Yao. Addressing machine learning bias to foster energy justice. *Energy Research & Social Science*, 116: 103653, 2024. doi: 10.1016/j.erss.2024.103653.

COSMIC Consortium. COSMIC — combined AI and data solutions for large scale resource optimization with green deal impact. `https://cosmic-horizon.eu/`, 2024. Horizon Europe project (Dec 2024–Dec 2027).

J. Gröger, F. Behrens, P. Gailhofer, and I. Hilbert. Environmental impacts of artificial intelligence: Evaluation of current trends and compilation of an overview study for greenpeace e.v., hamburg. Technical report, Öko-Institut Consult GmbH, Berlin, 2025. URL `https://www.oeko.de/fileadmin/oekodoc/Report_KI_ENG.pdf`.

P. Huber, D. Li, J. P. G. H. Muriedas, D. Kieckhefen, M. Götz, A. Streit, and C. Debus. Energy consumption in parallel neural network training, 2025. URL `https://arxiv.org/abs/2508.07706`.

M. Noorman, B. E. Apráez, and S. Lavrijssen. Ai and energy justice. *Energies*, 16(5):2110, 2023. doi: 10.3390/en16052110.

M. J. Page, D. Moher, P. M. Bossuyt, I. Boutron, T. C. Hoffmann, C. D. Mulrow, L. Shamseer, J. M. Tetzlaff, E. A. Akl, S. E. Brennan, R. Chou, J. Glanville, J. M. Grimshaw, A. Hrobjartsson, M. M. Lalu, T. Li, E. W. Loder, E. Mayo-Wilson, S. McDonald, L. A. McGuinness, L. A. Stewart, J. Thomas, A. C. Tricco, V. A. Welch, P. Whiting, and J. E. McKenzie. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. *BMJ*, 372:n160, 2021. doi: 10.1136/bmj.n160.

H. S. Sætra. A framework for evaluating and disclosing the ESG related impacts of AI with the SDGs. *Sustainability*, 13(15):8503, 2021. doi: 10.3390/su13158503.

N. Shahverdi, A. Saffari, and B. Amiri. A systematic review of artificial intelligence and machine learning in energy sustainability: Research topics and trends. *Energy Reports*, 2025. doi: 10.1016/j.egyr.2025.05.021. Advance online publication.

P. Slattery, A. K. Saeri, E. A. C. Grundy, J. Graham, M. Noetel, R. Uuk, J. Dao, S. Pour, S. Casper, and N. Thompson. The AI risk repository: A comprehensive meta-review, database, and taxonomy of risks from artificial intelligence, 2024. URL `https://arxiv.org/abs/2408.12622`.

B. C. Stahl, J. Antoniou, N. Bhalla, L. Brooks, P. Jansen, B. Lindqvist, A. Kirichenko, S. Marchal, R. Rodrigues, N. Santiago, Z. Warso, and D. Wright. A systematic review of artificial intelligence impact assessments. *Artificial Intelligence Review*, 56(11):12799–12831, 2023. doi: 10.1007/s10462-023-10420-8.