Interoperability for Energy-Related Ontologies
The ENERO Ontology Foundry for the Energy Domain

Mirjam Stappel[1,*] (iD), Amanda Wein[2,3] (iD), Till Mossakowski[1] (iD), Fabian Neuhaus[4] (iD),
Ludwig Hülk[5] (iD), Eugenio Arellano Ruiz[6] (iD), Silvia Weko[7] (iD), and Carsten Hoyer-Klick[6] (iD)

[1]Universität Osnabrück

[2]OFFIS - Institut für Informatik

[3]Carl von Ossietzky Universität Oldenburg

[4]Otto-von-Guericke Universität Magdeburg

[5]Reiner Lemoine Institut

[6]German Aerospace Center, Institute of Networked Energy Systems

[7]Friedrich-Alexander-Universität Erlangen-Nürnberg

*Correspondence: Mirjam Stappel, mirjam.stappel@uni-osnabrueck.de

Abstract. Energy researchers are becoming increasingly aware that ontologies support both research data management (like FAIRification of data) and a transparent publication of research results. With an increasing usage and development of ontologies, the demand for interoperability between ontologies rises. Based on lessons learned from the Open Biological and Biomedical Ontology Foundry (OBO Foundry) and other initiatives, this position paper presents the Energy-related Reference Ontologies Foundry (ENERO Foundry) to coordinate ontology development in the energy domain.

Keywords: ENERO Foundry, Ontologies, Interoperability, Energy Domain

1. Introduction

In research data management, ontologies enable the digitization and publication of scientific data in a way that allows reuse, as well as transparency and reproducibility of research results. The use of ontologies in biology and biomedicine has been well established for several decades as a means to systematically organize, curate, and interpret large volumes of research data. In other research domains as well as in more applied contexts, ontologies are moving in as well. For example, many of the German National Research Data Infrastructure (NFDI) consortia develop domain-specific ontologies. This holds also for energy-related research domains.

The growing awareness about ontologies leads to an increasing request thereof. With an expanding number of ontologies within a certain topic, the need for compatibility and interoperability between ontologies rises as well. For example, in [1] we showed that there exist several ontologies that define *energy* in contradicting and heterogeneous ways. Users and ontology developers are thus confronted with the question of which definition to choose for

reuse. To avoid redundant work and inconsistencies across ontologies, we want to facilitate the reuse of existing energy-related ontologies and the support of new and further developments, with a focus on reference ontologies, i.e. ontologies that are built for reuse in many contexts.

Inspired by initiatives like the Open Biological and Biomedical Ontology Foundry (OBO Foundry) and the Industrial Ontologies Foundry (IOF), we started the Energy-related Reference Ontologies Foundry (ENERO Foundry) in 2025 to support effective ontology development in energy-related research areas. We have the goal to coordinate ontology development in a way such that individual ontologies remain interoperable and can be used effectively with each other.

The ENERO Foundry provides a framework of common principles and guidelines for ontology developers from the energy domain, which will be complemented with common design patterns in the future. Each ontology is autonomously developed by a small team and committed to shared design and development principles. The reference ontologies have a well-defined scope and the goal to keep the terminological overlaps to a minimum.

With this paper, we want to introduce the ENERO Foundry to a larger community. We describe our goals and structure in Section 2 and the first set of principles and our architecture in Section 3. An overview over the first set of member ontologies is given in Section 4. Background information and the related work of OBO and other initiatives is part of Section 5. Finally, we conclude this paper with a community outreach and outlook on future activities.

2. Goals and Structure of the ENERO Foundry

The ENERO Foundry is an initiative that coordinates the development of a collection of energy-related formal ontologies. These ontologies are developed independently and under the responsibility, control and copyright of their various development teams. By joining the ENERO Foundry, the development teams commit to the jointly-developed principles that support the Foundry goals (see Section 3.1), and the ontologies become accessible for the whole community. They are designed to complement each other and to be used together without semantic inconsistencies. The quality and added value of each single ontology and its potential for reuse in the community will be increased by improving its interoperability with other ontologies. This has been confirmed by the long-term interoperability approaches of the OBO Foundry, which additionally leverage the ontologies' contributions "[...] towards the overall goals of making data Findable, Accessible, Interoperable, and Reusable (FAIR)" [2].

The ENERO Foundry is open to formal domain reference ontologies from the *energy domain*. This entails a narrower or broader relation to the provision, supply, conversion, distribution, use or regulation of energy. The scopes can focus on technical, socio-economic or environmental aspects thereof and can vary in the level of detail and granularity. Terminological overlaps to other domains and sectors are expected, including materials and resource use, climate change, greenhouse gas emissions and energy meteorology, transition and sustainability, transportation and mobility, markets, industry and production, land use and agriculture, buildings, social impacts of energy, and energy related policies.

The ENERO Foundry's governance consists of an Organizational Board that coordinates the Foundry activities, among others by community management and ontology metadata curation, and a Scientific Advisory Board that provides scientific and strategic guidance. Furthermore, the developer teams of the Foundry ontologies (the ENERO Foundry community) are asked for participation in the general decision processes. Feedback from ontology and metadata experts is considered, e.g. from the NFDI4Energy context. The discussions are documented in the ENERO GitHub repository. The ENERO Foundry organizes regular member workshops for exchanging experiences and for supporting collaboration between the ontology developers.

3. Principles and Architecture

3.1 ENERO Foundry Principles

A first set of guiding principles for ontology development have been formalized and published on the Foundry website, including a documentation of differences to OBO and IOF principles. It is summarized in Table 1. The principles range from specific design decisions to aspects of documentation and publication to collaboration within the foundry, some of which are binding and others are recommendations.

Table 1. *Overview of the initial ENERO Foundry principles for ontology development.*

Openness	ENERO ontologies are resources intended for reuse and interoperability among energy-related domains and communities. An explicitly-stated copyright license reduces legal risks for users and promotes use and reuse. Therefore, the ontologies must be available to all under an open license.
Common Format	ENERO ontologies must be made available in a common formal language (i.e. the Web Ontology Language OWL) in an accepted concrete syntax. This allows the maximum number of people to access and reuse an ontology.
Textual Definitions	ENERO ontologies are intended to provide a consensus view of a domain (to the extent possible) and the notions and terms used therein. As such they should be able to be used as a glossary for their domain. Each entity in an ontology must provide a human-readable understanding about what is a member of the associated class or property.
Identifier and Naming Conventions	A consistent identifier format allows users to understand where a class term (or other entity) is defined, helps in creating interoperable ontologies, and aids in the development of software that uses the ontologies. Each entity in an ontology should therefore contain an IRI/CURIE identifier (to identify the entity anywhere it is cited) and a unique label (to identify the main name of the entity).
Versioning	Ontologies are expected to change during their lifecycles, and users need to be made aware when changes have occurred. A versioning workflow is therefore required to help distinguish which and when changes to an ontology have been made.
Foundational Ontology	The use of a foundational ontology provides the basis for ontological consistency and facilitates semantic interoperability. We require either the use of BFO as a foundational ontology or a mapping to BFO's main structure.
Scope	The scope of an ontology is the extent of the domain or subject matter it intends to cover. Foundry ontologies must each have a clearly specified scope and content that adheres to that scope.
Documen-tation	Thorough ontology documentation allows potential users to easily ascertain if an ontology is of value to their use case, aids developers in modifying or extending an ontology, and serves as a marker of the ontology's quality.
AI Usage	To provide transparency, the usage of AI tools and automation in the ontology development process should be documented.
Collaboration and Respon-siveness	When terms from various ontologies are reused, it is expected that questions, change requests and discussions will arise, from both external ontology developers and the user community. To collaborate and address these requests, responsiveness is needed from all involved parties.

To arrive at this set, the Organizational Board reviewed the principles of the OBO Foundry and the IOF, evaluating their relevance for energy domain ontologies. Furthermore and based on own development experiences, additional topics for ontology interoperability have been collected. Potential principle drafts were presented to and discussed within meetings of the NFDI4Energy Metadata & Ontologies Working Group or Task Area 4. All discussions were documented in the Foundry GitHub repository. When a consensus on the text of a principle was reached, the principle was published on the ENERO Foundry website using a standardized content format.

3.2 Orthogonal Ontology Scopes Within the Foundry Architecture

As described in Section 3.1, one of the ENERO Foundry principles is about the definition and documentation of the ontology's scopes. In the following, we explain how ontologies with orthogonally defined scopes are able to complement each other in an initiative like ENERO Foundry. According to [2], the scope of an ontology refers to the subject matter the ontology intends to cover. The content of the ontology must adhere to that scope. Ideally, these scopes should be defined in an orthogonal way: the ontologies should have non-overlapping terminology [3], which means that within the Foundry ontologies each term should be defined in only one ontology [4]. An existing term can thus be reused in other ontologies by referring to it using its Internationalized Resource Identifier (IRI) [5]. In this way, the orthogonality helps to reduce arbitrary decisions between equivalent-seeming terms drawn from different ontologies [4] or contradicting definitions thereof. Referring to the OBO Foundry, [6] states that the content of the Foundry ontologies can either be approached as a set of independent ontologies (non-orthogonal view), or as an orthogonal collection in which the entities of all the ontologies are conceptually merged into one ontology (orthogonal view).
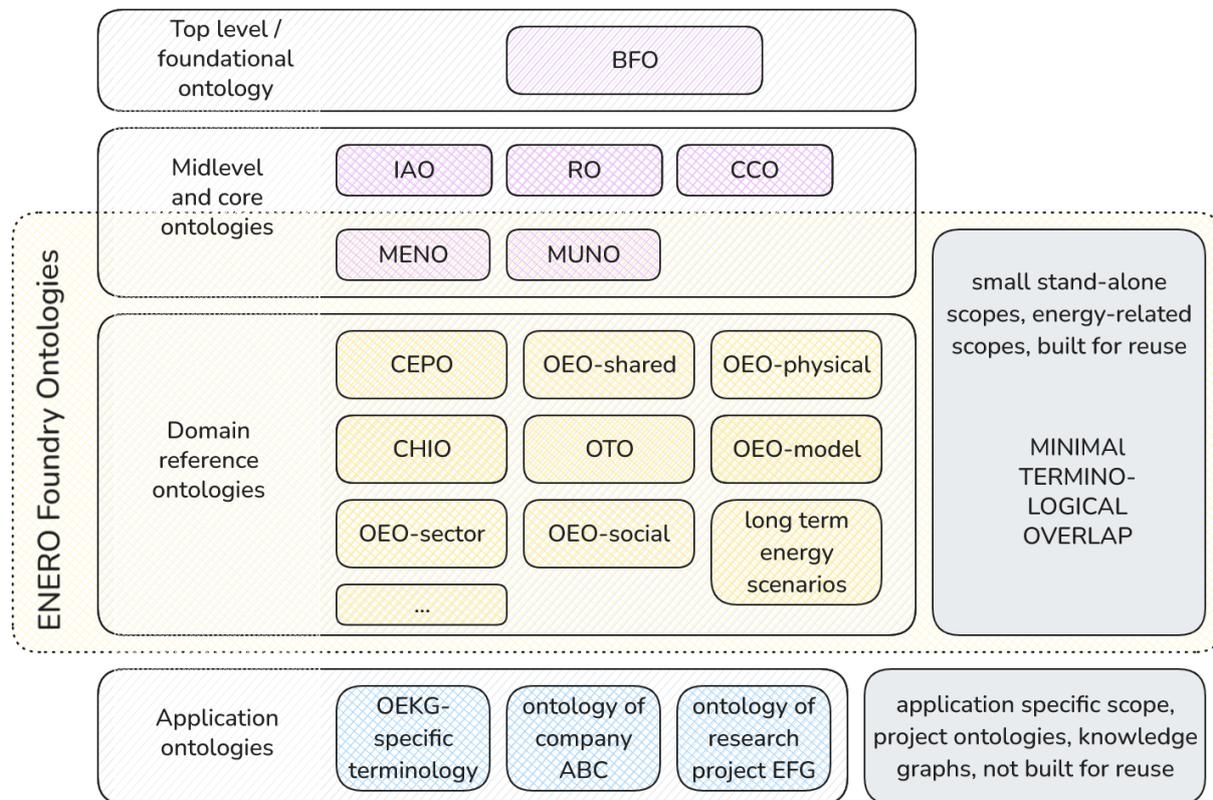

Figure 1. *Architecture of ENERO Foundry ontologies, including the first set of member ontologies and ontology modules.*

By creating a family of ontologies with orthogonal scopes, i.e. with a minimal terminological overlap between the ontologies, the ENERO Foundry aims at reducing the effort for coordination. The decision of whether a term should belong to an ontology or not can be eased, and irritation caused by contradicting definitions can be reduced. Based on the idea of orthogonal scopes and a common classification of ontology types ([7], [8]), an architecture for the ENERO Foundry has been developed that consists of four layers, illustrated in Figure 1:

1. The top layer refers to foundational ontologies which provide a basic structure for the categorization of entities/terms and are widely used in many communities. The commitment to a common foundational ontology is a basic prerequisite for interoperability between ontologies. The ENERO Foundry ontologies commit to the usage of (or provision of a mapping to) the Basic Formal Ontology (BFO, ISO/IEC 21838-2:2021)[9], [10] as a foundational ontology, see also Section 3.1.
2. Midlevel and core ontologies provide more structure with domain-agnostic terminology that is useful for different scopes and domains; however, they are too specific to be considered foundational ontologies. The usage of common midlevel ontologies, e.g. CCO [11], IAO [12] or SKOS [13] is furthermore recommended if useful.
3. Domain reference ontologies provide the logical formalization of the terminology of an ideally clearly defined domain-specific scope. They are built for reuse in other ontologies or applications. The ENERO Foundry ontologies are mainly domain reference ontologies. These ontologies are expected to have clearly defined, fairly narrow scopes, usually of different levels of granularity or detail, conforming to the idea of orthogonality; by reusing existing terminology and collaborating with other ontology teams, the terminological overlap is reduced to a minimum.
4. Application ontologies (and knowledge graphs) are built in the context of concrete applications or projects. They are not primarily built for reuse. Instead, they reuse domain reference ontologies and existing design patterns, and extend them with application-specific terminology.

4. Ontologies within the ENERO Foundry

At the time of submission, several ontology developer teams are engaged in the ENERO Foundry or have expressed their interest in participating. This section gives some examples of these efforts.

The Open Energy Ontology (OEO) [14] was one of the first open reference ontologies in the energy domain. Its scope focuses on energy system modeling, covering techno-physical, socio-economic and other related aspects thereof in five ontology submodules. With the beginning of the NFDI4Energy project, five energy-related ontologies have been planned and the need for harmonization with the OEO arose [15]. The Climate and Energy Policy Ontology (CEPO) is one of them, which has been developed in order to have a systematic way to record data on climate and energy policies and policy instruments; it has been designed from scratch following the Foundry principles.

Two spin-off ontologies from OEO have been published as domain-independent midlevel ontologies. The Mid-level Energy Ontology (MENO, [1]) focuses on modeling the ontological nature of energy and energy-related basic processes, like energy transformation and transfer. The Modelling Uncertainties Ontology (MUNO, [16]) is an ontological formalization of the Uncertainty Matrix by Kwakkel et al. [17] to describe uncertainties within the modeling process of real-world systems, like the energy system.

The Open Transportation Ontology (OTO) aims to provide a controlled vocabulary for data annotation in the transportation research domain to ease discoverability and data integration.

A further goal is to make the annotated data semantically accessible and interpretable by data science and AI approaches in the future. Its development is inspired by the OEO and builds upon the lessons learned during the development of the OEO. Beyond annotation of data coming from the transportation domain, the project has other intended applications like ontology-based data access (OBDA). Re-utilization of existing work is a central principle of the project; the development team's approach is to extract components from existing BFO-based ontologies like the OEO and the CCO to build independent context-specific modules. The Charging Infrastructure Ontology (CHIO, [18]) is another ontology related to e-mobility and energy.

There exist further semantic artifacts related to energy, some of which are already well established in their domain. A frequent and legitimate question is, if and how such artifacts are considered for the ENERO Foundry. For example, there is the Common Information Model (CIM) [19], which is a standard to describe electric power transmission and distribution, adopted by the International Electrotechnical Commission (IEC). CIM possesses characteristics of a common vocabulary, but it is not a scientific formal reference ontology. Another example is the Smart Applications REFerence Ontology (SAREF) [20], a modular set of versioned ontologies about different Internet of Things (IoT) vendor solutions. SAREF4ENER is an energy-related module thereof about smart home applications. The SAREF ontologies are interoperable with each other. However, they are not compliant to the ENERO principles, especially, since they are not based on a top level ontology, which impedes interoperability to other ontologies.

5. Related Work

The use of ontologies in the research area of biology and biomedicine is well-established to organize, curate and interpret huge amounts of research data.

The Open Biological and Biomedical Ontologies (OBO) project reaches back to the early 2000s, as the number of ontologies and their applications grew [4]. At the time, ontologists became aware that when developing ontologies independently, integrating multiple ontologies can lead to incompatibilities. By means of common standards and principles, a modular composition of ontologies was enabled and the technical and scientific quality of the ontologies guaranteed [2]. The OBO Foundry was initiated to curate and to develop these principles further, and to watch the quality of member ontologies. To date, there are more than 150 active member ontologies.

Additionally, central to the OBO Foundry ecosystem is the Ontology Development Kit (ODK [21]). It provides a standardized framework for developing, testing, and releasing ontologies following the OBO Foundry principles. For quality checks, ODK relies on ROBOT [22], using checks ranging from syntax validation to SPARQL-based validation and logic-based validation. Recently, the ODK has been enhanced with modern AI tools like large language models [23]. The OBO Dashboard [2] is a monitoring and evaluation platform that continuously assesses publicly-released ontologies in the OBO Foundry. It automatically runs ROBOT validation checks (and other metrics) across all registered ontologies and reports results through a web interface. The Dashboard focuses on ongoing compliance and transparency, helping the community identify issues such as missing metadata, logical inconsistencies, or outdated practices across OBO ontologies.

Similar to OBO, yet younger, the BSSO Foundry is an open community of practice and exchange for the development, adoption and use of ontologies in the behavioral and social sciences [24]. It provides a repository of domain ontologies committed to the OBO principles, and aims at creating a central resource for guidance on the development, adoption and use of

ontologies for behavioral sciences. The BSSO Foundry acts as a hub for collating and accessing ontology-related tools and workflows for researchers in the domain.

The Industrial Ontologies Foundry (IOF) aims to create a set of core and open reference ontologies that spans the entire domain of digital manufacturing. The IOF ontologies consist of a common midlevel ontology ("core") and several domain-specific ontologies. The ontologies are developed along technical principles which are close to the OBO Foundry principles. The core ontology is available on GitHub, however, membership in the IOF is fee-based.

The OBO Foundry requires that the domain of each member ontology covers a biological or biomedical research area, which is why energy-related techno-oriented ontologies are out of scope. The same holds true for the BSSO Foundry. The IOF could potentially cover energy-related domains, however it focuses on industrial applications; the IOF principles are, at least partially, designed for application ontologies rather than for scientific domain reference ontologies.

6. Outreach, Outlook and Conclusion

The ENERO Foundry community is still small, since the development of formal and open reference ontologies as well as their usage is still not yet a common practice in energy research data management. However, we are expecting this to change and are open to a growing community with a broadening spectrum of domains and an internationalization of the developer community in a continuous process.

The ENERO Foundry actively invites any individual developers and teams of energy-related ontologies to join. To get in touch and participate we recommend joining the mailing list enero-foundry@lists.rl-institut.de. To submit a new ontology to the ENERO Foundry we recommend to open an issue in the ENERO Foundry repository on GitHub: https://github.com/ENEROFoundry/ENEROFoundry. Further information is given on the Foundry website: https://enerofoundry.github.io/ENEROFoundry/.

As we work to grow and improve the ENERO Foundry, we aim to learn from the experiences of other initiatives and to coordinate guidelines across domains when possible. To this end, we've begun discussions with the NFDI Ontology Harmonization and Mapping Working Group regarding future collaborations on ontology development topics with the broader NFDI community. Furthermore, cooperation with international research data initiatives such as the RDA and EOSC is being considered.

Apart from the commitment to a harmonized ontology development based on the principles presented (and their further development), the ENERO Foundry will focus on other approaches for ontology interoperability and development support. The reuse, adaptation or development of tools for ontology integration, like ODK or the Dashboard from OBO, the ontology spreadsheet editor OntoSpreadEd [25] or AI supported methods are currently under consideration for implementation. The Foundry provides a template repository for new ontologies, based on the ontology development guide [26] by the Scientific Ontology Network. The development of common design principles is planned, in order to facilitate the usage of ontologies in scientific and other use cases, e.g. for the description of time series, transformation processes or complex technologies. For ontological annotation of data and other applications, the terminology of domain reference ontologies is, at least partially, not specific enough and needs further differentiation. With post-composition extensions, e.g. as suggested in [27], across ontologies the terminology will be multiplied and become more flexible without suffering interoperability losses.

With this paper, we present the ENERO Foundry and its activities to the community of energy research data management. With a growing community that uses and develops energy-related ontologies, we want to stress the importance of semantic interoperability between these artifacts,

and their benefits for users and developers. We introduce our approach of common principles and an architecture of orthogonal scopes to achieve this interoperability. We furthermore show that this approach is already being applied successfully in other research communities. We encourage the energy-related scientific community to participate and contribute to an infrastructure for FAIR data management and publication supported by interoperable formal ontologies.

Data availability statement

All data and resources related to this publication can be accessed via GitHub: https://github.com/ENEROFoundry/ENEROFoundry.

Author contributions

Mirjam Stappel: Conceptualization, Funding acquisition, Investigation, Project administration, Visualization, Writing – original draft, Writing – review & editing; **Amanda Wein:** Conceptualization, Project administration, Writing – original draft, Writing – review & editing; **Till Mossakowski:** Funding acquisition, Writing – original draft, Writing – review & editing; **Fabian Neuhaus:** Conceptualization, Writing – review & editing; **Ludwig Hülk:** Conceptualization, Writing – original draft, Writing – review & editing; **Eugenio Arellano Ruiz:** Writing – original draft; **Silvia Weko:** Writing – original draft; **Carsten Hoyer-Klick:** Writing – review & editing;

Competing interests

The authors declare that they have no competing interests.

Funding

Acknowledgements

References

[1] M. Stappel and F. Neuhaus, "Representing energy in the midlevel energy ontology (MENO)", in *Formal Ontology in Information Systems*. IOS Press, Dec. 2024, ISBN: 9781643685618. DOI: 10.3233/faia241293.

[2] R. Jackson et al., "OBO Foundry in 2021: Operationalizing open data principles to evaluate ontologies", *Database,* vol. 2021, Oct. 2021, ISSN: 1758-0463. DOI: 10.1093/database/baab069.

[3]   A. Ghazvinian, N. F. Noy, and M. A. Musen, "How orthogonal are the OBO Foundry ontologies?", *Journal of Biomedical Semantics*, vol. 2, no. S2, May 2011, ISSN: 2041-1480. DOI: 10.1186/2041-1480-2-s2-s2.

[4]   B. Smith et al., "The OBO Foundry: coordinated evolution of ontologies to support biomedical data integration", *Nature biotechnology*, vol. 25(11), pp. 1251–1255, 2007. DOI: https://doi.org/10.1038/nbt1346.

[5]   M. R. Kamdar, T. Tudorache, and M. A. Musen, "A systematic analysis of term reuse and term overlap across biomedical ontologies", *Semantic Web*, vol. 8, no. 6, G.-Q. Zhang, Ed., pp. 853–871, Aug. 2017, ISSN: 1570-0844. DOI: 10.3233/sw-160238.

[6]   F. J. Redondo-Aniorte, F. Abad-Navarro, and J. T. Fernández-Breis, "Analysis of the impact of orthogonality in the readability of the OBO Foundry ontologies", in *Good Practices and New Perspectives in Information Systems and Technologies*. Springer Nature Switzerland, 2024, pp. 160–169, ISBN: 9783031602214. DOI: 10.1007/978-3-031-60221-4_16.

[7]   N. Guarino, D. Oberle, and S. Staab, "What is an ontology?", in *Handbook on Ontologies*. Springer Berlin Heidelberg, 2009, pp. 1–17, ISBN: 9783540926733. DOI: 10.1007/978-3-540-92673-3_0.

[8]   T. Hahmann, "Ontology", in *Encyclopedia of Mathematical Geosciences*. Springer International Publishing, 2021, pp. 1–5, ISBN: 9783030260507. DOI: 10.1007/978-3-030-26050-7_231-1.

[9]   R. Arp, B. Smith, and A. D. Spear, *Building Ontologies with Basic Formal Ontology*. MIT Press, 2015.

[10] I. O. for Standardization (ISO), *Iso/iec 21838-2:2021*, https://www.iso.org/standard/74572.html.

[11] M. Jensen, G. De Colle, S. Kindya, C. More, A. P. Cox, and J. Beverley, "The common core ontologies", in *Formal Ontology in Information Systems*. IOS Press, Dec. 2024, ISBN: 9781643685618. DOI: 10.3233/faia241292.

[12] W. Ceusters and B. Smith, "Aboutness: Towards foundations for the Information Artifact Ontology", in *Proceedings of the Sixth International Conference on Biomedical Ontology (ICBO)*, Jul. 2015.

[13] A. Miles, "SKOS: Requirements for standardization", in *International Conference on Dublin Core and Metadata Applications*, 2006.

[14] M. Booshehri et al., "Introducing the Open Energy Ontology: Enhancing data interpretation and interfacing in energy systems analysis", *Energy and AI*, no. 5, 2021. DOI: 10.1016/j.egyai.2021.100074.

[15] A. Wein et al., "Developing interoperable ontologies for research data management in the energy domain", in *Proceedings of the Joint Ontology Workshops (JOWO) - Episode X: The Tukker Zomer of Ontology, and satellite events co-located with the 14th International Conference on Formal Ontology in Information Systems (FOIS 2024)*, Enschede, The Netherlands, Jul. 2024.

[16] M. Stappel, T. Mossakowski, F. Neuhaus, and S. Berendes, "Modelling model uncertainties ontologically", in *Formal Ontology in Information Systems*. IOS Press, Aug. 2025, ISBN: 9781643686172. DOI: 10.3233/faia250499.

[17] J. H. Kwakkel, W. E. Walker, and V. A. Marchau, "Classifying and communicating uncertainties inmodel-based policy analysis", *International Journal on Technology, Policy and Management*, vol. 10, no. 4, pp. 299–315, 2010.

[18] E. S. A. Ruiz, F. Miorelli, N. Wulff, and C. Hoyer-Klick, "A battery electric vehicle charging infrastructure ontology for interdisciplinary research", in *Proceedings of the Joint Ontology Workshops (JOWO) - Episode X: The Tukker Zomer of Ontology, and satellite events co-located with the 14th International Conference on Formal Ontology in Information Systems (FOIS 2024), Enschede, The Netherlands, July 15-19, 2024*, I. J. da Silva Oliveira et al., Eds., ser. CEUR Workshop Proceedings, vol. 3882, CEUR-WS.org, 2024. [Online]. Available: https://ceur-ws.org/Vol-3882/emsusto-1.pdf.

[19] J. J. Simmins, "The impact of pap 8 on the common information model (cim)", in *2011 IEEE/PES Power Systems Conference and Exposition*, 2011, pp. 1–2. DOI: 10.1109 /PSCE.2011.5772503.

[20] R. García-Castro, M. Lefrançois, M. Poveda-Villalón, and L. Daniele, *The etsi saref ontology for smart applications: A long path of development and evolution*, Jun. 2023. DOI: 10.1002 /9781119899457.ch7.

[21] N. Matentzoglu et al., "Ontology development kit: A toolkit for building, maintaining and standardizing biomedical ontologies", *Database J. Biol. Databases Curation*, vol. 2022, no. 2022, 2022. DOI: 10.1093/DATABASE/BAAC087. [Online]. Available: https://doi.org/1 0.1093/database/baac087.

[22] R. C. Jackson, J. P. Balhoff, E. Douglass, N. L. Harris, C. J. Mungall, and J. A. Overton, "ROBOT: A tool for automating ontology workflows", *BMC Bioinform.*, vol. 20, no. 1, 407:1– 407:10, 2019. DOI: 10.1186/S12859-019-3002-3. [Online]. Available: https://doi.org/10.11 86/s12859-019-3002-3.

[23] *AI4Curation: Bridging AI and Scientific Curation*, Platform pioneering the integration of artificial intelligence into scientific curation workflows, with focus on ontology development, biomedical knowledge curation, and gene annotation, 2025. Accessed: Nov. 21, 2025. [Online]. Available: https://ai4curation.io/.

[24] J. Hastings et al., "The BSSO Foundry: A community of practice for ontologies in the behavioural and social sciences", *Wellcome Open Research*, vol. 9, p. 656, Nov. 2024, ISSN: 2398-502X. DOI: 10.12688/wellcomeopenres.23230.1.

[25] B. Gehrke, M. Braun, P. Schenk, R. West, S. Michie, and J. Hastings, "OntoSpreadEd: Developing Ontologies with a Dedicated Online Template Spreadsheet Editor", *Wellcome Open Research*, vol. 10, p. 360, Jul. 2025, ISSN: 2398-502X. DOI: 10.12688/wellcomeop enres.24408.1.

[26] M. Glauer, M. Schilling, and M. Stappel, *A practical ontology development guide*, https://gi thub.com/scientific-ontology-network/ontology-development-guide/releases/download/v 0.1.0/ontology-guide.pdf.

[27] N. Köhler, M. Stappel, C. Muschner, L. Emele, C. Hofmann, and H. Förster, "OEOX – a post-coordination extension for the open energy ontology". [Online]. Available: https://ceur-ws.org/Vol-3882/emsusto-3.pdf.