# Developing Interoperable Ontologies for Research Data Management in the Energy Domain

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### Abstract

The NFDI4Energy consortium is developing several ontologies for use in a research data management platform for energy system researchers. The planned domain ontology will form a basis for multiple ontologies with more specialized focus areas; therefore, all ontologies must be designed for interoperability with this domain ontology and with each other. This paper presents an overview of NFDI4Energy's ontology development process, with a focus on the domain ontology. It describes the scope and purpose of this ontology, and the methodology for its ongoing development. Requirements for the ontology are summarized, and guidance provided for future ontology development in the energy domain.

### Keywords

ontology, energy, energy systems, research data management, FAIR data, metadata, Semantic Web, NFDI4Energy, NFDI

## 1. Introduction

Open science ensures the reproducibility of research findings and also enables easier control if research findings are not reproducible. Based on the rudiments of scientific discovery this guarantees scientific progress [1]. It is therefore crucial to spread the principles of open science to all research fields. One such crucial area is energy research, especially in light of the worsening climate crisis.

The energy domain is complex and multi-faceted. It is often too expensive or even impossible to conduct field tests for all experiments. Because of this, energy research heavily relies on simulation to test hypotheses. Simulation experiments use a substantial number of digital objects, such as power network topologies and time-series power usage datasets, but only a

*Joint Ontology Workshops (JOWO 2024) at the 14th International Conference on Formal Ontology in Information Systems (FOIS 2024), July 15–19, 2024, Enschede, Netherlands*

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small amount of these are published according to the FAIR (Findable, Accessible, Interoperable, Reusable) [2] principles. Without adherence to these principles for good data management, digital objects become difficult, if not impossible, to access and reuse.

The NFDI4Energy consortium - one of 26 consortia in the German NFDI (Nationale Forschungsdateninfrastrukur/National Research Data Infrastructure) association [3] - was founded in response to this need. Each NFDI consortium is made up of researchers from across Germany and is working to improve RDM in their particular scientific domain.

The overall goal of NFDI4Energy is to create an RDM platform that supports the use of FAIR digital objects in the energy research domain. It provides several services for users with varying levels of expertise in energy research [4]. To ensure that the final platform covers the RDM needs of such a diverse user base, the consortium will collect user data through various channels, such as surveys and workshops.

The platform under development aims to facilitate data management tasks: adding metadata to digital objects and enhancing their FAIRness. To this end, not only general metadata standards such as DataCite[1] are needed, but also more specialized standards containing domain knowledge. Therefore, NFDI4Energy is simultaneously developing several ontologies covering different aspects of energy systems research. The core of this development is the domain ontology, which serves two purposes: first, it provides a controlled vocabulary that is utilized to define domain metadata for existing digital objects, and second, it forms the foundation for the other NFDI4Energy ontologies that are developed to be interoperable with it. A crucial factor in the development of these ontologies (especially the domain ontology) is the specific goal for the ontologies to be used in conjunction if need be, but also be viable as singular ontologies.

This paper describes the initial development of a domain ontology by the NFDI4Energy consortium. After reviewing the existing ontology development methodologies, NeOn Methodology [5], Semi-Automatic Ontology Development Framework [6] and LOT Methodology [7] are selected as base methods to be reused. All of these ontology development methodologies have similar steps at the beginning: ontology scope definition, ontology requirements definition, existing ontology investigation and foundation ontology selection. Therefore, this work follows the same steps to develop the NFDI4Energy domain ontology.

In Section 2, we outline the applications of the ontology and the proposed ontology scope to cover those applications, with a focus on the required interoperability between this domain ontology and several related ontologies also being developed by NFDI4Energy. Section 3 reviews the requirements that this ontology must fulfill, and the development challenges stemming from the nature of the energy domain and the projected use-cases of the ontology. Sections 4 and 5 delve into the first steps of the domain ontology development: an investigation into current energy-related ontologies, and the selection of a foundation ontology to build from, respectively. Finally, we examine the future ontology development plans and conclude the paper in Section 6.

## 2. Ontology Scope and Applications

NFDI4Energy is developing five ontologies to be used in its RDM platform, each with varying scopes and intended use cases.

[1]https://datacite.org/

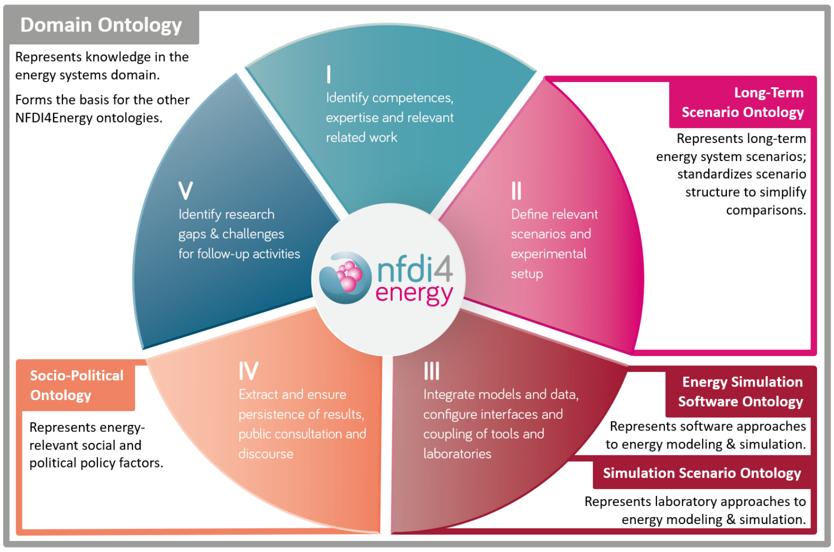


**Figure 1:** The relationships of the NFDI4Energy ontologies to each other and the five-stage research project life cycle. While the domain ontology encompasses the field as a whole and provides terminology relevant to all stages of an energy systems research project, the other four ontologies will be designed for more specialized use cases at specific project stages. (Figure adapted from [4].)

- A *domain ontology* will represent knowledge in the energy systems domain and provide a controlled vocabulary for the other ontologies and for NFDI4Energy's metadata standards.
- A *long-term scenario ontology* will represent long-term energy system scenarios.
- An *energy simulation software ontology* will represent various software approaches to the modeling and simulation of energy systems.
- A *simulation scenario ontology* will represent scenarios of energy system modeling and simulation and also address hardware-in-the-loop and laboratory testing.
- A *socio-political ontology* will represent social and political policy factors which are relevant in energy system models and scenarios.

The domain ontology has the widest scope and will form the basis for the development of the other four more-specialized ontologies.

## 2.1. Ontology Purpose

NFDI4Energy intends to make each ontology available for use by anyone who needs them for their own research projects or other applications. As the ontologies that are developed have different scopes, they also are intended to be used at different stages in the life cycle of a research project. Figure 1 outlines this life cycle.

A project focused on energy systems typically goes through five stages. The domain ontology is relevant in all stages, providing underlying definitions of and relationships between energy domain concepts, which carry through into the four specialized ontologies.

When starting a new project, a researcher first identifies existing work related to their idea, and recruits partners to assist them. Next, the experiment setup is defined, often in the form of energy system scenarios to be simulated. The long-term scenario ontology will help researchers in this phase; it will standardize descriptions of scenarios, making it easier to compare one scenario to another.

The research team then combines data and models into their desired simulations. Here, two specialized NFDI4Energy ontologies come into play. The energy simulation software ontology will be used for differentiating simulation software and adding domain specific metadata to the software registry entries. The simulation scenario ontology will be used to align the different simulation tools in use in the NFDI4Energy consortium, and will also support the comparison of short term scenarios by supplying additional metadata.

After the research team runs their simulations, the results of their work are disseminated. The socio-political ontology can be of use in this stage, helping to link energy-specific data to the political domain and society as a whole, so that non-energy experts can better understand the project's ramifications in relation to non-energy domains. This ontology may also be used earlier when simulations are defined, allowing for socio-political factors to be accounted for in energy system scenarios. Finally, the researchers look for gaps in their work and identify activities for project follow-up, beginning the cycle anew.

### 2.2. Working Group

As the creation of ontologies is happening more or less simultaneously by different teams of experts, a need to align the viewpoints of the teams to ensure ontology compatibility became apparent. To fill this need, the different teams of experts are coordinated in a Metadata & Ontologies Working Group that was created shortly after the different groups started working on the ontologies. The working group meets regularly to discuss overarching issues pertaining to all ontologies being developed and the general creation process. By doing so, the ontologies can be designed with interoperability in mind from the start.

This strategy follows the example of the NFDI association, which supports multiple sections where members of diverse consortia can work together on cross-disciplinary RDM topics [8]. Included is a "(Meta)data, Terminologies, and Provenance" section [9] focused on tasks such as ontology harmonization and mapping. Similarly, other NFDI consortia (e.g., NFDI4Ing [10], NFDI4Earth [11], NFDI4Objects [12], NFDI4Culture [13]) have also formed specialized groups to manage the development of ontologies and other semantic resources among numerous teams.

## 3. Ontology Requirements

The purpose of the domain ontology is to define a fixed set of meanings for its entities throughout the energy domain. It will also serve as a base for the other ontologies being developed. This means the main concern of the ontology is to portray the energy domain to the best of its capabilities, while maintaining a certain amount of modularity, thus making it interoperable with other ontologies.

As the scope of this ontology is the whole domain of energy research, the construction of the ontology is not without challenges. The energy domain is a large and complex domain

| Ontology Requirements Specification Document | |
|---|---|
| Ontology Name | NFDI4Energy Domain Ontology |
| Responsible Team | Task Area 4, Measure 4.1 |
| 1 | **Purpose**<br>This ontology will represent the energy domain and serve as a base for the development of additional ontologies in other TAs and measures, as well as providing a controlled vocabulary for metadata standards. |
| 2 | **Scope**<br>This ontology will focus on the energy system research domain. Care should be taken that the ontology is not defined too broadly nor too narrowly, as either would make it unusable. |
| 3 | **Implementation Language**<br>OWL |
| 4 | **Intended End-Users**<br>• Measure 4.3 team (metadata standards development)<br>• Measure 4.2 team (long-term scenario ontology development) |

**Figure 2:** A section of the version 0.5 Ontology Requirements Specification Document (ORSD) for the NFDI4Energy domain ontology. Document template adapted from [14].

containing interdisciplinary knowledge from different fields. Thus, without limiting the scope, the development of a holistic ontology for the energy domain would not be feasible within a single project, but would be more of a continuous process. Because of these reasons, we have decided to limit the scope of the ontology, making it easier to construct and use.

To make sure the ontology is constructed with its requirements and limits in mind, an Ontology Requirements Specification Document (ORSD) was started at the beginning of the development process. This tool was suggested by Suárez-Figueroa et al., and their template document [14] was adapted for the purposes of NFDI4Energy.

The ORSD contains the requirements for the domain ontology, both at a more abstract level (ontology scope, ontology purpose, etc.) and at a more technical level (implementation language, intended end-users, etc.). It is to act as a guide throughout the development process, and was filled in by the team working on the domain ontology while consulting the analysis done in other task areas of the NFDI4Energy consortia. The ORSD is to be consulted when questions arise during the ontology development, to ensure the quality of the ontology created. A fragment of the draft ORSD (version 0.5) is presented in Figure 2 to give the reader a sample of its contents.

Each of the other NFDI4Energy ontologies will also have its own ORSD, written such that the ontologies will all be developed along similar lines and that the final ontologies will be compatible with each other.

A key component of each ORSD will be a set of competency questions - questions which should be answerable by information encoded according to the terms and relations defined in the ontology. This is a common measure of ontology completeness and accuracy, used in several development methodologies [14, 5, 7]. The language used in the competency questions also provides developers with insights into vocabulary to consider including in the ontology [14].

# 4. Existing Ontology Investigation

The Metadata & Ontologies Working Group began the ontology development process by first examining the current state of the field, collecting a list of 41 existing energy-related ontologies and associated metadata (see Appendix A for the ontology list). The primary goal of this task was to help determine if any might make suitable starting points for adaptation into the planned NFDI4Energy ontologies. Since many existing ontologies are open source and include information that falls under the scopes of one or more of the NFDI4Energy ontologies, the consortium intends to reuse these existing resources where possible instead of starting from scratch.

An additional goal of this ontology collection was to create an energy-focused Terminology Service cataloguing ontologies in this domain. The Terminology Service[2], developed by TIB, allows users to search for and compare ontologies that are registered in the service; within the NFDI4Energy collection[3], only those ontologies deemed relevant to the energy research domain are listed. This collection therefore provides precisely curated results to energy system researchers seeking ontologies for their projects.

Following the completion of their ontology list, the working group narrowed it down from 41 entries to 20 entries of the highest interest for the consortium's purposes. Criteria considered for each ontology were the scope, licensing, findability, and activity history; preference was given to ontologies more closely matched with NFDI4Energy's needs, with more permissible and open licenses, easily accessible files, and active development teams.

Finally, inspired by the work of the NFDI4Cat consortium [15], the working group then sorted the remaining 20 ontologies into categories based on their scopes, purposes, and content. This activity allowed team members to take a closer look at each ontology and also further narrowed down the list of potential starting points for the planned specialized ontologies, so that these specialized development teams could focus on just the ontologies that were closest in scope to those they were tasked with constructing for NFDI4Energy.

After a discussion-based process, the working group settled on the following categories and definitions for the content of the ontologies:

- *Energy Life Cycle*: Ontologies describing technical aspects of the stages in the life cycle of energy.
  - *Energy Generation*: Ontologies describing the conversion of different energy forms into electric energy.
    - *Renewable Energy Generation*: Ontologies describing conversion methods based on renewable resources (e.g., photovoltaic technologies).
    - *Non-Renewable Energy Generation*: Ontologies describing conversion methods based on non-renewable resources (e.g., coal based electric energy generation).
  - *Energy Storage*: Ontologies describing the storage of electric energy by conversion for later use.
  - *Energy Consumption*: Ontologies describing the consumption of electric energy by conversion.

[2] https://terminology.tib.eu/ts
[3] https://terminology.tib.eu/ts/ontologies?collection=NFDI4Energy

- *Energy Markets*: Ontologies describing the buying and selling of electric energy.
- *Energy Domain*: Ontologies describing the energy domain as a whole.
- *Smart Grid*: Ontologies describing technologies used in smart grids.
- *Smart Home*: Ontologies describing technologies used in smart homes (e.g., thermostats, appliances, Internet of Things [IoT] devices).
- *Energy Efficiency in Buildings/Construction*: Ontologies describing the efficient use of energy in the construction and use of buildings.
- *Sustainability Factors*: Ontologies describing the sustainable generation and use of energy (e.g., energy efficiency technologies, efficient construction standards, greenhouse gas emission reduction).
- *Society*: Ontologies describing factors external to the energy domain that have a strong impact on the energy domain (e.g., politics, environment, human behavior).

It quickly became apparent in this categorization process that the content of many ontologies overlapped with many categories and could not be easily limited to a single category. Therefore, an additional layer of categorization was added to assess the scope of each ontology:

- *Good Match*: This ontology contained only the specified content category at a complete or near-complete level.
- *Broader*: This ontology contained the specified content category at a complete or near-complete level, as well as information relevant to other content categories.
- *Narrower*: This ontology contained some information relevant to the specified content category, but did not offer a complete representation of the content category.

The fit into the scope was then decided based on the defined scope in the paper or similar document introducing each ontology.

The resulting chart (see Figure 3) yielded a precise visualization of the domains of these existing energy-related ontologies of interest, to be used for reference in NFDI4Energy's further ontology development work.

## 5. Foundation Ontology Selection

Following the previously described investigation of existing ontologies, the working group opted to proceed in collaboration with the existing Open Energy Ontology (OEO)[4] [16], extending this ontology to fit the needs of the NFDI4Energy platform. The OEO was deemed the best option for multiple reasons. It is licensed under CC0-1.0, placing it in the public domain and alleviating any concerns regarding usage permissions. It currently has an active development community with personnel links to NFDI4Energy, which simplifies the process of arranging this collaboration and bringing the NFDI4Energy developers up to speed on the OEO development. Content-wise, this ontology falls into seven of the 11 categories shown in Figure 3, demonstrating that while this ontology still has room for growth, it already covers many topics that are of interest to the consortium. Furthermore, the OEO development is taking place openly on GitHub and the development process is well-defined.

[4]https://openenergy-platform.org/ontology/

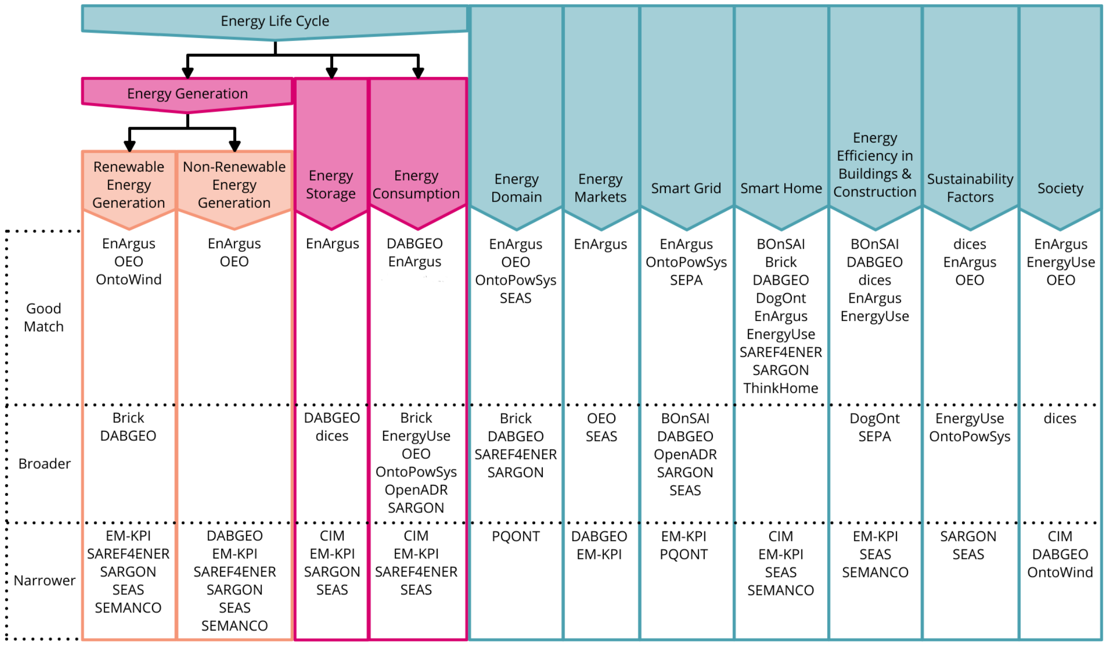


**Figure 3:** The ontology categorization completed by the NFDI4Energy Metadata & Ontologies Working Group. Content categories (Renewable Energy Generation, Energy Storage, Energy Markets, etc.) are listed across the top, and scope categories (Good Match, Broader, Narrower) are listed along the left side.

The final key points in the selection of the OEO are features that lend themselves to easier interoperability between this ontology and other ontologies. For one, the OEO is built according to the Basic Formal Ontology (BFO), a popular top-level ontology [17, 18]. Top-level ontologies contain classes and relations between them that are defined at a very abstract level to allow for mapping onto any domain of interest; the BFO in particular is recognized as an ISO standard and has been used as a base for over 350 existing ontologies [18]. This gives the domain ontology development team a wealth of published material from which to learn how best to work with the BFO. Use of the BFO as a common ontological base also simplifies the task of mapping terms between separate ontologies, as the structures of two BFO-based ontologies will be quite similar to each other thanks to their generically-defined base concepts. This structure is demonstrated in Figure 4, where domain-specific OEO classes such as ”hub height” and ”rotor diameter” are established as subclasses of the domain-nonspecific BFO classes ”quality,” ”specifically dependent continuant,” ”continuant,” and finally ”entity” at the top of the hierarchy.

Additionally, the OEO allows for flexibility thanks to its modular structure and makes it possible for users to download and use only a small subsection (module) of the ontology if needed. As NFDI4Energy plans to develop multiple ontologies that will be based on our domain ontology and must be interoperable with the domain ontology, this modular structure yields the possibility of planning our additional ontologies as separate modules of the domain ontology. Through this framework, the domain ontology could either be used as a whole or in smaller parts, with each module having well-defined links to the other modules and to the entire overarching

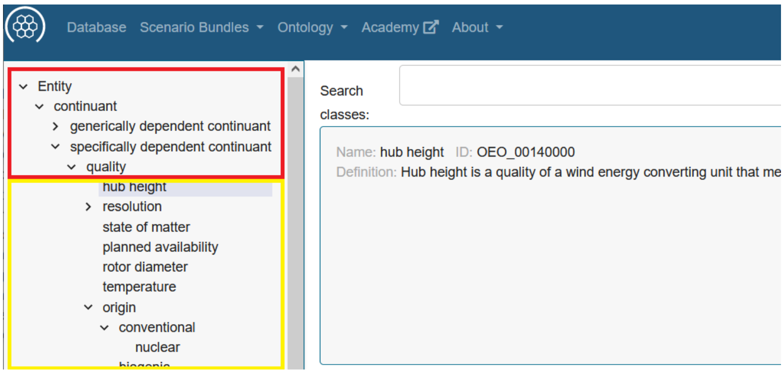


**Figure 4:** Interaction of OEO classes and BFO classes within the OEO. Terms highlighted in the red box come from the BFO, while terms highlighted in the yellow box are specific to the OEO. Screenshot taken from https://openenergyplatform.org/viewer/oeo/ on April 16, 2024; colored boxes for emphasis added by paper author A. Wein.

domain ontology.

## 6. Conclusion

We have outlined the foundational steps taken towards the development of a domain ontology for the NFDI4Energy RDM platform, from scope and requirements definition to an examination of the currently available ontologies in this field.

The further development of the Open Energy Ontology will be a collaboration between this ontology's current developers and the NFDI4Energy ontology development teams. The Metadata & Ontologies working group will be heavily involved in this process to ensure that each specialized module is fully interoperable with the domain ontology, and that the specifications laid out in each ORSD are met.

Prior to the version 1.0 releases of the ORSDs, appropriate competency questions are to be written for each ontology. Formulating these questions requires a thorough understanding of the use cases for each ontology, ideally with input from the domain experts who will be the end users of the NFDI4Energy platform. Therefore, the ontology development teams are currently working with the consortium's outreach-focused Task Areas, getting feedback from user groups (energy researchers, the energy industry, societal and political stakeholders) regarding their RDM needs and their expectations for the platform. Each ORSD, when completed, will include a section with competency questions and a section with potential ontology terms extracted from the questions [14].

With this groundwork laid, NFDI4Energy's ontology development teams are well-positioned to move forward with the construction of a set of interoperable ontologies for energy system research.

## Acknowledgments

The authors would like to thank the German Federal Government, the German State Governments, and the Joint Science Conference (GWK) for their funding and support as part of the NFDI4Energy consortium. The work was funded by the German Research Foundation (DFG) – 501865131 within the German National Research Data Infrastructure (NFDI, www.nfdi.de)

The authors of this article have used various preparatory works from NFDI4Energy to create this portrait, and references have been made where possible. We are grateful to all the people who have helped to shape and support the structures and results presented here. With regard to this article, special thanks go to the members of the Metadata & Ontologies Working Group for their assistance in the NFDI4Energy ontology development process: Nilesh Chavada, Felix Engel, Robin L. Grether, Christian Hofmann, Nan Liu, Ramiz Qussous, Jan Reinkensmeier, Mirko Schäfer, Philipp Schmurr, Uwe Stucky, and Wolfgang Süß.

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# A. Ontology List

**Table 1**
Ontologies listed in alphabetical order. **Bold font** indicates inclusion in the categorization described in Section 4.

| | Abbreviation | Full Name |
|---|---|---|
| 1 | | ∀Platform ontology |
| 2 | BFO | Basic Formal Ontology |
| **3** | **BOnSAI** | **Smart Building Ontology for Ambient Intelligence** |
| **4** | | **Brick** |
| 5 | | Building Energy Ontology |
| **6** | **CIM** | **Common Information Model** |
| **7** | **DABGEO** | **Domain Analysis Based Global Energy Ontology** |
| 8 | | DECENT Ontology |
| 9 | DEHEMS | Digital Environment Home Energy Management System Ontology |
| **10** | **dices** | **Digital Construction Energy** |
| 11 | DIMMER | District Information Modeling and Management for Energy Reduction |
| 12 | DNAS | Drivers-Needs-Actions-Systems Ontology |
| **13** | **DogOnt** | **Domotic OSGi Gateway Ontology** |
| 14 | ee-district | Energy Efficient District Ontology |
| 15 | | Electricity Markets Ontology |
| **16** | **EM-KPI** | **Energy Management - Key Performance Indicator Ontology** |
| **17** | | **EnArgus** |
| 18 | | Energy-saving Ontology |
| **19** | | **EnergyUse** |
| 20 | | Facility Ontology |
| 21 | GAZ | Gazetteer |
| 22 | | Generic Ontology of Energy Consumption in Households |
| 23 | | Integrated heat and electric energy ontology |
| 24 | LCC | Languages, Countries, and Codes |
| 25 | NewOSEIM | New Ontological Solution for Energy Intelligent Management |
| **26** | **OEO** | **Open Energy Ontology** |
| 27 | OEMA | Ontology for Energy Management Applications |
| 28 | OntoMG | Microgrid Ontology |
| **29** | | **OntoPowSys** |
| 30 | Onto-SB | Smart Building Ontology |
| **31** | | **Ontowind** |
| **32** | **OpenADR** | **Open Automated Demand Response Ontology** |
| **33** | **PQONT** | **Power Quality Ontology** |
| 34 | ProSGv3 | Prosumer Oriented Smart Grid Ontology |
| **35** | **SAREF4ENER** | **Smart Applications REFerence Ontology for the Energy Domain** |
| **36** | **SARGON** | **SmArt eneRGy dOmain oNtology** |
| **37** | **SEAS** | **Smart Energy Aware Systems Ontology** |
| **38** | **SEMANCO** | **Semantic Tools for Carbon Reduction in Urban Planning Ontology** |
| **39** | **SEPA** | **Smart Electric Power Alliance Ontology** |
| 40 | | Solar Soft Cost Ontology |
| **41** | | **ThinkHome Ontology** |