The representation of energy, energy carriers and fuels in the Open Energy Ontology

Mirjam Stappel[1], Lukas Emele[2], Ludwig Hülk[3] and Hannah Förster[2]

[1]*Fraunhofer Institute for Energy Economics and Energy System Technology (IEE), Joseph-Beuys-Str. 8, 34117 Kassel*
[2]*Öko-Institut (Institute for Applied Ecology), Borkumstraße 2, 13189 Berlin, Germany*
[3]*Reiner Lemoine Institute (RLI), Rudower Chaussee 12, 12489 Berlin, Germany*

Abstract

The Open Energy Ontology (OEO) is a BFO-based ontology for the domain of energy system analysis. Core of this domain is the concept of *energy*. Since the concept of energy is ambiguous and has not (yet) been introduced into BFO, we describe why the OEO classifies energy as a quality. We present how energy is differentiated from energy carriers, fuels and other related concepts. The process of energy conversion makes it possible to depict many different types of its generation and usage. Further, we describe the concept of origin of matter and energy. In this article, we define the core concepts of the OEO according to the BFO. We thus demonstrate how the OEO enables the consistent use of core concepts throughout the energy system analysis domain.

Keywords

CEUR-WS, ontology, energy, energy carrier, energy system analysis, fossil, fuel, renewable

1. Introduction

Researchers in the domain of energy system analysis (ESA) use energy system models to explore current and future energy systems. Such models are often applied to questions involving the expansion of the use of renewable energy sources, energy storage and to investigate how energy and climate policy impact the energy system. ESA is a heterogeneous and multidisciplinary domain. Experts in engineering, natural and social sciences, physics, mathematics, computer science, economics, meteorology, and geography developed different nomenclatures and conceptualisations for similar or the same things. These different terminologies are reflected in the respective documentation of research data, models, and results. Due to this heterogeneity, challenges arise regarding transparency and reproducibility. For example, time needs to be invested to identify where and if a nomenclature is documented and how it differs from one's own. To address these challenges, the Open Energy Ontology (OEO) was created and we maintain and develop it openly and collaboratively across institutes and research projects [1]. The OEO is part of the Open Energy Family, a modular and collaborative framework for climate and energy

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mirjam.stappel@iee.fraunhofer.de (M. Stappel); l.emele@oeko.de (L. Emele); ludwig.huelk@rl-institut.de (L. Hülk); h.foerster@oeko.de (H. Förster)
https://www.oeko.de/ (L. Emele)
0000-0003-3722-5564 (M. Stappel); 0000-0002-1720-2501 (L. Emele); 0000-0003-4655-2321 (L. Hülk); 0000-0003-2320-7808 (H. Förster)

related research data management. The OEO is also integrated into the Open Energy Platform (OEP), a web interface to an open database for energy and climate data [2].

Although energy is everywhere and we use it versatilely in our daily lifes, energy cannot be grasped intuitively. Neither is it easy to represent in an ontology. But, as the name of the OEO suggests, we consider energy as one of the ontology's core topics. Thus, we have to properly represent, classify and define the concept of energy and related subjects in the OEO and pay special attention to it. Based on the book *Building Ontologies with Basic Formal Ontology* (BFO) by Arp et.al. [3] we derived some basic principles for the OEO[1]. The OEO is written in OWL2 Manchester Syntax and consists of several OEO-owned modules and some external ontologies that are (partially) imported [1]. The majority of the energy-related concepts we discuss in this paper are included in the module *oeo-physical*, where concepts of physical entities are stored. In this article, we refer to OEO version 1.10.1[2].

In the following, we describe the ontological representations and definitions of energy (section 2), energy carriers and fuels (section 3), energy transformations (section 4). Implications of the design choices are discussed in section 5.

2. Wave or particle – what is energy?

2.1. Energy in the OEO

Energy appears in various forms and humans use and transform it in many different ways. In physics, energy is described both as matter-bound and immaterial. Energy can occur in different states and can be transformed from one state into another. Examples for matter-bound energies used in the domain are the chemical energy in wood or diesel, the kinetic energy of wind (moving air) and the thermal energy of steam. In contrast, radiative energy that moves through space without a material carrier is an example of immaterial character of energy in the energy system analysis domain. These different forms of appearance of energy make the classification of energy in an ontology neither intuitive nor self-explaining.

In the OEO development process, described in [1], we made the following design choice: energy is classified as a *quality* (BFO:0000019) of, and thus being specifically dependent on, material entities[3]. We defined energy as follows:

> *Energy is a quality of material entity which manifests as a capacity to perform work (such as causing motion or the interaction of molecules).*[4]

Our design choice underlines the material-bound perspective to energy, which plays an important role. To also depict the perceived immaterial aspects of energy, we introduced as a vehicle the concept of photons[5], understood as light particles. We axiomatised photons as bearer of those aspects of energy, that are not perceived as matter-bound. The description of the BFO

[1] https://github.com/OpenEnergyPlatform/ontology/wiki/Best-Practice-Principles
[2] https://github.com/OpenEnergyPlatform/ontology/releases/tag/v1.10.1
[3] material entity, BFO_0000040, http://purl.obolibrary.org/obo/BFO_0000040
[4] https://openenergy-platform.org/ontology/oeo/OEO_00000150
[5] *A photon is a portion of matter that is a light particle.* https://openenergy-platform.org/ontology/oeo/OEO_00230021

class “material entity”, states the concept “photon” explicitly as material entity in its examples of usage. Due to the nature of the OEO – focusing on matter-bound aspects of energy – we thus decided to ignore the wave nature of photons. If we classified a photon as a wave in addition, this may pose a challenge to upper-level ontologies such as the BFO: it would break the distinction between continuants and occurrents.

The intention of BFO2 is, that matter could encompass both mass and energy. It is planned to introduce “portion of energy” in a later release of the BFO [4]. Yet, in the current state of the BFO, (portion of) energy is not available and applicable. In BFO, a quality is a *specifically dependent continuant*, which means it relies on a specific bearer for its existence. Quality is further explained as *a specifically dependent continuant that, in contrast to roles and dispositions, does not require any further process in order to be realized.*[6] From the perspective of physics, where mass and energy can be seen as equivalents, as Einstein explained, the classification of energy as a quality, alongside with mass, is reasonable. Material entities are bearers of energy in its various subtypes. For example: the potential energy of a material entity is a persistent attribute. Its value depends on the system of reference: the height of an object, and thus its potential energy, is always relative to the height of the observer. Induced by a transformation process, the contained amount or type of energy can be changed, see section 4.

In the OEO we differentiate energy into several subclasses. The subclasses categorise common physical types of energy, i.e. chemical energy, electrical energy, kinetic energy, nuclear binding energy, potential energy, radiative energy and thermal energy. From these, we derive further energy subclasses with relevance for energy systems analysis (ESA). Subclasses are, for example, wind energy[7] and solar energy[8]. Other energy types depicted in the OEO are distinguished by their origin[9] (see also section 5), i.e. renewable energy and fossil energy. Renewable energy sums up all energies that replenish on a human time scale, like solar energy, wind energy, etc. Fossil energy is chemical energy that is stored in fossil combustion fuels, e.g. natural gas or gasoline. We defined both classes, renewable energy and fossil energy, by using an equivalence of concepts. Since we classify energy and its subclasses as qualities of material entities, we have to consider their relation with their bearer, which we describe in section 3.

2.2. Energy in other ontologies

We extensively reviewed literature, analysed other energy-related ontologies and compiled the result:[10]

OEO refers to the *capacity to perform work*, when defining energy. This fundamental physical interpretation of **energy** is also chosen by PATO (the Phenotype And Trait Ontology)[11] [5] and ENVO (the Environment Ontology)[12] [6], both ontologies are based on BFO. PATO is an ontology

[6]see elucidation in http://purl.obolibrary.org/obo/BFO_0000019

[7]*Wind energy is the kinetic energy of moving air.* https://openenergy-platform.org/ontology/oeo/OEO_00000446

[8]*Solar energy is radiative energy of the sun.* https://openenergy-platform.org/ontology/oeo/OEO_00000384

[9]https://openenergy-platform.org/ontology/oeo/OEO_00000316

[10]https://github.com/OpenEnergyPlatform/ontology/wiki/use-of-external-ontologies

[11]*A physical quality inhering in a bearer by virtue of the bearer’s capacity to do work.*, http://purl.obolibrary.org/obo/PATO_0001021

[12]*A disposition which is realized during the execution of work, the emission of heat, or the possession of mass.*, http://purl.obolibrary.org/obo/ENVO_2000015

on phenotypic qualities (properties, attributes or characteristics)[13], hence, the classification as *physical quality* is not surprising. For OEO, we do not see the need to distinguish between physical and other qualities, though. In ENVO, energy is defined as a *disposition*, which is also a specifically dependent continuant, yet its realisation needs to get triggered by a process. A comment in ENVO indicates that it is considered to align with PATO in the future.[14] Although PATO and ENVO chose similar definitions and classification for the concept of energy, we decided to not re-use them, but create an OEO-owned class *energy*, mostly because of the central relevance for the ESA domain.

Other ontologies also have concepts related to energy, but do not strictly apply an upper-level ontology that allows a comparison of classification. The enArgus ontology [7] has a similar domain as the OEO, but is in German language. It does not apply any upper-level ontology. The class **Energie** is defined as follows: *Energie ist eine physikalische Größe mit der Einheit Joule (J) oder Wattsekunde (Ws). Sie hat das Formelzeichen E. Energie kann in unterschiedlichen Energieformen vorliegen und wird mitunter auch Arbeit bezeichnet.* [15]

The Saref4ener[16] ontology defines **saref:Energy** as *A saref:Property related to some measurements that are characterized by a certain value measured in an energy unit (such as Kilowatt_Hour or Watt_hour).* Other energy-related ontologies to not explicitly classify it. For example the OEMA (Ontology network for Energy Management Applications) [8] or the energyCIM[17] ontology, which contains the concept of **EnergySource** and several energy related classes.

3. The difference between energy carrier and fuel

3.1. Material entities and energy

Every material entity is bearer of energy. Only a part of that energy is useful energy (*exergy*), while the other part (*anergy*) cannot be exploited by any technical apparatus [9]. As anergy is not usable, it is of low interest for the ESA domain as ESA focuses on material entities that additionally contain usable energy. Ontologically, these material entities possess the disposition to carry energy. We define this *energy carrier disposition* as: *An energy carrier disposition is a disposition of an material entity that contains energy for conversion as usable energy.*[18] Consequently, we call material entities that have the disposition to carry energy *energy carriers*: *An energy carrier is a material entity that has an energy carrier disposition.*[19] As every material entity that carries energy is an energy carrier, we axiomatised energy carrier as an equivalent class:

[13]Quality is defined as *A dependent entity that inheres in a bearer by virtue of how the bearer is related to other entities* http://purl.obolibrary.org/obo/PATO_0000001, subclass of BFOs *specifically dependent continuant*

[14]Comment in ENVO_2000015: "Consider replacing with PATO class; note that PATO class is not a disposition. This should likely go into OBO Core and also have a physicist look at it."

[15]https://www.enargus.de/pub/bscw.cgi/d3048-2/*/*/Energie.html?op=Wiki.getwiki Translation: *Energy is a physical quantity with the unit Joule (J) or Watt second (Ws). It has the formula sign E. Energy can be present in different forms of energy and is sometimes also called work.*

[16]https://saref.etsi.org/core/Energy

[17]https://github.com/smart-data-models/dataModel.EnergyCIM/

[18]https://openenergy-platform.org/ontology/oeo/OEO_00000151

[19]https://openenergy-platform.org/ontology/oeo/OEO_00020039

```
'energy carrier' EquivalentTo: 'material entity' and
    ('has disposition' some 'energy carrier disposition')
```

How exactly are material entities related to energy? Let us take water as an example: Water can be hot (contain thermal energy), can be moving (contain kinetic energy) or be elevated (contain potential energy), but its energy value can also be zero. How can hot water and other heated material entities be grouped and related to thermal energy? How can moving water and other accelerated material entities be related to kinetic energy? In the OEO, we created "anonymous classes" (general class axioms) to establish these relations. For example, the fact that all "moving/accelerated things" have kinetic energy is axiomatised as:

```
'material entity' and ('bearer of' some 'kinetic energy')
   SubClassOf: 'has disposition' some 'energy carrier disposition'
```

Similarly, we created anonymous classes for all "heated things" that contain thermal energy, all "electrically charged things" that contain electrical energy, all "combustible things" that contain chemical energy, all "elevated things" that contain potential energy.

Radiative energy is a special case, since it represents the wave-like characteristics of energy. To conform to the scheme of material entities being the bearer of the quality *energy*, we defined photons as light particles. Photons are the only (relevant) energy carriers for radiative energy, thus we axiomatised as follows:

```
photon SubClassOf: 'has quality' some 'radiative energy'
photon SubClassOf: 'has disposition' some 'energy carrier disposition'
```

A photon can also behave like a wave. This is in almost all cases irrelevant to the domain of ESA. Thus, we excluded this aspect from the definition and axiomatisation of photon.

3.2. A portion of matter with a role

An important concept, we introduced in the OEO, is *portion of matter*[20]. This class encompasses materials like coal, gasoline, water, carbon dioxide, methane, air, uranium, steel and minerals [1]. Some of these contain useful energy, which can be released by processes that transform the portion of matter into a different kind of portion of matter (for transformations in general see section 4). An example is the oxidation of a portion of carbon with a portion of oxygen. This forms carbon dioxide in the process (and releases heat). Those portions of matter that contain useful energy have an energy carrier disposition and of these the ones that can be transformed in such a process, have additionally a *fuel role*:

> *A fuel role is a role of a portion of matter that has the disposition to be an energy carrier and is used in a process that releases the carried energy by transforming the portion of matter into a different kind of portion of matter in a way that releases heat or does work.*[21]

[20] *A portion of matter is an aggregate of material entities that have a state of matter.* http://openenergy-platform.org/ontology/oeo/OEO_00000331

[21] http://openenergy-platform.org/ontology/oeo/OEO_00000001

We call portions of matter which have a fuel role *fuels*[22], implemented as equivalent class. As a consequence, all portions of matter which have a fuel role can be inferred as subclass of fuel. But not all material entities which have the energy carrier disposition are portions of matter with a fuel role. This answers our initial question of this section: All fuels are energy carriers, but not all energy carriers are fuels.

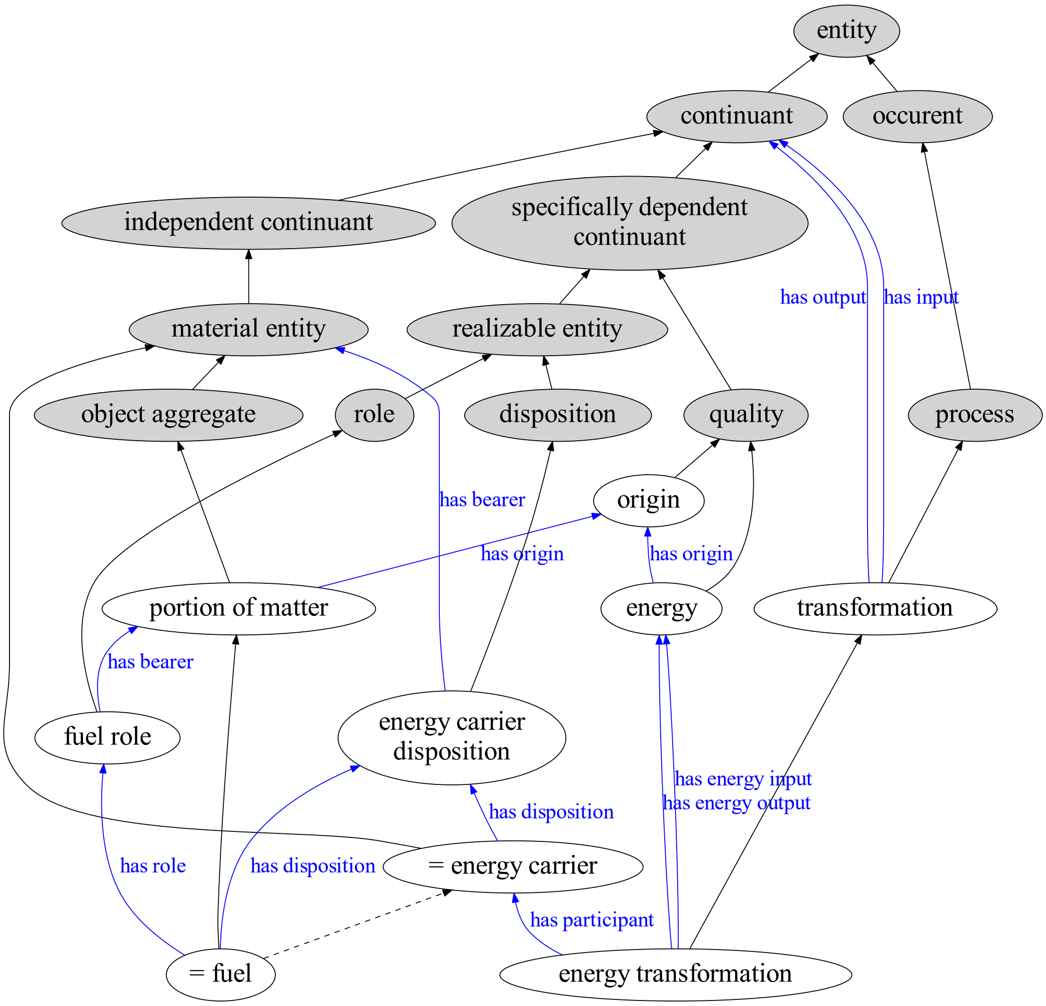

Figure 1: Aligning energy-related classes with the upper-level ontology (BFO)
Ellipses: BFO class (grey), OEO class (white), OEO class defined via equivalence of concepts (white, with equal sign). Arrows: *Is a* relation (black), other relation (blue, annotated), inferred relation (dashed). Anonymous classes and their relations are not shown.

[22] *A fuel is a portion of matter that has the disposition to be an energy carrier and which has a fuel role.* http://openenergy-platform.org/ontology/oeo/OEO_00000001

To further differentiate between different types of fuels, we distinguish fuels depending on whether they release their energy content by using some kind of chemical reaction (e.g. combustion)[23] or in a nuclear reaction, notably nuclear fission (nuclear fusion does not (yet) play any role in the ESA domain)[25].

Figure 1 summarises how the OEO classes we described relate to each other and how they fit into the upper hierarchical structure of the BFO using object properties from both the Relation ontology (RO) and newly defined in the OEO. We introduce the energy transformation class shown in the graph in the next section.

4. How to use energy? Transform it.

While our everyday language describes how energy is produced (generated) or consumed (used), the laws of thermodynamics tell us that it is all about changes in form. Energy possesses the ability to be converted from one type into another. In the OEO, we defined a *transformation* as a *process that transforms one or more inputs into at least one output.*[27] For our domain, a relevant subclass is *energy transformation*

> *Energy transformation is a process in which one or more certain types of energy as input result in certain types of energy as output.*[28]

We defined this broadly so as to allow any kind of energy transformation sub-process. This also includes the so called "energy losses", e.g. in the form of waste heat.

We created an object property called *has energy participant*: *A relation between an artificial object or a process and an energy, where the energy is used in the artificial object or process.*[29] with the sub-properties *has energy input* and *has energy output.* They relate the energy transformation processes and the involved energies, see Figure 1.

The relevant facilities where the energy transformations take place are grouped in the class *energy transformation units*[30]. Examples for energy transformation units are power plants or power-to-gas systems. Their internal components which are performing the transformation, like turbines or electrolysers, are grouped into the class *energy converting component*[31].

[23] *A combustion fuel is a fuel that realises its fuel role in processes that release energy in the form of heat or work by chemical reaction with other substances.*[24]

[25] *A nuclear fuel is a fuel that realises its fuel role in processes that release energy in the form of heat or work by undergoing nuclear fission.*[26]

[27] https://openenergy-platform.org/ontology/oeo/OEO_00000429

[28] https://openenergy-platform.org/ontology/oeo/OEO_00020003

[29] https://openenergy-platform.org/ontology/oeo/OEO_00010238

[30] *An energy transformation unit is an artificial object that transforms, changes or transfers a certain type of energy.*, https://openenergy-platform.org/ontology/oeo/OEO_00020102

[31] *An energy converting component is an artificial object that is usually a discrete part of an energy transformation unit with the function of transforming, transferring or changing a certain type of energy.* http://openenergy-platform.org/ontology/oeo/OEO_00000011

5. Implications regarding BFO and RO imports

We decided to define energy as quality, which is a specifically dependent continuant in BFO. But, as described in Section 2, classifying energy is ambiguous. Therefore, and because energy plays such an important role for the ESA domain, it becomes necessary that, unlike other specifically dependent continuants, energy itself needs to be bearer of qualities and roles. This is a special case that is not foreseen in BFO. But for the central concept of energy, we decided to make an exception here. This exception entails some implications, we describe in the following.

One of the most important ongoing research topics in the ESA domain is to find solutions for the climate crisis. A central aspect here is the question of where the energy comes from, e.g. if it is renewable or not. The questions of origin is also asked for the portion of matter carrying the energy. Thus we introduced *origin* as a quality of both energy and a portion of matter:

> *Origin is a quality of a portion of matter or energy based on where it comes from. It is inherited from its primary sources.* [32]

To relate a portion of matter or energy to its origin we created the object property *has origin*[33] with the domain `energy or 'portion of matter'`. To distinguish between several types of origins, we defined several subclasses. Some subclasses are limited to being a quality of either portion of matter or energy.

We mentioned in section 2 two important subclasses of origin: renewable and fossil. *Renewable* is an origin of energies only, defined as: *Renewable is an origin of energies that replenish on a human time scale.*[34] As counterpart to renewable, there is *conventional*[35] as further origin of energies.

As *fossil* in the ESA domain is ultimately connected to some energy carrying materials like coal, oil or natural gas extracted from the ground, it is thus an origin of portions of matter. *Fossil is a geogenic origin of portions of matter created from organic material by geological processes lasting thousands or millions of years.*

The origin quality is transferred if the portion of matter or energy is transformed and the output of the process inherits the origin: Crude oil has clearly a fossil origin, but also gasoline or heating oil are fossil as they are produced from crude oil. Similarly, the kinetic energy of moving air (usually called wind energy) has a renewable origin. When transforming wind energy into electrical energy, the latter inherits the renewable quality and thus electrical energy generated in a wind turbine has renewable origin, in contrast to electrical energy generated in a coal power plant. Other subclasses of origin that inhere in portions of matter are: *anthropogenic*[36],

[32] http://openenergy-platform.org/ontology/oeo/OEO_00000316

[33] *x has the origin of y* http://openenergy-platform.org/ontology/oeo/OEO_00000530

[34] http://openenergy-platform.org/ontology/oeo/OEO_00030004

[35] *Conventional is an origin of energies that don't replenish when transformed / consumed.* http://openenergy-platform.org/ontology/oeo/OEO_00020147

[36] *Anthropogenic is an origin of portions of matter or energies created by human activity.* http://openenergy-platform.org/ontology/oeo/OEO_00030000

synthetic[37], *biogenic*[38], and *geogenic*[39]. We currently discuss an origin *sustainable* for portions of matter.[40]

Apart from origin, energies can also bear roles, i.e. the commodity role. Electrical energy is commonly traded at energy market exchanges as a commodity, similarly to fuels like oil. Thus we needed to weaken the domain of the object properties *bearer of*[41] and *has role*[42]. In the OEO, their range has been extended to `energy or 'independent continuant'`.

We introduced the object property *has energy participant* and its subproperties in section 4 to axiomatise artificial objects or processes to energies. These special object properties reduce the need to weaken object properties like *has participant*[43] and subproperties, imported from RO.

6. Conclusion and future work

Energy is challenging to classify ontologically due to its dual character. Some ontologies in the energy domain avoid to classify energy, either by not using an upper-level ontology or by avoiding the concept at all. For the use cases of the OEO and due to its design, an appropriate classification is worthwhile. With this paper we demonstrate why it is useful for the domain of energy systems analysis to classify energy as a quality of material entities. We showed that the current version of BFO is not optimal for classifying energy. We were able to depict the different aspects of energy and related concepts like energy carriers and transformations, though.

In the ESA domain there is often no clear distinction between a material entity, its capability to carry energy and the energy itself. This means that a lump of coal and the energy contained in that lump of coal is often treated as the same: An energy systems modeller requires to depict the energy contained in that lump of coal and thus does not quantify that lump of coal other than directly in an energy unit (J). But to calculate CO_2 emissions from its combustion, the properties calculated in a mass unit (kg) or a volumetric unit (m^3) get relevant.

The OEO does not yet cover all aspects of energy. For example the distinction between usable energy (exergy) and non-usable energy (anergy) is currently under discussion.[44] Despite classifying energy as a quality, energy itself can be bearer of roles. In the OEO we covered this so far for electrical energy having a commodity role as it is traded at energy market exchanges. However, there are likely more roles of different types of energy to explore.

The OEO also distinguishes between energy and power, as well as the concepts of installation capacities. However, this goes beyond the scope of this paper and may be content of a later publication.

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[37] *Synthetic is an anthropogenic origin of portions of matter created artificially by a chemical process.* http://openenergy-platform.org/ontology/oeo/OEO_00030005

[38] *Biogenic is an origin of portions of matter made by or produced from life forms.* http://openenergy-platform.org/ontology/oeo/OEO_00030001

[39] *Geogenic is an origin of portions of matter or energies that are the result of geological processes.* http://openenergy-platform.org/ontology/oeo/OEO_00030003

[40] https://github.com/OpenEnergyPlatform/ontology/issues/872

[41] http://purl.obolibrary.org/obo/RO_0000053

[42] http://purl.obolibrary.org/obo/RO_0000087

[43] http://purl.obolibrary.org/obo/RO_0000057

[44] https://github.com/OpenEnergyPlatform/ontology/issues/1166

With clear definitions of energy and related classes as well as axioms describing the relations between these classes, the OEO not only represents the knowledge of the domain. It will function as the foundation of the *Open Energy Knowledge Graph*[45] which is currently under development as part of the Open Energy Family in the SIROP project. We see further applications of the OEO in data annotation and in facilitating comparisons of energy scenario studies.

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References

[1] M. Booshehri, L. Emele, S. Flügel, H. Förster, J. Frey, U. Frey, M. Glauer, J. Hastings, C. Hofmann, C. Hoyer-Klick, L. Hülk, A. Kleinau, K. Knosala, L. Kotzur, P. Kuckertz, T. Mossakowski, C. Muschner, F. Neuhaus, M. Pehl, M. Robinius, V. Sehn, M. Stappel, Introducing the Open Energy Ontology: Enhancing data interpretation and interfacing in energy systems analysis, Energy and AI (2021). doi:10.1016/j.egyai.2021.100074.

[2] K. Reder, M. Stappel, C. Hofmann, H. Förster, L. Emele, L. Hülk, M. Glauer, Identification of user requirements for an energy scenario database, International Journal of Sustainable Energy Planning and Management (2020). doi:10.5278/ijsepm.3327.

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

[4] B. Smith, Basic Formal Ontology 2.0 – Specification and user's guide, 2015. https://github.com/bfo-ontology/BFO/wiki.

[5] P. M. Mabee, M. Ashburner, Q. Cronk, G. V. Gkoutos, M. Haendel, E. Segerdell, C. Mungall, M. Westerfield, Phenotype ontologies: the bridge between genomics and evolution, Trends in Ecology & Evolution 22 (2007) 345–350. doi:10.1016/j.tree.2007.03.013.

[6] P. L. Buttigieg, E. Pafilis, S. E. Lewis, M. P. Schildhauer, R. L. Walls, C. J. Mungall, The environment ontology in 2016: bridging domains with increased scope, semantic density, and interoperation, Journal of Biomedical Semantics (2016). doi:10.1186/s13326-016-0097-6.

[7] L. Oppermann, S. Hirzel, A. Güldner, K. Heiwolt, J. Krassowski, U. Schade, C. Lange, W. Prinz, Finding and analysing energy research funding data: The EnArgus system, Energy and AI (2021). doi:10.1016/j.egyai.2021.100070.

[8] J. Cuenca, F. Larrinaga, E. Curry, A unified semantic ontology for energy management applications, in: WSP/WOMoCoE@ISWC, 2017. URL: http://ceur-ws.org/Vol-1936/paper-08.pdf.

[45] https://github.com/OpenEnergyPlatform/oekg

[9] P. O'Callaghan, S. Probert, Exergy and economics, Applied Energy 8 (1981) 227–243. doi:10.1016/0306-2619(81)90020-9.

A. Online Resources

The Open Energy Ontology (OEO) can be downloaded via the Open Energy Platform (OEP).[46] For easy access, the OEP provides an ontology class viewer.[47] The OEO is mainly developed on GitHub[48] and in developper meetings[49] that take place online usually every fortnight.

[46] https://openenergy-platform.org/ontology/oeo/
[47] https://openenergy-platform.org/viewer/oeo/
[48] https://github.com/OpenEnergyPlatform/ontology/
[49] https://github.com/OpenEnergyPlatform/ontology/wiki/OEO-developer-meetings