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Representing Energy in the Midlevel Energy Ontology (MENO)

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Abstract. Energy is a fundamental phenomenon of physics, but energy also plays an important role in the representation of many domains, since many processes involve energy transformation or transfer. However, energy is represented very differently in existing ontologies. Even in ontologies that share BFO as top-level ontology, energy is sometimes treated as disposition, as quality, and as a material entity. As we discuss in the paper, there are reasons for each choice, which makes the ontological representation of energy a challenging subject.

In this paper we present an ontological analysis of energy in a BFO-based midlevel ontology (MENO), including the different kinds of energy, their relations to dispositions as well as their realisation in processes.

Keywords. domain ontology track, energy, transformation, transfer, quality, disposition, BFO

1. Introduction

Energy is present everywhere in the physical world around us and our daily lives: all natural and technical processes are driven by energy. Some examples are: our bodies gain energy from the food we eat, our computers require a source of electrical energy to function and the plants need sunlight to be able to perform photosynthesis. Energy is a core concept in sciences, especially in physics, chemistry, and biology, and their applications. It is also a major topic for engineering and technology questions.

Even though energy plays such a vital role in many fields, its ontological representation is open to question. As we will discuss in Section 2, different domain ontologies represent energy in incompatible ways. The cause may be illustrated by considering the following statements about energy, which – at least prima facie – seem to be all true.

1. Energy is the capability to perform work.
2. $E = mc^2$
3. Energy can exist independently of matter.
4. Energy cannot be destroyed.

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Statement (1) is the textbook definition of energy. Since capabilities are either dispositions or some disposition-like kind of realisable entity, it seems that (1) determines the ontological nature of energy.

However, Statement (2) seems to support another view. According to the principle of mass–energy equivalence, all entities with mass have a corresponding intrinsic energy. If mass and energy are equivalent, it seems plausible that they are of the same ontological type. Since mass is one of the prototypical examples of qualities, this would entail that energy is a quality, too. Even if we disregard the principle of mass-energy equivalence, it is the case that other physical properties (e.g., mass, temperature, speed, height) that are connected to energy in physical laws are considered to be qualities. Thus, it would be odd, if energy belonged to another ontological category.

The observation that solar radiation transmits energy without any medium (i.e., some "aether") leads to Statement (3). This seems to imply that energy is not existentially dependent on material entities (in the sense of Basic Formal Ontology (BFO) [1]).[2] This conclusion is further supported by Statement (4), which is an immediate consequence of the first law of thermodynamics, i.e. the principle of conservation of energy. Because if energy is indestructible, it cannot existentially depend on entities that can be destroyed. For example, the energy contained in a candle persists, even after the candle is burned. Hence, the energy of the candle does not existentially depend on the candle. Because dispositions and qualities existentially depend on their bearers, Statements (3) and (4) seem to indicate that energy is neither a quality nor a disposition, but rather an independent continuant.

As Statements (1-4) illustrate, the ontological nature of energy is not obvious, which explains why it is represented differently by domain ontologies. The goal of this paper to provide an ontological analysis of energy, which is represented in the **m**idlevel **en**ergy **o**ntology (MENO)[3]. MENO is based on the Basic Formal Ontology (BFO), since it is an upper ontology that is widely used for scientific ontologies. MENO extends BFO by offering an ontological structure to describe specific types of energy, energy-based dispositions, and energy transformation and transfer processes.

BFO has its limitations for the purpose of representing energy; most importantly, it lacks the support of frames of reference. However, the primary purpose of MENO is to be a reusable resource for domain ontologies that represent macroscopic entities that are located on Earth (e.g., ontologies in the engineering domain such as the Open Energy Ontology [4]). Thus, for the intended use cases of MENO, it is sufficient to assume some fixed frame of reference. An in-depth representation of energy from a physical point of view is *not* the goal of this ontology.

The paper is structured as follows. In Section 2 we present an overview of how existing domain ontologies represent energy. This is followed by different energy-related aspects and their realisation in the MENO Ontology: the description of energy transformation and transfer processes (Section 3), which are the realizations of energy-based dispositions (Section 4). Furthermore, we define energy and specific kinds of energy in Section 5. Finally, we discuss material entities and fields as bearers of energy in Section 6 in the context of BFO.

[2]BFO distinguishes between three types of material entities: objects, object aggregates, and fiat object parts.
[3]`https://github.com/stap-m/midlevel-energy-ontology`

Table 1. Listed are domain ontologies which include a concept for energy: the tables contains information on the domain, on the usage of an upper ontology, the classification of energy and their identifier.

	Domain	Upper Ontology	Classification	ID
OEO	energy systems, modeling, engineering, climate	BFO	quality	oeo:00000150
ENVO	environments, environmental processes, ecosystems, habitats, and related entities	BFO	disposition	envo:2000015
PATO	phenotypic qualities (properties, attributes or characteristics)	BFO	quality	pato:0001021
AFO	equipment, material and results of laboratory analytical processes	BFO	material entity	amf:0000880
NCIt	cancer, including cancer related diseases, findings and abnormalities	-	physical property	ncit:C48058
OPB	physics for biology	(BFO)	primitive continuant	opb:01494
OM	units of measure	-	quantity	om:Energy

2. Energy in existing domain ontologies

The transfer and the transformation of energy are ubiquitous in the processes that are studied by scientists or engineers. Nevertheless, as [20] states, few ontologies include *Energy* explicitly as an entity. Some of them, especially ones that provide proper hierarchies and definitions, are listed in Table 1. The Open Energy Ontology (OEO), a domain ontology for energy system modeling [4], represents energy as one of its core concepts [20]. Further, the Environment Ontology (ENVO) covers environmental questions [5]. Several ontologies from biochemical and biomedical domains include energy as well, i.e. the Phenotype And Trait Ontology (PATO) [10], the Allotrope Merged Ontology Suite (AFO) [12], the NCI Thesaurus (NCIt) [18] and the Ontology of Physics for Biology (OPB) [6], as does the Ontology of units of Measure (OM) [14].[4]

Most of the mentioned ontologies are based on BFO or influenced by it (marked in parenthesis in Table 1). The ontologies agree that energy is a kind of continuant, but differ on the specifics. Most ontologies see energy as specifically dependent continuant, i.e. as quality or disposition. NCIt classifies it as a "physical property" (since BFO is not applied), whereas AFO declares energy as a material entity, being an independent continuant. Table 2 contains the definitions of energy as provided in the cited domain ontologies. All ontologies refer in their definition of *energy* to the capacity to perform work (besides OMIT, which does not provide a definition). This seems to be common knowledge of energy. Some of the domain ontologies also include a reference to heat (ENVO, AFO). The ENVO definition further mentions the possession of mass as a realization of energy. The capability to be transformed and the concept of energy conservation is part of AFO's definition. OEO states that the bearer of energy is a material entity.

Almost all of the cited ontologies provide a substructure, which mainly distinguishes into the different forms of energy, e.g. potential, thermal, kinetic/mechanical, electric energy, and others. Also, a distinction between renewable or fossil energy and respective manifestations like solar, wind, or geothermal energy are found in several ontologies. Some of the ontologies also refer to energy-related processes like energy transformation and transfer, storage, production, and consumption. ENVO also covers rest energy.

[4] Note that the energy concepts of ENVO and PATO are reused in third ontologies, i.e. ECTO and RBO (ENVO) as well as AGRO, FLOPO, MICRO, MS, and OBA (PATO). The field of application varies from energy and environmental-related sciences to biomedical or biochemical domains.

Table 2. Domain ontologies and their definitions of energy

OEO	*Energy is a quality of material entities which manifests as a capacity to perform work (such as causing motion or the interaction of molecules).*
ENVO	*A disposition which is realized during the execution of work, the emission of heat, or the possession of mass.*
PATO	*A physical quality inhering in a bearer by virtue of the bearer's capacity to do work.*
AFO	*Energy must be transferred to an object in order to perform work on, or to heat the object. It can be converted in form, but not created or destroyed. [Wikipedia]*
NCIt	*The capacity of a physical system to do work [NCI]*
OPB	*Physics primitive that is capacity to do physical work.*
OM	*Energy can be defined as the ability to do work. It is a derived quantity in the International System of Units.*

In conclusion, we can observe that energy is categorised quite differently by existing ontologies, even though most of them are based on BFO. For MENO, we propose a classification of energy as quality and explain the context of this interpretation in the following sections.

3. Transformation and transfer processes

As a starting point for our introduction to MENO we will discuss the kinds of processes, in which we encounter energy; in particular, energy transformation and transfer processes. In Section 4, we analyse the dispositions these processes realise. Based on these results, we define energy and various kinds of energies (thermal, kinetic, chemical energy, etc.) in Section 5. In these sections we will cover the most important classes and relationships of the MENO ontology. Figure 1 provides an overview of its hierarchical structure. Please note that for the sake of readability, we use terms like "energy", "kinetic energy" etc. in examples and to explain the design of MENO before they are defined in Section 5. Nevertheless, the definitions of these terms in the ontology are *not* circular.

There is a countless variety of different processes in the natural world. To describe them systematically humans focus on certain recurring patterns of experience in these processes, e.g., regarding the amount of effort it takes to lift different objects, whether an object swims or sinks in water, or how much fuel a fire consumes. Via these patterns, physical qualities like mass, density, or others are discovered. These qualities characterise the dispositions of their bearers and may be used to quantifiably predict the realisation of these dispositions in processes. Particularly useful for this purpose are natural laws, which use equations to describe systematic connections between qualities of participants in processes. E.g., the ideal gas law $pV = nRT$ represents a systematic relationship between pressure p, volume V, temperature T for some given amount of gas n, with R being the ideal gas constant. These kinds of equations are particularly useful because they enable a quantitative prediction of how the change in one quality will affect another quality in a *quality transformation* process. E.g., pressurisation is a quality transformation, where one quality (the volume) is reduced and some other is increased (the pressure). A related kind of processes are *quality transfer processes*, where the quality of one entity is reduced while a quality of the same type of some other entity is increased. E.g., in a system of two communicating vessels the water level of one vessel will decrease

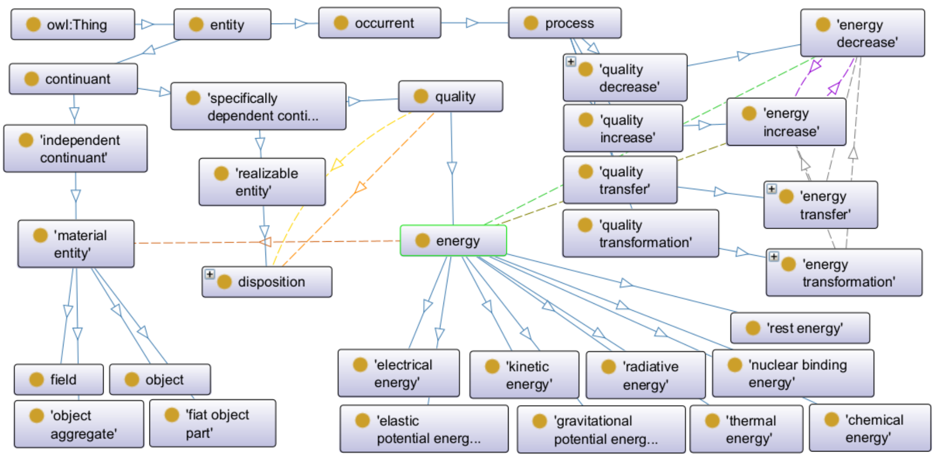

Figure 1. MENO classes visualised with OntoGraf. Blue arrows show is_a relations, other colors show non-hierarchical relations.

while the water level of the other increases until balance is achieved. Quality transfers and transformation processes are not limited to physical qualities (e.g., pressure, volume and water levels). For example, a bank transfer is a quality transfer, where the balance of one account is decreased and the balance of the other is decreased.

Potential energy, kinetic energy, thermal energy etc. play a similar ontological role as the (other) physical qualities we mentioned so far: they enable systematic descriptions of processes, which are realisations of dispositions of their bearers; they are systematically connected to qualities in physical laws; and they are involved in transfer and transformation processes. For these reasons they are qualities in MENO.

One important question we need to address is why potential energy, kinetic energy, etc. are considered to be kinds of energy, but other qualities (e.g., pressure, temperature or volume) are not. To be able to address this question in Section 5 we need to have a closer look at quality transfer and transformation processes. Figure 2 provides two (extremely simplified) examples for transformation and transfer of energy qualities.[5] The left diagram illustrates the energy transformation in a combustion engine: the chemical energy that is contained in the fuel is transferred into the kinetic energy of some vehicle, which is observable in the form of its motion. The right diagram illustrates energy transfer in a Newton's cradle (coupled pendulums): the kinetic energy of one moving pendulum is transferred to another pendulum, which is at rest at first, but due to the transfer starts to move.

Quality transformation and transfer are defined in MENO as follows:

> ***Quality transformation*** *is a process in which one quality is decreased, and, causally interconnected, one or more qualities are increased and all of these qualities inhere in the same bearer.*

[5] In reality, e.g. under not ideal conditions, processes in which energy plays a role, are complex. Triggering the respective disposition and inducing the process causes a sequence of overlapping energy transformation and transfer processes, whose choreography depends on plenty of constraints.

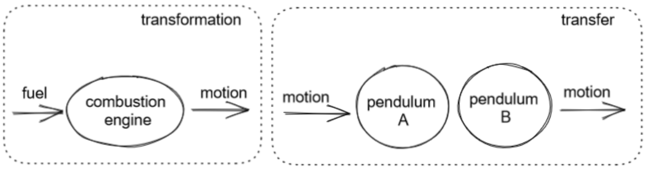

Figure 2. Illustrating energy transformation (left) and energy transfer (right) using simplified examples.

> ***Quality transfer*** *is a process in which one quality is decreased in one bearer and, causally interconnected, another quality that inheres in a different bearer is increased.*

Quality transformations and transfers have as part the causally related sub-processes of quality increase and quality decrease. Note that quality increase and decrease causally depend on each other and, thus, the processes occur simultaneously. We derive the definition of quality increase and decrease from Relations Ontology (RO) relations *positively regulates characteristic* and *negatively regulates characteristic*[6] that are also used to relate these processes to the energy qualities.

> ***Quality increase*** *is a process that positively regulates a quality which results in a rise in the intensity or magnitude of that quality.*
> ***Quality decrease*** *is a process that negatively regulates a quality which results in a reduction in the intensity or magnitude of that quality.*

Although natural and technical processes often have both, energy transformations and energy transfers, as part, a separate ontological description of these two processes is sometimes required, e.g. when the description of losses is neglected.

Figure 3 illustrates the complex interrelations of a quality transformation process under the assumption that both qualities are types of energy: Energy transformations have energy increase and energy decrease as sub-processes, which are causally related to each other. The energy increase and energy decrease processes regulate the distinct energy qualities that inhere in the same bearer, i.e. some material entity. Hence, the sub-processes energy increase and energy decrease occur within this bearer, i.e. they have the same material entity as participant. The structure illustrated in Figure 3 is an instance of the formal definition of quality transformation in FOL as shown in Listing 1:

Listing 1: Definition of quality transformations in First Order Logic (FOL)

```
(forall (?qt) (iff (QualityTransformation ?qt)
  (exists (?qd ?qi ?qu1 ?qu2 ?me)
    (and (QualityDecrease ?qd) (has_part ?qt ?qd)
      (QualityIncrease ?qi) (has_part ?qt ?qi)
      (causally_related_to ?qd ?qi) (causally_related_to ?qi ?qd)
      (Quality ?qu1) (Quality ?qu2) (not (= ?qu1 ?qu2))
      (negatively_regulates ?qd ?qu1) (positively_regulates ?qi ?qu2)
      (MaterialEntity ?me)  (inheres_in ?qu1 ?me) (inheres_in ?qu2 ?me)
      (has_participant ?qd ?me) (has_participant ?qi ?me) ))))
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[6] http://purl.obolibrary.org/obo/RO_0019001 and http://purl.obolibrary.org/obo/RO_0019002

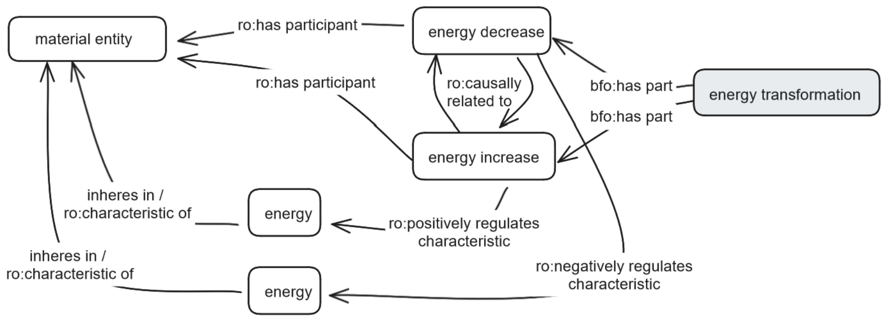

Figure 3. Axioms describing an idealized energy transformation process.

Figure 4 illustrates the interrelations of a quality transfer with the help of an energy transfer process with its sub-processes, the energy qualities and their bearers: Energy transfers have energy increase and energy decrease as sub-processes, which are causally related to each other. In contrast to energy transformation, these two sub-processes occur within distinct bearers, i.e. material entities, and thus have distinct material entities as participants. (In some cases (e.g., heat losses) one participant may be the environment.) The energy increase process positively regulates an energy quality in the first bearer, whereas the energy decrease negatively regulates the same type of energy quality inhering in the second bearer.

As mentioned above, energy transfers as shown in Figure 4 are kind of quality transfers. The definition of quality transfer is shown in Listing 2:

Listing 2: Definition of quality transfer in FOL

```
(forall (?qt) (iff (QualityTransfer ?qt)
  (exists (?qd ?qi ?qu1 ?qu2 ?me1 ?me2)
    (and (QualityDecrease ?qd) (has_part ?qt ?qd)
      (QualityIncrease ?qi) (has_part ?qt ?qi)
      (causally_related_to ?qd ?qi) (causally_related_to ?qi ?qd)
      (Quality ?qu1) (negatively_regulates ?qd ?qu1)
      (Quality ?qu2) (positively_regulates ?qi ?qu2)
      (MaterialEntity ?me1) (MaterialEntity ?me2)
      (not (= ?me1 ?me2)) (not (= ?qu1 ?qu2))
      (has_participant ?qd ?me1) (inheres_in ?qu1 ?me1)
      (has_participant ?qi ?me2) (inheres_in ?qu2 ?me2) ))))
```

As we will define in Section 5, energy transformation and transfer processes are subtypes of quality transformation and quality transfer processes, which are applied to various kinds of energies. Under real-world circumstances, energy transformation and transfer usually coincide, e.g. due to dissipation. Therefore, additionally to the classes energy transformation and energy transfer, MENO contains the defined concept of energetic conservation process, which comprise all processes that have energy transfers or energy transformations as part [7]. One interesting phenomenon is that in energy trans-

[7] The term 'energetic conversion' is chosen as collective term for energy transformations and energy transfers. However, literature is ambiguous in its interpretation, since some sources refer to energy conversion as synonym for energy transformation only.

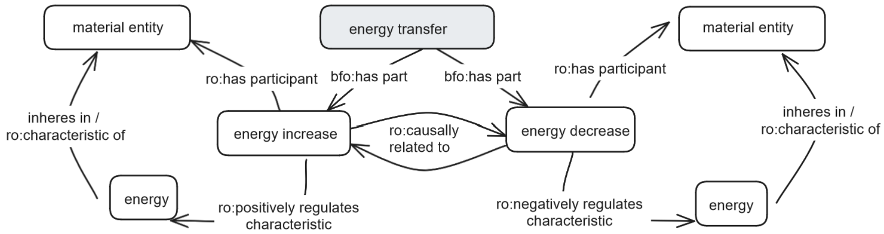

Figure 4. Axioms describing an idealized energy transfer process.

formations and transfers the quality increase always balances the decrease. Hence, in a closed system the sum of quantity values of the types of energy of the entities is constant (*law of energy conservation*).

4. Energy-based dispositions

In the previous section, we describe how energy is transformed and and transferred in processes that realise dispositions. As examples of such a disposition, apart from the often cited but unspecific "capability to perform work", one could mention the disposition of an object to fall when pushed, the disposition of a fuel to burn (i.e. chemically react with oxygen), or the disposition of a heater to heat this room.

In BFO, dispositions are defined as "A realizable entity (...) that exists because of certain features of the physical makeup [material basis] of the independent continuant that is its bearer" [1, p. 178]. There, dispositions are further described as internally grounded realizable entities, which implies that if a disposition ceases to exist, then the physical makeup of the bearer is thereby changed.

Many dispositions of material entities are grounded in "properties", i.e. qualities, of that material entity, see [17], where it is called "interplay of micro-level structures and their properties". Following this approach, these dispositions are based on (energy) qualities which provide the *categorical basis* of the realizable entities, as proposed by [17]. The categorical basis of a realizable entity consists of "a quality or a sum of qualities of the bearer of a realizable entity such that the quality (sum) makes the realizable entity causally relevant to its realization." [21] Typical examples for realizable entities which rely on a categorical basis are the fragility of glass or the solubility of NaCl. *These qualities substantially and systematically determine the realization processes*: for example, the mass (amongst other qualities) of a cannon ball determines the damage the cannon ball realizes when it hits a target. Similarly, energy qualities determine (in connection with other qualities) the realisation of energy transformation and transfer processes. For the above mentioned energy-related examples, the categorical basis of the disposition of an object to fall is a quality called gravitational potential energy, and the categorical basis for the disposition to burn is, amongst others, the chemical energy of the fuel.

One may argue that the above-mentioned approach is unable to depict the fact that some energy-related dispositions (in a general meaning) are not (fully) grounded internally, which contradicts the BFO definition of dispositions. For example, the disposition of this heater to heat this room, where this room is extrinsic to this heater. Toyoshima et al. [21] propose a solution of extrinsic dispositions based on the idea of dispositional pluralism by [11]. An alternative approach would be to claim that in these cases the energy-related dispositions inhere in a system of entities (e.g., the mereological sum or, alternatively, the object aggregate consisting of heater and room).

5. Energy and Energies in MENO

There is one phenomenon that all of the energy transformations or transfers in real-world processes have in common: a certain share of the transformed or transferred energy quality is always transformed into thermal energy and transferred to the surroundings, which is also called heat losses. In this context, thermal energy has a distinguished role among energy qualities, and thus, we choose to define it first and derive "energy" as such from it. Thermal energy is a quality energy that is caused by chaotic movement of particles in macroscopic (mass-possessing) material entities.

The faster the particles, e.g. molecules, move, the more thermal energy the bearer possesses. Indicators for thermal energy are temperature and pressure, although not proportional ones. The amount of thermal energy affects the state of matter of a material entity. For MENO, we define it as follows:

> ***Thermal energy*** *is a quality that a material entity possesses due to the undirected motion of its constituent parts (e.g. molecules and atoms).*

Thermal energy is volatile, i.e. it spontaneously transfers in the form of heat to a place of lower temperature via conduction, convection, or radiation.[8]

Joule, as the unit of measurement for energy, was originally defined as 'the heat generated in one second by the current of an Ampère flowing through the resistance of an Ohm.'[22] Given the definition on its own, this unit of measurement does not seem in any way suitable to measure, for example, the gravitational potential energy of an object, since it determines primarily the disposition to fall. Since the different energy types are convertible, it is possible to link the potential energy of a book on a shelf to the corresponding amount of heat that it could be converted into and, thus, use the same unit of measurement for potential energy and heat. Thus, the different types of energy qualities are distinguished from other qualities by the fact that they are commensurable.

Considering this, we define energy for MENO as a quality that is transformable into thermal energy.

> *x is* ***energy*** *if and only if x is thermal energy or x is a quality that belongs to a type of qualities that is (possibly indirectly) transformable to thermal energy via quality transformation or transfer.*

Based on the definition of energy, **energy transformation**, **energy transfer**, **energy increase**, and **energy decrease** are defined by restricting the definitions presented in Section 3 to energy. It follows from our definition that energy is a superclass of thermal energy and various types of other qualities. Hence, entities have no energy simpliciter, instead they have chemical energy, kinetic energy, etc. Since in physics these types of entities are used to systematically describe energy transformations and transfers, often

[8]Thermal energy can be distinguished in further sub-qualities, e.g., internal energy, enthalpy, or heat. However, for MENO it is sufficient to use the umbrella term 'thermal energy'. Users may need to extend MENO with a more fine-grained classification depending on their use case.

the different kinds of entities occur in the same equations. E.g., during a fall of an object from a stationary position the following holds $E_{\text{potential}} + E_{\text{kinetic}} = \textit{constant}$. However, this does not mean that there is a quality that corresponds to the sum of both kinetic and potential energy. Rather, the equation just describes a dependency between the different qualities.

Of course, since types of energy are commensurable, it is possible to define "the energy" of an object as the sum of all of its types of energies. For example, we could calculate "the energy" of a battery that is falling off a shelf by determining its chemical, kinetic, gravitational potential, rest energy, etc. and summing up the result. However, since the different types of energies are linked to very different kinds of capabilities, this sum will not be useful to describe (and predict) the behavior of that battery or its interaction with its environment. This example illustrates why defining "the energy" in this sense seems not particularly useful.

There exist different energy qualities that may vary a lot from each other, even though these are all considered kinds of energy. It is important to point out, that not every kind of energy is usable in the sense of providing a disposition of an entity to "perform work"[9]. For example, the mentioned heat losses dissipate into the surroundings and are "lost" for usage. For MENO, we define the basic subcategories of energy, based on consultations with energy engineering experts, and describe them in the following (apart from thermal energy, which we already introduced above). A more detailed substructure can be extended, if required, e.g. the differentiation of kinetic energy into rotational and translational kinetic energy.

The energy that is stored in the molecular bonds is called chemical energy and provides the categorical basis for the disposition to release (or store) energy in a chemical reaction, which is a type of energy transformation process. One of the culturally most important chemical reactions is combustion, i.e. burning material like wood, to provide heat, e.g. for heating or cooking.

> ***Chemical energy*** *is an energy that inheres in a material entity due to the structure and the type of its molecular bonds.*

Nuclear binding energy is defined similarly to chemical energy, but on the level of nuclei instead of molecular bonds.

> ***Nuclear binding energy*** *is an energy that inheres in material entities due to the bindings of the parts of their atomic nuclei.*

Moving entities contain usable energy in the form of kinetic energy. Since kinetic energy depends on a material entity and a frame of reference, it is a relational quality (in contrast to chemical energy, for example). The kinetic energy depends on the velocity and the mass of the moving object.

> ***Kinetic energy*** *is an energy that inheres in a material entity due to its movement relative to a static frame of reference.*

Gravitation causes objects to fall, as Newton's famous apple fell from a tree. To lift an object, this force has to be overcome by performing work and, thus, providing

[9] This is an obstacle for any attempt to define energy via work.

gravitational potential energy to the object. It is a relational quality since it depends on other material entities that exercise gravitational forces and is dependent on its drop height.

> ***Gravitational potential energy*** *is an energy that inheres in a material entity because it is influenced by the resulting gravitational forces exercised by other material entities and relative to the drop height of the material entity.*

Stressing a spring, as deforming any other elastic material entity, costs us some effort. The material entity gains this "effort" in the form of elastic potential energy and releases it again, once we stop pulling the spring or stressing the material entity.

> ***Elastic potential energy*** *is an energy that inheres in a material entity due to being deformed, related to its unstressed material structure.*

Radiative energy is emitted by material entities, but its transmission, i.e. transfer, does not depend on a material (i.e. mass-possessing) bearer. Instead it is transferred by electromagnetic fields, which consists of photons[10], see also Section 6. For example, solar radiation of different wavelengths transmits radiative energy from the Sun to Earth, e.g. ultraviolet or thermal radiation.

> ***Radiative energy*** *is an energy that inheres in photons and is dependent on the frequency and wavelength of the photon. Radiative energy is transferred as electromagnetic waves in radiation processes.*

Our daily lives are surrounded by tools that need electricity to run. Electrical energy is induced by forces on electrically charged particles. It is effective in the movement of charged particles (electric current) or its potential due to spatial separation.

> ***Electrical energy*** *is an energy that inheres in material entities due to the potential or kinetic energy of charged particles that are part of them.*

Another type of energy is not at all involved in the transformation and transfer processes of our daily live, but is tied to the very quality of matter, *mass*. Rest energy is considered to include the majority of internal energy [7] of matter. However, it is not usable. Rindler [15, p. 83] describes the vastness of the internal energy of a particle: The releasable part of energy resides in matter in form of thermal energy, chemical energy or in the nuclear bonds. However, about 99% of the internal energy of matter "resides simply in the mass of the ultimate particles and cannot be further explained. Nevertheless, it can too be liberated under suitable conditions, e.g. when matter and antimatter annihilate each other." Thus, while providing a theoretically important connection between mass and energy, rest energy is not of significant interest for most domain ontologies.

> ***Rest energy*** *is energy that inheres in the mass of subatomic particles.*

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[10]Depending on circumstances of measurements, light or radiation is able to behave either like particles or waves. The characteristics of particles, being always explicitly located, and waves, possessing a spatial and temporal extension, are exclusive, as explained e.g. in [9]. However, for the purposes of our paper it does not matter whether the constituent parts of electromagnetic fields are particles or waves.

6. Bearers of energy

In BFO qualities are dependent particulars that inhere in some independent continuants. Many types of energy inhere in a single material entity, e.g., chemical and rest energy. Other types of energy depend on two (or more) material entities or a system of multiple material entities[11].

These are relational qualities in the sense of BFO. However, as we saw in Section 5, for some types of energies their bearers are more problematic.

For example, the kinetic energy of an object is relative to a frame of reference. Currently, the treatment of frames of references in BFO is a well-known open question [1, p. 115]. Until this question is answered, the analysis of kinetic energy in BFO will be incomplete. However, for many practical applications this is not a limitation, because we can assume a fixed frame of reference (e.g., Earth) and neglect the frame of reference.

Another problematic case is radiative energy, e.g. from the Sun to Earth, which is transferred via an electromagnetic field that consists of photons. Unfortunately, the ontological nature of fields is a difficult topic, which requires more research.[12] An in-depth discussion of fields is beyond the scope of this paper. However, we suggest to distinguish between electromagnetic field and the mereological sum of a particular collection of photons. Similarly to a river, which consists of a particular collection of water molecules at any given time, but which is continuously gaining and losing components, the electromagnetic field of the Sun is the emergent result of a continuous stream of photons that are emitted by the nuclear fusion process of the Sun. While a flow of water is an occurrent, a river, which consists of flowing water, is an independent continuant in BFO. Analogously, while a stream of photons is an occurrent, an electromagnetic field is an independent continuant. This independent continuant is the bearer of radiative energy, that is, in this example, transferred from the Sun to Earth.

Unfortunately, electromagnetic fields do not fit well into the current structure of BFO. In BFO material entities are independent continuants that have portions of matter as parts [1, p. 107]. However, the BFO does not contain *portion of matter* as class, but according to Smith [19, p. 29] portion of matter includes anything that has elementary particles among its parts, including photons. Thus, electromagnetic fields are a kind of material entity. In BFO there are three types of material entities: objects, object aggregates, and fiat object parts. This distinction concerns a given level of granularity. Hence, while the human body is made from cells, the human body is an object and not an object aggregate. For the same reason, electromagnetic fields are not object aggregates (of photons). In BFO objects 'are tied together by relations of connection in such a way that if one part of the object is moved in space then its other parts will likely be moved also (the parts share [...] a *common fate*)' [1, p. 91]. Since the photons that are part of the electromagnetic field of the Sun move in all possible directions and interact with other entities independently, it is not an object in the sense of BFO. Further, fields are obviously not fiat object parts. Thus, to be able to represent the bearers of radiative energy properly, we include the class *Field* as a fourth subtype of material entity in MENO:

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[11] System (RO_0002577): A material entity consisting of multiple components that are causally integrated.`http://purl.obolibrary.org/obo/RO_0002577`

[12] In [3] fields are independent continuants. NEMO ontology defines electromagnetic fields as (spatial) quality [8]. In [2] fields are discussed as 'a property of the material wave', but there is no unequivocal conclusion. [16] considers fields both as qualities of spatial regions and as entities in their own right.

A ***field*** *is a material entity without mass that is bearer of some type of energy.*

Field in this sense is limited to fields that are independent continuants [13] and occupy spatial and tempo-spatial regions. They need to be distinguished from a wider notion of ‘field’, which are spatial or tempo-spatial distributions of physical properties like mass, density, temperature, or force. Fields differ from other kinds of material entities that are included in BFO because they all have mass. Note that while fields occupy spatial regions, they differ from spatial regions, because fields are bearers of dispositions and may be participants in occurrents (neither is the case for spatial regions in BFO). Examples include electromagnetic, electrostatic, and magneto-static fields.

7. Conclusion

Regardless of whether one discusses the climate crises, the economy of the Middle East or the health effects of fast food, energy plays an important role. These examples illustrate that although energy is not a foundational category (like continuant or object), it is relevant for many domains. However, as we discussed in Section 2, energy has been represented inconsistently in existing domain ontologies. For this reason, we present MENO as a BFO-based midlevel ontology to support energy-related domain ontologies with a structure. Our main use case of MENO is its integration into the Open Energy Ontology, a domain energy for energy system modeling. However, we hope that it will be integrated into other domain ontologies as well.

In this paper, we addressed the question of whether energy is an independent continuant, a realisable entity, or a quality. Our main conclusion is that thermal energy, chemical energy, kinetic energy, etc. are all qualities. These qualities differ significantly both from a physical and an ontological perspective since they are the basis for dispositions, which are realised in very different processes. However, they have in common that they are qualities that are (possibly indirectly) transformable into thermal energy via quality transformation or transfer processes. This is the characteristic of energy qualities that distinguishes them from other qualities. Energy always inheres in material entities, although some kinds of energies are relational qualities and some inhere in material entities that have no mass (i.e., fields). Since energy qualities are part of the categorical basis of disposition to participate in energy transformation and energy transfer processes, they are closely related to disposition (thus, realisable entities), but not realisable entities themselves. The law of conservation is a consequence of the fact that in energy transformation or transfer processes, energy increase and energy decrease processes are causally intertwined. In the future we will extend our analysis to power, which is the time derivative of energy, since it is a significant property of energy transformation and transfer processes. This is an interesting challenge, since BFO does not stipulate attributes of processes.

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