A Unified Semantic Ontology for Energy Management Applications

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Abstract. Current research evidences an increase of use of Semantic Web technologies within city energy management solutions. Different ontologies have been developed in order to improve energy data interoperability. However, these ontologies represent different energy domains, with different level of detail and using different terminology. This heterogeneity leads to an interoperability problem that hinders the full adoption of these ontologies in real scenarios. This paper presents the OEMA (Ontology for Energy Management Applications) ontology network. This ontology is an attempt to unify existing heterogeneous ontologies that represent energy performance and contextual data. The paper describes the OEMA ontology network development process, which has included ontology reuse, ontology engineering and ontology integration activities. The paper also describes the main OEMA ontology network modules.

Keywords: Semantic Web, energy, ontology network, ontology integration

1 Introduction

Energy management in current cities is evolving towards the future Smart Grid. Smart Grid managers aim to improve current grid efficiency, sustainability and resilience through Information and Communication Technologies (ICT)-based Energy Management Systems (EMSs). The efforts to improve energy efficiency concentrate on enhancing EMS to optimize the use of renewable and non-renewable energy sources. Energy sustainability measures include the suggestion of actions to change energy management behavioural patterns for economic, social and ecological purposes. Citizens are the main actors and the interoperability between them and EMS is essential. Regarding resilience, the objective is to avoid and react to power outages caused by power peak periods or natural disasters. Again, human-machine collaboration is crucial.

Current EMSs mainly focus on improving energy efficiency. However, energy sustainability and resilience systems require new data representation and exchange technologies [8]. Sustainability and resilience systems are required to exchange, extract knowledge and make decisions from large volumes of energy data collected at high rates and in most cases in real time. In addition, energy data belong to many domains and includes energy performance data (i.e., energy quantities, energy performance indicators, etc.) and energy-related and contextual data (i.e., buildings/infrastructures data, geographical data, weather data, etc.). ICT-based systems gather and store these data. Traditionally, these systems operate in functional silos and rely on heterogeneous technologies that pose new interoperability challenges for new EMSs. These challenges include the creation of a common energy data representation model and common vocabularies for human-machine interaction.

Current research in energy management shows the use of the Semantic Web to overcome these challenges ([6], [11], [7]). From the beginning of the current decade, Semantic Web technologies have been applied to create ontologies that represent energy data for different domains. These ontologies are the knowledge base of energy sustainability and resilience applications. However, not all ontologies represent the same energy data domains and at the same level of detail. In addition, the ontologies use different vocabularies to describe the same energy concepts. Hence, there is the need of an unified energy ontology that can be used in a wide variety of Smart Grid scenarios (i.e., Smart Homes, microgrids, etc.).

This paper presents the OEMA (Ontology for Energy Management Applications) ontology network. This ontology network is an attempt to unify existing heterogeneous ontologies that represent different energy-related data. The OEMA ontology network represents energy performance as well as contextual data. The paper explains the methodology and main steps followed to develop the OEMA ontology network. The paper also explains the OEMA ontology network modularized structure. Finally, the paper discusses learnt lessons from the OEMA ontology network development process and how future EMSs can benefit from the ontology. The paper is organised as follows: Section 2 provides a state-of-the-art of ontologies that represent energy domains. Section 3 emphasises on the need of a standardized energy ontology. Section 4 explains the methodology followed to develop the OEMA ontology network. Section 5 explains the main components of the OEMA ontology network and the energy data it represents. Finally, in Section 6 the conclusions of the research are presented.

2 Related Work

Within recent research projects and initiatives, semantic ontologies have been proposed to represent energy related data used by different Smart Grid EMSs. These systems are deployed in different Smart Grid scenarios: Smart Homes, urban environments (i.e., building, district, city, etc.), organizations, microgrids or Virtual Power Plants (VPPs) and Smart Grid Demand Response (DR) management.

The ThinkHome ontology [11] represents home energy consumption, production and energy contextual data, i.e., building details, weather conditions, etc. The DEFRAM project ontology [2] represents energy audits and measures of industrial organizations and recommendations for improving energy management given after previous audits. The SAREF4EE ontology [7] represents home equipment, flexibility operations, home spaces and home environmental conditions. The ontology BOnSAI [18] represents the following energy data: building equipment and structure data, user location and energy and environmental condition measures. This ontology is implemented within an EMS that monitors building energy performance and shows this information to allow users taking actions to increment energy savings.

The ontology EnergyUse [3] represents the following information: home user profiles, home appliances, and Heating, Ventilation and Air Conditioning (HVAC) systems data, home sensors and actuators data, home appliances energy consumption measures and energy tips discussion data. This ontology is the base for a collaborative web platform that is focused on raising home end users' climate change awareness [4]. The ProSGV3 ontology [9] represents the following data: infrastructure data, electrical appliances data, energy generation and storage systems data, weather report data, events, energy production and consumption and information about energy producers and consumers. The final purpose is to use this ontology as the knowledge base of EMSs focused on improving Smart Grid DR and sustainability by predicting Smart Grid energy consumption and production.

The Mirabel ontology [20] represents different energy actors' (i.e., home end-users) energy flexibility for specific devices. The DERI Linked Dataspace [6] represents energy related data from different enterprise domains. These domains include the following: enterprise business entities (i.e., employees, products, etc.), enterprise infrastructures energy consumption, energy consumption measurement sensors and business information, i.e., finance, facility management, etc. This linked dataspace is used by an enterprise observatory system that is focused on improving enterprise energy management at different levels from both economic and ecological perspectives.

The Km4city ontology [4] represents data domains about cities. These domains include energy, mobility, statistics, street graph, sensors, cultural heritage, etc. Represented energy domains include organisation and weather data. The SEMANCO ontology [5] represents the following energy domains: building energy consumption data as well as associated energy performance indicators (i.e., energy costs), consumed energy sources, building features, building equipment, weather conditions, buildings geographical location, demographic, environmental and socio-economic data. The objective of this ontology is to provide models for urban energy systems to be able to assess the energy performance of an urban area [5]. Finally, the LCC ontology [15] represents different buildings energy consumption data. This ontology has been developed to publish energy consumption data about cities' infrastructures as Linked Data.

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[3] `http://www.essepuntato.it/lode/http://socsem.open.ac.uk/ontologies/eu`

[4] `http://www.essepuntato.it/lode/http://www.disit.org/km4city/schema`

[5] `http://semanco-tools.eu/ontology-releases/eu/semanco/ontology/SEMANCO/SEMANCO.owl?`

3 The Need of a Unified Ontology

The energy ontologies reviewed in Section 2 represent different energy data domains depending on the Smart Grid scenario where they are applied. Table 1 shows the level of detail with which some of the available reviewed energy ontologies represent the main energy domains. We consider that an ontology represents an energy domain with a high level of detail when it includes a wide variety of terms and complex class hierarchies about that domain. A medium level of detail representation of an energy domain includes fewer terms and less complex class hierarchies. Finally, a low level of detail representation includes only few classes and virtually no class hierarchies.

As we can observe in Table 1, none of these ontologies represents all types of energy performance and contextual data that should be taken into account for energy management and the data are also represented at different levels of detail. In addition, different terms are used to represent the same energy concepts.

ontology energy domain	**ThinkHome ontology [11]**	**SAREF4EE ontology [18]**	**BOnSAI ontology [7]**	**ProSGV3 ontology [9]**
Infrastructure technical data	H	L	M	M
Energy consumption systems data	H	M	L	H
Energy performance data	H	H	H	H
Sensors/actuators data	H	M	M	M
Energy stakeholders' data	M	-	L	L
Weather/climate data	H	L	L	M
Geographical data	-	-	-	L
Environmental data	M	-	M	-
Distributed energy sources data	M	L	L	M
Energy DR operations	-	M	-	L

Table 1: Energy domains representation level of detail (H=High/M=Medium/L=Low)

This term and domain representation diversity, called *semantic heterogeneity* [12], leads to an interoperability problem that hinders the full adoption of these ontologies in real scenarios. Hence, there is the need of creating a unified ontology that represents all energy domains providing a common terminology. This ontology can be a standard knowledge base of EMSs applied in any Smart Grid scenario. Moreover, a unified ontology would reduce the effort spent by energy management developers when creating energy ontologies and enable them to be more focused on application implementation.

An ontology can be developed as a whole or as a set of interconnected ontologies, what is known as an ontology network [19]. An ontology network allows classifying energy data from different domains into domain ontologies that can be linked by establishing top-level relations between energy concepts from different domains. Hence, this modularized approach would improve the ontology reusability.

Considering all this, the authors have developed the OEMA ontology network. It represents all identified energy domains in different existing energy ontologies at a high level of detail. The OEMA ontology network provides a common representation of concepts that belong to different energy domains. The following sections explain the ontology development process and the ontology structure.

4 Ontology Development Process

This section explains the OEMA ontology network development process with phases for requirements definition, ontology selection for reuse, otology implementation and integration and ontology evaluation. The development process has followed the steps and guidelines defined by [15] and [19]. [15] provides ontology development steps and explains them through an application example that corresponds to an energy ontology. [19] provides the so-called NeOn methodology for developing ontologies and ontology networks. The following subsections explain the different OEMA ontology network developing phases.

4.1 Ontology Requirements Definition

During this phase, the OEMA ontology network functional and non-functional requirements have been defined. These requirements have been defined taking as a reference requirements defined in [15] and guidelines proposed in [19]. As it is developed to be used by different energy management applications, the OEMA ontology network must represent all energy data domains that are shown in Table 1 at a high level of detail. The domains include energy performance data and energy-related contextual data. The next step has been the definition of the top-level relations among these domains.

The OEMA ontology network non-functional requirements cover the following aspects:

- Represented energy domains must be classified in different sub-ontologies or modules, which are known as domain ontologies. This modularized structure will ease ontology reuse and modification when adapting it to different energy management scenarios/applications.
- One of the goals of the OEMA ontology network is to provide a common representation of energy data. Hence, each ontology element (class, property) must be named using only one term in order to avoid semantic heterogeneity.
- The Web Ontology Language (OWL-2 [6]) and ontology elements naming notation (CamelCase) have also been defined.

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[6] `http://www.w3.org/TR/2004/REC-owl-guide-20040210/`

4.2 Ontology Selection for Reuse

The next step was the selection of existing energy ontologies and terms to be reused during the OEMA ontology network development. The ontologies (include the ones reviewed in Section 2) have been evaluated taking into account the ontology requirements defined previously. The authors checked whether previous ontologies represent the energy data domains shown in Table 1. The authors also considered the level of detail when representing the energy domains (see Table 1).

The ThinkHome ontology is one of the ontologies that represents most energy domains with a high level of detail. Although it is designed to be used by home energy management applications, the ontology can also be extended to other Smart Grid scenarios, i.e., organisations energy management, microgrids energy management, etc. In addition, the ThinkHome ontology classifies energy concepts in different domain ontologies. Due to its completeness and its modular approach, the ThinkHome ontology has been selected to be the base for the OEMA ontology network.

Other energy ontologies have also been selected for reuse in order to complement OEMA. They have been used to represent missing concepts in specific energy domains and to enrich the ThinkHome ontology. Additionally, authors selected also DBpedia [1] and FOAF [3] ontologies for reuse. As an example, Table 2 shows which ontologies and concepts have been selected by the authors for reuse to represent the energy consumption systems domain.

These concepts have been selected semi-automatically with the help of the AgreementMaker ontology mapper. AgreementMaker has helped to find the ontologies that represent the same concepts with different terms and class hierarchies. It also has allowed identifying those classes and properties related to a certain term that are represented by one ontology but not by others. Based on the ontology mapper results, unique terms and class hierarchies have been chosen to represent repeated concepts among different energy ontologies. The criteria followed to choose terms and class hierarchies has been to select a target class hierarchy that represents each energy concept in the most detail. Terms from other energy ontologies are then selected in order to enrich the selected class hierarchy. This criteria is considered an asymmetric ontology merging method and is used to merge ontologies avoiding overlapping concepts [16].

4.3 Ontology Implementation

The next stage is the implementation/development of the ontology. During the development process, the selected energy ontologies have been merged according to selected concepts and class hierarchies in the previous step. The OEMA ontology network development process has been performed in five iterations: ontology structure definition, ontology reuse, adding new information to the ontology, ontology integration and ontology evaluation.

First, the OEMA ontology network base structure was defined. As detailed in Section 4.2, the ThinkHome ontology is the base of the OEMA ontology network. The ThinkHome domain ontologies have been restructured to adapt them

Energy domain	**Ontology**	**Reused concepts**
Energy consumption systems data	ThinkHome ontology	HVAC systems, communication appliances, entertainment appliances, office automation devices, lighting systems, white goods, acoustic systems, domotic network components, energy facilities, device state, device commands, equipment manufacturer, external and internal equipment
	SAREF4EE ontology	Appliances working modes and power profiles, device manufacturer and device model.
	EnergyUse ontology	Wearable devices.
	ProSGV3 ontology	Body care devices, pressing devices, water heating devices, charging devices, lighting systems, entertainment devices, cleaning devices and electrical appliance category.

Table 2: Reused ontologies and concepts

to other Smart Grid scenarios in addition to the Smart Home energy management scenario. This restructuring process consisted of renaming and including new super-classes for domain ontologies. For example, the ThinkHome building ontology represents building physical elements, building internal and external equipment, and building geometrical features. The *owl:Infrastructure class* has been added to this ontology in order to represent infrastructures (i.e., microgrids) in addition to homes and buildings. Then, all top-level classes of the ThinkHome building ontology that refer to homes and buildings have been included as subclasses of *owl:Infrastructure* class. As a result, the *OEMA infrastructure ontology* has been created. This process has been repeated in all of the ThinkHome ontologies and as a result the first OEMA domain ontologies have been created: *OEMA infrastructure ontology*, *OEMA Smart Grid stakeholders ontology*, *OEMA external factors ontology*, *OEMA energy and equipment ontology.* Energy concepts represented by each of these ontologies are later explained in Section 5.

After defining the OEMA ontology network structure, the previously selected energy concepts (see Table 2) and associated statements have been merged and added to each OEMA domain ontology. During the ontology reuse process, the following techniques have been applied:

1. *Specialization*: adding reused classes and properties of one ontology as subclasses and subproperties of another ontology. For example, infrastructure types reused from other ontologies have been added as subclasses of the OEMA infrastructure ontology *owl:Infrastructure* class.
2. *Generalization*: adding reused classes and properties of one ontology as super-classes and super-properties of another ontology. For example, white goods types (i.e., cleaning devices) reused from other ontologies have been added as super-classes of cleaning and cooking white goods of OEMA energy and equipment ontology.

In addition, the following ontology engineering activities have been performed:

A *Knowledge extension*: creating new classes and properties for relating reused concepts with concepts from different ontologies. For example, when reusing infrastructure premises (i.e., residential premises, business premises, etc.) in the OEMA infrastructure ontology, the *owl:hasPremise* property has been created in order to relate the *owl:Infrastructure* class with reused infrastructure premises classes.

B *Renaming ontology elements*: renaming reused ontology classes or properties by changing their identifiers. This change has been performed to unify all reused ontology resources naming according to CamelCase notation.

C *Changing property domains and ranges*: adding new domains and ranges to properties of reused ontologies. For example, the *owl:contains-Building* property from OEMA infrastructure ontology had only the *owl:Cam-pus* class as a domain. This property has been changed to have also the *owl:Infrastructure* class as a domain. With this change the ontology asserts that other infrastructures apart from campuses (i.e., power stations) contain buildings.

D *New ontologies creation*: The DBpedia ontology includes many concepts about geographical, persons and organisations data. Adding all these concepts to any of the OEMA ontologies would hinder the ontology maintenance. Hence, two new ontologies have been created: *OEMA geographical ontology* and *OEMA person and organisation ontology*. In addition, some units of measure (i.e., volume, currency, etc.) are linked with concepts represented in different OEMA ontologies. Hence, a new ontology has also been created in order to modularize this aspect: the *OEMA units ontology*.

E *Knowledge relocation*: moving knowledge from one ontology to another. The purpose of this change is to group all concepts of a specific domain in one ontology in order to improve the OEMA ontology network maintainability. For example, population socio-economic factors have been moved from the OEMA geographical ontology to OEMA external factors ontology.

F *Ontology Design Patterns (ODP) application*: the N-ary ODP [13] has been reused to restructure reused concepts.

The next step was to add missing concepts not represented in the reviewed ontologies that are used in different EMSs or are present in well-known standards such as USEF and OpenADR [10]. Some of these concepts are: energy saving tips, Electric Vehicle (EV), energy market roles, etc. This step has led to the creation of a new domain ontology: *the OEMA energy saving ontology*. This ontology adds infrastructures and equipment energy saving recommendations to OEMA ontology network.

Finally, OEMA ontology network domain ontologies were integrated. The OEMA ontology network .owl file has been created and all domain ontologies have been imported in this file. After importing each ontology, the following tasks have been performed:

1. *Ontology linking*: the top-level relations between different OEMA domain ontologies have been stablished through new properties.
2. *Duplication removal*: duplicate concepts among domain ontologies have been eliminated. Disjoint relations have been established between classes that use

the same terms to describe different concepts, i.e., operational device *state* and country *state*.AgreementMaker has been used again in order to detect duplicate concetps among domain ontologies.

4.4 Ontology Evaluation

Finally, the OEMA ontology network has been evaluated with the OOPS! Pitfall Scanner [14], which detects common pitfalls made during the ontology development process. According to OOPS! feedback, the OEMA ontologies pitfalls have been corrected. The logical consistency of OEMA ontologies has been also evaluated with the Pellet reasoner [17].

5 The OEMA Ontology Network

In this section, the OEMA ontology network is described. The OEMA ontology network is made up of eight interconnected domain ontologies. Each ontology represents one or more energy domains. These ontologies are connected by a core ontology. OEMA top-level structure is shown in Figure 1.

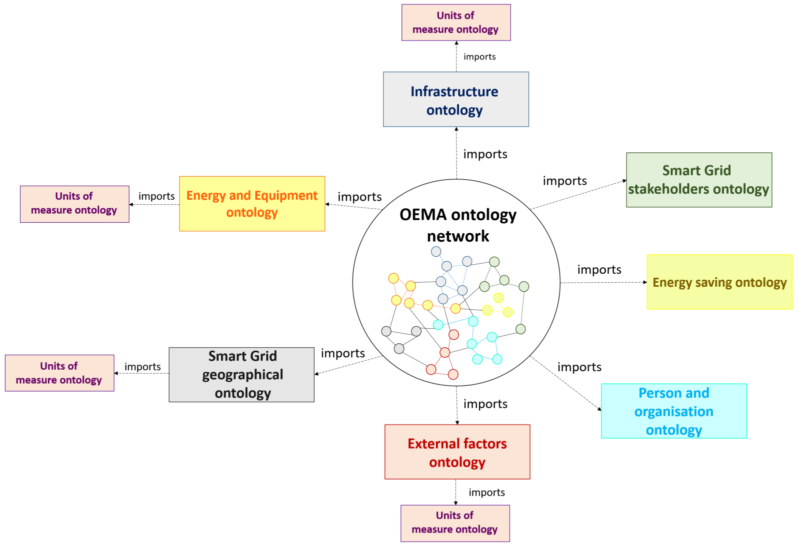

Fig. 1: OEMA ontology network structure

– *OEMA infrastructure ontology*[7]: contains data about Infrastructures/buildings. These data include infrastructure/building types (i.e., household, microgrid, etc.), technical data (i.e., material, surface, etc.), spaces data (i.e., floors, rooms, etc.), geometrical data (i.e., floor area), etc.

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[7] `www.purl.org/oema/infrastructure`

- *OEMA energy and equipment ontology*[8]: represents energy equipment such as building automation system resources (sensors, actuators/controllers and HVAC systems), industrial equipment (i.e., construction and manufacturing equipment), energy generators (i.e., EVs, Home Power Plants, etc.), loads (white and brown goods), power storage/energy carriers, etc. The ontology also represents the energy equipment features such as devices' power curve and power profile or device state.
- *OEMA geographical ontology*[9]: represents geographical data about infrastructures and energy equipment locations. These data includes populated places (i.e., country, city, district, etc.), natural places (i.e., mountain, sea, etc.) and places geographical attributes such as altitude, depth or area.
- *OEMA external factors ontology*[10]: captures external factors that can influence energy usage. These factors include climate type (i.e., alpine, continental, etc.), environmental conditions (i.e., lighting, noise, etc.) household socio-economic factors (i.e., household income, housing price, etc.), people socio-economic factors (i.e., salary, education level, etc.), population socio-economic factors (i.e., density, main origin, etc.), and weather phenomenon (i.e., temperature), etc.
- *OEMA person and organisation ontology*[11]: represents person and organisation data: person and person attributes (i.e., age, gender, etc.), organisation, organisation internal structure (i.e., departments), organisations economic data (i.e., endowment, net income, etc.), person roles in organisations (i.e., role in project, occupation), etc.
- *OEMA energy saving ontology*[12]: represents general and personalized energy saving recommendations.
- *OEMA Smart Grid stakeholders ontology*[13]: represents Smart Grid stakeholders and roles in the energy market (i.e., energy consumers, energy suppliers, Distribution System Operators (DSOs), etc.) and energy flexibility operations, (i.e. market processes, flex-offers exchange), etc.
- *OEMA units ontology*[14]: represents different units of measure used by the OEMA domain ontologies. These units of measure include energy units, area units, capacity units, currency, density units, etc. The OEMA units of measurement ontology is reused by OEMA infrastructure, energy and equipment, geographical, and external factors ontologies.

6 Conclusion and Outlook

This paper presents the OEMA (Ontology for Energy Management Applications) ontology network. This ontology network is an attempt to unify existing

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[8] `www.purl.org/oema/enaeq`

[9] `www.purl.org/oema/geographical`

[10] `www.purl.org/oema/externalfactors`

[11] `www.purl.org/oema/pao`

[12] `www.purl.org/oema/energysaving`

[13] `www.purl.org/oema/sgstakeholders`

[14] `www.purl.org/oema/units`

heterogeneous energy ontologies that represent energy performance and energy contextual data.

The diversity of terminology and level of detail of energy domains represented by reused energy ontologies have brought the main challenges of the OEMA ontology network development process. Hence, reused ontologies concepts selection and ontology engineering activities for linking concepts of different energy ontologies have been the most complex and time-consuming tasks for the ontology network development process. Energy consumption systems data and infrastructure data are energy domains that present more heterogeneity among existing energy ontologies. Thus, the energy concepts selection task has been particularly challenging when selecting terms that belong to these energy domains. Most concepts and statements from existing energy ontologies have been copied into the OEMA ontology network instead of importing them. Hence, changes that reused ontologies may suffer in the future will not have an impact on the OEMA ontology network. However, new concepts added to reused ontologies must be analysed in order to include them or not in the OEMA ontology network.

The OEMA ontology network is made up of eight interconnected domain ontologies. Each ontology represents one or more energy domains. These domains include both energy performance and contextual data. The OEMA ontology network will enable energy applications to extract knowledge and make decisions about large volumes of energy data from different domains. In addition, the modularized approach of the OEMA ontology network approach will facilitate reuse and modification when adapting it to different Smart Grid scenarios and energy management applications. The main contributions of the OEMA ontology network are:

1. *Common representation of energy domains*: it represents in a unified manner and at a high level of detail energy domains that are described by existing energy ontologies using different vocabularies and varying levels of detail.
2. *Integration of different energy domains*: it represents all energy domains captured in different energy ontologies in a single ontology network.

Considering these benefits, the OEMA ontology network provides a starting point for a widely accepted energy ontology. Future work will focus on the OEMA ontology network validation by implementing it in real Smart Grid scenarios, i.e., microgrid energy management, home energy management, etc.

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