An Ontology-based Decision Support Tool for Optimizing Domestic Solar Hot Water System Selection

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Abstract. In an effort to tackle climate change most countries utilize renewable energy sources. This is more pronounced in the building sector, which is currently one of the major consumers of energy, mostly in the form of heat. In order to further promote the use of domestic solar hot water systems in buildings, an ontology-based decision support tool has been developed and is presented in this paper. The proposed tool aids non-technical consumers to select a domestic solar hot water system tailored to their needs, containing up-to-date information on its components and interrelationships, installation costs etc., in the form of an ontology formulated in OWL (Web Ontology Language). The optimum system configurations are computed based on various specific parameters, such as number of occupants, daily hot water requirements and house location. The backbone of the proposed system is an ontology that represents the application domain and contains information regarding the various domestic solar hot water system components along with their interrelationships. Ontologies are a rapidly evolving knowledge representation paradigm that offers various advantages and, when deployed specifically in the domestic solar hot water systems domain, deliver improved representation, sharing and re-use of the relevant information. As a conclusion, this paper presents an ontology-driven decision support system for facilitating the selection of domestic solar hot water system, which delivers certain advantages, such as sustainability of the decision support system itself, due to its open and

interoperable knowledge-base, and its adaptability/flexibility in decision making policies, due to is semantic (ontological) nature.

1 Introduction

Heating and cooling accounts for a significant portion of the world's total energy demand. According to the International Energy Agency, heat represented 47% of the final energy consumption in 2009 (International Energy Agency, 2011), with the building sector accounting for more than 40% of the final energy consumption in the EU. Space heating represented 68% of the total household consumption, followed by water heating at 12% as presented in Figure 1 (European Environment Agency, 2010).

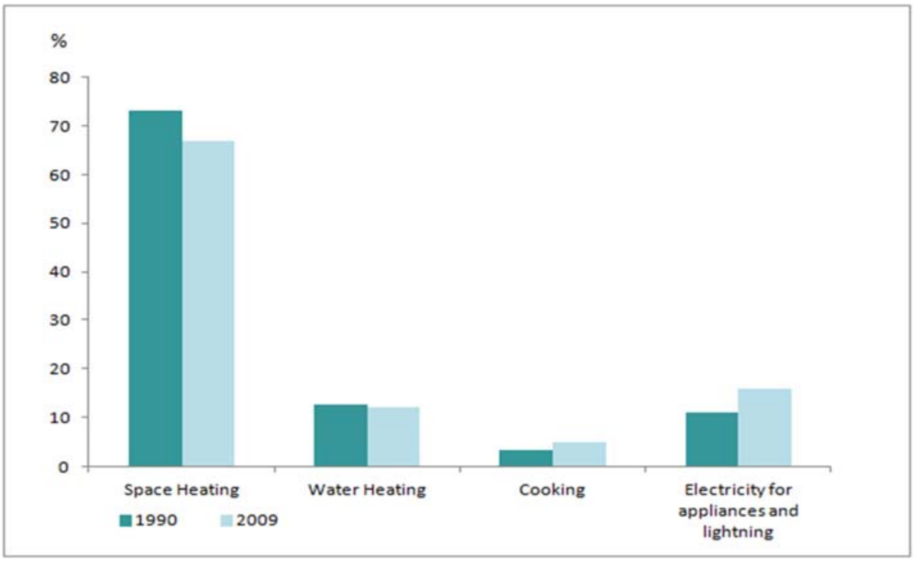

Fig. 1. Final energy consumption by energy use in EU households (International Energy Agency, 2011).

In an effort to reduce CO_2 emissions and promote the use of renewable sources, the EU passed Directive 2009/28/EC (EU, 2009), as renewable energy sources are thought of as having the potential to tackle current environmental as well as energy related problems. According to the Directive, member states should take measures, in order to increase their use of renewable energy sources along with energy efficiency and savings by 20% until 2020. Towards this direction, solar energy systems for heat production are becoming a viable solution; furthermore, the legislation in some countries (Spain being the pioneer) mandates that such systems are installed in newly built or renovated buildings.

By the end of 2011, the estimated worldwide capacity of solar thermal collectors in operation was 234 GW_{th}, positioning solar heating technologies second only to wind power, excluding traditional sources like biomass and hydro. From the total installed capacity, more than 65% is located in China, with Europe accounting to about 17% mainly in the form of flat plate collectors (International Energy Agency, 2013).

In the European market, Domestic Solar Hot Water Systems (DSHWS) are a mature technology, especially in countries like Greece, Austria, Cyprus and Germany (ESTIF, 2015). However, in order for DSHWS to increase their market share, it is imperative to provide consumers with basic information, avoiding technical terms as much as possible, and offering the necessary tools in order for them to select an appropriate system that covers their needs. Undoubtedly, defining the appropriate DSHWS configuration according to certain criteria (initial and total cost, environmental friendliness, thermal load coverage, system sizing etc.) is a non-trivial process, especially for end-users that are not acquainted with the explicit notions of the domain.

This article presents the design and implementation of a user-friendly ontology-based online decision support system that aids non-technical consumers in selecting a DSHWS tailored to their needs and that can be easily accessed via a Web browser. Ontologies constitute a rapidly evolving knowledge representation approach, offering a variety of advantages when compared to more mainstream solutions, like e.g. databases. As discussed subsequently, specifically for the DSHWS domain, ontologies deliver improved representation, sharing and re-use of the relevant information. The proposed system contains up-to-date information on DSHWS and their components, as well as details about the total cost for the installation of the system etc., delivering certain advantages, such as sustainability and adaptability in decision making policies. The optimum system configurations are computed based on certain parameters, like e.g. the number of occupants, their daily requirements in hot water and the location of the house.

The article is structured as follows: Section 2 gives a brief overview of ontologies that constitute the primary domain modeling tool in this work, as well as the Semantic Web, which is the environment ontologies and the rest of the related semantic technologies operate in. Section 3 outlines the main related work paradigms that apply semantic technologies in the Energy domain, followed by the backbone of the article (Sections 4 and 5) that describes the proposed approach, its scope and the developed decision support system. Finally, the article concludes with the final remarks and possible directions for future work.

2 The Emergence of the Semantic Web

The *Semantic Web*, originally introduced by Berners-Lee, Hendler and Lassila (Berners-Lee et al, 2001), constitutes an effort to improve the current Web, by converting the current unstructured and semi-structured collection of Web documents into a "*web of data*". The initiative aims at "*providing a common framework that allows data to be shared and reused across application, enterprise, and community boundaries*" (W3C, 2013). This common framework provides the infrastructure for seamless, platform-independent machine-to-machine interoperation (i.e. software agents and/or heterogeneous applications) as well as between machines and human users. The notion of semantics in the Semantic Web setting is typically coupled with *metadata*, which is often described as "*data about data*" and is used to facilitate the understanding, use and management of other data.

As illustrated in Figure 2, the Semantic Web is based on a layered architecture of technologies, not all of which have acquired adequate maturity yet. Currently, the more fundamental layers up to ontologies (sophisticated conceptual hierarchies – see next subsection) and query languages have reached a "W3C standard" status, while the most recent research efforts have shifted towards logic, proofs and trust. The latter will allow machines to reason over the represented data, drawing conclusions that seem obvious to humans but not to machines, but also to provide explanations (proofs) for the conclusions drawn. Proofs eventually increase user trust and confidence towards these automated systems.

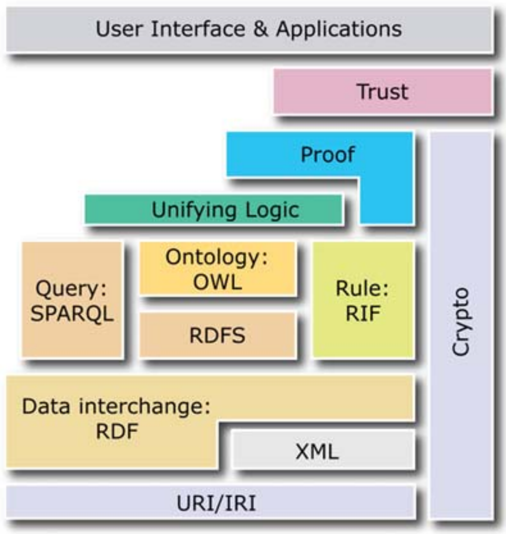

Fig. 2. The layered architecture of the Semantic Web. The following acronyms are included in the figure: XML (eXtensible Markup Language), RDF (Resource Description Framework), RDFS (RDF Schema), SPARQL (SPARQL Protocol and RDF Query Language), OWL (Web Ontology Language), RIF (Rule Interchange Format).

Nevertheless, a variety of focused Semantic Web applications (top layer) have already emerged that perform integration of heterogeneous scientific data or optimization of enterprise search and navigation, as well as applications that enhance the effectiveness of recruiting services or identify patterns and insights in data (Stephens, 2007).

2.1 Ontologies: Basic Notions

According to one of the most popular definitions, an ontology is "*an explicit specification of a conceptualization*" (Gruber , 1993), meaning that it formally describes a domain of interest via an abstract model, providing a common vocabulary shared by a (Web) community. The term *explicit* implies that the type of concepts used and the constraints on their use are explicitly defined and *formal* means that the ontology should be machine understandable (Kalibatiene and Vasilecas, 2011). This shared formalization offers a two-fold advantage, (a) allowing intercommunication across heterogeneous applications, and, (b) providing a comprehensible mechanism for easily extending ontologies and enriching them with more elaborate notions. Nowadays, ontologies are used in many scientific domains, like e.g. web development, biology, chemistry etc.

The opposite of these domain-specific ontologies are *upper ontologies*, also known as *top-level* or *foundation ontologies*, which describe overly general concepts that are common across all knowledge domains (Kiryakov et al, 2001). The primary goal of upper ontologies is to provide a common ontological foundation for the more specific domain ontologies, strengthening the semantic interoperability across multiple domains (Schorlemmer and Kalfoglou, 2003).

The main components of an ontology are:

1. *concepts*, usually represented by classes of objects,
2. *attributes*, which refer to features that the objects have, and,
3. *relationships* between the concepts, typically represented by properties.

Depending on the expressiveness of the ontology language (see next subsection), more advanced ontology components might include (but are not limited to) the following:

- *properties of relations* (symmetry, transitivity);
- *cardinality of relations*;
- *rules*, which are statements describing the logical inferences that can be derived from assertions;
- *axioms* that represent the core knowledge assumed to be true during reasoning;
- *restrictions*, namely, descriptions of what must be true in order for some assertion to be accepted as input.

2.2 Motivation for using Ontologies

The rapidly increasing deployment of ontology-based solutions is motivated by an array of factors, which are presented below. Although these factors apply in most domains, a brief discussion is also given for each one of them that further justifies the motivation for using ontology-based technologies in the DSHWS domain.

Common terminology and formal semantics: Ontologies offer a *technology-agnostic* and *application-independent* common terminology for domain representation that can be utilized by human and machine agents alike. Thus, they deliver a sustainable conceptual model that can be used in multiple diverse applications, offering facilities for reuse and interoperability. And, more importantly, the use of *formal semantics* facilitates knowledge transfer between humans and machines by excluding unwanted interpretations (Bürger and Simperl, 2008). This feature is important in any domain that involves sophisticated terminologies and several stakeholders (humans or machines) and is, thus, equally important in the DSHWS domain, with the various standards and the frequent interactions among the stakeholders.

Consistency Checking: Ontology-based technologies provide inference capabilities for *consistency checking*, *derivation* (i.e. deriving implicit knowledge) and *classification* (Bürger and Simperl, 2008; Hepp, 2008). Specifically for a decision support system, this advantage proves critical when checking the consistency of the numerous complex DSHWS components contained in the knowledge base or when attempting to classify a new entry into an existing class of components.

Integrating heterogeneous data: Ontology-based solutions are also highly suitable for integrating heterogeneous data from multiple diverse sources, ensuring this way the interoperability both at data and process level (Hepp, 2008). This advantage becomes even more vital when one wishes to create decision support systems utilizing a variety of heterogeneous information sources, like the proposed system presented in this work.

Reuse and interoperability: A vital feature for every Semantic Web application is interoperability with other applications, which is typically accomplished through *ontology reuse*. The latter refers to the process of taking advantage of existing ontologies (i.e. achieving interoperability) and extending them via introducing new notions, in the cases when the existing definitions prove inadequate or unsuitable (Heflin and Hendler, 2000). The ontology reuse feature has been also deployed in this work (see Section 5.1) and plays a key role in the core ontology of the proposed decision support system.

2.3 Ontology Languages and Ontology Engineering

Ontologies are constructed using appropriate formal languages, called *ontology languages*, and are typically based on first-order predicate logic, frames or description logics. According to the literature (Pulido et al, 2006), an ontology language "*must describe meaning in a machine-readable way. Therefore, an ontology language needs not only to include the ability to specify vocabulary, but also the means to formally define it in such a way that it will work for automated reasoning*".

Especially nowadays, with the rapid evolution of the Web and the recent emergence of the Semantic Web, significant emphasis is placed on Web-compliant ontology languages, which are based on established Web standards. Contemporary Web ontology languages allow defining diverse vocabularies and letting them evolve and are specifically designed for facilitating interchange on the Web (Kalibatiene and Vasilecas, 2011; Pulido et al, 2006). A number of such languages exist, both proprietary and standards-based, with *RDF+RDF Schema* (*Resource Description Framework*) (W3C RDF Core Working Group, 2013) and *OWL* (*Web Ontology Language*) (W3C OWL Working Group, 2004) being the most dominant. The former is a vocabulary description language for describing properties and classes of RDF resources, while the latter is a richer vocabulary description language that can also describe relations between classes, cardinality, equality etc. Both languages deploy a syntax based on *XML* (W3C XML Core Working Group, 2008), a standard language for exchanging information on the Web.

Ontology (or *Ontological*) *Engineering*, on the other hand, refers to the set of processes, methods and methodologies for developing an ontology (Gómez-Pérez and Ruiz, 2010). The ontology life cycle and the suites of tools that support these processes are also encompassed by the notion of ontological engineering. Towards this direction, various methodologies and tools have been proposed, like *METHONTOLOGY* (Fernandez-Lopez et al, 1997), *NeOn* (Suárez-Figueroa et al, 2012) and *On-To-Knowledge* (Staab et al, 2001), or even the simple yet quite popular knowledge engineering method (Noy et al, 2001). Surveys on the tools, languages and methodologies can be found in the literature (Corcho et al, 2003; Gómez-Pérez et al, 2007).

3 Related Work

When browsing the relevant literature, one come across several approaches in the generic domain of environmental modeling for decision making that rely on the deployment of semantic technologies in general and ontologies in particular. For example, the work presented in (Muñoz et al., 2013) features an ontological framework for the environmental assessment of enterprises. The underlying ontology encompasses the relevant information and knowledge models and provides an enterprise decision-making supporting tool, facilitating the assessment of the environmental performance of enterprises. Another example is the educational tool for sustainable development presented in (Macris and Georgakellos, 2006). The relevant representations deployed by the tool are captured as a knowledge network based on a reusable ontology of domain-specific knowledge. The knowledge network is accompanied by a set of educational scenarios that serve as the building blocks for environmental training using the specific tool. A more recent example of environmental decision making based on semantic modelling is (Trokanas, et al. 2015), where the authors present a systemization of Industrial Symbiosis environmental metrics and a semantic approach based on knowledge modelling using ontologies to facilitate calculation of respective indicators. Industrial Symbiosis (IS) is a growingly accepted paradigm for processing waste into material, energy and water with benefits to participants measured by economic, environmental and social gains. Yet, there are earlier works describing decision support tools for environmental best-practices which are not based on open Semantic Web standards, but rather on close conventional databases (Georgopoulou, et al, 2008).

Moving on to the more specific domain of Energy, *PV-TONS* (Abanda et al, 2013) (*Photovoltaic Technology Ontology System*) is a software tool that facilitates decision-making in recommending appropriate photovoltaic (PV) system configurations. PV-TONS is based on semantic technologies, integrating an *OWL 2* (W3C OWL Working Group , 2012) ontology for representing domain knowledge (i.e. PV systems) and a reasoning mechanism for providing decision support. The ontology constitutes an extended version of an existing ontology proposed by the same authors (Tah and Abanda, 2011); the latter version of the ontology was extended to include a variety of external factors that play a role in PV systems, like climatic conditions.

In another similar example an ontology-based framework, developed particularly for ICT energy management is presented, where the focus is on energy-related semantics of resources and their properties (Daouadji et al, 2010). The main contribution of this work is an energy-oriented ontology for ICT equipment as well as a description of grid resources based on the proposed ontology. The latter is built in RDF and contains a hierarchy of semantically linked ICT elements and their interrelationships with the use of energy of various types (e.g. solar, gas, etc.).

In the same context, Shah et al. proposed a domestic electrical appliances domain ontology (Shah et al, 2011)that is a component of the *Digital Environment Home Energy Management System* (*DEHEMS*) project[1]. The project provides transparency to the consumers' energy consumption habits and suggests advice for more efficient energy consumption. More specifically, the electrical appliances ontology encompasses knowledge of home appliances and their corresponding energy consumption schemes, their context, causality and relationships. Mechanical and physical properties of the appliances that do not influence energy consumption are not considered. Interestingly, the ontology also incorporates household information, in order to associate the usage of the various appliances with the family members individually and/or collectively. A special piece of software called "reasoner" can then inform family members of their combined and individual energy usage, in order to assist them in achieving their weekly/monthly set targets for energy consumption.

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[1] Digital Environment Home Energy Management System: http://www.dehems.eu/about

A further ontology developed with a similar goal is *DogOnt* (Bonino and Corno, 2008) that aims at representing the different ways of producing energy, depending on the building, the number of occupants living in it, the devices/appliances used etc. DogOnt offers the ability to describe the location and capabilities of a domotic[2] device and its possible configurations, supporting device/network independent description of houses, including both "controllable" and architectural elements. States and functionalities are automatically associated to the modeled elements through proper inheritance mechanisms and by means of properly defined rules, which ease the modeling process, while automatic device recognition is achieved through classification reasoning. DogOnt handles notions like buildings and building environments, device configurations and functionalities as well as the various features of domotic network components and aims at establishing an interoperability scheme between diverse domotic systems.

A final paradigm is *SynCity* (short for "*Synthetic City*"), a platform for modeling urban energy systems (Keirstead et al, 2009; Keirstead and Van Dam, 2010). The SynCity *UES* (*Urban Energy Systems*) ontology, developed in OWL, serves mainly as a library of domain-specific components, consisting of a number of object classes that describe the main elements of an urban energy system and specific instances of these classes. The main categories of classes included in the ontology are: (a) *Resources*, namely, energy resources, like electricity or natural gas, which are described via an array of physical, economic and model attributes, (b) *Infrastructures* that describe the physical structure of the model, including e.g. buildings and networks, and, (c) *Processes*, which describe technologies that convert one set of resources into another set, ranging from simple conversion technologies as well as more complex transportation and storage processes.

Conclusively, numerous energy-related approaches deploying Semantic Web technologies that deal with various appliances and types of energy exist. From the approaches presented

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[2] The term "*domotic*" refers to the application of computer and robotic technologies to domestic appliances.

above, our work is more closely related to PV-TONS (Abanda et al, 2013), although the two domains are diverse. Both systems are ontology-based and offer decision support mechanisms for proposing system configurations. However, when compared to the implementation of PV-TONS, our implemented approach is strictly user-centric, featuring a transparent and unified web-based interface that relieves the user from needing to type in complex axioms and rules.

The rest of the related work paradigms deploy ontologies merely as a domain representation tool and do not offer decision making functionalities. Their primary aim is to achieve standardization, via proposing ontologies for representing explicit domains that have not yet been adequately addressed. Our aim is, however, to offer an end-user tool that will assist consumers in choosing the optimum system configuration according to their custom needs.

4 Problem Description – Scope of the Article

Defining the appropriate DSHWS configuration according to certain criteria (initial and total cost, environmental friendliness, thermal load covered, system sizing etc.) is a non-trivial process, especially for end-users that are not acquainted with the explicit notions of the domain.

Common DSHWS consist of solar collectors, a storage tank, a mounting base and the necessary plumbing. They convert solar radiation to useful energy in the form of hot water with an average efficiency that varies between 30%-40% (Tian and Zhao, 2013; Martinopoulos et al, 2013).

A typical flat plate solar collector includes the absorber, which converts the absorbed solar radiation to heat. The absorber is painted black, with either selective or non-selective paints, in an attempt to maximize solar radiation absorbance. Heat in turn is transferred to a fluid, flowing through pipes. The back and the sides of the absorber are insulated in order to minimize heat losses to the environment, while the front side is covered by a transparent cover that allows solar radiation to reach the absorber, reducing at the same time heat losses to the atmosphere. All the above are “packed” in a case that provides protection from the climatic conditions (Duffie and Beckman, 1991).

For the absorber materials with high thermal conductivity, like copper, aluminum or in some cases steel, are typically used. The transparent cover is mostly low-iron tempered glass (3-5 mm thickness), while the casing consists of aluminum profiles for the sides and galvanized steel sheet for the back. The mounting base usually comprises of galvanized steel.

Hot water storage tanks are usually made of steel and employ a mantle type heat exchanger. Furthermore, an electrical resistance heater and/or a coil for connection with the central heating system are also used as a backup (Duffie and Beckman, 1991).

The different possible combinations of materials and techniques for DSHWS have a direct influence onto the system’s technical characteristics and its overall efficiency, as well as to the final cost (Martinopoulos et al, 2013). In deciding the optimum size of a DSHWS for their needs, consumers have to take into account different factors before the final selection, like initial and total cost, energy production and environmental benefits among others.

In the proposed approach, the ontology serves mainly as the domain modeling tool, incorporating restrictions for the correct sizing and matching of typical DSHWS components (containing various technologies and/or materials). However, the proposed approach also benefits from the advantages described in Section 2.2, while the use of ontologies offers the required flexibility for integrating even more advanced features in future releases of the proposed system (see Section 6 discussion on future improvements). The aim is to provide final users with all the necessary information needed to decide what best suits their needs, like the initial and total cost, energy production or protection of the environment, in an easy, convenient and non-technical way.

In order to estimate the thermal energy needed for hot water production covered by the various DSHWS, the “f-chart method” is adopted (Duffie and Beckman, 1991; Brinkworth, 2001). In order to estimate the total energy gain by the DSHWS, the daily consumption of hot water was assumed to comply with the daily profile of the f-chart and an initial volume of 50 dm^3 of hot water per person at 45°C temperature was assumed, according to the Greek legislation (Technical Chamber of Greece, 2010a). The meteorological data needed for all calculations (air and water temperature, solar irradiance) were taken from the relevant literature (Technical Chamber of Greece, 2010b), while the values listed in Table 1 were used for the functional characteristics of the DSHWS. In this table, Fr(τα) denotes the collector's maximum efficiency, while F_rU_L denotes the collector's heat losses. The inclination of the collector is set at 45°, well within the recommendation (latitude ± 15°) of the literature (Shariah et al, 2002).

Table 1. Solar system technical characteristics.

Feature	Value
Collector Type	Flat-Plate, Copper Tube with Copper Foils
Glazing	Single Sheet Clear Tempered Glass (4mm)
Selective Paint	α=0,94±0,02 ε=0,05±0,02
Collector Inclination	45°
Collector Area	1,5 – 2 – 3 – 4 – 4,5 – 6 m^2
Storage Capacity	0,12 – 0,16 – 0,18 – 0,2 – 0,24 m^3
F_RU_L	5 – 7,5 W/m^2K (high-low)
$F_R(\tau\alpha)_n$	0,75 – 0,8 (high-low)

More details regarding the f-chart method, and cost calculation can be found in the literature (Martinopoulos and Tsalikis, 2014).

5 Implemented System

This section describes the system implemented for optimizing the configuration of DSHWS. To begin with, the following state-of-the-art technologies and tools are deployed in the proposed system:

- The open-source ontology editor *Protégé* (Horridge et al, 2004), together with the *Hermit* reasoner (Glimm et al, 2010) plug-in.
- The ontology query language *SPARQL* (W3C SPARQL Working Group, 2008).

- *JSP*[3] (*Java Server Pages*), the popular Java-based technology for creating dynamic web content.
- *JFreeChart*[4], an open source Java library that provides the means to create charts and graphs embedded in Java applications.
- *Jena*[5], a Java framework for building Semantic Web applications.
- *Apache Tomcat*[6] Web server and servlet container for hosting the web application.

An overview of the involved technologies and the role they play in the project is displayed in Table 2.

Table 2. Technologies deployed in the proposed system.

System Aspect	Technology Used
Ontology Language	*OWL*
Ontology Editor	*Protégé* (v.4.3)
Reasoner	*Hermit* (v.1.3.8)
Query Language	*SPARQL*
Front-end / UI	*JSP* (v.2.2)
Front-end / Graphs & Charts	*JFreeChart* (v.1.0.16)
Libraries	*Jena* (v.2.10.1)
Web Server	*Apache Tomcat* (v.7.0.42)

According to the above, Figure 3 illustrates the overall system architecture and includes the basic components of the system and the interactions between them. The components can be divided in two categories, the Front-End (FE) and the Back-End (BE), while the communication between the two is established via the Apache Tomcat server.

The FE consists basically of the User Interface (UI) and is the client part of the program, where the user enters the initial input to the system (household parameters) and retrieves the results, along with graph-based visualizations. On the other hand, the BE consists of the ontology itself, along with the Jena and SPARQL modules as well as external CSV files, containing additional information regarding the available DSHWS.

[3] Java Server Pages (JSP): https://jsp.java.net/
[4] JFreeChart Java chart library: http://www.jfree.org/jfreechart/
[5] Jena Semantic Web framework: http://jena.apache.org/index.html
[6] Apache Tomcat: http://tomcat.apache.org/

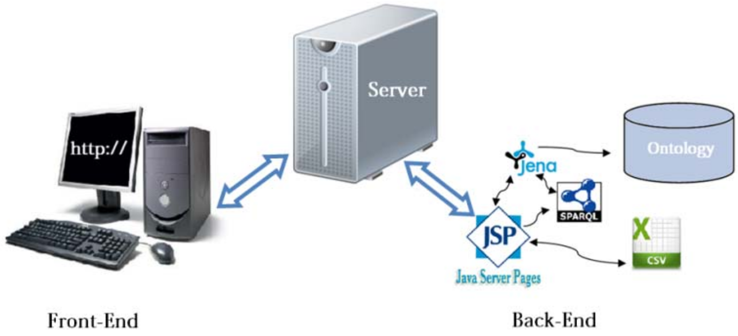

Fig. 3. Overall system architecture.

Appropriate JSP files are responsible for displaying information to the user and, also, for the communication with Jena. The latter is used for loading and manipulating the ontology and for submitting SPARQL queries to it. Finally, the results retrieved from Jena serve in extracting more information about the retrieved result-set of appropriate DSHWS from CSV files that are externally consulted.

All the required executable files for the web application, along with installation instructions, are available online at http://rad.ihu.edu.gr/DSHWS/DSHWS.rar.

5.1 Ontology Design

For designing the ontology of the system, the method proposed by Noy and McGuinness was adopted (Noy et al, 2001), which consists of discrete steps for determining the following:

Domain and scope of the ontology: The subject and the information that will be contained in the ontology have to be thoroughly considered and specified. Thus, the proposed ontology deals with the modeling of DSHWS and their components.

Consider reusing existing ontologies: To the best of our knowledge, no ontologies exist for explicitly representing DSHWS. The ontologies described in the "Related Work" section (excluding the UES ontology – see next paragraph) have the closest relationship to DSHWS, but, again, they all handle vastly different domains (Abanda et al, 2013; Daouadji et al, 2010; Shah et al, 2011; Bonino and Corno, 2008) deal respectively with photovoltaic system configurations, energy consumption of ICT equipment, domestic electrical appliances and domotic environments). Thus, based on the ontology reuse principle mentioned in Section 2.2, no existing ontology seemed suitable for reuse in this affair.

An alternative solution was to consider an ontology representing more “high-level” notions and explicitly specialize a subset of these notions to fit the proposed solar water heating domain. Towards this direction, the UES ontology deployed in the SynCity toolkit (Keirstead et al, 2009 Keirstead and Van Dam, 2010) – see “Related Work” section) is highly suitable, since it aims at modeling urban energy systems and offers a higher level of representation for resources, infrastructures and processes. Thus, we resorted to deploying this ontology as a basis for extensions in the context of the proposed system; our decision is more thoroughly motivated in the following subsections.

Determine the important notions that the ontology should represent: Figure 4 illustrates a generic overview (as a UML class diagram) of the required constructs and their interrelationships. The two main entities are ‘*Household*’, representing a typical domestic household along with certain essential properties, and ‘*System*’ that represents a DSHWS and is composed of its various components: ‘*Collector*’, ‘*Tank*’, ‘*Aperture*’, ‘*Hydraulics*’ and ‘*Installation*’. All the constructs displayed in the figure are required to be present in the ontology that will serve as the knowledge base for the system.

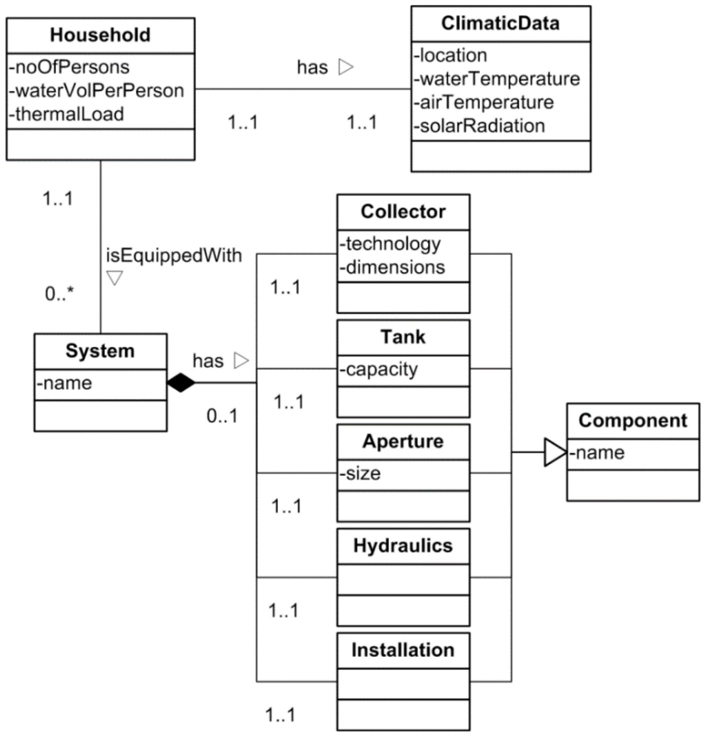

Fig. 4. Overview of the required constructs for the proposed system.

The next subsections describe in detail the implemented classes and properties of the ontology, according to the above guidelines. As already mentioned, Protégé was the ontology editor used for developing and extending the ontology integrated into the proposed system.

5.2 Ontology Development

The core UES ontology was extended with a number of additional classes; three of the key classes added are: `Household`, representing user-defined households that can be parameterized, and, `System` and `SystemComponent`, which represent the DSHWS and its various components, respectively. These three classes are all introduced as subclasses to the existing `Nodetype` UES class that represents nodes in an energy system network. Consequently, several properties are inherited from the parent class, a subset of which was also used in the newly appended classes and is contained in Table 3, along with a description of the use of each property in the context of the extended ontology.

`MinCapacity`, `MaxCapacity`, `CapitalCost` and `OperatingCost` are all UES classes associated with respective measuring units, which are represented as instances of a further UES class called `Unit` and its subclasses (examined later on).

Table 3. Existing properties and their use in the extension. Prefixes are omitted for reasons of brevity.

Name	Range	Use
has_min_capacity	MinCapacity	*Used for representing the min & max number of household inhabitants, respectively.*
has_max_capacity	MaxCapacity	
has_capital_cost	CapitalCost	*Used for representing the various types of costs for the DSHWS and components.*
has_operating_cost	OperatingCost	
has_maintenance_cost	OperatingCost	
name	string	*Used for assigning names and short names to households, DSHWS and components.*
short_name	string	

A number of classes is introduced as subclasses to SystemComponent and represent the components of a DSHWS: Aperture, Collector, Hydraulics, Installation and Tank. Figure 5 displays the class hierarchy below the Infrastructure core UES class; the introduced classes are represented in boldface fonts.

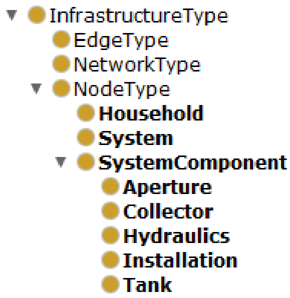

Fig. 5. Part of the ontology hierarchy - the boldface class names correspond to added classes that extend the imported ontology.

Table 4 contains the properties associated with the system components.

Table 4. Properties associated with the DSHWS components.

Property Name	Domain	Range	Use
hasApperture	System	Aperture	*Associates a DSHWS with an aperture.*
hasSize	Aperture	Size	*Size of the aperture.*
hasCollector	System	Collector	*Associates a DSHWS with a collector.*
hasDimensions	Collector	Area	*Collector dimensions.*
hasTechnology	Collector	Technology	*Collector technology.*
hasHydraulics	System	Hydraulics	*Associates a DSHWS with hydraulics.*
hasInstallation	System	Installation	*Associates a DSHWS with an installation.*
hasTank	System	Tank	*Associates a DSHWS with a tank.*
has_min_capacity	Infrastructure	MinCapacity	*Min and max capacity of the tank (inherited).*
has_max_capacity	Infrastructure	MaxCapacity	
name	Infrastructure	string	*Names and short names of components (inherited).*
short_name	Infrastructure	string	

Since the UES core ontology does not explicitly represent the DSHWS domain, most of the properties above are newly introduced into the extension. However, the last four properties in the table are the exception, since they are inherited from the Infrastructure core class.

The classes Size, Area and Technology are newly introduced classes representing physical properties that are subclasses of PhysicalProperty and siblings of MinCapacity and MaxCapacity (presented above). All UES Property classes are associated with a respective measuring Unit (via core property has_unit) and value (via core property value). The hierarchy of Unit classes is displayed in Figure 6.

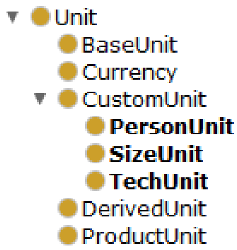

Fig. 6. The hierarchy of classes representing measuring units.

Class PersonUnit constitutes a unit for measuring people and is used for representing the size of a household assuming integer values. Class SizeUnit represents the size of the aperture and assumes one of the values "small", "medium" and "large", while TechUnit represents the collector technology and assumes one of the values "low" and "high". Finally, the surface of the collector and the volume of the tank are represented via the DerivedUnit class (i.e. units created by combining or transforming base units).

A final additional class, ClimaticData, extends the existing Resource UES class and encompasses all climatic properties (solar radiation, air temperature, grid water temperature) that are related to the installation zone of the DSHWS.

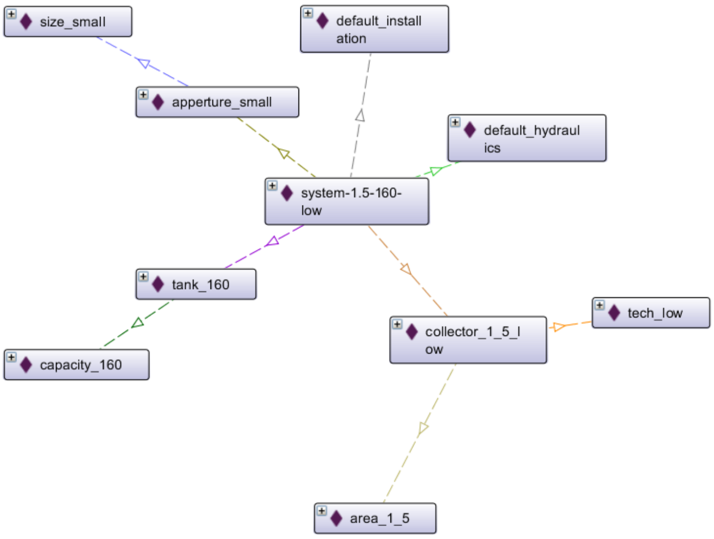

Fig. 7. Sample `System` instance.

After introducing new classes and properties, the final step is to create instances; an instance is an individual that belongs to a specific class and has values for the properties that refer to that class. Figure 7 displays a sample instance of the `System` class. For the different instances the values used are in accordance with the relevant literature (Martinopoulos and Tsalikis, 2014).

5.3 Ontology Evaluation

Before deploying the ontology in the end-user application (see next subsection), we evaluated it by submitting it to *OOPS*[7], an online up-to-date ontology evaluator that detects some of the most common pitfalls (found in literature) that appear when developing ontologies (Poveda-Villalón et al, 2012). Table 5 contains the detected pitfalls, along with a brief description and the way each one of them was handled.

Table 5. Ontology pitfalls detected by OOPS and how they were handled.

Pitfall	Description	How it was handled
Missing annotations (36 cases | Minor)	Ontology terms lack annotation properties that would improve the ontology understanding and usability from a user point of view.	Where missing, annotation properties (mostly `rdfs:label` and/or `rdfs:comment`) were added.
Missing disjointness (whole ontology | Important)	The ontology lacks disjoint axioms between classes or properties that should be defined as disjoint.	Added disjointness between (a) the `CustomUnits` and (b) the `SystemComponents`.
Missing domain or range in	Relationships and/or attributes	There were some missing

[7] OntOlogy Pitfall Scanner: http://oeg-lia3.dia.fi.upm.es/oops/index-content.jsp

Pitfall	Description	How it was handled
properties (6 cases | Important)	without domain or range are included in the ontology.	domains, which were restored.
Missing inverse relationships (12 cases | Minor)	When a relationship has no inverse relationship defined.	Improved expressiveness by adding inverse relationships.

Not all issues reported were resolved, since some of them involved the UES ontology, which we didn't want to interfere with. The current version of the ontology is available at http://rad.ihu.edu.gr/DSHWS/DSHWS.owl.

5.4 System Functionality and User Interaction

This subsection gives a detailed description of the system functionality and the user interaction with the interface through a specific use case example. Additionally, specifications regarding the usability of each part of the web application are given.

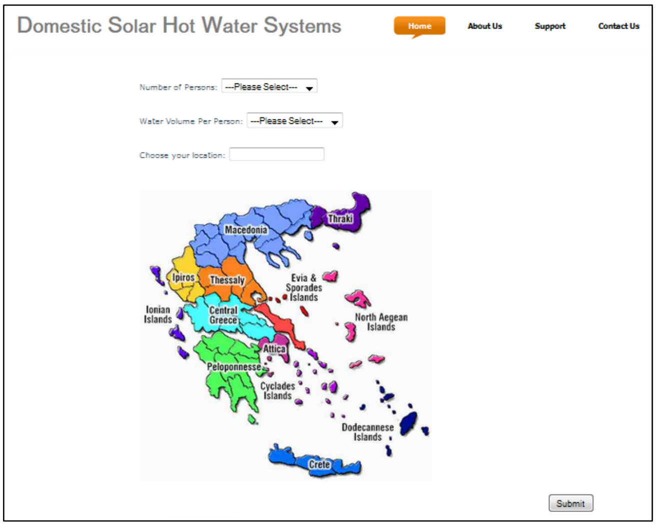

Fig. 8. Homepage of the proposed system.

Thus, suppose that a user wishes to retrieve suitable DSHWS configurations for an apartment with e.g. two (2) occupants in the city of Thessaloniki, Greece and with daily hot water requirements of 45 dm^3 per person. The user navigates to the URL of the proposed system and is presented with the homepage displayed in Figure 8. This is a JSP page connected with a Java class through a servlet. The form fields in the upper part (number of occupants, water volume per person, location) must be filled in with the above parameter values. The map in the lower part is a clickable image that contains all major cities in Greece; when the user chooses a location it is automatically displayed in the third text field in the top.

After the user has filled in the appropriate values ("2", "45" and "Thessaloniki", respectively), the form is submitted and the appropriate results based on the input parameters will be shown in the next page. Figure 9 illustrates the appropriate DSHWS configurations and additional information for the above parameters.

Best Configuration:

System Name	Technology	Coverage (%)	Cost (Eur) ▾	NPV-Elec (Eur)	NPV-OIL (Eur)	NPV-NG (Eur)
1.5/120/2	Low	57.4	400	1812.2	2893.3	1509.7
1.5/120/2	High	54.8	460	1652.5	2680.7	1378.6
2/120/2	Low	64.6	480	1999.5	3223.6	1620.6
2/120/2	High	70	550	2129.328351	3461.374012	1693.819444
3/120/2	Low	75.3	600	2278.4	3718.6	1786.8
3/120/2	High	79.2	690	2330.85	3848.824409	1799.289128

Fig. 9. Results retrieved according to input parameters.

More specifically, the results table consists of seven columns:

- **System name**: The name of each system consists of three parts: Solar Collector Area (m^2), Storage Tank Size (dm^3) and Number of Occupants. For example, the first result (3/120/2) represents a system with a $3m^2$ solar collector, a 120 dm^3 storage tank and it is appropriate for two-person households.
- **Technology**: The type of the technology used in the DSHWS, which can be "low" or "high". The technology type influences the DSHWS technical characteristics as well as the initial cost, as can be illustrated in Figure 9.
- **Coverage**: The percentage of thermal load covered by the system.
- **Cost**: The initial cost of investment for the specific system.
- **NPV-Elec**: Net Present Value of investment compared to an electrical water heater (with an average cost of 0.14/kWh_{el} according to the Public Power Company of Greece).
- **NPV-Oil**: Net Present Value of investment compared to an oil water heater (with an average cost of 1.40 €/dm^3 (Martinopoulos and Tsalikis, 2014)).

- **NPV-NG**: Net Present Value of investment compared to a natural gas (NG) water heater (with an average cost of 0.08/kWh_{el} (Martinopoulos and Tsalikis, 2014)).

Section 4 gives an insight regarding the calculation of the values in the figure, also giving relevant references to literature. All columns in the table are sortable; e.g. the results in Figure 9 are sorted in ascending order according to the cost. Also, each result set is accompanied by an illustrative graph that offers a clearer picture to the user. Figure 10 demonstrates the graph that corresponds to the previous results.

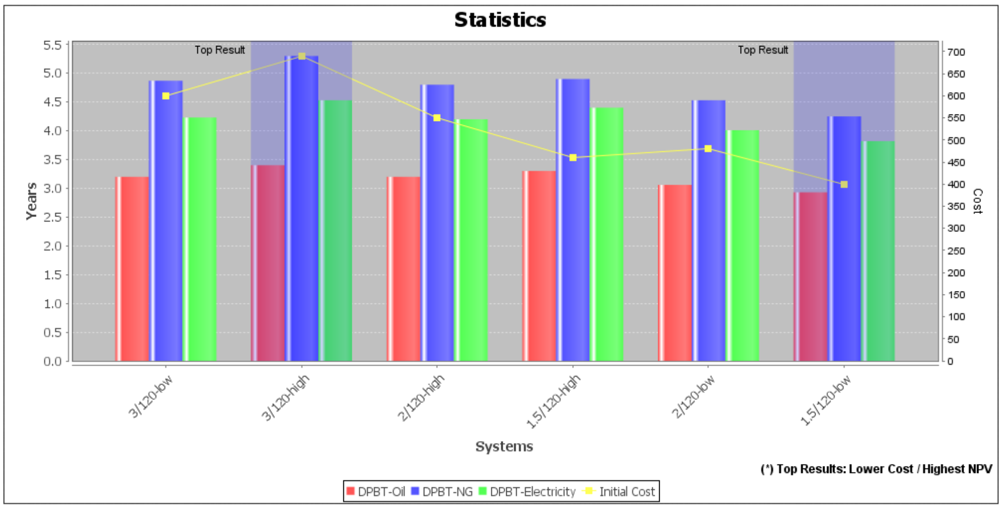

Fig. 10. Graph corresponding to the retrieved results.

The graph is in essence a dual axis graph that contains the following data:

- **Years** (left axis): Refers to the payback period (in years) for all types of energy: oil, electricity, NG.
- **Cost** (right axis): Refers to the initial cost of investment for each system in euro (€).
- **Systems** (bottom axis): Displays the systems that are more appropriate for each set of input parameters.

The two columns with the light blue background represent the two top results: (a) the one with the highest payback period, and, (b) the one with the lowest cost. Consequently, based on the initial input parameters, the user can now study the respective results and choose a system configuration that suits his/her prerequisites.

5.5 Determining the Result Set

The result set for each input parameter set (number of persons, water volume per person, household location) is retrieved through appropriate SPARQL queries submitted to the ontology via Jena. More specifically, the SPARQL queries retrieve the system configurations for DSHWS that match the input parameters, Then, the retrieved systems are matched against an external repository (CSV files) that contains all the results for the different DSHWS options calculated by the f-chart method, along with the corresponding values for the economic and environmental cost, according to the location that the user gave initially. The CSV files contain all the information that appears in the results table (Figure 9) for each system:

- Results of the optimization for various criteria selection.
- Comparison of the validation with published data for a typical household.

These external files are currently stored on the server. Storing this information independently from the ontology offers higher flexibility to the management of the system, as this data can be regularly updated separately, without interfering in the content and structure of the domain model (ontology). However, in the current version of the system the external files are only manually updated; this is a non-trivial process that would need to be (fully) automatic in future releases, possibly through web content scraping and/or metadata harvesting from appropriate web sources. Improvements towards this direction will also involve the deployment of a persistent storage that will ensure the reliability, persistence and security of the stored data, but at the same time keep the system’s flexibility, by maintaining the existing SPARQL querying information-retrieval interface.

6 Conclusions

This article presents a user-friendly ontology-based online decision support system that can help consumers select the appropriate DSHWS according to specific criteria, like e.g. initial and total cost, environmental friendliness, thermal load coverage, system sizing etc. The optimum system configurations are computed based on certain parameters, like e.g. the number of occupants, their daily requirements in hot water and the location of the house.

The backbone of the proposed system is an ontology that represents the application domain and contains information regarding the various DSHWS components along with their interrelationships. As discussed, ontologies are a rapidly evolving knowledge representation paradigm that offers various advantages and, when deployed specifically in the DSHWS domain, they deliver improved representation, sharing and re-use of the relevant information. Thus, the proposed tool delivers certain advantages, such as sustainability of the decision support system itself, due to its open and interoperable knowledge-base, and its adaptability/flexibility in decision making policies, due to is semantic (ontological) nature.

However, this work is still in its initial stages, aiming at the typical consumer. Our imminent plans include developing a more sophisticated version of the tool aimed at engineers and constructors, which will take into account all the relevant legislation as described in the Greek Directive for the Energy Performance of Buildings. Additionally, future plans involve integrating other renewable energy sources as well for heating and cooling, all in the context of modern urban environments.

In order to take advantage of the benefits introduced by the use of ontologies, we will attempt to integrate data from heterogeneous external sources into our system, like e.g. meteorological data etc. Also, the process of importing new DSHWS models and components into the system – possibly from external sources as well – could be facilitated by the reasoning mechanisms coupled with the ontology, while the results could be exported and made publicly available as *Linked Open Data*[8].

Finally, a further improvement could involve the use of rules, either in the form of *SWRL* (W3C, 2004) or SPIN[9], for determining more effectively the DSHWS configuration, while an end-user evaluation of the existing system would also reveal shortcomings and lead to improvements in its usability.

References

Abanda F. H., J. H. Tah and D. Duce, "PV-TONS: A Photovoltaic Technology Ontology System for the Design of PV-Systems," *Engineering Applications of Artificial Intelligence,* vol. 26, no. 4, pp. 1399-1412, April 2013.

Berners-Lee T., J. Hendler and O. Lassila, "The Semantic Web," *Scientific American,* vol. 284, no. 5, pp. 34-43, May 2001.

Bonino B., F. Corno, "DogOnt - Ontology Modeling for Intelligent Domotic Environments," in *The Semantic Web - ISWC 2008*, Springer Berlin Heidelberg, 2008, pp. 790-803.

Brinkworth B. J., "Solar DHW system Performance Correlation Revisited," *Solar Energy,* vol. 71, no. 6, p. 377–387, 2001.

Bürger T. and E. Simperl, "Measuring the Benefits of Ontologies," in *On the Move to Meaningful Internet Systems: OTM 2008 Workshops*, Monterrey, Mexico, 2008.

Corcho O., M. Fernández-López and A. Gómez-Pérez, "Methodologies, tools and languages for building ontologies: where is their meeting point?," *Data & Knowledge Engineering,* vol. 46, no. 1, pp. 41-64, July 2003.

Daouadji A., K. K. Nguyen, M. Lemay and M. Cheriet, "Ontology-Based Resource Description and Discovery Framework for Low-Carbon Grid Networks," in *2010 1st IEEE Int. Conf. on Smart Grid Communications (SmartGridComm)*, Gaithersburg, MD.

Duffie J. A. and W. A. Beckman, Solar Engineering of Thermal Processes, Wiley Publication, 1991.

European Solar Thermal Industry Federation (ESTIF), "Solar Thermal Markets in Europe - Trends and Market Statistics 2014", 2015.

European Environment Agency, "Consumption and the Environment - State and Outlook,"

[8] Linked Data, by T. Berners-Lee (18-Jun-2009): http://www.w3.org/DesignIssues/LinkedData.html, last accessed: July 2015.
[9] SPARQL Inferencing Notation, http://spinrdf.org/, last accessed: July 2015.

2010.

European Parliament & Council of the European Union, "Directive 2009/28/EC - On the Promotion of the Use of Energy from Renewable Sources," 2009.

Fernandez-Lopez M., A. Gomez-Perez and N. Juristo, "METHONTOLOGY: from Ontological Art towards Ontological Engineering," in *Proc. AAAI97 Spring Symposium*, 1997.

Georgopoulou E., V. Hontou, N. Gakis, Y. Sarafidis, S. Mirasgedis, D.P. Lalas, A. Loukatos, N. Gargoulas, A. Mentzis, D. Economidis, T. Triantafilopoulos, K. Korizi, "BEAsT: a decision-support tool for assessing the environmental benefits and the economic attractiveness of best available techniques in industry", in *Journal of Cleaner Production*, 16(3), 2008, pp. 359-373.

Glimm B., I. Horrocks, B. Motik and G. Stoilos, "Optimising Ontology Classification.," in *9th Int. Semantic Web Conf. (ISWC 2010)*, Shanghai, China, 2010.

Gómez-Pérez A., M. Fernández-López and O. Corcho, Ontological Engineering: with examples from the areas of Knowledge Management, e-Commerce and the Semantic Web. (Advanced Information and Knowledge Processing), Springer-Verlag New York, Inc., Secaucus, NJ, USA, 2007.

Gómez-Pérez J. M. and C. Ruiz, "Ontological Engineering and the Semantic Web," in *Advanced Techniques in Web Intelligence - I*, vol. 311, J. D. Velásquez and L. C. Jain, Eds., Springer Berlin Heidelberg, 2010, pp. 191-224.

Gruber T. R., "A Translation Approach to Portable Ontology Specifications," *Knowledge Acquisition,* vol. 5, no. 2, pp. 199-220, June 1993.

Heflin J. and J. A. Hendler, "Dynamic Ontologies on the Web," in *17th National Conf. on Artificial Intelligence and 12th Conf. on Innovative Applications of Artificial Intelligence*, 2000.

Hepp M., "Ontologies: State of the Art, Business Potential, and Grand Challenges," in *Ontology Management*, vol. 7, M. Hepp, P. De Leenheer, A. De Moor and Y. Sure, Eds., Springer US, 2008, pp. 3-22.

Horridge M., H. Knublauch, A. Rector, R. Stevens and C. Wroe, "A Practical Guide To Building OWL Ontologies Using The Protégé-OWL Plugin and COODE Tools Edition 1.0," 2004.

International Energy Agency, "Key World Energy Statistics," 2011.

International Energy Agency, "Solar Heat Worldwide: Markets and Contribution to the Energy Supply 2011," 2013.

Kalibatiene D. and O. Vasilecas, "Survey on Ontology Languages," in *Perspectives in Business Informatics Research: Proc. 10th Int. Conf. BIR 2011, Riga, Latvia, October 6-8,* *2011.*, vol. 90, J. Grabis and M. Kirikova, Eds., Springer Berlin Heidelberg, 2011, pp. 124-141.

Keirstead J. and K. H. van Dam, "A Comparison of Two Ontologies for Agent-based Modelling of Energy Systems," in *1st Int. Workshop on Agent Technologies for Energy Systems (ATES 2010) at AAMAS*, Toronto, Canada, 2010.

Keirstead J., N. Samsatli and N. Shah, "SynCity: An Integrated Tool Kit for Urban Energy Systems Modeling," in *5th Urban Research Symposium*, Marseille, France, 2009.

Kiryakov A., K. I. Simov and M. Dimitrov, "OntoMap: Portal for Upper-level Ontologies," in *Proc. Int. Conf. on Formal Ontology in Information Systems (FOIS '01)*, 2001.

Macris A. M., and Georgakellos, D. A. "A new teaching tool in education for sustainable development: ontology-based knowledge networks for environmental training", in *Journal of Cleaner Production*, *14*(9), 855-867, 2006.

Martinopoulos G. and G. Tsalikis, "Active Solar Heating Systems for Energy Efficient Buildings in Greece: A Technical, Economic and Environmental Evaluation," *Energy and Buildings,* vol. 68, pp. 130-137, January 2014.

Martinopoulos G., G. Tsilingiridis and N. Kyriakis, "Identification of the Environmental Impact from the Use of Different Materials in Domestic Solar Hot Water Systems," *Applied Energy,* vol. 102, pp. 545-555, 2013.

Muñoz E., Capón-García, E., Laínez, J. M., Espuña, A., and Puigjaner, L. "Considering environmental assessment in an ontological framework for enterprise sustainability", in *Journal of cleaner production*, *47*, 149-164, 2013.

Noy Natalya F., Deborah L. McGuinness, "Ontology Development 101: A Guide to Creating Your First Ontology," *Stanford Knowledge Systems Laboratory Technical Report KSL-01-05 and Stanford Medical Informatics Technical Report SMI-2001-0880,* 2001.

Poveda-Villalón M., M. C. Suárez-Figueroa and A. Gómez-Pérez, "Validating Ontologies with OOPS!," in *18th Int. Conf. EKAW 2012*, Galway City, Ireland, 2012.

Pulido J. R. G., M. A. G. Ruiz, R. Herrera, E. Cabello, S. Legrand and D. Elliman, "Ontology Languages for the Semantic Web: A Never Completely Updated Review," *Knowledge Based Systems,* vol. 19, no. 7, pp. 489-497, November 2006.

Schorlemmer M. and Y. Kalfoglou, "Using Information Flow Theory to Enable Semantic Interoperability," in *6th Catalan Conference on Artificial Intelligence (CCIA '03)*, Palma de Majorca, Spain, 2003.

Shah N., K.-M. Chao, T. Zlamaniec and A. Matei, "Ontology for Home Energy Management Domain," in *Int. Conf. on Digital Information and Communication Technology and its Applications (DICTAP 2011)*, Dijon, France, 2011.

Shariah A., M. Al-Akhras and I. A. Al-Omari, "Optimizing the Tilt Angle of Solar

Collectors," *Renewable Energy,* vol. 26, no. 4, pp. 587-598, August 2002.

Staab S., R. Studer, H.-P. Schnurr and Y. Sure, "Knowledge Processes and Ontologies," *Intelligent Systems,* vol. 16, no. 1, pp. 26-34, January 2001.

Stephens S., "The Enterprise Semantic Web," in *The Semantic Web: Real-World Applications from Industry*, J. Cardoso, M. Hepp and M. Lytras, Eds., 2007, pp. 17-37.

Suárez-Figueroa M. C., A. Gómez-Pérez and M. Fernández-López, "The NeOn Methodology for Ontology Engineering," in *Ontology Engineering in a Networked World*, M. C. Suárez-Figueroa, A. Gómez-Pérez, E. Motta and A. Gangemi, Eds., Springer Berlin Heidelberg, 2012, pp. 9-34.

Tah J. H. and H. F. Abanda, "Sustainable Building Technology Knowledge Representation: Using Semantic Web Techniques," *Advanced Engineering Informatics,* vol. 25, no. 3, pp. 547-558, August 2011.

Technical Chamber of Greece, "TOTEE 20701-1/2010: National Parameters For the Calculation of Buildings' Energy Efficiency and Issuing Certificates of Efficiency (in Greek)," 2010a.

Technical Chamber of Greece, "TOTEE 20701−3/2010: Climatic Data for Various Areas in Greece (in Greek)," 2010b.

Tian Y. and C. Y. Zhao, "A Review of Solar Collectors and Thermal Energy Storage in Solar Thermal Applications," *Applied Energy,* vol. 104, pp. 538-553, April 2013.

Trokanas N., Cecelja F., Raafat T., Semantic approach for pre-assessment of environmental indicators in Industrial Symbiosis, in *Journal of Cleaner Production*, 96(1), 2015, pp. 349-361.

W3C OWL Working Group, "OWL 2 Web Ontology Language - W3C Recommendation," 11 December 2012. [Online].

W3C OWL Working Group, "OWL Web Ontology Language - W3C Recommendation," 10 February 2004. [Online].

W3C RDF Core Working Group, "RDF Vocabulary Description Language 1.0: RDF Schema - W3C Recommendation," 10 February 2004. [Online].

W3C SPARQL Working Group, "SPARQL Query Language for RDF - W3C Recommendation," 15 January 2008. [Online].

W3C XML Core Working Group, "Extensible Markup Language (XML) 1.0 - W3C Recommendation," 26 November 2008. [Online].

W3C, "SWRL: A Semantic Web Rule Language - W3C Member Submission," 21 May 2004. [Online].

W3C, "W3C Semantic Web Activity," 19 June 2013. [Online].