Semantic Interoperability for Managing Energy-Efficiency and IEQ: A Short Review

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Abstract. With the rise of the Internet of Things and Smart Home industries, there is a real opportunity to increase the energy efficiency of buildings and improve the indoor experience of their occupants. However, as these industries continue to grow, so does the number of data sources in the energy sector in recent years. This can lead to suboptimal exploitation of these data and even to dualities and misunderstandings. As a result, semantic interoperability in the energy sector is now more necessary than ever. Combining event processing to handle data quantities, semantics to manage numerous data streams, and background ontologies will increase prompt identification of all information. In this context, this short review aims to explore state-of-the-art semantic ontologies and their utilization in the energy sector, with an additional emphasis on the indoor environment and air quality. Furthermore, a semantically enriched framework for a smart home will be proposed.

Keywords: Semantics · Energy sector · Energy efficiency · Energy management · Indoor Environmental Quality

1 Introduction

The recent invasion of Ukraine by Russia brought the issue of Europe's dependence on external energy sources once again into the limelight. In response, the European Commission presented the REPowerEU [1] plan, which includes

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"saving energy" as a critical point of action. Energy savings can of course be achieved by adjusting the public's mindset and tendencies when it comes to how much energy they consume. However, significant energy savings can also be achieved by increasing the energy efficiency of the building stock, which has been one of the go-to demand-side measures over the past decades. This particularly applies to Europe, where 49% of the building stock was built before 1970 [2], which naturally results in higher energy losses and consumption.

Energy flexibility is a more recent form of a demand-side solution that builds on energy efficiency measures, offering the ability to adapt load and generation based on weather conditions, user preferences, and energy network capabilities [3]. Nevertheless, the interventions to increase the energy efficiency of the building stock should not affect the health, comfort and well-being of building users, which are key aspects of Indoor Environmental Quality (IEQ) according to Rohde et al. [4]. Standards and proper communication workflows are essential for these energy efficiency and flexibility interventions to avoid overlaps and create integrated solutions since they can include a variety of data sources such as traditional demand-response (DR) schemes, behind-the-meter distributed energy resources (DER) like on-site generation, thermal and battery storage, and electric vehicles [3].

Furthermore, the rapid growth in Building Information Model (BIM) and Digital Twin (DT) technologies, and their increasing integration into Building Energy Management Systems (BEMS), combined with the fact that Artificial Intelligence (AI) models are consistently deployed at both the building and the grid levels, introducing additional data sources (electricity meters, IoT equipment, etc.), renders the call for interoperability at both syntactic and semantic levels, increasingly acute.

In order to achieve interoperability between all systems, management and automation levels, certain semantic and syntactic requirements must be met [5]. In [6] the authors propose an initial novel implementation of a semantic digital twin technique for smart buildings while observing, monitoring, and optimizing comfort levels along with energy consumption. The idea behind the suggested semantic digital twin strategy is to reuse existing related semantic models to express integrated knowledge for both the physical and digital twins of smart buildings. The Semantic Digital Twin's prototype is being used to highlight analytics and comfort with visualization (SDT). Yet, real-time actuation of semantically annotated real building assets as well as semantically integrated real-time sensor data is also exhibited.

As stated in [7] the capacity of computer systems to exchange data with explicit, formal, agreed and shared meaning is known as semantic interoperability. In order to enable machine-computable automated reasoning, inference, knowledge discovery, and data federation amongst information systems, semantic interoperability is necessary. Returning to the example of the Digital Twins interoperability provides meaning to the content of all data. This is achieved by providing data (metadata) that describes the meaning of the main data content and is transmitted along with the main data content as a holistic information package. These metadata links each element of the main data content to a shared vocabulary and its associated links to an ontology, enabling machine interpretation, inference, and logic [7].

Within this context, this short review endeavors to review semantic interoperability in the context of the energy sector with a particular focus on IEQ. This is achieved by examining whether and to what extent semantics are utilized in the energy and IEQ sectors while presenting the most prevalent ontologies for each case. Finally, the aim is to suggest an applied solution for a semantically enriched smart home.

The remainder of this paper is structured as follows: Sect. 2 presents the state of semantic interoperability in the energy sector in terms of smart control and data management, IoT, smart cities, and the latest research. Section 3 describes the role of semantics in the IEQ and the air quality of interior spaces. Section 4 proposes a new semantically enriched edge architecture. Section 5 presents the challenges that hinder semantic interoperability in the energy and IEQ sectors. While Sect. 6 section contains the conclusions of this work.

2 Semantics in the Energy Sector

As already mentioned, the rapid introduction of new data sources in the energy sector, such as Demand Response (DR) and other flexibility services, Renewable Energy Sources (RES), Digital Twins (DT), Building Energy Management systems (BEMS), Artificial Intelligence (AI algorithms), etc., create an overwhelming amount of data. As Rahman and Hussain emphasize in [19] it is important to convert this raw data into information, then knowledge and finally actionable wisdom utilizing semantics.

2.1 Semantics for Smart Control and Data Management

In recent years, there has been an increasing deployment of BEMS to increase energy efficiency and decrease the energy consumption of buildings, as well as coordinate and deploy energy flexibility services. The operation of BEMS is based on the communication and synergy between automation-level technologies and management-level components, by exploiting high-quality data [5].

Dimara et al. [5] emphasize the utility of an intermediate semantic layer between the automation and management levels of a BEMS, to promote interoperability and provide semantic meaning to raw data from various sources with the objective of extracting knowledge. Some of the main energy-related ontologies can be found below:

– The DogOnt ontology was originally meant for home automation equipment but was later expanded to include all the components of an indoor IoT system [8].
– The PowerOnt ontology refers to the power that electrical devices and appliances consume in smart homes. This ontology is usually integrated with DogOnt [9].
– The SESAME ontology addresses the energy profile of the user, automation, representing meter data and energy pricing [10].

- The BASont ontology is utilized during a variety of the Building Automation System's (BAS) lifecycle's phases, such as design, operation, and refurbishment [11].
- The ThinkHome ontology addresses the critical aspects of analyzing the energy profile of residential buildings by gathering knowledge related to energy providers and their trading conditions, climate conditions, users, spatial knowledge, automation networks, and finally, indoor comfort [12].
- Smart Appliances REFerence (SAREF) ontology utilizes the ETSI TS 103 267 framework [13] to facilitate synergies between other standards and protocols [14].
- The SAREF4ENER ontology is an extension of SAREF and aims to increase the interoperability between smart components of a household and maximize energy efficiency and efficiency in DR schemes participation [15].
- The Generic Ontology of Energy Consumption Households describes a household in terms of energy consumption (appliances), energy production (RES), energy storage (BESS), and consumption profile of the user [16].
- The DEHEMS ontology aims to maximize the volume and quality of data available from home appliances by utilizing a taxonomy that includes the properties of an electric appliance [17].
- The ComfOnt ontology acts as a knowledge base for both energy savings and improvement of IEQ. [18] This ontology is described in detail in Sect. 3.1.

2.2 Semantics for the Internet of Things

In [19] the authors emphasize the heterogeneous and dynamic nature of IoT systems due to the integration of various IoT equipment with vast heterogeneity in devices, hardware, software, requirements, protocols, data formats, etc. This heterogeneity prevents not only the maximum exploitation of the available data but also the further development and deployment of IoT systems.

Technical and syntactic interoperability is not enough for the correct operation of IoT systems. Assuming that in the example of such a system, data can be transmitted from one component to another (technical interoperability) and one component is aware of what type of data to expect from the other (syntactic interoperability), these data still do not have any meaning for the various components. To better understand this point, assuming a smart home system, let T_{EXT} be the outdoor temperature and T_{DHW} be the temperature of domestic hot water (DHW). Both of these temperature values are measured in Celsius ($^{\circ}C$) and can be transmitted from one component of the system to another. However, with no semantic values, these temperatures can be misidentified and lead to faults in the system's operation.

Despite the apparent need for semantic interoperability within IoT ecosystems, as Ganzha et al. mention in [20], the implementation of semantic practices is almost entirely limited within the scientific community. The authors continue to investigate the ontologies of various sectors and conclude that there is a lack of high-level ontology standardization and guidelines, as in each sector and in some cases organizations, different ontologies and standards are utilized.

Finally, the authors warn that due to the "additional effort" required to make them compatible, the abundance of domain- and use-case-specific ontologies may in and of itself provide difficulties when developing interoperable solutions inside and across domains.

2.3 Smart City Ontologies

As stated in [21] a smart city is an urban ecosystem with social, technological, and digital aspects, aiming to improve its inhabitants' quality of life. The recent deluge of available urban data from different smart city services led De Nicola and Villani [21] to review the various ontologies of different smart city sectors utilized to build the foundation for optimal smart city services.

Some of these sector-specific ontologies include a semantic web model that enables the formation and customization of virtual communities [22], ontologies revolving around emergency situations such as natural or anthropogenic disasters and are utilized for the optimal operation of emergency responders, the management and planning during these situations, the exchange of information and knowledge, and spatiotemporal changes during these events [23–28], ontologies aiming to connect smart cities with the industry and business sector, add value propositions, store transaction data, and execute contracts among others [21].

In the context of the energy sector in smart cities, the ontologies presented in Sect. 2.4 are naturally prevalent. Additionally, in [21] the authors include the Energy Knowledge Graph (EKG) ontology model, which is used to conceptualize microgrids, their components as well as the relationships between them, and classify smart energy services related to specific scenarios. In addition, the Generic Ontology for a Prosumer-Oriented Smart Grid collects knowledge regarding different aspects of the smart grid from the generation of power, energy consumption and the climate to the relationships between prosumers and energy providers.

2.4 Semantics in the Energy Sector Latest Research

As already mentioned, the plethora of data from various decentralized sources with different granularities, formats, protocols, etc., can lead to suboptimal utilization of these data and even dualities and misunderstandings. As Wu et al. point out in [29] a new decentralization-oriented BEMS could lead to major benefits in terms of energy consumption and emission reduction. The authors also note that due to the overwhelming amount of data, researchers tend to utilize data-driven techniques such as AI, which, however, can lead to unreliable and irreplicable results, since the data are extremely project specific and the energy sector has many interdependencies with various other sectors. On these projects, interoperability is limited to its technical and syntactic forms focusing more on message transmission, while semantic interoperability is often neglected.

To address these issues, Wu et al. created new ontology models focused on the interdependencies between energy consumption and variables from third-party sectors such as climate variables. To achieve this the authors follow a knowledge-driven approach by building systematic semantics for decentralized households and converting data generated from the household to Linked Data so as to facilitate the semantic integration with third-party sector data over the web. To validate their findings the authors conduct a test case by analysing household energy consumption and production (PV production, refrigerator/freezer energy consumption, and grid energy import) against temperature data. They finally conclude that climate data may be beneficial for data-oriented models.

In [30] Li and Hong take a knowledge-focused approach to the topic of energy flexibility in buildings. They propose EFOnt (an Ontology for Energy Flexibility of buildings), the first known domain-oriented ontology focused on building energy flexibility to be utilized as a tool for standardizing knowledge co-development and optimizing the integration of different energy efficiency applications. EFOnt gathers all the necessary terminologies and semantic components on the topic of building energy flexibility and creates hierarchical semantic relationships between them while providing an open-source, technology-agnostic, and extensible foundation for shared knowledge for the scientific community and industry backed by the highly interoperable semantic web.

3 Semantics for the Indoor Environmental Quality

3.1 Semantics for Indoor Comfort

A smart home is a home where various smart IoT devices create an ecosystem to enable energy efficiency, improve safety measures, provide ease to the inhabitants during everyday tasks and enhance their feeling of comfort and well-being [31]. However, as stated in [32], there is a lack of scientific work dedicated to standardizing indoor comfort semantic metrics.

To this end, Spoladore et al. [32] continue to propose ComfOnt, a set of domain ontologies that leverages the work done during three Italian research projects, with the aim of adding value to the sector of domain ontologies describing knowledge necessary to facilitate smart home services, including comfort semantics. ComfOnt can be utilized to describe the comfort conditions in the indoor environment and continue to actuate processes to increase the well-being and/or safety of occupants, based on its interpretation of reasoning processes. At the same time, ComfOnt, as a knowledge base, serves smart home inhabitants with suggestions regarding their energy-consuming activities, acting as the foundation for both IEQ improvement and energy consumption reduction. For the purposes of this subsection, ComfOnt will be examined through its comfort managing qualities.

ComfOnt is then validated serving as the knowledge base of the prototypical DECAM smart home management application, directed toward the elderly to assist them in living more independently, with the ability to extend its utilization for all smart home occupants. When it comes to comfort, the occupants have a clear view of the indoor environment conditions (temperature, humidity, illuminance, and CO_2 concentration) as illustrated in (Fig. 1). And have the ability to adjust and save their preferences according to their specific needs/impairments, while their presence is detected and adjustments to the environment are made in advance.

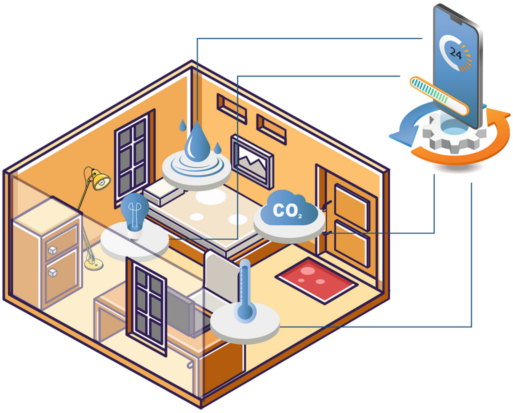

Fig. 1. ComfOnt's temperature, humidity, CO_2, and illuminance sensors.

In [33] a similar ontology framework is developed to optimize the comfort of cruise cabin guests via a mobile application, called Smart Cabin. This framework utilizes IoT sensors and actuators to take real-time action to improve the passengers' indoor experience based on occupancy, health requirements, preferences, activities, and feedback. Semantic web technologies are deployed to enable the knowledge exchange between these heterogeneous devices as well as their sharable and machine-understandable representation and visualization. Smart Cabin is based on four pillars; smart devices, the smartphone application, the knowledge base including the domain ontologies (Passenger's status ontology, Passenger's preferences ontology, ontology including the activities performed by a passenger, Cabin and devices ontology) and finally middleware Java program.

Eleftheriou et al. [34] follow a semantic digital twin approach. The authors demonstrate a semantic digital twin prototype oriented towards optimizing comfort levels, saving energy, analytics and visual comfort metrics visualization by efficiently providing integrated knowledge to decision-making components via the digital twin.

Their approach is founded on four layers; the physical twin layer contains the monitored room and its assets, both physical properties and smart devices, IoT equipment and actuators. The digital twin layer consists of the virtual room, as well as its assets and virtual sensors. The virtual room is an accurate digital representation of the monitored room and its assets, while the virtual sensors are utilized to simulate and visualize data streams in order to optimize decision-making processes and in some cases control the actual sensors. The service layer facilitates all the monitoring, actuation, optimization and scheduling processes. Finally, the semantic layer enables the knowledge exchange between the previously mentioned layers by semantically enriching data and information for the optimal operation of the system.

3.2 Semantics for Indoor Air Quality

When discussing the well-being of indoor spaces occupants, one should not neglect to take indoor air quality into account. According to the World Health Organization's (WHO) ambient air quality database [35] 90% of people around the world breathe polluted air, causing the deaths of 7 million people each year, mainly in low-income countries where immediate action is required. With the rapid growth of smart home and IoT technologies, there is a real opportunity to improve the indoor air quality of residents. However, as stated in [36], due to the inconsistent, blurry and vague nature of the data on the topic of air quality and the uncertainty when specifying the "degree of pollution", conventional ontologies are not optimal for the job. Neither are type-1 fuzzy logic systems (T1FS) that are shown to perform poorly on this topic.

To address this deficiency of the previously mentioned ontologies, the authors of [36] propose a new IoT-based method to assess indoor air quality, utilizing type-2 fuzzy logic systems (T2FS) to extract knowledge from the vague data, with promising results. In [37] the authors attempt to tackle the lack of modeling between sensor-acquired environmental health data and their association with medical terminology by semantically enriching data streams and extracting patterns from medical terminology and coding systems.

In [38] Jude et al. developed an ontology for proactive indoor air quality monitoring and control, as well as an indoor air quality index that was generated utilizing said ontology, which was then validated in a real-world case study in Durban, South Africa, to facilitate reasonable decision-making to improve IEQ. This ontology is developed utilizing the "Methontology" ontology engineering method [39] and enables a proactive framework to proactively warn the users when critical levels of indoor pollutants tend to rise to dangerous levels.

4 Proposed Approach

In [40] a new semantically enriched edge IoT is suggested (SEDGE). The SEDGE architecture adheres to the web of things (WoT) architecture requirements to minimize ambiguity and promote interoperability between diverse edge devices and other external systems (Fig. 2). The term "WoT" refers to the W3C standards for REST, RDF, and HTTP, which promote the effective communication and use of IoT network components. Edge devices are serialized in JSON-LD format and are semantically defined in a human-readable and machine-understandable representation that includes semantic metadata about them. The descriptions are built on common vocabularies and ontologies, which enables external systems to interpret the functionalities of various cooperating and interacting edge devices in a consistent way. With a WoT scripting API, edge devices are made visible and accessible to the web, allowing users to access the given interactions.

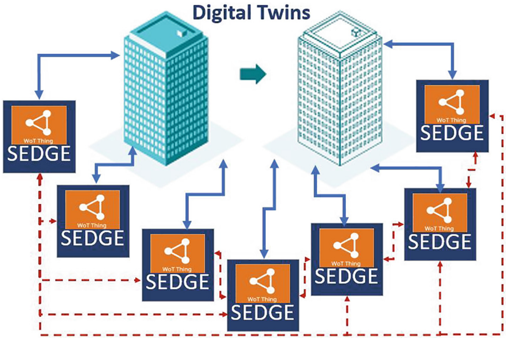

Fig. 2. SEDGE WoT to Digital Twin architecture

5 Discussion in Challenges for Managing Energy-Efficiency and IEQ

There are a few challenges when it comes to semantics in the energy sector. One challenge is that the energy sector is constantly evolving, so it can be difficult to agree on a single definition for certain terms. Another challenge is that the energy sector can be quite complex, so it can be difficult to communicate complex concepts clearly and accurately. Additionally, the energy sector can be quite political, so it can be difficult to agree on certain terms or policies. As a result, the ontologies will have to be constantly updated with new entities.

Furthermore, there are a few challenges in semantics for indoor comfort. One challenge is that people often have different definitions of what "comfort" means. Another challenge is that there is no one-size-fits-all definition of comfort since what feels comfortable to one person may not feel comfortable to another person. Additionally, the definition of comfort can change depending on the weather, the time of day, and other factors. Likewise, well-known semantics like SAREF could be extended to include comfort and IED entities.

6 Conclusions

In this short study, an attempt was made to review the current state of semantic interoperability in the energy sector. A thorough examination of the utilization of semantics and ontologies of the energy sector revealed that despite the variety of ontologies available, there is still a lack of semantic interoperability standardization, since many of these ontologies are developed on a case-by-case basis and often are abandoned. This issue was shown to be even more prevalent on the topic of IEQ and air quality, where the data are more blurry and vague. However, the rapid growth of the IoT industry in combination with the emerging prevalence of semantics in the research community allows an optimistic view of semantic interoperability in the energy sector.

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