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A non-functional requirements-based ontology for supporting the development of industrial energy management systems

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ABSTRACT

Non-functional requirements (NFRs) are essential in the development of industrial energy management systems (IEMS). This paper presents a comprehensive ontology model for NFRs in IEMS, derived from an extensive survey of NFRs in both the software industry and the energy domain. The proposed ontology encompasses four critical factors influencing the quality attributes of IEMS: technologies, stakeholders, markets, and regulations. Implemented using the OWL 2 DL standard, the ontology model aims to provide a clear and consistent understanding of NFRs and their relationship to the energy domain, as well as identify which factors have a significant impact on the environmental performance of IEMS. The ontology is evaluated through various methods, such as technical validation, user evaluations, its applications in RDF data management, and application-based evaluation, including software architecture, knowledge base data model design, and regulatory framework design. By understanding the link between software quality requirements and the characterizing factors of the energy domain, as provided by our ontology model, this information can be used to inform life cycle assessments and quantify potential reductions in energy consumption, emissions, waste generation, and other environmental impacts associated with implementing cleaner and more sustainable solutions. The results demonstrate that the proposed ontology effectively supports IEMS development and serves as a foundation for developing reusable and adaptable software systems across different industrial domains.

1. Introduction

The optimization of energy systems in industrial software development is a critical challenge facing the scientific community today. With the emergence of concepts such as smart cities and smart energy cities, intelligent energy transmission and distribution networks have been developed, allowing for the optimization of energy resources through data management and analysis (Vincenzo et al., 2011). However, the energy domain is complex and dynamic, with factors that vary from country to country, making it difficult to fully understand and manage. To address this issue, the development of industrial energy management systems (IEMS) must be supported by a framework that highlights the main factors of the energy domain that impact the quality requirements of the system.

In this context, both functional requirements (FRs) and non-functional requirements (NFRs) are important for the design and deployment of IEMS. While FRs describe the specific features and functionalities of the system, NFRs focus on the system's performance, reliability, and other essential qualities such as security, scalability, and availability (Chung et al., 2012). NFRs play a crucial role in the successful operation of IEMS and must be taken into account during the development process. The significance of NFRs in the energy sector lies in their ability to influence the system's overall performance and user experience. However, a thorough understanding and management of NFRs in the development of IEMS can be a daunting task due to the complexity and dynamic nature of the energy domain.

Ontology, a concept in computer science and information systems research, can aid in addressing these challenges (Zou et al., 2019). An ontology provides a formal representation of knowledge, helps identify inconsistencies and incompleteness, and establishes a shared vocabulary within a specific domain for improved information sharing. In software engineering, ontologies have been used to promote the reuse of domain knowledge and to make explicit domain assumptions that can be easily changed when the domain knowledge evolves. In the

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energy sector, although several ontologies have been developed for the energy sector such as (Hippolyte et al., 2018; Haghgoo et al., 2020; Booshehri et al., 2021), they exhibit gaps when it comes to supporting IEMS development, mainly due to the field's recent emergence as mentioned in Cuenca et al. (2020). The continuous evolution of the energy context and revolutionary advances in information and communication technology (ICT) necessitate constant reworking of the domain's ontology. These advances are driving a shift towards carbon-free, robust energy systems that heavily exploit renewable energy sources (RES) on the grid scale and a greater prevalence of small-scale micro-sources on the demand side (Shahinzadeh et al., 2019). The large-scale integration of RES introduces a new paradigm, making demand and supply balancing a highly complex task due to the unpredictable behavior of RES. This influences not only the electricity system but also the heating and cooling systems due to the considerable link between these subdomains. Addressing these problems requires collaboration among multiple stakeholders to provide solutions, and models of such solutions are essential to explore the interactions between consumption, production, transportation, and economic, environmental, and technical phenomena.

The impact of NFRs on the energy sector is particularly significant as they directly influence the efficiency, reliability, and security of IEMS. Understanding and managing NFRs in IEMS development enables the creation of systems that better address the needs of the energy sector and its stakeholders. In light of this, the purpose of this paper is to develop an energy domain ontology that adequately supports IEMS development by capturing the NFRs for the energy domain and their relationship to four critical factors: technologies, stakeholders, markets, and regulations. The research question guiding this study is, "How can an ontology support the development of IEMS by addressing the NFRs and their relationship to the energy domain?" The underlying hypothesis is that an ontology model considering both the software quality requirements and the critical factors of the energy domain can effectively support IEMS development by providing a clear and consistent understanding of NFRs and their interdependencies and impacts on system performance.

To address this research question and test the hypothesis, we first analyze software NFRs and compile a comprehensive catalog to reduce ambiguities in selecting these requirements. We identify the critical factors in the energy domain that impact the essential quality attributes of energy management systems development. Then, we construct the ontology[1] based on the identified critical factors, including technologies, stakeholders, markets, and regulations, aimed at supporting IEMS development. Our ontology assists in understanding how multiple entities work, interact, and influence each other with conflicting objectives. The ontology's validation involves not only testing its structure but also submitting it to a team of experts for developing an industrial energy management platform and testing its coverage in terms of classes and relationships representative of the energy domain using a Name Entity Recognition (NER) methodology and extracting ontological mapping.

In summary, the contributions of this paper are threefold:

- Compilation of a comprehensive catalog of software non-functional requirements and identification of critical factors in the energy domain that impact the essential quality requirements of industrial energy management systems development.
- Construction of a comprehensive ontology that considers both the software quality requirements and the critical factors of the energy domain that support the development of industrial energy management systems.
- Evaluation of the proposed ontology through formalization, validation, applications, user evaluation, and a case study, demonstrating its potential to support the development of other energy management software in the future.

The remainder of this paper is structured as follows: Section 2 reviews the literature related to non-functional requirements and the ontologies for the development of IEMS; Section 3 describes the proposed ontology in detail; Section 4 evaluates the proposed ontology; Section 5 discusses the related issues of the ontology; and Section 6 concludes the paper and presents the future work.

2. Literature review

This section will first review the NFRs related to industrial software system development, then will review the NFRs-based ontologies for IEMS.

2.1. Non-functional requirements for industrial energy software systems

NFRs describe the properties, characteristics, constraints, or quality attributes a software system must exhibit (Mairiza et al., 2010b). Understanding the system's purpose and how it supports users' goals is crucial to ensure the software product meets the necessary NFRs (Sommerville, 2005). Historically, NFRs were often neglected by the software industry, but their importance was recognized at the start of the 21st century when addressing both functional and non-functional requirements became essential to improve the success rate of IT projects (Umar and Khan, 2011). Neglecting NFRs can lead to software failures, such as the systemic failure in the London Ambulance System (Breitman et al., 1999; Finkelstein and Dowell, 1996) and the performance and scalability failure in the New Jersey Department of Motor Vehicles Licensing System (Boehm and In, 1996).

Selecting NFRs for industrial energy management systems is a complex task influenced by developers' subjective opinions and experiences. This has led to a need to identify the most critical NFRs for these systems. Previous studies have focused on identifying requirements that are widely shared across different case studies, aiming to make an ontology more generalizable. For example, Mairiza et al. (2010a,b) conducted an in-depth investigation of NFRs in the context of energy management systems, providing a comprehensive overview of the most commonly used NFRs. There are ambiguities surrounding NFRs definitions, with fourteen different definitions identified in the literature, some of which are analyzed in the study (Glinz, 2007). The definition proposed by Mairiza et al. (2010b) comprises two perspectives. The first includes system constraints, business rules, external interfaces, quality attributes, and other requirements not describing the system's functionality. The second perspective considers only quality attributes as NFRs, such as maintainability, reusability, and usability.

Quality requirements (QRs) are a subset of NFRs directly related to the system's quality attributes, such as reliability, availability, maintainability, and performance (Chung et al., 2012). QRs play a crucial role in ensuring energy management systems meet desired quality standards and perform optimally under various operating conditions. However, selecting QRs is challenging due to the numerous NFRs relevant to energy management systems, leading to ambiguity in NFR selection and difficulty for developers to prioritize requirements based on their relative importance and potential impact on system quality (Chazette and Schneider, 2020). To address this challenge, it is essential to carefully select and prioritize QRs based on their relevance to system quality. By focusing on a subset of NFRs directly related to quality, developers can more effectively manage and control these requirements throughout the development process. This can help reduce ambiguity by providing a clear set of criteria for evaluating whether a particular requirement meets desired quality standards.

In contrast to previous work, this paper conducts a comprehensive survey of NFRs to identify the critical factors that impact software

[1] **Disclaimer**: The ontology presented in this paper is a conceptual model that does not contain any complex axioms or instances. It is intended to be a starting point for further development and refinement, rather than a final and complete specification of the domain.

Table 1
Comparison of the current ontologies for the energy domain.

Ontology	Coverage	Focus	Granularity	Adaptability	Prioritization
ThinkHome (Kofler et al., 2012)	Smart home domain	Devices, services, users, goals	Medium	Low	No
DABGEO (Cuenca et al., 2020)	Energy domain	Energy subdomains	High	High	No
OEMA (Cuenca et al., 2017)	Energy domain	Energy performance, context, market, regulations	High	Low	No
Our ontology	Energy domain	NFRs and critical factors	High	Medium	Yes

quality. We develop an NFRs-based ontology tailored to support IEMS development, which addresses several limitations of existing energy domain ontologies. These limitations include inadequate coverage of the energy domain, insufficient focus on NFRs, limited granularity, restricted adaptability to evolving smart city contexts, and a lack of prioritization guidance for NFRs. Our work considers the recent emergence of smart cities and the unique requirements of smart energy management systems. The proposed ontology model provides a robust framework for organizing and structuring QRs, facilitating a deeper understanding of their interdependencies and impacts on system performance. By employing this model, developers can make more informed decisions on prioritizing QRs based on their relative importance and potential impact on system quality.

2.2. Ontologies in energy domain

Ontologies are models that represent classes and relationships in a specific domain using a common vocabulary. They can facilitate data integration, interoperability, and knowledge extraction in energy management applications (Cuenca et al., 2020). However, not all ontologies are equally suitable for different energy management scenarios and applications. Depending on their coverage, focus, granularity, adaptability, and prioritization of NFRs, ontologies may vary in their usefulness and effectiveness for addressing specific problems or questions in the energy domain. Therefore, it is important to compare and evaluate existing ontologies to identify their strengths and weaknesses, as well as the gaps and opportunities for improvement.

The energy domain is characterized by a complex array of issues that encompass technological, political, social, and cultural aspects. To understand and optimize the mechanisms of the energy context, ontologies have been developed and systematically formalized over time. These models, often focused on specific aspects of the domain, have been shown to be useful and effective. For example, Kofler et al. (2012) presented ThinkHome ontology for smart home energy management applications, Daniele et al. (2016) and Burel et al. (2016) presented ontologies for smart home energy management applications, while (Curry et al., 2013), Stavropoulos et al. (2012), and Blomqvist and Thollander (2015) presented ontologies for building, facility and organizational energy data representation. However, these models are often limited in their coverage, focus, granularity, adaptability, or prioritization of NFRs. In this section, we review some of the existing ontologies for the energy domain that have been proposed in the literature. We focus on four global ontologies that aim to cover a wide range of aspects in the energy domain: ThinkHome ontology (Kofler et al., 2012), DABGEO (Cuenca et al., 2020), OEMA (Cuenca et al., 2017), and our NFRs-based ontology. We compare these ontologies based on five criteria: coverage, focus, granularity, adaptability, and prioritization of NFRs. Table 1 summarizes the comparison of these ontologies.

In particular, when it comes to IEMS, it is important to focus on the development of detailed information on all the NFRs factors that can affect its quality characteristics. IEMS are comprised of various functions that enable efficient management and control of energy resources. Some of the primary functions of IEMS include monitoring of energy consumption to identify usage patterns and detect inefficiencies (Curry et al., 2013), providing alerts and alarms for potential energy-related issues (Stavropoulos et al., 2012), handling exceptions and failures in energy systems (Blomqvist and Thollander, 2015), and facilitating decision-making for energy conservation and cost reduction (Kofler et al., 2012). These systems often integrate advanced data analytics, machine learning algorithms, and control strategies to optimize energy consumption and reduce operational costs (Daniele et al., 2016). Therefore, it is necessary to develop the ontology to support the development of IEMS by addressing the critical factors in the energy domain that impact the system's NFRs and by providing a comprehensive knowledge base for understanding the interplay between various entities and factors within the energy sector.

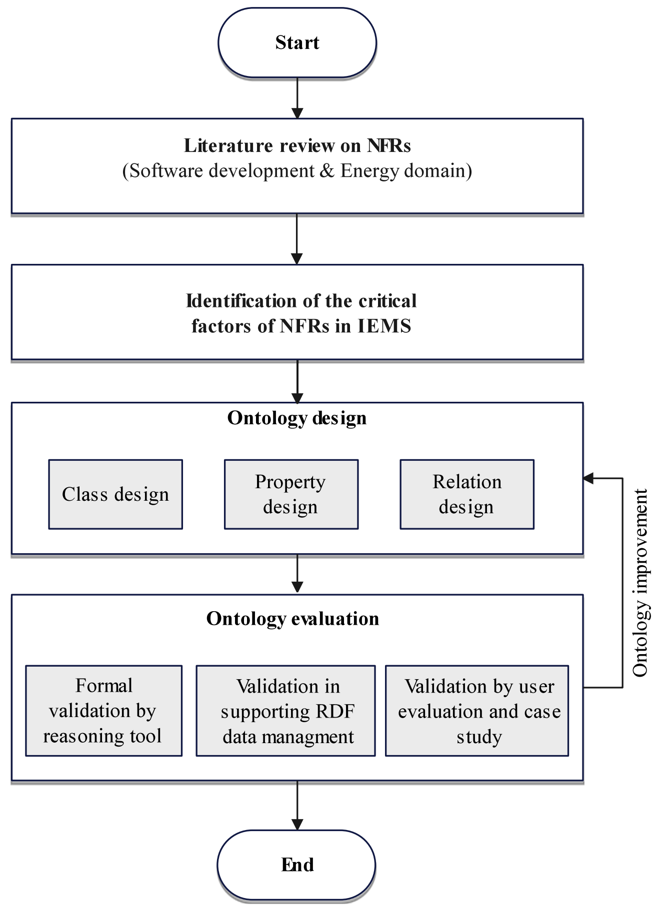

Fig. 1. Overview of the ontology design process.

3. Methods

3.1. Overview

In this paper, we aim to construct an ontology model that captures the NFRs for the energy domain and supports the development of

Table 2
272 NFRs for the development of software systems.

Category	Description	NFRs
Scalability	The ability to handle increasing workloads or users without significant degradation in performance	Scalability
Replicability	The ability to reproduce the same results or behavior in different environments or scenarios	Replicability, Repeatability
Flexibility	The ability to adapt to changing requirements or conditions	Flexibility, Adaptability, Modifiability
Usability	The ease of use for the intended users	Usability, User-friendliness, User error protection, Accessibility, Auditability, Localizability
Security	The protection of the system and its data from unauthorized access or damage	Security, Confidentiality, Integrity, Non-repudiation, Availability, Data privacy, Regulatory compliance
Maintainability	The ease of maintaining and updating the system	Maintainability, Testability, Monitorability, Serviceability
Performance	The efficiency and effectiveness of the system	Performance efficiency, Resource utilization, Responsiveness, Elasticity, Efficiency
Interoperability	The ability to work with other systems or components	Interoperability, Compatibility, Co-existence, Internationalization
Correctness	The accuracy and reliability of the system's results or behavior	Correctness, Functional correctness, Functional completeness, Functional appropriateness, Functional suitability, Analyzability, Additivity, Complexity/Simplicity, Concurrency, Configurability, Consistency, Controlability/Testability, Credibility, Data accessibility, Data integrity, Debuggability, Evolvability, Expandability, External consistency, Fidelity, Improvability, Installability, Interchangeability, Maturity, Nomadicity, Observability, Openness, Operability, Persistence, Privacy, Readability, Reconfigurability, Reporting, Reproducibility, Resource Utilization, Robustness, Schedulability, Simplicity, Sustainability, Time behavior, Trainability, Usability, User interface aesthetics, User-friendliness, Verifiability
Learnability	The ease of learning how to use the system	Learnability, Trainability
Accessibility	The ability for users with disabilities to use the system	Accessibility, Auditability, Localizability
Availability	The ability for the system to be accessible and usable when needed	Availability, Continuity of operation, Backup, Recoverability
Modularity	The ability to divide the system into smaller, independent parts that can be developed, tested, and deployed separately	Modularity, Composability, Extendability, Extensibility
Robustness	The ability of the system to handle unexpected or exceptional input or conditions without failure	Robustness, Fault tolerance, Immunity, Stability
Portability	The ability of the system to be transferred or moved to different environments or platforms	Portability, Transferability
Transparency	The ability of the system to be easily understood and predictable in its behavior	Transparency, Understandability, Traceability, Verifiability
Others	Other NFRs	Acceptability, Agility, Appropriateness, Attractiveness, Authenticity, Autonomy, Changeability, Concurrency, Configurability, Consistency, Controlability/Testability, Credibility, Data accessibility, Data integrity, Debuggability, Evolvability, Expandability, External consistency, Fidelity, Improvability, Installability, Interchangeability, Maturity, Nomadicity, Observability, Openness,

IEMS. Fig. 1 illustrates the main steps of our ontology construction process. We start by conducting a comprehensive literature review to gain a thorough understanding of the NFRs that are relevant for both industrial software development and the energy domain. Based on this review, we create a catalog of NFRs that covers various aspects such as security, performance, usability, and scalability. Next, we identify the critical factors of NFRs that affect the specific energy domain in its current state of complexity and dynamics. These factors include technologies, stakeholders, markets, and regulations that influence the quality attributes of IEMS. Based on these factors, we design and implement the ontology model using the OWL 2 DL standard (Motik et al., 2009). We define classes, properties, and relations to represent the classes and relationships of NFRs in the energy domain. Finally, we evaluate the ontology model using various methods to ensure its validity, usefulness, and applicability. We use a reasoning tool to check the consistency and completeness of the ontology model. We use RDF data management to demonstrate how the ontology model can support data integration and querying in the energy domain. We use user feedback to assess the usability and understandability of the ontology model. We use a case study to show how the ontology model can support IEMS development in a real-world project. We iterate the design and evaluation process to improve the ontology model based on the feedback and results.

3.2. Non-functional requirements selection

In this study, we conducted a literature review to investigate NFRs in the software industry. We identified 272 types of NFRs and organized them into 17 broad categories in Table 2. We found that only a small portion of these NFRs had been clearly defined, with the majority being unclear or fitting only specific cases. To address this problem, we created a comprehensive catalog of NFRs and defined 153 of them. This catalog is available on GitHub at https://github.com/RobertoMonaco/Energy-Framework and serves as a valuable resource for developers in the field. Compared to previous studies (ISO/IEC JTC 1/SC 7 Software and systems engineering, 2017; ISO, ISO, 2005), which listed 252 NFRs with only 52 being defined, our catalog constitutes a significant improvement in knowledge on the subject. Additionally, our study highlights the interconnectedness of NFRs and the importance of considering them holistically in the design and development of industrial software for the energy domain.

For the development of IEMS, we identified three key NFRs, including Scalability, Replicability, and Flexibility. These NFRs were considered important for ensuring that the energy management systems are usable, reliable, and perform well in practice, and are described below.

- **Scalability**: Scalability refers to the ability of a system to change its scale to meet growing demand, and is a desirable attribute of a network, system, or process. Poor scalability can result in poor system performance, necessitating the re-engineering or duplication of systems (Philippe and Hansman, 2008).
- **Replicability**: Replicability denotes the property of a system that allows it to be duplicated at another location or time. A replicable project refers to a project that successfully performs under different boundary conditions (e.g. simulation of market designs of different countries) (Sigrist et al., 2016).
- **Flexibility**: Flexibility refers to the ease with which a system or component can be modified for use in applications or environments other than those for which it was specifically designed. The platform is expected to be flexible enough to allow a large number of different types of industrial sites/parks to use it, i.e., it should allow many energy intensive process characterizations irrespective of the industrial sector and geographic location, and should also take into account supply–demand dynamics (ISO/IEC JTC 1/SC 7 Software and systems engineering, 2017).

After selecting these key NFRs, it is important to conduct an analysis of the energy domain to understand the factors that impact these requirements. This analysis will aid in designing energy management systems that effectively address the unique needs and challenges of the energy industry.

3.3. Energy domain critical factors

The critical factors of the energy domain that affect the quality requirements of energy management software operating on smart grid and district heating have been identified by analyzing similar studies. In particular, the study by Sigrist et al. (2016) highlighted the critical factors that would affect the scalability and replicability of energy transmission networks. These factors are grouped into four categories: technical, economic, regulatory and stakeholder acceptance.

1. **Technical factors** determine whether the solution developed in a particular project is inherently scalable and/or replicable, i.e., whether it is feasible to scale up and/or to replicate.
2. **Economic factors** reflect whether it is viable to pursue scaling up or replication. This step, validating whether investment analysis (e.g., internal rate of return, net present value, etc.) and business models hold at a larger scale or in a different setting than the original case, is often neglected and constitutes a major barrier.
3. **Regulatory factors** reflect the extent to which the current regulatory environment is ready to embrace a scaled-up version of a project.
4. **Stakeholder acceptance** is the extent to which stakeholders are ready to embrace a new/enlarged project. For the successful implementation of a solution, it is important that all involved stakeholders accept and support the scheme.

The identification of classes for the ontology was carried out by considering these four points of view, in order to develop an exhaustive and complete framework. This framework will help to ensure that the energy management systems are designed in a way that addresses the specific needs and challenges of the energy industry.

3.4. Design of the NFRs-based ontology

In this section, we will delve into the design of an ontology that incorporates the three key NFRs of Scalability, Replicability, and Flexibility. This is an essential step in ensuring that energy management systems effectively address the unique challenges and requirements of the energy industry. We will outline the process of creating the ontology and identify the key classes, subclasses, relationships, and properties that comprise it.

3.4.1. Classes identification

In order to thoroughly understand the requirements and factors impacting the scalability, replicability, and flexibility of energy management systems, we have identified and analyzed four main classes for the NFRs-based ontology: Regulations, Stakeholders, Technologies and Markets. Each of these classes was further broken down into relevant subclasses, which were assigned their respective object and data properties. Through this process, we were able to explore the relationships between classes and subclasses, allowing us to gain a comprehensive understanding of the energy domain. The development of this ontology was carried out using the Protege software, which provides a graphical user interface and a set of tools for creating and editing ontologies. This approach ensured that the ontology was complete and exhaustive, providing a framework for understanding and addressing the specific needs and challenges of the energy industry.

3.4.2. Regulations class

Regulatory and legal issues can greatly impact the scalability and replicability of energy management systems. Regulations define the roles and responsibilities of agents, the rules and requirements to provide services, and the rules on how to remunerate regulated activities, as well as the rules on interaction between agents. In terms of scalability, regulation is understood in terms of its impact on the size and scope of the project. The rules and requirements to provide certain services can mostly affect scalability. Our analysis of the regulations considers whether there are any regulatory barriers with respect to the size and scope of the solution. Regulations vary from country to country and there is no single European regulation. For this reason, each regulation is associated with a country in which it is in force and can also have a range of regional, national or even European validity. The regulations can also be push or pull and can include taxes, subsidies or compliance with standards as specified in several studies as (Steg et al., 2006; Brückmann and Bernauer, 2020). This is illustrated in Fig. 2, which represents the relation between the Regulations class and its subclasses. The Regulations class is closely connected with the Stakeholders class as policy makers promote new policies while users influence their acceptability. These relationships are intended to provide a clear and organized view of how different elements in the energy domain are related to each other. It is important to note that these relationships may change over time as new information becomes available or as the energy domain evolves.

Subclasses.

1. **Taxes**: Taxes are a means by which governments can raise revenue and can be imposed on individuals or entities. They can serve a variety of purposes, such as funding government expenditures, influencing economic behavior, or redistributing wealth. Taxes can take many forms, such as taxes on fuel input, heat output, capacity, or electricity consumption (Encyclopedia Britannica, 2023b).
2. **Subsidies**: Subsidies are financial support provided by governments to private firms, households, or other governmental units in order to achieve a public objective. These can take various forms, such as direct payments, economic concessions, or privileges, and can be used to promote certain industries, incentivize certain behaviors, or address market failures. Identification of subsidies can be challenging due to the complexity of the instruments, objectives, and effects (Encyclopedia Britannica, 2023a).

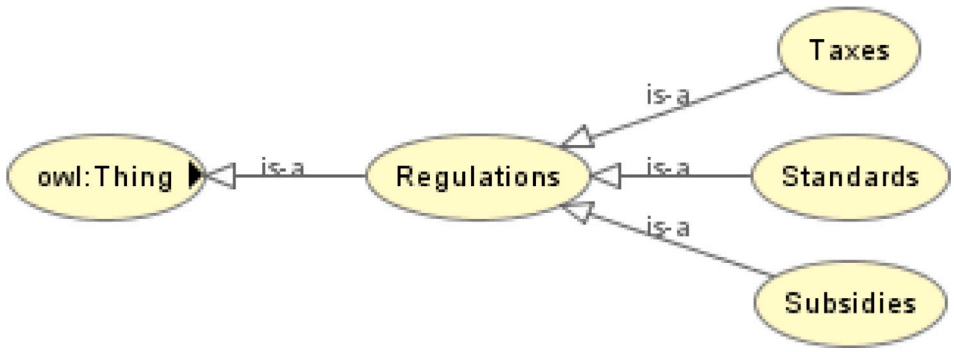

Fig. 2. Regulations class and Its subclasses.

3. **Standards**: Standards are regulations and targets established by governments or international organizations that are intended to be met. They can vary in scope and impact, from country-specific regulations to international agreements, and can cover a wide range of issues such as environmental protection, safety, or quality control, for example, reduction of CO2 emission before a target year.

Object properties.

- **Rule**: Regulations have a significant impact on the behavior of stakeholders by influencing their decisions. They also play a role in defining the different market contexts in which energy management systems operate. Additionally, regulations also play a role in shaping the use of new technologies.
  - Regulations **RULE** Stakeholders;
  - Regulations **RULE** Markets;
  - Regulations **RULE** Technologies;

Data properties.

- **Country**: Regulations can vary between countries, thus it is important to identify in which country a particular regulation is valid.
- **Range**: Regulations can have different ranges of application, such as regional, national, or international.
- **Push or Pull**: Regulations can be classified as push or pull measures depending on whether they increase or decrease the cost of environmentally unsound behavior. This distinction is important in understanding the acceptability of a particular regulation among stakeholders. For example, a carbon tax would be considered a push measure as it increases the cost of carbon-emitting activities, while a subsidy for renewable energy would be considered a pull measure as it decreases the cost of environmentally friendly activities.
- **Name**,**Value**,**Year** (subclasses data properties): The main class "Regulations" is divided into three subclasses: Standard, Taxes, and Subsidies. Each of these subclasses is characterized by a specific name, value, and the year it was issued.

Relations. In the end, we can see that the "Regulations" class has relationships with four other classes:

- **Stakeholders**: Regulations can affect the objectives and targets of stakeholders and therefore have a direct impact on their behavior. On the other hand, stakeholders must also accept new regulations. This aspect is crucial as regulations should not only regulate and protect, but also encourage stakeholders to invest in the sector by providing appropriate policies. Therefore, the acceptance factor of stakeholders becomes fundamental and cannot be ignored. If regulations are not suitable, actors involved in the energy sector will not feel protected, leading to a decrease in investments and a decline in the entire sector.
- **Policy makers** (Stakeholders subclass): Policy makers are responsible for enacting regulations. While it may seem straightforward, it is also important to consider this type of relationship. Policy makers operate in different environments and are driven by different objectives, which leads to the issuance of different regulations aimed at satisfying different needs in different countries.
- **Technologies**: The use of certain technologies is regulated by specific standards and regulations. The type of regulation associated with a particular technology is very important and can affect the flow of investments. Given the regulatory differences across Europe, it is possible to find different technologies in different countries, as some regulations provide more incentives for the use of certain technologies while others provide more incentives for the use of others.
- **Markets**: Each market is characterized by different rules. In fact, the type of regulations can be used to classify different types of products.

3.4.3. Stakeholders class

The stakeholders of the platform, but more generally of the energy domain, play a crucial role in the scalability of a project. They are not only the direct users of the platform, but they also influence the creation and acceptance of new energy policies. As previously mentioned, regulations have a significant impact on scalability, making the relationship between stakeholders and regulations important in understanding the scalability of a project. Public acceptability is an essential factor in the design of effective policy, as highlighted in studies such as (Bicket and Vanner, 2016). Policies for a transition to sustainable resource use will likely involve a significant change in behavior and practices, making the consent and cooperation of actors at various levels, from the individual to the multinational, crucial. Stakeholders from different countries have different attitudes towards the acceptability of new technologies and energy policies, which is why one of the properties of this class is the country of origin. In this model, stakeholders are primarily classified as users of the generic industrial energy management platform. They can be classified as sinks or sources based on their type of business and energy usage. The Stakeholder and Regulations classes are closely connected, as policy makers promote new policies while users influence their acceptability. The same applies to the Technologies class. This is illustrated in Fig. 3, which represents the relation between the Relations class and its subclasses.

Subclasses.

1. **Policy makers**: These are individuals or entities who have the authority to create and implement regulations in the energy field. They play a crucial role in shaping the direction and trajectory of the sector, and their decisions can significantly impact the choices and investments of other stakeholders.
2. **Investors**: This subclass encompasses the various entities that invest in the energy field, such as utility companies, municipalities, DHN operators, and excess heating producers. They are motivated by different business goals and purposes, and their investment decisions are influenced by the policies and regulations in place.

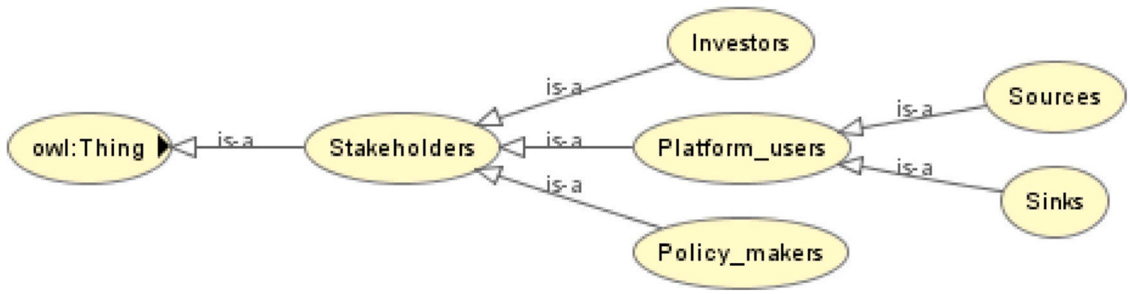

Fig. 3. Stakeholders class and its subclasses.

3. **Platform users**: These are the individuals or entities that use the platform and are directly involved in the energy domain. They can be further divided into two subclasses:
   - **Sinks**: These are users who represent the demand for energy. They have different business types and energy usage requirements and can be characterized by data properties such as Business and Energy Usage.
   - **Sources**: These are users who make their excess energy production available on the platform. They represent the supply side of the market and can be characterized by data properties such as Business and Energy Production.

Object properties.

- **Accept**: The acceptance of new regulations and technologies by stakeholders is a crucial factor in assessing the scalability and replicability of new projects in the energy domain (Toft et al., 2014).
  - Stakeholders **ACCEPT** Regulations;
  - Stakeholders **ACCEPT** Technologies;
  - Policy Makers **ENACT** Regulations;

Data properties.

- **Country**: Stakeholders can come from different countries and have different perspectives and cultural views on energy issues.
- **Energy sector type**: Each stakeholder may have an interest or involvement in a specific type of energy sector, such as the gas sector, smart grid, district heating and cooling, etc.
- **Business**: Each stakeholder may have a different business or industry that they are involved in, within the energy sector.
- **Scope**: Each stakeholder may have different objectives and goals, depending on their role and the market environment they operate in.

Relations.

- **Regulations**: Stakeholder acceptance is a crucial factor in determining the scalability and replicability of new projects in the energy domain. Therefore, it is important to understand how stakeholders interact with regulations in order to develop a comprehensive framework;
- **Technology**: The introduction of new technologies also means an increased need for knowledge. If stakeholders do not perceive a need for a new technology or do not have incentives to use it, the technology is likely to fail. Therefore, it is important that new technologies are designed to be user-friendly and positively perceived by stakeholders (Toft et al., 2014);
- **Cloud security**: Stakeholders must be adequately protected with regard to the security of their data and work data. Data integrity is particularly important in the cloud environment where public cloud computing is, by its nature, a shared environment and virtual machines (VMs) are sharing infrastructure, hardware and software with other cloud tenants. Therefore, it is important to thoroughly research your cloud provider to ensure that all applicable cloud security mechanisms are implemented and functioning as designed.

3.4.4. Technologies class

The technologies class in our model encompasses a range of tools and technologies that impact the scalability of energy management platforms. These tools can be divided into two categories: those that directly impact scalability, such as cloud and software technologies, and those that have an indirect impact, such as technologies for energy transmission, such as smart grids and district heating and cooling (DHC) networks. The direct scalability of energy management platforms depends on the use of advanced software and cloud technologies that enable efficient and effective energy management. For example, the use of cloud computing can greatly enhance the scalability of energy management platforms by allowing for remote access, data sharing and collaboration, and easy scalability of resources. Similarly, the use of advanced software tools and algorithms can enable more accurate forecasting, monitoring, and optimization of energy usage. The indirect scalability of energy management platforms depends on external factors such as energy policies and the acceptance of stakeholders. For instance, the scalability of smart grid and DHC networks also depends on the regulatory framework and the acceptance of users. It is important to note that the introduction and implementation of new technologies, such as smart grids, also requires new regulations and standards to be in place in order to ensure their proper functioning and safety. Furthermore, the acceptance of stakeholders is crucial for the successful implementation of new technologies, as it is their willingness to adopt and use these technologies that ultimately determines their scalability. Technologies class and its subclasses, as well as its relations to other classes, are presented in Fig. 4.

In summary, the technologies class in our model is closely connected to the regulations and stakeholders classes, as the introduction and implementation of new technologies are governed by regulations, and the scalability of these technologies is determined by the acceptance of stakeholders.

Subclasses.

1. **Cloud tools**: In a smart grid environment, multiple devices such as smart meters, substations, micro-grids, home appliances, sensor nodes, and communication network devices are implemented. These devices generate massive data for real-time communication with the utilities, and to handle this data efficiently and effectively, smart grid relies on advanced information technologies such as cloud computing, storage, and security. Cloud computing, in particular, is considered a next-generation computing and storage paradigm, offering benefits such as rapid deployment, flexibility, low up-front costs, and scalability, which makes it virtually universal among organizations of all sizes, often as part of a hybrid/multi-cloud infrastructure architecture (Checkpoint, 2021). Cloud storage enables businesses and consumers to save data securely online, making it accessible at any time from any location and easily shared with those who are granted permission. Additionally, it also offers a way to back up data to facilitate recovery off-site (Investopedia, 2021). Cloud security refers to the technologies, policies, controls, and services that protect cloud data, applications, and infrastructure from threats (Checkpoint, 2021).

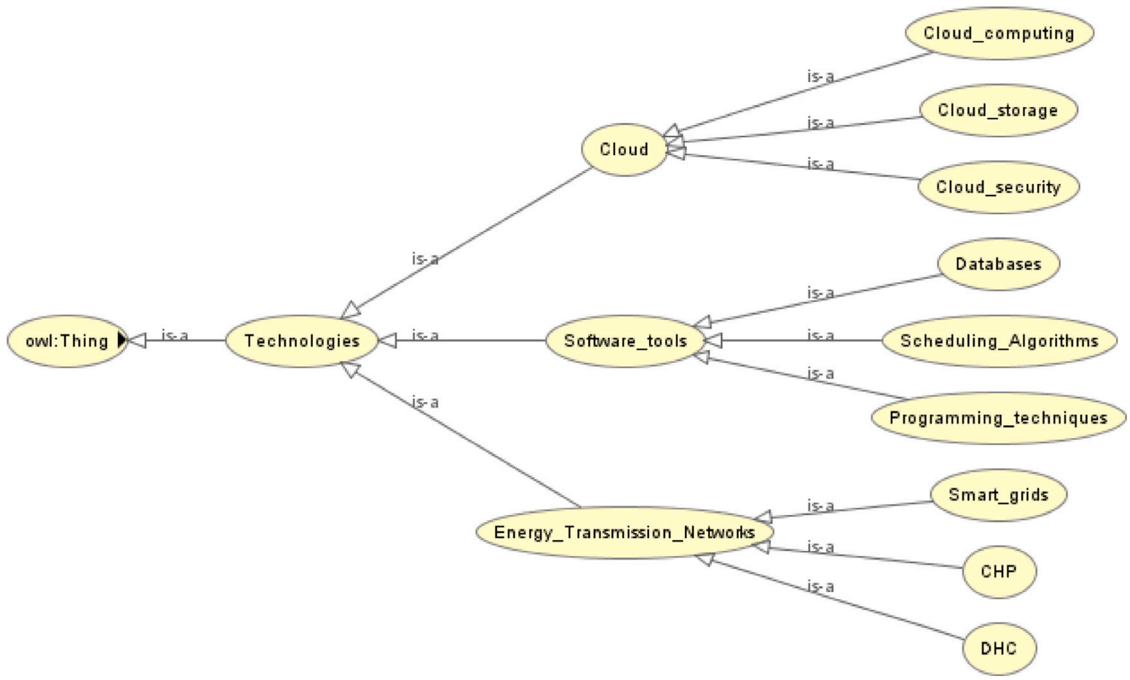

Fig. 4. Technologies class and Its subclasses.

2. **Software tools**: The software tools used for the development of Industrial Software Platforms are fundamental for the hypothetical future scalability and replicability of the results. The growing amount of data to be managed must be stored efficiently and must not lead to a decline in instrument performance. This depends on the purely IT structure of the platform, which includes tools such as the database and scheduling algorithms. This factor presents a series of subclasses, including:

- **Database**: The capacity and structure of the database affects both performance and system scalability.
- **Scheduling algorithms**: Systems with poor load scalability may exhibit it because they engage in wasteful activity, have poor scheduling algorithms, cannot fully take advantage of parallelism, or are algorithmically inefficient (Bondi, 2000).
- **Energy transmission networks**: Energy transmission networks are varied and differ in the type of energy they distribute in the network. Different networks imply different structures and a different system of regulation. In some contexts, the construction and maintenance of these networks can be a determining factor in the scalability and replicability of the project. Examples of energy transmission networks include traditional power grids, microgrids, and district heating and cooling (DHC) networks (Toft et al., 2014). The scalability of these networks is dependent on factors such as energy policies, regulations, and stakeholder acceptance.

Overall, the technologies class plays a crucial role in the scalability and replicability of a project in the energy domain. The use of cloud tools, software tools, and energy transmission networks all contribute to the effectiveness and efficiency of the project, and must be carefully considered when developing and implementing an energy management platform. Factors such as regulations, stakeholder acceptance, and data management must also be taken into account in order to ensure the long-term success of the project.

Object properties.

- **Safeguard**: Ensuring data integrity is a crucial aspect of cloud security, as it helps to protect the interests of all stakeholders. This can be achieved through various measures such as encryption, access controls, and regular security audits. Additionally, compliance with industry standards and regulations, such as the General Data Protection Regulation (GDPR) and the Federal Risk and Authorization Management Program (FedRAMP), can further enhance the security of the cloud environment and safeguard the interests of stakeholders.
  - **Cloud security** measures such as encryption, access controls, and regular security audits **SAFEGUARD** Stakeholders by ensuring the integrity of their data.

Data properties.

- **Type** (“Programming techniques” subclass property): Various programming techniques, such as sparse matrix methods or compression, can be used to achieve space scalability in software tools. However, it is important to note that the use of compression techniques may come at the cost of load scalability, as compression typically requires additional computational resources.
- **Type** (“Scheduling Algorithms” subclass property): Scheduling algorithms are used to manage the allocation of resources in software tools. Different scheduling algorithms, such as FIFO, Earliest Deadline First Scheduling, and Shortest Remaining Time, have different objectives and trade-offs. For example, FIFO (first in, first out) prioritizes the requests that were made first, while Earliest Deadline First Scheduling prioritizes requests with the nearest deadline.
- **Type** (“Databases” subclass property): Databases can come in various forms, such as relational databases, object-oriented databases, distributed databases, data warehouses, NoSQL databases, graph databases, and OLTP databases. Each type of database has its own strengths and weaknesses, and is suited to different use cases.
- **URL** (“Databases” subclass property): Each database is identified by a unique URL, which allows for easy access and identification of the database.
- **Triggers**[2] (“Databases” subclass property): Triggers are an important aspect of database management, as they allow for automated actions

[2] A database trigger is procedural code that is automatically executed in response to certain events on a particular table or view in a database. The trigger is mostly used for maintaining the integrity of the information on the database.

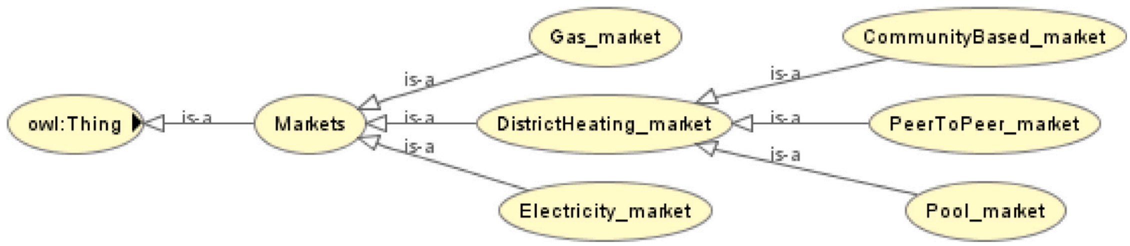

Fig. 5. Markets class and Its subclasses.

to be taken in response to specific events, such as the insertion or deletion of data. This can help to ensure the integrity of the data stored in the database.

Relations.

- **Regulations**: As already explained in previous paragraphs, the Regulations Class dictates the use and implementation of technologies in the energy management platform. The use of certain tools and technologies is regulated by specific standards and regulations, which can greatly impact the flow of investments in a particular technology.
- **Stakeholders**: The acceptance and perception of new technologies by stakeholders is crucial for their success. The proposed technology must be user-friendly and positively perceived by its intended users in order to gain acceptance and avoid failure (Toft et al., 2014).
- **Markets**: The type of energy used on an industrial level is regulated by different markets, which in turn dictate the use and implementation of different energy transmission systems. Regulations and policies vary between states and regions, which can greatly impact the viability of investments in certain energy networks.

3.4.5. Markets class

The markets class in the energy sector is a complex and dynamic aspect that plays a crucial role in determining the scalability and sustainability of energy projects. The type of energy, the regulatory framework, and the actors involved all impact the design and functioning of the market. For example, the market for electricity is different from that of district heating or gas, and this can lead to different configurations of market clearing prices and energy dispatch. The markets class in our model includes different types of markets, such as liberalized and regulated markets, and different market actors, such as generators, transmission system operators, and retailers. The interactions between these actors and their roles and responsibilities are also considered in this class. Furthermore, the market class also takes into account the tariff structure, taxes, and subsidy schemes that may apply to different energy markets. The markets class is closely connected to the Regulations and Stakeholders classes, as the regulatory framework and the acceptability of stakeholders are key factors that influence the functioning and design of the market. Users of the model must be able to explore different market designs, from centralized to decentralized, to determine the best market framework for their interests, which can be economic, environmental, or social. This is illustrated in Fig. 5, which represents the relation between the market class and its subclasses.

Subclasses.

1. **Gas market**: The gas market is a complex system that encompasses the production, transportation, storage, and distribution of natural gas. It is essential for the functioning of the energy sector and has significant impact on the economy and the environment. The gas market is influenced by various factors such as supply and demand, technological advancements, regulatory framework and geopolitical considerations.
2. **District heating market**: District heating is a cost-effective and efficient way of supplying heat to buildings and communities. The heat is generated in a centralized location and distributed through a network of insulated pipes to various buildings such as offices, residential and industrial buildings. The heat is used for various residential and commercial heating such as room or floor heating and water heating. The heat is generally achieved by geothermal heating, central solar heating, and waste heat from the nuclear power plant. The district heating market is influenced by various factors such as energy efficiency, environmental regulations and policies, and the cost of energy sources.
   - **Pool market**: The pool market is a centralized market design that uses the merit order mechanism to determine the market clearing price through the intersection of supply and demand curves. The goal of the pool market is to maximize social welfare by accepting lower offers from producers and higher offers from consumers. This market design is widely used in countries with regulated energy markets and is subject to regulatory oversight and intervention (Faria et al., 2021);
   - **Peer to peer market**: Peer-to-peer (P2P) energy trading allows for two different parties to trade energy on a bilateral basis, without the need for a third-party intermediary. P2P energy trading allows for greater flexibility and autonomy for energy consumers and producers, and has the potential to increase the efficiency and resilience of energy markets (Sorin et al., 2018).
   - **Community-based market**: Community-based energy markets are designed to promote decentralized energy trading within communities. These markets are characterized by a more hierarchical structure of bilateral peer trades. Communities are composed of members who share common interests or are geographically close. In this model, there is a community manager responsible for the community's energy management. This manager supervises all the trading activities within the community, as well as serves as an intermediary in the energy trade with other communities or with the main grid (Sousa et al., 2019);
3. **Electricity market**: The electricity market is a complex system that encompasses the generation, transmission, distribution, and consumption of electricity. It is essential for the functioning of the energy sector and has significant impact on the economy and the environment. The electricity market is influenced by various factors such as supply and demand, technological advancements, regulatory framework and geopolitical considerations.

Object properties.

- **Impact**: The type of market has a significant impact on the decision-making process of the stakeholders. Furthermore, in the energy context, each type of energy source follows its own market patterns and consequently the technologies are also influenced by the type of market. In particular, for each type of market a particular energy distribution network is used and for this reason this relationship must be considered.
  – Market **IMPACT** Stakeholders' decision-making process;
  – Market **IMPACT** Energy Transmission Networks' design and operation.

Fig. 6. Identified classes for the Energy Framework Ontology.

Relations.

- **Stakeholders**: The type of market in which a company operates can have a significant impact on the decision-making process of its stakeholders. Different regulations and interactions between market players can influence the choices and actions of stakeholders.
- **Energy transmission networks**: Different energy sources require different energy transmission systems. The type of market that regulates a specific energy source can also influence the choice of energy transmission network. Regulations and policies vary across different states and regions, and can affect the decision of investors to invest in a particular energy network.
- **Regulations**: The policies and regulations that govern a specific market play a crucial role in shaping the market design. They dictate the prices, relationships between market players, and standards that must be followed in that market. These regulations can vary across different markets and can have a significant impact on the functioning of the market.

4. Evaluation

In this section, we will evaluate the proposed ontology (see Fig. 6) from four different perspectives. First, we perform a technical validation of the ontology's syntactic and semantic features by utilizing a reasoner to verify the formal structure of the ontology. Second, we assess the ontology in terms of its support for RDF data management. Third, we evaluate the proposed ontology through user evaluations to gather feedback on its usability and applicability. Lastly, we evaluate the ontology by examining its ability to support the development of a real-world case study of IEMS, including the development of a knowledge base platform and the establishment of a regulatory framework.

4.1. Technical validation

We utilized the HermiT reasoner (v1.3.8) (Shearer et al., 2008) on the Protege platform to formally validate the syntactic and semantic features of our ontology. The Protégé ontology editor (Horridge and Bechhofer, 2011) was used to define the classes and their relationships, providing a user-friendly interface for creating and editing ontologies. It allowed us to define classes, properties, and axioms using a variety of built-in tools. For subclasses explicitly defined in the ontology, Protégé displays them without having to run a reasoner, allowing us to quickly view and edit the class hierarchy without having to wait for time-consuming reasoning tasks to complete.

However, for more complex ontologies with many inferred relationships or complex axioms, it may be necessary to use a reasoner such as HermiT to fully explore the class hierarchy and ensure its consistency. We first ran HermiT on the ontology to check for any inconsistencies or errors. The reasoner identified no errors or inconsistencies in the model, indicating that it was well-formed and consistent. Next, we used HermiT to perform inferences on the data and extract information from the ontology. For example, we used SPARQL-DL (Sirin et al., 2007) to pose queries to our ontology and obtain answers from HermiT. We used these queries to answer specific research questions or test hypotheses related to our domain. For example, we queried for the direct sub-classes of "energy:Markets" to identify the different types of markets in our ontology, and we found that the two sub-classes: "energy:Electricity_market" and "energy:Gas_market" were returned correctly. To get more insights from our ontology, we also used HermiT's explanation feature (Horridge et al., 2008; Kalyanpur et al., 2006) to find out the reasons and evidence for certain logical consequences or contradictions in our model. For instance, we asked HermiT to explain how it inferred that "energy:Electricity_market" is a sub-class of "energy:Markets". HermiT showed us the true value, which means that "energy:Electricity_market" is a more specific type of "energy:Markets". The used HermiT command and the query ontology are shown in Listing 1 and 2, respectively.

Listing 1: Hermit command for check ontology entailments

```
java -jar Hermit.jar --premise=file:///ontology.
    owl --conclusion=file:///query.owl --
    checkEntailment
```

Listing 2: query.owl

```
<?xml version="1.0"?>
<!DOCTYPE rdf:RDF [
    <!ENTITY owl "http://www.w3.org/2002/07/owl#" >
    <!ENTITY xsd "http://www.w3.org/2001/XMLSchema#" >
    <!ENTITY rdfs "http://www.w3.org/2000/01/rdf-schema#" >
    <!ENTITY rdf "http://www.w3.org/1999/02/22-rdf-syntax-
         ns#" >
]>
<!ENTITY Energy_Framework "http://www.semanticweb.org/
     robertomonaco/ontologies/2021/5/Energy_Framework#" >
<rdf:RDF xmlns="http://www.semanticweb.org/robertomonaco/
     ontologies/2021/5/Energy_Framework#"
    xml:base="http://www.semanticweb.org/robertomonaco/
         ontologies/2021/5/Energy_Framework"
    xmlns:rdfs="http://www.w3.org/2000/01/rdf-schema#"
    xmlns:owl="http://www.w3.org/2002/07/owl#"
    xmlns:xsd="http://www.w3.org/2001/XMLSchema#"
    xmlns:rdf="http://www.w3.org/1999/02/22-rdf-syntax-ns#
         ">
   <owl:Ontology rdf:about="http://www.semanticweb.org/
        robertomonaco/ontologies/2021/5/Energy_Framework"
        />
   <owl:Class rdf:about="&Energy_Framework;
        Electricity_market"/>
   <owl:Class rdf:about="&Energy_Framework;Markets"/>
   <rdf:Description>
       <rdf:type rdf:resource="&owl;Axiom"/>
       <rdfs:label>SubClassOf(Electricity_market Markets)
            </rdfs:label>
       <owl:annotatedSource rdf:resource="&
            Energy_Framework;Electricity_market"/>
       <owl:annotatedProperty rdf:resource="&rdfs;
            subClassOf"/>
       <owl:annotatedTarget rdf:resource="&
            Energy_Framework;Markets"/>
       <rdfs:subClassOf>
           <rdf:Description rdf:about="&Energy_Framework;
                Markets"/>
       </rdfs:subClassOf>
   </rdf:Description>
</rdf:RDF>
```

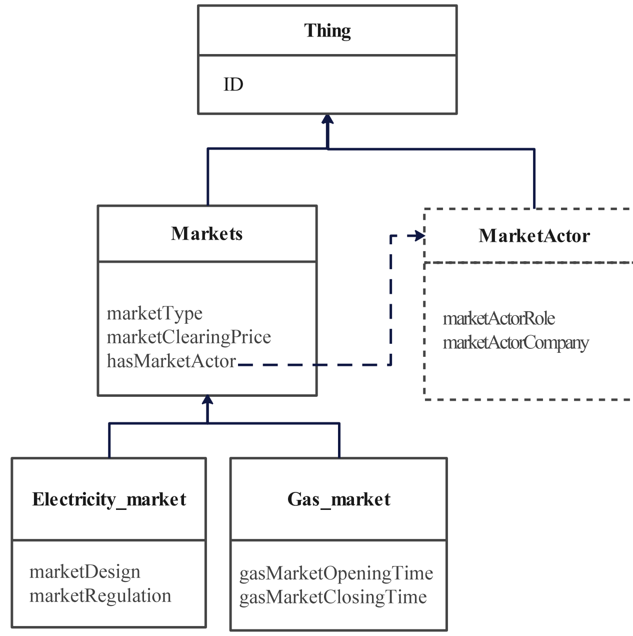

Fig. 7. Ontology for markets.

The above tests show how we used HermiT to obtain useful and relevant information from our ontology. HermiT was a powerful and efficient tool for ontology reasoning and query answering. It helped us to validate the consistency and correctness of our ontology, as well as to extract detailed information about the classes and relationships in the energy domain. It also helped us to understand the logical consequences of our ontology and debug any errors or anomalies. By using SPARQL-DL queries and explanations, we were able to answer specific research questions or test hypotheses related to our domain. For example, we learned the different types of markets in our ontology and their properties, such as "energy:Electricity_market" and "energy:Gas_market".

4.2. Evaluation by RDF data management

In our paper, we evaluate the proposed ontology model by creating an RDF/OWL store and querying the RDF triples. RDF is a standard model for data interchange on the web that provides a way to describe resources and their relationships with other resources in a machine-readable format using triples (Liu et al., 2011, 2012). By using RDF, we can store and query information about energy management systems in a machine-readable format that can be easily shared and processed by other software systems. Without losing generality, this experiment will evaluate a subset of the proposed ontology, specifically the Markets class and its subclasses including the Electricity_market and Gas_Market. For each of the classes, we will add dataProperty and for the Market class, an objectProperty called "marketActor" is created, which references the MarketActor class that we created for this evaluation. The root class of all classes is Thing, which has a single dataProperty, "ID". The obtained hierarchical structure of the classes and their properties are shown in Fig. 7.

Next, we generate synthetic RDF triple data based on the ontology's structure and properties, as we did not have access to real-world data for this newly designed ontology. We then populate the triples into the

RDF/OWL data store, Apache Jena. Jena is a popular RDF data store that provides a set of libraries for working with RDF data in Java. It is a widely used and well-established tool in the field of semantic web technologies and has been used in many academic and industry projects. Jena provides efficient querying and inference capabilities, and has a rich set of APIs and features that allow for easy integration with other tools and frameworks, such as SPARQL and OWL reasoners. Additionally, Jena has a strong community contributing to its development and continues to support it, which makes it a reliable and stable option for this experiment.

The proposed ontology is evaluated through a series of tests that assess its validity and applicability. The first test involves validating the ontology itself using Jena API (see Listing 3). This test allows us to ensure that the ontology is consistent, that all classes and properties are correctly defined and that all relationships between classes and properties are logical. The second test involves querying the RDF data stored in the Jena triple store using SPARQL, a query language for RDF data (see Listing 4). This test allows us to evaluate the ability of the ontology to support data retrieval and analysis. The third test involves performing inferences on the data using the reasoner in Jena (see Listing 5), which is capable of classifying complex ontologies. This test allows us to evaluate the ability of the ontology to support reasoning and decision-making.

Listing 3: Validate the ontology

```
// Create an ontology
OntModel ontModel = ModelFactory
        .createOntologyModel(OntModelSpec.
            OWL_MEM);

// Read the ontology file
ontModel.read(``~/ontology.owl", ``RDF/XML"
     );

// Create a data model
Model dataModel = ModelFactory.
     createDefaultModel();

// Read the data file
dataModel.read(``~/data.rdf", ``RDF/XML");

// Bind the data model to the ontology
ontModel.addSubModel(dataModel);

// Validate the data against the ontology
ValidityReport report = ontModel.validate()
     ;
if (report.isValid()) {
     System.out.println(``Data is valid
          according to the ontology.");
} else {
     System.out.println(``Data is not valid
          according to the ontology:");
     for (Iterator i = report.getReports();
          i.hasNext(); ) {
          System.out.println(`` - " + i.next
               ());
     }
}
```

Listing 4: Query data from RDF tripple store using SPARQL

```
PREFIX en: http://www.semanticweb.org/
     robertomonaco/ontologies/2021/5/
     Energy_Framework#
SELECT ?marketActor
WHERE {
?electricMarket en:hasMarketActor ?
     marketActor.
?electricMarket rdf:type en:
     Electricity_market .
?marketActor en:marketActorRole ``Generator
     "^^xsd:string
}
```

Listing 5: Perform inferences based on the ontology

```
// Create an empty model
Model model = ModelFactory.
     createDefaultModel();

// Read the ontology into the model
model.read(``~/ontology.owl", ``RDF/XML");

// Create an inference model using Jena's
    OWL reasoner
Reasoner reasoner = new Reasoner();
InfModel infModel = ModelFactory.
     createInfModel(reasoner, model);

// Perform the inference
infModel.prepare();

// Query the inferred triples
String queryString = ``SELECT ?x WHERE {?x
     rdf:type Markets}";
Query query = QueryFactory.create(
     queryString);
QueryExecution qe = QueryExecutionFactory.
     create(query, infModel);
ResultSet results = qe.execSelect();

// Print out the results
while (results.hasNext()) {
     QuerySolution solution = results.next()
          ;
     System.out.println(solution.get(``x"));
}
```

For the Listings 3, 4 and 5, we can obtain the proper following samples of the outputs:

```
Data is valid according to the ontology.
```

```
http://www.semanticweb.org/robertomonaco/
    ontologies/2021/5/Energy_Framework#
    MarketActor_MA001
http://www.semanticweb.org/robertomonaco/
    ontologies/2021/5/Energy_Framework#
    MarketActor_MA002
...
```

```
http://www.semanticweb.org/robertomonaco/
     ontologies/2021/5/Energy_Framework#
     ElectricityMarket1
http://www.semanticweb.org/robertomonaco/
     ontologies/2021/5/Energy_Framework#
     ElectricityMarket2
...
http://www.semanticweb.org/robertomonaco/
     ontologies/2021/5/Energy_Framework#
     GasMarket1
http://www.semanticweb.org/robertomonaco/
     ontologies/2021/5/Energy_Framework#
     GasMarket2
...
```

The proposed ontology was successfully validated by using triple data that conforms to the model. We performed three test queries to evaluate the ontology. The first query returned all the market actors in the ontology. The second query returned all the market actors that have the role of "Generator" and are related to an `electricMarket` of type `en:Electricity_market`. The third query returned all the subclasses of the `Markets` class, including `en:Electricity_market` and `en:Gas_market`. These queries demonstrate that the ontology can support data integration and inference in the energy domain.

4.3. Evaluation by user evaluations

In order to evaluate the proposed ontology, we conducted user evaluations within the team of our EMB3Rs project (https://www.emb3rs.eu). The EMB3Rs platform is a simulation tool for optimizing the matching of excess heat sources and sinks of heat consumers, and the proposed ontology aims to support its development.

Before conducting a survey, we presented the proposed ontology in the project meeting and demonstrated how it could be used to support various aspects of energy management software development, such as identifying relevant classes and relationships within the energy domain and facilitating communication between developers with different backgrounds and expertise. Specifically, we provided examples of how different classes and properties within the ontology could be used to represent important classes related to energy management, such as energy sources, consumption patterns, and market actors. We also demonstrated how these classes could be linked together through relationships such as "is-a", "part-of", and "has-property". After the demonstration, we conducted the survey to evaluate the usability and effectiveness of the proposed ontology in supporting the development process of the EMB3Rs platform (see the survey questions in the support materials). We received evaluations from 25 participants, including nine developers who were involved in the implementation of the EMB3Rs platform. The evaluations were carried out through in-depth conversations with the developers, and the ontology was used as a reference in their database and software architecture design, and knowledge base design. Therefore, their opinions were particularly important in our evaluation.

The results were overwhelmingly positive, with an average satisfaction rating of 4.6 out of 5. Participants agreed that the ontology was easy to navigate and understand, providing a clear and organized structure for the development of the energy management platform. They also noted that the model's clear representation of relationships between different classes and properties in the energy domain was particularly useful in supporting the development of the EMB3Rs platform. Participants reported that the ontology was useful in understanding the relationships between different technologies, stakeholders, markets, and regulations. The majority of participants stated that the ontology was beneficial in supporting the development of energy management software systems, particularly in terms of scalability and replicability of the platform. Lastly, participants suggested that the ontology could be further enhanced by incorporating additional classes and properties, such as those related to renewable energy sources and carbon emissions. These results demonstrate the efficiency and effectiveness of the proposed ontology in supporting the development of IEMS.

4.4. Evaluation by a real-world case study of IEMS

The proposed ontology model for IEMS was evaluated through both user evaluations and a real-world case study of its implementation in the EMB3Rs platform. The user evaluations have highlighted the usefulness of the ontology in understanding relationships between different technologies, stakeholders, markets, and regulations within the energy domain. The ontology was also found to be beneficial in supporting various activities related to energy management software development, including identifying relevant classes and relationships within the domain, facilitating communication between team members with different backgrounds and expertise, and supporting scalability and replicability of software platforms. To further understand the impact of the ontology on the development of the EMB3Rs platform, we present a case study on the development of the Knowledge Base (KB) and Regulatory Framework (RF) within the platform, demonstrating the ontology's effectiveness in addressing scalability and replicability challenges within the platform.

The EMB3Rs platform is a web-based tool that aims to provide solutions for industrial excess heat/cold recovery and utilization by matching local supply and demand. The platform targets different types of stakeholders, such as industrial sites, energy communities, energy service companies, and public authorities. The platform consists of several modules that perform different tasks, such as data collection and management, techno-economic analysis, environmental impact assessment, business model development, and regulatory framework analysis. The platform is designed to be adaptable and scalable to different scenarios, contexts, and domains that involve energy management.

4.4.1. Support for EMB3Rs platform knowledge base design

The KB of EMB3Rs platform provides access to a structured database for all data needs, including input and output data for the platform's analysis modules. The KB supports simulations by filling in gaps in information on excess heat recovery and demand, allowing for the pre-population of analysis modules with default/reference data and estimations. The KB includes a pre-built library of technological options for energy recovery, storage, and distribution, which can be expanded upon by platform users. The library also includes data on excess heat sources, heating/cooling needs in different sectors, district heating and cooling network information, and business models. The KB's architecture also allows for the storage of analysis outputs from users and accommodates different APIs, scalability, and data privacy needs.

The design of the KB was based on the proposed ontology model for IEMS. The ontology provided a clear and consistent representation of the energy domain concepts and their relationships, which facilitated the identification and organization of the relevant data for the KB. The ontology also helped to define the structure and schema of the database tables and fields, as well as the queries and operations for data manipulation and retrieval. Moreover, the ontology enabled the integration and interoperability of data from different sources and formats, such as CSV files, XML files, RDF files, web services, etc., by providing a common vocabulary and a shared understanding of the data semantics. Furthermore, the ontology supported the scalability and replicability of the KB by allowing for easy addition or modification of data according to different scenarios or domains. For example, new technological options or business models can be added to the library by using the ontology classes and properties as templates. Similarly, new excess heat sources or demand profiles can be added to the database by following the ontology structure and definitions.

To illustrate how the ontology helped to design the KB for the EMB3Rs platform, we present a real-world project where we applied our approach to support an industrial site in Portugal that produces ceramic tiles. The site has an excess heat source from a kiln that operates at 900 °C with a thermal power output of 2 MW. The site also has a heating demand from a dryer that operates at 200 °C with a thermal power input of 1 MW. The site is interested in finding solutions for recovering and utilizing its excess heat to reduce its energy costs and environmental impact.

We used our ontology model to identify and collect relevant data for this project from various sources, such as online databases (e.g., ENTSO-E Transparency Platform), web services (e.g., Google Maps API), CSV files (e.g., historical weather data), XML files (e.g., energy prices), RDF files (e.g., GHG emissions), etc. We then organized this data into a structured database using our ontology as a guide. For example, we used our ontology classes and properties to define the data fields for the excess heat source (e.g., type: kiln; temperature: 900 °C; power: 2 MW; location: Portugal; etc.) and the heating demand (e.g., type:

Table 3
Regulatory Framework within the EU (illustrative sample data).

Country	Tax/subsidy	Value	Year of issue	Regulation type
Denmark	Carbon Tax	20 €/tonne	2021	Push
Spain	Renewable Energy Subsidy	0.15 €/kWh	2020	Pull
Italy	Energy Efficiency Tax	0.05 €/kWh	2019	Push
Austria	Nuclear Power Tax	50 €/MWh	2018	Push
Portugal	Solar Power Subsidy	0.30 €/kWh	2017	Pull
France	Gas Tax	0.15 €/m3	2021	Push
Germany	Hydro Power Subsidy	0.20 €/kWh	2020	Pull
Sweden	Wind Power Tax	0.10 €/kWh	2019	Push
Netherlands	Biomass Subsidy	0.25 €/kWh	2018	Pull
Greece	Coal Tax	30 €/tonne	2017	Push

dryer; temperature: 200 °C; power: 1 MW; location: Portugal; etc.). We also used our ontology classes and properties to define the data fields for the technological options for energy recovery, storage, and distribution (e.g., type: heat exchanger; efficiency: 0.8; cost: 1000 €/kW; lifetime: 20 years; etc.). We also used our ontology to define the data fields for the stakeholders involved in the project (e.g., type: industrial site; role: excess heat supplier; name: Ceramic Tiles S.A.; etc.), the market structure and business models applicable to the project (e.g., type: energy community; role: excess heat consumer; name: Local Municipality; etc.), and the regulations and policies relevant to the project (e.g., type: carbon tax; value: 25 €/tCO2; scope: national; etc.).

By using our ontology model to design the KB for this project, we were able to collect and organize all the necessary data for the EMB3Rs platform in a systematic and consistent way. The KB provided input data for the analysis modules of the platform, such as the Techno-Economic Module, the Environmental Impact Module, and the Market Module. The KB also stored the output data from these modules, such as the optimal technological solutions, the energy and cost savings, the GHG emissions reduction, and the market simulations. The KB enabled us to perform different types of analysis and simulations for this project, such as comparing different technological options, evaluating different business models, and assessing different scenarios of energy demand and supply. The KB also allowed us to reuse and adapt the data for different projects with similar or different characteristics, such as different locations, sectors, technologies, stakeholders, markets, or regulations.

4.4.2. Support for EMB3Rs platform regulatory framework design

To further illustrate how the ontology helped to design the RF for the EMB3Rs platform, we present a sample of the data that can be found in the RF, specifically the taxes and subsidies for energy production and management in industrial sites in different EU countries. Table 3 presents a sample of the data that can be found in the RF, specifically the taxes and subsidies for energy production and management in industrial sites in different EU countries. The table also indicates the ontology classes and properties that were used to identify and organize these regulations in the RF database. The table illustrates how the ontology helped to design the RF for the EMB3Rs platform by providing a structured and organized framework for the data. The table also demonstrates how the ontology supported the integration and interoperability of data from different sources and formats by providing a common vocabulary and a shared understanding of the data semantics.

In addition, we present a real-world project where we applied our approach to support an industrial site in Spain that produces paper products. The site has an excess heat source from a biomass boiler that operates at 300 °C with a thermal power output of 5 MW. The site also has a cooling demand from a refrigeration system that operates at 10 °C with a thermal power input of 2 MW. The site is interested in finding solutions for recovering and utilizing its excess heat to reduce its energy costs and environmental impact. We used our ontology model to identify and collect relevant data for this project from various sources, such as web pages, PDF files, XML files, RDF files, etc. We then organized this data into a structured database using our ontology as a guide. For example, we used our ontology classes and properties to define the data fields for the regulations and policies applicable to this project in Spain, such as the carbon tax (e.g., type: carbon tax; value: 20 €/tCO2; scope: national; etc.), the renewable energy target (e.g., type: renewable energy target; value: 32%; scope: EU; etc.), the energy efficiency standard (e.g., type: energy efficiency standard; value: 20%; scope: EU; etc.), etc. We also used our ontology to define the data fields for the regulations and policies applicable to other countries or regions that could be relevant for similar or different projects, such as Portugal, France, Germany, etc.

By using our ontology model to design the RF for this project, we were able to collect and organize all the necessary data for the EMB3Rs platform in a systematic and consistent way. The RF provided information on the legal and regulatory aspects of implementing energy recovery and utilization solutions in Spain and other countries or regions. The RF also supported decision making by providing information on the potential benefits and risks of different solutions in terms of compliance, incentives, penalties, etc. The RF enabled us to perform different types of analysis and simulations for this project, such as comparing different solutions in terms of their regulatory feasibility, evaluating different scenarios of regulatory changes or uncertainties, and assessing different opportunities or barriers for cross-border energy exchange. The RF also allowed us to reuse and adapt the data for different projects with similar or different characteristics, such as different locations, sectors, technologies, stakeholders, markets, or regulations.

5. Discussion

The proposed ontology presented in this work serves as a valuable tool for supporting the development of industrial energy management software. By understanding the link between software quality requirements (NFRs) and the characterizing factors of the energy domain, the ontology allows for a clear understanding of which factors of the energy context have a significant impact on the NFRs of the software they are intended to satisfy. The ontology was used to focus on four requirements considered fundamental in the development of energy management software: technologies, stakeholders, markets and regulations. However, the ontology presented in this paper is a conceptual model that defines the main classes and properties within the energy domain, without specifying any logic constraints or axioms that would capture the domain semantics in a more formal and rigorous way. This is a deliberate choice, as our goal is to provide a common vocabulary and a structured representation of the domain knowledge that can be easily understood and shared by different stakeholders and software components. The ontology is intended to be a starting point for further development and refinement, rather than a final and complete specification of the domain. Therefore, we do not claim that the ontology is logically consistent or complete, but rather that it is useful and effective in supporting the development of IEMS.

Ontology modeling is a powerful tool for organizing and structuring information in complex domains such as industrial energy management. However, one challenge that can arise in ontology modeling is the issue of relationship conflict. Relationship conflict occurs when two or more relationships between classes or properties are incompatible or contradictory. To address this issue, it is important to carefully define subclass relationships and part-whole relationships to avoid overlap or ambiguity. In addition, it may be necessary to regularly review and update ontology models to ensure their accuracy and completeness. In our study, we did not encounter any significant issues with relationship conflict in our ontology model. However, we recognize that this can be a challenging issue for ontology developers and recommend that future research explore best practices for avoiding or resolving relationship conflicts in ontology modeling. Another concern is about the danger of validity of our approach. For example, our ontology may not accurately represent the classes and relationships of NFRs in the energy domain. This could affect the reliability and usefulness of our ontology for the development of IEMS. To minimize this danger, we used various techniques to evaluate the validity of our ontology, such as RDF data management, application-based evaluation, and user feedback. We compared our ontology with an existing ontology that is considered as a reference or a benchmark for the energy domain. We evaluated our ontology in an operational environment after it was integrated into a real-world project. We also collected feedback from potential users and experts to assess the usability and understandability of our ontology. These techniques helped us to identify and correct any errors or inconsistencies in our ontology and to improve its quality and usefulness for the energy domain.

As part of the EMB3Rs project, the proposed ontology made it possible to work on some gaps present at a very high level of detail. The working group applied the knowledge developed in the model to optimize the construction of the knowledge base of the EMB3Rs platform. In particular, the structure proposed in the "Regulations" class was used as a starting point for the development of the Regulatory Framework of the platform. The consultation with the proposed ontology has given way to consider a wider and more detailed structure, including data that had not been considered previously. The importance of considering a precise data structure within the database is relevant, and in fact, allows the platform to be replicable in its outputs in context with different boundary conditions. This clearly highlights how the proposed model is useful to support the development of energy management software.

In order to ensure that the database is scalable and replicable, it is necessary to investigate aspects linked to the data properties attributed to the various classes which then constitute the data populating the platform's database. In particular, in addition to verifying the consistency of the database created through the use of synthetic data generators, it is necessary to ascertain the actual availability of the real data in a simple way. If the proposed data to be used in the database are not easily accessible, this would compromise the updating and performance of the platform. This complex process is actually currently underway in line with the development of the EMB3Rs project. Furthermore, the effectiveness of the proposed ontology needs to be tested with other real cases aimed at developing energy management software platforms with functionalities similar to the platform developed in the case study analyzed in this study. This can be done by conducting case studies in other countries and industries, with the goal of testing the scalability and replicability of the proposed model in different contexts.

Besides, it is essential to consider the scope and limitations of our work, as our approach makes certain assumptions. For instance, we assume that alerts and alarms are not considered part of the ontology model itself, as these are typically handled separately within specific software implementations. Additionally, our ontology model is focused on representing knowledge about the energy domain itself, rather than specific software implementation details. We believe these assumptions are reasonable given our focus on developing a general-purpose ontology-based approach for supporting industrial energy management software development. By concentrating on representing knowledge about the energy domain itself rather than specific implementation details such as alerts and alarms, we can provide a more flexible and adaptable approach that can be applied across a wide range of industrial contexts. However, future work should consider how these assumptions may impact the effectiveness and applicability of our approach in specific industrial contexts. For example, in some contexts, alerts and alarms may be critical components of an effective energy management system and should be integrated into the ontology model itself.

To summarize, the proposed ontology provides a valuable tool for supporting the development of energy management software by providing a comprehensive understanding of the factors that influence the scalability, replicability, and flexibility of the software. The model's usefulness is further highlighted by its ability to optimize the construction of the knowledge base of the EMB3Rs platform and its potential for reuse in other energy management software development projects. However, further studies are needed to test the model's scalability, replicability, usability, and to explore new relationships and factors in the energy context to provide a more accurate view and better support for the development of energy management systems. Overall, our study demonstrates the value of ontology modeling as a tool for supporting the development of industrial energy management software. By providing a clear and organized view of how different classes and properties are related to each other, ontology models can help developers create more effective and efficient software systems that support sustainable energy management practices. Future research should continue to address the challenges and limitations associated with ontology modeling, such as relationship conflicts, and contribute to the development of best practices that ensure the accuracy, completeness, the support for complex axioms or instances, and usability of ontology models in the context of industrial energy management software development.

6. Conclusions and future work

The energy management software industry is a rapidly growing field that is becoming increasingly important as we move towards a more sustainable future. In this study, we developed a comprehensive ontology model that supports the development of industrial energy management systems (IEMS) by capturing non-functional requirements (NFRs) and their relationship to four critical factors in the energy domain: technologies, stakeholders, markets, and regulations. The ontology model provides a clear and consistent framework for understanding the NFRs of IEMS, enabling the development of more effective and adaptable software systems across different industrial domains. By understanding the link between software quality requirements and the characterizing factors of the energy domain, as provided by our ontology model, this information can be used to inform life cycle assessments and quantify potential reductions in energy consumption, emissions, waste generation, and other environmental impacts associated with implementing cleaner and more sustainable solutions. We surveyed 272 NFRs and identified 153 of them as a valuable resource for future software development, reducing ambiguity and speeding up the process of selecting quality requirements. The ontology was comprehensively evaluated through formalization, validation, applications, user evaluation, and a case study based on our EMB3Rs project. The results demonstrated the ontology's effectiveness in supporting RDF data management, software system architecture design, and knowledge base implementation, leading to the inclusion of previously unconsidered data.

Despite the ontology's demonstrated success, opportunities for further advancement exist. Future work should investigate the model's reusability and evaluate its effectiveness in real-world scenarios of IEMS development. It is also worth noting that ontology design is a subjective process, influenced by the specific application and the designer's understanding of the domain. Future studies could build upon the current model by exploring new relationships and providing a more detailed understanding of the energy context, further enhancing the development of energy management software and contributing to a sustainable future.

CRediT authorship contribution statement

Roberto Monaco: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing. **Xiufeng Liu:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Teresa Murino:** Conceptualization, Writing – review & editing. **Xu Cheng:** Conceptualization, Methodology, Writing – review & editing. **Per Sieverts Nielsen:** Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data are available at https://github.com/RobertoMonaco/Energy-Framework.

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Appendix A. Supplementary data

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