Integrating Building and IoT data in Demand Response solutions

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Abstract. DR (Demand Response) programs have a big potential in the residential sector to reduce peak energy demands. However, the poor user-engagement is one of the main barriers of their adoption and success. The RESPOND H2020 project aims to bring DR programs to neighbourhoods across Europe and in this article, focus is placed on the approach implemented to solve the challenging integration of building topological data and data produced by IoT systems within houses including sensors, meters and actuators. In this regard, RESPOND leverages Semantic Technologies to represent building data, while it uses Time Series Databases (TSDB) to store IoT data. The combination of these technologies is expected to enhance the data querying, which is of utmost importance for its display in the RESPOND mobile app.

Keywords: Demand Response · Buildings · IoT · Semantic Technologies

1 Introduction

Peak energy demand has a negative impact on many aspects including energy grid capital, operational cost and environmental pollution. This is a direct consequence of the carbon-intense generation plants that grid operators deploy in order to satisfy energy demand during peak periods [4]. Demand side management activities including load curtailment (i.e. a reduction of electricity usage) or load reallocation (i.e. a shift of energy usage to other off-peak periods) have a huge potential to match energy demand with energy supply side, thus avoiding these undesirable peaks. As a matter of fact, Demand Response (DR) programs are introduced into the smart grids so that reliable and economical operation of power systems are ensured. DR can be understood as the set of technologies or programs that concentrate on shifting energy use to help balancing energy supply and demand [17].

DR programs traditionally had a bigger presence on the industrial sector compared to residential or commercial sectors, considering that buildings such as industrial plants are extensive energy consumers [11]. However, DR potential is particularly promising for the still largely untapped residential sector. The residential sector is characterized by a large number of end consumers with relatively low individual energy demand, but with very high demand when considered in terms of home clusters, districts and residential communities. For example, in

2016 the residential sector represented the 25.4% of final energy consumption and 17.4% of gross inland energy consumption in the EU[1]. Furthermore, the residential sector is characterized by a huge variety in user behaviour and habits, thus representing a big challenge but at the same time, a great potential for DR programs.

Renewable Energy Sources (RES) are increasingly penetrating the energy production side, and in combination with DR programs and improvement in energy storage options, could contribute to significantly reduce peak demands. However, the integration of the different systems and technologies involved in the distributed energy consumption and generation is a big challenge. Moreover, due to the intermittent nature of RES, their availability commonly does not match the distribution of energy demand in time, which may hinder their management and exploitation.

Being able to accurately predict the amount of energy to be produced over a period of time, and knowing in advance when demand peaks will occur, can definitely contribute to a better management of their disparity, thus allowing the suggestion of the most suitable DR programs to end-users. Likewise, this helps improving end-users' engagement, which is the key to the success of DR programs. However, the successful implementation of DR programs in the residential sector is a problematic scenario with yet many unsolved challenges. The RESPOND H2020 project aims to bring DR programs to neighbourhoods across Europe and in special, delve into the adaptation of energy demand to the renewable energy produced locally. In this article, focus is placed on RESPOND's approach towards the integration of building topological data and data produced by IoT systems including sensors, meters and actuators.

The rest of the article is structured as follows. Section 2 introduces the RESPOND project. Section 3 presents RESPOND's approach to integrate building data with IoT data. Section 4 describes the semantic representation of the pilot sites. Finally, the conclusions of this work are presented in Section 5.

2 The RESPOND project

The RESPOND (integrated demand REsponse Solution towards energy POsitive NeighbourhooDs) project[2] funded by EU's H2020 program[3], aims to deploy and demonstrate an interoperable, cost effective, user centred solution, entailing energy automation, control and monitoring tools, for a seamless integration of cooperative DR programs into the legacy energy management systems. In this endeavour, RESPOND will be leveraged upon an integrated approach for real-time optimal energy dispatching, taking into account both supply and demand side, while exploiting all energy assets available at the site.

[1] http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_consumption_in_households
[2] http://project-respond.eu
[3] https://cordis.europa.eu/project/rcn/212867_en.html

The RESPOND solution being developed is foreseen to be flexible and scalable, thus being capable of delivering a cooperative DR both at building and district levels. Furthermore, in order to enable the integration of the DR enabling elements and ensure a high replicability, RESPOND is based on open standards. Likewise, the use of these open standards enables the interoperability with smart home devices and automation systems, as well as the connectivity and extendibility towards smart grid and third-party services such as weather forecasting services and energy price providers.

Underpinned by the smart energy monitoring infrastructure, RESPOND will leverage data coming from heterogeneous sources to perform various data analytics tasks. On the one hand, sensing, metering and actuating devices deployed in pilot houses will be exploited to develop energy demand forecasting services and ensure dwellers' comfort levels. On the other, the monitoring and forecasting of outdoor conditions will enable the estimation of renewable energy production. Ultimately, the overall objective of all these data analytic tasks is to detect potential energy conservation opportunities, and to adapt in real time to the operational environment.

With the purpose of demonstrating the RESPOND solution, it is being implemented in different types of residential buildings (i.e. apartments, single-family and multi-family houses), situated in different climate zones (i.e. Mediterranean, oceanic and humid continental climate), having different forms of ownership (i.e. rental and home-ownership), population densities and underlying energy systems. Namely, the three RESPOND pilot sites are located in Aarhus (Denmark), the Aran Islands (Ireland) and Madrid (Spain).

Having such a heterogeneous group of end-users hinders the diffusion and impact of DR solutions, and it makes more difficult to ensure sustained user engagement with DR programs. This is why, interaction with end-users is recognized as a key point in the RESPOND project. Consequently, a set of tools and services are planned to deliver measurement driven suggestions to end-users for energy demand reduction and influence their behaviour making them an active indispensable part of DR loop. One of these tools is a multilingual and cross-platform mobile app which is expected to contribute in the user-engagement matter. One of the app's functionalities includes the display of house information, the deployed IoT devices and their measurements (e.g. a dishwasher's energy consumption or the kitchen temperature). The display of this information requires from a previous integration of building topology and IoT data, which is this article's focal point. Furthermore, this data integration enables many data analytic tasks such as energy demand and user comfort forecasting.

3 RESPOND's approach for Integrating Building and IoT data

Energy consumption is an outcome of performing everyday practices like showering, cooking and laundering. Usually people do not recognize energy consumption as an activity in itself, and they often find it difficult to establish the link between daily practices and the corresponding energy consumption [2]. This lack of awareness is tackled by the RESPOND mobile app and the gamification techniques it implements. This way, dwellers can check for example their energy consumption, compare themselves with their neighbours and get rewards depending on how efficient they behave from an energy expense viewpoint. Ultimately, these strategies aim to improve-user engagement.

The mobile app relies on the available data to display relevant information to the dwellers. This data includes, on the one hand, the topological information of a house which gives insight of its distribution, the appliances installed, and the different monitoring and actuating devices deployed in the house. And on the other, the measurements registered by these IoT devices including an appliance's energy consumption, a room's humidity or a window's state (i.e. opened or closed).

The advent of BIM (Building Information Model) supports the representation of the former data source, that is, building information. BIM is a process used by different stakeholders involved in the construction process of a building, and deals with the digital representation of functional and physical characteristics of a building [6]. Each of these stakeholders adds domain knowledge to a common model which keeps information of the whole building life cycle. A BIM model may contain static information of a building element. For example, in the case of a window, data about its location, the material it is made of, and even when it was installed is available and can be queried. Nevertheless, it is not possible to know whether the window is opened or closed in a given moment.

Even with the development of BIM, the current practice of architectural design and construction still relies on conventional document-centric approaches [16]. This means that although file format and exchange standardization efforts are made, parsing, interpretation, serialisation and deserialisation workflows that are prone to errors and inefficiencies are still used. Recent research have showed promising results in the use of Semantic Technologies to overcome document-centric based approaches in the building domain [8].

With regards to the IoT devices, they generate time series data which commonly consists of at least 2 parts: time and value. Despite this simple structure, IoT data is characterized by its abundance and it is estimated that in 2019 the IoT will generate more than 500 zettabytes in data [3]. This data needs to be stored in suitable storage systems which are able to manage such an amount of data while ensuring a high performance. In this regard, time series databases (TSDB) can be considered as the best option since they are optimized for handling time series data. Based on the architecture of different TSDBs, each data object can contain additional information apart from the required value and timestamp attributes. The goal of this additional attributes is to better differentiate the data and filter it easier. However, a balance needs to be found, as adding too many variables may penalize the overall performance.

Summarizing, the RESPOND mobile app will leverage building information data and IoT data. The former data will be stored in an RDF Store and the latter in a TSDB towards an optimal data management and querying performance.

3.1 Pilot Site Characterization

In order to implement the presented approach, first of all each pilot site's characterization was performed. This task was undertaken by the RESPOND partners in charge of these pilot sites, who had no previous knowledge of Semantic Technologies. Therefore, an intermediate step was found necessary prior to representing building information with appropriate ontological terms. Previous experiences of RESPOND partners [14,15] were taken into account and it was decided that the simplest way to fill this information were Excel sheets.

An Excel file was created for every pilot site, and in each of them, meters, sensors and actuators deployed in pilot houses were represented with the following information:

- Identifier of the device.
- Gateway to which the device is connected to send gathered data.
- Location of the device in terms of building, house and room.
- Location of the device within the room (e.g. floor or east wall).
- Type of device (e.g. humidity sensor or smart plug actuator).
- For actuators, the type of appliance controlled, its brand and model.
- The label and URI of the quality measured or controlled by the device (e.g. temperature or energy consumption).
- Query to retrieve data gathered by the device stored in the TSDB.

Figure 1 shows an excerpt of the Excel file filled for the Danish pilot site.

Location		Device	Appliance	
Apartment_id	Location in the apartment	Device_type	Type	Brand
Aarhus_03	kitchen	actuator_smart_plug	Dishwasher	LG
Aarhus_03	basement	actuator_smart_plug	WashingMachine	LG
Aarhus_03	basement	actuator_smart_cable	TumbleDryer	Whirlpool

Fig. 1. Excerpt of the Excel file with Danish pilot site information.

3.2 The RESPOND Ontology

Once pilot houses are characterized, this information needs to be semantically annotated using appropriate ontology terms. For this purpose, the RESPOND ontology was used, which is available online in `https://w3id.org/respond`.

Ontologies must be carefully designed and implemented, as these tasks have a direct impact on their final quality. Therefore, the use of well-founded ontology development methodologies is advised. For the development of the RESPOND ontology, the NeOn Methodology [13] was followed mainly because unlike other methodologies it does not prescribe a rigid workflow, but instead it suggests a variety of paths. These paths are classified as scenarios which consist of different tasks that ontology engineers must follow towards the development of a final ontology that satisfies the tackled problem.

The reuse of ontological resources built by others that have already reached some degree of consensus is a good practice in ontology development processes [12]. According to W3C's Data on the Web Best practices [1], the reuse of an existing vocabulary not only captures and facilitates consensus in communities, but also increases interoperability and reduces redundancies. Furthermore, this practice brings other important benefits:

- It increases the quality of the applications reusing ontologies, as these applications become interoperable and they are provided with a deeper, machine-processable and commonly agreed-upon understanding of the underlying domain of interest.
- It reduces the costs related to ontology development because it avoids the reimplementation of ontological components, which are already available on the Web and can be directly (or after some additional customization tasks) integrated into a target ontology.
- It potentially improves the quality of the reused ontologies, as these are continuously revised and evaluated by various parties through reuse.

Following these best practices, the RESPOND ontology's core is built by reusing and extending three well-known ontologies: BOT to represent the dwelling topology, and SAREF and SEAS Feature Of Interest ontologies to represent devices, features of interest and qualities monitored and controlled by sensors and smart appliances. The selection of these ontologies was based on a study of related ontologies, which is out of the scope of this article.

BOT. The Building Topology Ontology[4] [10] (BOT) is a minimal OWL DL ontology for covering core concepts of a building and for defining relationships between their subcomponents. A first design principle for the design of BOT has been to keep a light schema that could promote its reuse as a central ontology in the AEC (Architecture, Engineering and Construction) domain.

BOT describes sites comprising buildings, composed of storeys which have spaces that can contain and be bounded by building elements. Sites, buildings, storeys and spaces are all non-physical objects defining a spatial zone. These basic concepts and properties make the schema no more complex than necessary and this design makes the ontology a baseline extensible with concepts and properties from more domain specific ontologies. Therefore, BOT serves as an ontology to be shared. As a matter of fact, BOT is aligned with other related domain ontologies including ifcOWL, which provides an OWL representation of the EXPRESS schemas of the open standard IFC (Industry Foundation Classes) developed by buildingSMART[5].

[4] `https://w3id.org/bot`
[5] `https://www.buildingsmart.org/`

SAREF. The Smart Appliances REFerence (SAREF) ontology[6] [5] is a shared model of consensus that facilitates the matching of existing assets in the smart appliances domain. The ontology provides building blocks that allow the separation and recombination of different parts of the ontology depending on specific needs. The central concept of the ontology is the *saref:Device* class, which is modelled in terms of functions, associated commands, states and provided services. The ontology describes types of devices such as sensors and actuators, white goods, HVAC (Heating, Ventilation and Air Conditioning) systems, lighting and micro renewable home solutions. A device makes an observation (which in SAREF is represented as *saref:Measurement*) which represents the value and timestamp and it is associated with a quality (*saref:Property*) and a unit of measurement (*saref:UnitOfMeasure*). The description of these concepts is focused on the residential sector.

The modular conception of the ontology allows the definition of any new device based on building blocks describing functions that devices perform. As previously stated, for the building-related concepts SAREF provides the link to the FIEMSER data model. Furthermore, SAREF can be specialized to refine the general semantics captured in the ontology and create new concepts. The only requirement is that any extension/specialization may comply with SAREF.

One of these specializations is the SAREF4ENER ontology[7], which focuses on the energy domain. However, at the moment of writing this article, this ontology was inconsistent.

SEAS Feature of Interest. The SEAS Ontology[8] [7] is an ontology designed as a set of simple core ODPs (Ontology Design Patterns) that can be instantiated for multiple engineering related verticals. It is planned to be consolidated with the SAREF ontology as part of ETSI's Special Task Force 556[9]. The SEAS ontology modules are developed based on the following three core modules: the SEAS Feature of Interest ontology[10] which defines features of interest (*seas:FeatureOfInterest*) and their qualities (*seas:Property*), the SEAS Evaluation ontology[11] describing evaluation of these qualities, and the SEAS System ontology[12] representing virtually isolated systems connected with other systems.

On top of these core modules, several vertical SEAS ontology modules are defined, which are dependent of a specific domain. Moreover, the SEAS ontology offers a set of alignments to ontologies like SOSA/SSN and QUDT.

The RESPOND ontology reuses BOT, SAREF and SEAS Feature of Interest ontologies. Furthermore, some terms from QUDT UNIT ontology[13] are reused to

[6] `http://ontology.tno.nl/saref`
[7] `https://w3id.org/saref4ener`
[8] `https://w3id.org/seas/`
[9] `https://portal.etsi.org/STF/STFs/STFHomePages/STF556`
[10] `https://w3id.org/seas/FeatureOfInterestOntology`
[11] `https://w3id.org/seas/EvaluationOntology`
[12] `https://w3id.org/seas/SystemOntology`
[13] `http://qudt.org/1.1/vocab/unit`

represent units of measurements (e.g. *unit:DegreeCelsius*) and other terms from M3-Lite taxonomy[14] to represent qualities observed or controlled by installed devices (e.g. *m3-lite:Humidity*). However, there are other RESPOND requirements that remain unsolved and a set of new axioms had to be defined to satisfy them by extending these reused ontologies.

On the one hand, the list of appliances defined by SAREF was extended to represent new ones including air conditioner (*respond:AirConditioner*) and tumble dryers (*respond:TumbleDryer*). Furthermore, the list of qualities provided and the list of units of measurements provided by M3-lite and QUDT Unit respectively were not sufficient to represent all the use cases within the RESPOND pilots. Therefore, these ontologies were extended with the definition of new qualities such as gas consumption (*respond:GasConsumption*) and new units of measurements such as parts per million (ppm) (*respond:ppm*).

On the other, there are requirements that are intrinsic to the RESPOND project and which existing ontologies do not satisfy. In the context of the project, it is essential to know which is the gateway to which each device is connected in order to send their measurements or control actions. This relationship is represented with the definition of the *respond:connectsToInternetThrough* object property and a new class *respond:Gateway* as a subclass of *saref:Device*. Furthermore, it is necessary to know how to query data gathered by a given device which is stored in a TSDB. This information can be represented leveraging *respond:hasDBQuery* data property, and its subproperty *respond:hasInfluxDBQuery* for InfluxDB TSDB. As for assigning the icons to be shown in the mobile app, the *respond:hasIcon* data property relates a resource with its corresponding icon. Regarding the representation of space features such as the volume or area, a set of data properties (e.g. *respond:hasNetVolume*) has been defined inspired by the IFC4 specification. The representation of these data properties is expected to be addressed by the W3C LBD (Linked Building Data) Community Group's[15] future PROPS ontology[16].

Figure 2 shows the RESPOND ontology's main classes and properties.

4 Semantic Representation of Pilots

With regards to the semantic representation of pilot sites, an application based on Apache Jena[17] was developed. Apache Jena is a free and open source Java framework for building Semantic Web and Linked Data applications. The developed Jena service extracts the information contained in the Excel sheets, semantically annotates it with appropriate ontology terms, and stores it into an RDF Store where it will remain accessible via SPARQL queries. Firstly, this information was stored in a Stardog[18] version 6.0.1 repository, but due to the

[14] `http://purl.org/iot/vocab/m3-lite`
[15] `https://www.w3.org/community/lbd/`
[16] `https://github.com/w3c-lbd-cg/props`
[17] `https://jena.apache.org/`
[18] `https://www.stardog.com/`

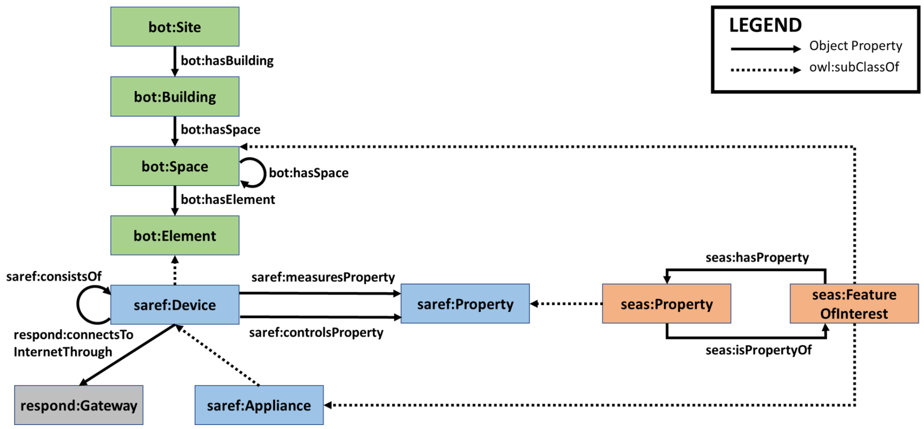

Fig. 2. RESPOND ontology's main classes and properties.

cease of its Community version after 31 March 2019, this information is now stored in an Openlink Virtuoso Server[19] version 07.20.3217. Figure 3 depicts the representation of a Smart Plug developed by Develco Products[20] and deployed to measure the electric consumption and control the activation and deactivation of a dishwasher installed in the kitchen of a pilot house in Denmark.

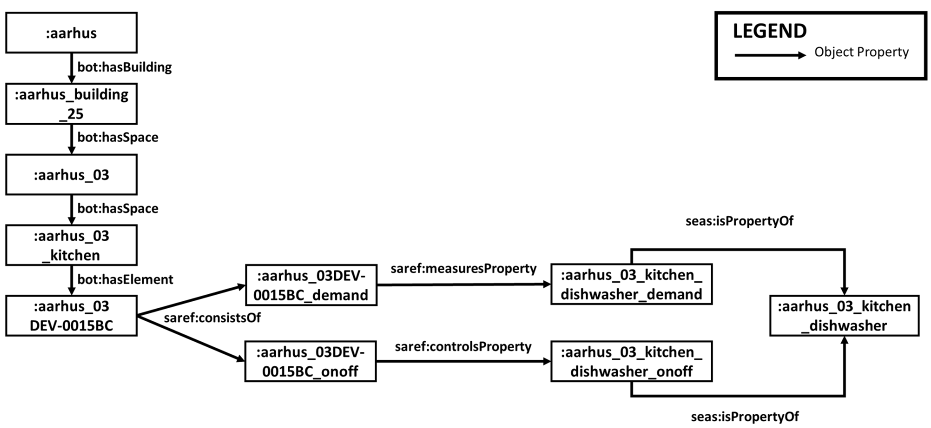

Fig. 3. Excerpt of a Smart Plug device deployed in a pilot house in Denmark.

[19] https://virtuoso.openlinksw.com/
[20] https://www.develcoproducts.com/

4.1 IoT data storage

Both practice and research suggests the use of a graph-based format to capture building data, nevertheless keeping numeric data explicitly out of the semantic graph for computational performance reasons [9]. This approach is followed in RESPOND, thus storing the data gathered by deployed meters, sensors, actuators and other IoT devices in a TSDB. More specifically, the open source TSDB InfluxDB[21] is used for this purpose. The selection of the InfluxDB was preferred as it is part of the TICK Stack[22], which is employed in other developments of the RESPOND project.

4.2 Data Discovery via mobile app

In order to hurdle the inherent diffusion and impact problems of DR solutions in heterogeneous group of end-users, the RESPOND project plans to develop a set of tools and services. These ones are expected to deliver measurement driven suggestions to end-users for energy demand reduction and influence their behaviour making them an indispensable active part of DR loop.

One of these tools is a mobile app developed both for iOS and Android and available in three languages to ease interaction with end-users from the pilot sites: in English, Danish and Spanish. The mobile app will offer different functionalities that require from an integration of building topology and IoT data, which has been tackled in previous sections of this article.

One of the app's functionalities displays users the list of devices installed within their houses, as shown in Figure 4. The display of this information is based on a SPARQL query executed over the RDF Store that contains the building topological information. Namely, the SPARQL query executed for this purpose is shown in Listing 1.1, where the wild card *$HOUSE_ID* is replaced by the corresponding user's house ID.

[21] `https://www.influxdata.com/time-series-platform/influxdb/`
[22] `https://www.influxdata.com/time-series-platform/`

Fig. 4. Devices deployed within an Irish pilot house shown in the RESPOND mobile app.

```
PREFIX dc: <http://purl.org/dc/terms/>
PREFIX bot: <https://w3id.org/bot#>

SELECT DISTINCT ?deviceID
WHERE{
        ?space dc:identifier $HOUSE_ID;
                bot:hasSpace*/bot:hasElement ?deviceID.
}
```

Listing 1.1. SPARQL query to retrieve all the sensors and actuators deployed within a house.

Users can also check data collected by deployed meters, sensors or actuators deployed in their houses. For example, Figure 5 displays the electric consumption of a Spanish pilot house in real-time shown by the RESPOND mobile app. The electric consumption of a house, which is gathered by an electricity meter, is stored in InfluxDB. However, in order to query this information, it is necessary to know how to get the values of the electricity meter at hand. To do so, the SPARQL query shown in Listing 1.2 is executed, where the wild card *$HOUSE_ID* is replaced by the corresponding user's house ID.

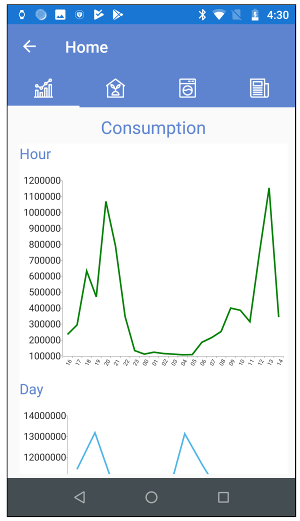

Fig. 5. Real-time electric consumption of a Spanish pilot house shown in the RESPOND mobile app.

```
PREFIX respond: <https://w3id.org/def/respond#>
PREFIX seas: <https://w3id.org/seas#>
PREFIX dc: <http://purl.org/dc/terms/>
PREFIX saref: <https://w3id.org/saref#>

SELECT ?dbQuery
WHERE{
        ?device saref:measuresProperty ?property;
            dc:identifier ?deviceID.
        ?property rdf:type respond:ElectricConsumption;
            seas:isPropertyOf ?foi;
            respond:hasDBQuery ?dbQuery.
        ?foi dc:identifier $HOUSE_ID.
}
```

Listing 1.2. SPARQL query to retrieve the TSDB query retrieving a house's electricity consumption.

5 Conclusions

DR programs in residential buildings have a big potential in terms of maximizing the exploitation of locally produced renewable energy. Likewise, the exploitation of this type of energy paves the way for reducing peak energy demands. However, DR programs' success in this sector is scarce mainly due to user's lack of engagement. The RESPOND mobile app is developed as a way to increase user-engagement with DR programs.

This mobile app leverages both building and IoT data, which are two disparate data sources that need to be carefully managed. In order to avoid a problematic document-centric approach, RESPOND proposes the use of Semantic Technologies to represent building data. More specifically, building topological data is represented using appropriate ontological terms coming from well-known ontologies, and it is stored in a Virtuoso RDF Store. With regards to the abundant IoT data, RESPOND leverages the InfluxDB TSDB with the objective of obtaining an enhanced performance. Finally, the proposed approach is aimed at easing the scalability of the approach, as it enables the distribution of the data according to specific needs.

5.1 Future work

So far, the RDF Store used in RESPOND hosts the topological information of a limited number of test houses. Whether it could afford storing information for thousands of houses while ensuring a high querying efficiency, still remains an open issue. This aspect deserves further research in future stages of RESPOND.

Furthermore, at the moment of writing this article, all RESPOND mobile app's functionalities are not developed. The personalized DR suggestion to users or the ability to activate or deactivate appliances are just some of the services that are being developed and are expected to further increase the user-engagement with DR programs.

Last but not least, the research of integrating IoT data with data sources containing more complex building information (e.g. BIM models) is of interest.

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