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An intelligent semantic system for real-time demand response management of a thermal grid

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ABSTRACT

"Demand Response" energy management of thermal grids requires consideration of a wide range of factors at building and district level, supported by continuously calibrated simulation models that reflect real operation conditions. Moreover, cross-domain data interoperability between concepts used by the numerous hardware and software is essential, in terms of Terminology, Metadata, Meaning and Logic. This paper leverages domain ontology to map and align the semantic resources that underpin building and district energy management, with a focus on the optimization of a thermal grid informed by real-time energy demand. The intelligence of the system is derived from simulation-based optimization, informed by calibrated thermal models that predict the network's energy demand to inform (near) real-time generation. The paper demonstrates that the use of semantics helps alleviate the endemic energy performance gap, as validated in a real district heating network where 36% reduction on operation cost and 43% reduction on CO_2 emission were observed compared to baseline operational data.

1. Introduction

The growing interest in thermal grids requires new business and technology platforms to handle the increasing amount of multi-aspects data and the level of complexity and diversity of the urban energy landscape (Howell, Rezgui, Hippolyte, Jayan, & Li, 2017; Reynolds, Ahmad, Rezgui, & Hippolyte, 2019). Moreover, the load profile fluctuation, from both heat demand and heat generation, requires informed decision-making to explore a wide range of configuration options that contribute to reduce heat energy demand and carbon emissions (Kuster, Rezgui, & Mourshed, 2017; Li, Rezgui, & Zhu, 2017; Reynolds, Rezgui, & Hippolyte, 2017). Therefore, the smart control of a thermal grid that factors in predicted changes is crucial to ensure effective real-time demand response. Conversely, the use of machine learning has paved the way to new ways of addressing the endemic energy performance gap (Wang et al., 2019; Wu, Shahidehpour, & Khodayar, 2013), while promoting flexibility and scalability of current generation of decentralized and multi-vector energy systems (Li et al., 2017; Petri, Yuce, Kwan, & Rezgui, 2018).

Intelligent systems involve reliance on smart sensors, monitoring and control devices, and computing networks, powered by machine learning (Talebi, Haghighat, Tuohy, & Mirzaei, 2019; Wang et al., 2019). However, current research in the energy management field reveals: a) difficulties in embracing the increasing complexity of current and future energy systems; b) limited potential in handling real-time dynamic conditions; and c) lack of holistic approaches to integrate seamlessly all hardware, protocols, software, and occupants involved (Howell, Rezgui, Hippolyte et al., 2017; Reynolds et al., 2019).

Moreover, managing a complex energy system such as a district heating (DH) network requires a holistic approach to elicit and represent the data structures of the underpinning hardware and software components (Li, García-Castro, Mihindukulasooriya, O'Donnell, & Vega-Sánchez, 2019). Ontology is a computer and human readable formalisation of a domain that can be used to interpret semantically related concepts using classes, relations and attributes. The development of ontology requires expert knowledge to conceptualize the underpinning domain artefacts. The constructed semantic maps are applied to illustrate the relationship and map the corresponding instances. The authors have successfully applied semantics to address building energy management (Howell, Wicaksono, Yuce, McGlinn, & Rezgui, 2018) and water urban management (Howell, Rezgui, & Beach, 2017).

This paper proposes an intelligent system for dynamic DH network monitoring to deliver real-time energy management through a dedicated ontology developed with the Web Ontology Language (OWL), augmented with semantic rules capable of handling heterogeneous data sources. The complex energy system is broken down into discrete but

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related elements, governed by dependent and independent variables and their interaction through mathematical approximations. The proposed system involves a building energy prediction engine to automatically calibrate building energy models and forecast building energy demand, a simulation engine to support distribution network heat loss modelling, and an optimization engine to optimize the operational schedule of the generation units. The proposed solution is tested and validated in a real case study, a brownfield development in Wales, UK.

The rest of the paper is organised as follows: Section 2 presents a critical review of related work. In Section 3, the overarching methodology and the underpinning components demonstrating the novelty of our approach is described. The subsequent section details the prediction, simulation and optimization engines. Section 5 presents the results, which are then discussed in Section 6. The last section provides concluding remarks.

2. Related work

Recent advances in smart sensors together with low cost communication solutions have paved the way for a wide range of smart management solutions of energy systems through artificial intelligence (AI), including prediction and optimization algorithms (Reynolds et al., 2017).

These techniques have been applied at building or district scale, and as such involve a bottom-up or a top-down approach (Kazas, Fabrizio, & Perino, 2017). The bottom-up models calculate the energy from a single building or a group of buildings and then aggregate or scale the results to the district level (Shimoda, Fujii, Morikawa, & Mizuno, 2004). The annual energy can be obtained by summing up simulation results from various household categories. Each category is simulated separately and then multiplied by the number of households. The top-down approach involves a data driven model to predict energy demand according to statistical techniques or machine learning (Mastrucci, Baume, Stazi, & Leopold, 2014; Tian & Choudhary, 2012). This approach studies the building stock at hand without investigating individual buildings, which are relegated as nodes in the complex urban fabric. A large amount of dataset is required to construct the prediction model (Howell, Rezgui, Beach et al., 2017).

The problem of mismatch between energy supply and energy demand is pronounced in the urban energy landscape (Zhang, Xu, Liu, Zang, & Yu, 2015), including in the context of district heating. A wide range of optimization models such as linear programming (LP), mixed-integer linear programming (MILP) and non-linear programming (NLP) have been applied for DH network optimization (Wang, Abdollahi, Lahdelma, Jiao, & Zhou, 2015). Cho et al. Cho, Mago, Luck, and Chamra (2009) developed a linear model for load dispatch with the purpose of reducing operation cost and carbon emission. Ameri and Besharati Ameri and Besharati (2016) developed a MILP model to identify the best energy mix in a complex district energy system to meet energy demand with minimum operation cost. Fonseca (Fonseca, Nguyen, Schlueter, & Marechal, 2016) developed a non-linear k-means clustering algorithm computational framework for the optimization of building energy systems in an urban scale. Significant savings in operation cost, primary energy and CO_2 emission were achieved. Ommen et al. Ommen, Markussen, and Elmegaard (2014) conducted a comparison of linear, mixed integer and non-linear programming to examine their impacts on energy dispatch. Results revealed that NLP and MILP exhibited better results than LP, corresponding to an improvement of 32% and 23%, respectively, in the performance of the generation units. The authors claimed that MILP is the best option from the runtime and accuracy perspectives.

Model Predictive Control (MPC) has been extensively applied in the energy optimization process to mitigate the negative impacts caused by predictive uncertainties (Reynolds et al., 2019). Reynolds et al. Reynolds et al. (2019) have examined the MPC for supply and demand management in a multi-vector district energy system. Zhang et al. Zhang, Zhang, Wang, Liu, and Guo (2015) compared the MPC with the traditional day-ahead control in a MILP based optimization process. Case study results demonstrated that MPC strategy provided more significant operation cost reduction.

Recent research has seen the development of dynamic district energy simulation solutions (Wang et al., 2015) capable of predicting energy demand of the building stock, while providing a wide range of functionality, including manipulation and analysis of collected data. Schiefelbein (Schiefelbein et al., 2019) developed an urban energy system modelling platform through OpenStreetMap, with simulated space heating demand reflecting measured consumption.

Interoperability and integration between the components of an energy system require the use of common or semantically aligned models to promote seamless data exchange between the constituents of these systems (Shang, Ding, Marianantoni, Burke, & Zhang, 2014). These semantic models are best reflected in the linked data and semantic Web efforts (W3C, 2019). The paper proposes an approach for DH energy management underpinned by semantics and powered by AI, to inform real-time management of a thermal grid. This paper takes the overarching hypothesis that an accurate simulation of a thermal grid and its associated buildings, augmented with machine learning techniques fed by real-time sensory data, can alleviate the endemic energy performance gap in thermal grids. This is elaborated in the following section.

3. Methodology

This section gives an overview of the methodology employed to develop the proposed intelligent semantic system to monitor and optimize thermal grids. i.e. DH networks. The objective is to deliver a holistic real-time energy prediction and optimization process. A semantic Web-based approach is adopted to conceptualize the DH network and its constituent buildings, factoring in the enhanced sensing and actuation infrastructure.

The developed solution represents an intelligent system to (a) collect and integrate real-time data from heterogeneous data sources, (b) analyse the collected data, and c) provide continuous feedback while informing decision making with the objective to reduce the gap between predicted and actual energy consumption. The proposed solution translates into three layers: the sensing and actuation layer, the data interoperability layer and the intelligence layer, as illustrated in Fig. 1.

The sensing and actuation layer represent energy and environmental sensing and actuation nodes in the complex energy system used to gather real-time data and apply, in response, adapted actuation strategies. Sensed data includes real-time supply and return temperatures of the distribution network, the amount of fuel available for use, the amount of hot water available in the storage tank, and energy demand of the connected buildings. This is augmented with environmental data from the UK Met Office weather service, including temperature, humidity, solar radiation, wind speed, and wind direction. The actuators are linked with devices for smart control and fault detection, e.g. the external shading blinds in windows (within buildings) are activated when the solar radiation reaches a certain level, or an alert is sent to the energy manager to signal that unoccupied spaces are being heated.

The interoperability layer integrates all sensed and heterogeneous data in a form that is exploitable by the intelligent analytics and visual components using data models in the form of semantics. The district energy management system (DEMS) and the building energy management system (BMS) can thus inter-operate, despite their different native communication protocols, through a proposed Web service interface. As such, the interoperability layer acts as a mediator to integrate diverse and heterogeneous data sources and bring them in a form exploitable by the intelligence layer. Moreover, data from smart devices and modelling tools are converted into computer readable language and shared in a common ontology, promoting interoperability and facilitating communication. The main concepts forming the resulting