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Indoor air quality and energy management through real-time sensing in commercial buildings

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ABSTRACT

Rapid growth in the global population requires expansion of building stock, which in turn calls for increased energy demand. This demand varies in time and also between different buildings, yet, conventional methods are only able to provide mean energy levels per zone and are unable to capture this inhomogeneity, which is important to conserve energy. An additional challenge is that some of the attempts to conserve energy, through for example lowering of ventilation rates, have been shown to exacerbate another problem, which is unacceptable indoor air quality (IAQ). The rise of sensing technology over the past decade has shown potential to address both these issues simultaneously by providing high-resolution tempo-spatial data to systematically analyse the energy demand and its consumption as well as the impacts of measures taken to control energy consumption on IAQ. However, challenges remain in the development of affordable services for data analysis, deployment of large-scale real-time sensing network and responding through Building Energy Management Systems. This article presents the fundamental drivers behind the rise of sensing technology for the management of energy and IAQ in urban built environments, highlights major challenges for their large-scale deployment and identifies the research gaps that should be closed by future investigations.

Contents

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1. Introduction

The issues of energy demand and air quality go hand in hand in city environments. A major proportion (up to 40%) of the total global energy demand is consumed by urban buildings [1]; of which, up to ∼40% is consumed by commercial buildings [2]. Given that many nations are actively pursuing carbon reduction plans, and thus energy efficiency, improved energy management is a key priority. Clearly, the commercial built environment is a major consumer of energy, but this also offers an opportunity to save energy through advanced management [3]. Yet, saving energy by, for example, reducing power assisted ventilation results in build-up of pollutants generated indoors by internal sources, including its occupants. However, replacing indoor with outdoor air in fact can create a problem for indoor air quality (IAQ) if the air outdoors is polluted, which is often the case in many urban environments [4,5]. This is because vehicular emissions pollute outdoor air and its infiltration leads to deterioration of IAQ [6,7]. Further complexity is added by the changing climatic conditions and the human expectations of comfortable indoor environments; both of which increase building energy requirements for heating, cooling, lighting, and the use of other electrical equipment [3]. Taken together, all these aspects elicit a need to understand the patterns of energy consumption, both spatially and temporally, in the urban built environments, and optimise in a manner which would not compromise IAQ.

Optimal energy use is the key for sustainable building operation and hence there is a need for the correct combination of energy-efficient building designs, energy saving technologies, informed behavioural choices, and optimisation based on local climatic conditions that can lead to substantial reductions in energy consumption [3]. Whilst newly constructed commercial buildings can offer considerable energy efficiency improvements, about 60% of the buildings that will be standing in 2050 have already been built. Previous research has attempted to address the issues of energy management, but adequate answers to many of the relevant questions are still unavailable. These are elaborated upon below.

Indoor air constitutes in an environment that is particularly rich in different types of pollutants, including gases such as carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2), nitrogen oxides (NO_x), and particulate matter (PM) of various sizes, as well as an array of organic compounds which can be in both particle and gaseous phase [8,9]. The pollutants originate from indoor sources and penetrate from outdoors. Under the protective enclosure of the building envelope, pollutants mix and interact or grow (when considering microbes). Some of the pollutants, such as those products originating from combustion can be sourced simultaneously from both indoors and outdoors.

In most commercial situations, occupants have little opportunity to directly influence their working environment. A move towards more intelligent and autonomous control systems may enable buildings, when in use, to better respond to occupants' needs by adopting new technologies that enable people to be 'connected' to the system, which through smart control approaches learn from users' preferences. Some of the key requirements to address the above challenges are the availability of required data (including energy consumption patterns, human occupancy and environmental conditions), both in real-time and long-term, for different building types in order to develop fundamental understandings of their interrelationships. Today this is possible, given that both the energy management and air quality monitoring paradigms are changing rapidly due to advances in the development of portable, low or medium cost sensors [10] (Table 1). Along with complementary wireless communication infrastructure, these sensors are capable of reporting highly time resolved data in near-real time to allow fine-grid mapping of energy demand and consumption patterns [11] as well as IAQ conditions [12].

Many modern buildings, such as the Massachusetts Institute of Technology (MIT) Media Lab, are embedded with such smart sensors and high-tech data management companies [13] provide software tools to manage, analyse and interpret the data. A network of such sensors enables monitoring of energy consumption patterns together with IAQ parameters which inform energy management strategies. Furthermore, development and applications in indoor sensing are evident from a number of recent research articles, showing their usefulness for a wide range of applications. In particular, recent research has shown development and application of sensors such as a thermostat capable of responding to grid incentives in residential buildings for saving energy and cost without sacrificing thermal comfort [14], sensors for surface temperature and heat flow in historical buildings such as museums [15], carbon dioxide (CO_2) sensors for determining occupancy disturbances in commercial buildings [16], demand-based supervisory temperature control sensors for measuring temperature at breathing levels in large-scale rooms [17,18] or integrated sensing systems for indoor applications [19,20]. Furthermore, Cartalis [21] presented a review of definitions, challenges and prospects for resilient cities and pointed out that resilience should not be confined to the ability of a system to return to its stable state after disruption, but should also include the ability to adapt and adjust to changing internal or external processes. Related legislation also plays a crucial role in technology deployment. For example, Kokkaliaris and Maria [22] reported that the legislative initiatives for smart metering are a precondition to zero-energy buildings (ZEB) for the following reasons: (i) smart metering is expected to increase consumers' awareness of the importance of investments in improving the energy performance of their buildings, and (ii) improved capture of benefits of distributed micro-generation through smart meters is likely to increase the penetration of renewable energy sources in electricity generation. Related to ZEB, Salom et al. [23] analysed grid interaction indicators in net zero-energy buildings with sub-hourly collected data, and concluded that sub-hourly analysis would give more accurate and thus useful information. It has been shown that differences between peak values measured with hourly and sub-hourly time resolution can be significant. Also, if detailed grid interaction analysis at the individual building level is required, attention should be given to detai sub-hourly analysis [23]. However, a number of questions still remain: (i) currently is there a need for advanced energy and IAQ management systems enabled by low-cost sensing, and if yes, why? (ii) Does low-cost sensing have the potential to alter the traditional way of energy monitoring in the future? (iii) What is the current state-of-the-art of available energy management and IAQ sensors? (iv) What are the major challenges in their production and large-scale deployment in the built environments and associated data processing? Finally, (v) what are the associated research gaps and where should future research focus? Targeting these questions and focusing on the urban built environment (for commercial buildings), this article presents a comprehensive overview and highlights recent advancements, research challenges and a way forward for future research.

2. The need

Global energy consumption for commercial buildings has increased over the recent decades, mainly due to increasing populations and economic development worldwide [2,24]. For example, the percentage of energy used for transportation, domestic and service sectors from 1991 to 2011 in the UK has exceeded the