Building and Environment 139 (2018) 125–133

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Estimation of temperature setpoints and heat transfer coefficients among residential buildings in Denmark based on smart meter data

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ARTICLE INFO

Keywords:
Smart meter data
Temperature setpoints
Housing stock model
Thermal comfort preferences
U-values
Urban scale

ABSTRACT

Thermal comfort preferences of occupants and their interactions with building systems are top influential factors of residential space heating demand. Consequently, housing stock models are sensitive to assumptions made on heating temperatures. This study proposes a heat balance approach, inspired by the classical degree-day method, applied to an extensive urban dataset. The goal of this analysis is to determine heterogeneous characteristics, such as temperature setpoints of heating systems and thermal envelope characteristics from an overall population of residential buildings. Measured energy data are utilized for the purpose of the study from the city of Aarhus, Denmark, where the energy usage for heating of circa 14,000 households was monitored over time via smart meters. These data are combined with actual weather data as well as data extracted by a national building database. Using linear regression and heat balance models, temperature setpoints for the whole dataset are determined with a median and average of 19 °C and 19.1 °C, respectively. Furthermore, building related characteristics such as thermal and ventilation losses per building and overall heat transfer coefficients are extracted at urban scale. The reliability of the method over its complexity is discussed with regards to the big sample that has been applied to. In general, the overall performance of the approach is satisfactory achieving a coefficient of determination with an average of 0.8, and is found to be in line with previous findings, considering also the high uncertainty associated with building-related input parameters. The extracted setpoint distribution should be transferrable across Scandinavia.

1. Introduction

A number of modeling methodologies have been developed to obtain information on physical resource flows through the building stock [1]. These are mainly used to characterize and predict energy demand of residential building stocks and to estimate energy savings after energy retrofitting strategies. Housing stock models can thus play an important role in supporting energy policy-making. In order to be useful, they should be reliable, efficient and interpretable [2]. Housing stock models can be broadly classified into two categories: top-down and bottom-up approaches. Top-down models rely on historical energy data and cannot model in detail individual end-uses [3]. Bottom-up models consist of engineering-based and statistical models. Statistical methods usually include macroeconomic and socio-economic effects, enable the determination of end-use energy consumption and are easy to develop and be used [4]. However, they cannot model the impact of specific technologies implemented and are less flexible. Engineering-based housing stock models use actual building physics and overcome some of the limitations induced by statistical models [2]. However, the majority of them are developed at national scale to support policy making and disregard heterogeneity within a country. They are also usually time intensive and are fully dependent on input data, hence inducing a high degree of uncertainty. Therefore, there is a need to focus on regional housing stock models that handle heterogeneity.

According to the International Energy Agency in the Energy Buildings and Communities Program (IEA EBC) Annex 53: Total Energy Use in Buildings, the six driving factors of energy use in building stock are: i) climate, ii) building envelope, iii) building energy and services systems, iv) indoor design criteria, v) building operation and maintenance, and vi) occupant behavior. Even though significant progress has been made in quantifying these primary drivers, more emphasis on energy related occupant behavior in buildings is needed to develop reliable and standardized methods [5,6]. Neglecting this aspect can lead to severe miscalculations and inaccurate conclusions about the energy performance of the building stock [7]. Occupants' interaction with building systems affects significantly the total energy use of

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https://doi.org/10.1016/j.buildenv.2018.05.016
Received 3 March 2018; Received in revised form 6 May 2018; Accepted 8 May 2018

buildings. The occupants' gratification with their thermal environment defines thermal comfort [8]. Therefore, the occupants' perception of comfort or satisfaction in the built environment drives them to perform various controls (e.g. on HVAC systems and window operations) [9]. The adjustment of thermostat setpoints and indoor thermal environment are the most influential factors of heating loads along with heated areas [10]. Some studies have even classified occupants as active, medium and passive users based on their heating setpoint preferences which impact the indoor thermal environment and energy consumption [11,12]. Therefore, thermostat setpoints are crucial input parameters to building energy models due to their big influence on residential energy use [9]. Currently, the understanding of occupant behavior is still insufficient both in building design, operation and retrofit, leading to incorrect simplifications in modeling and analysis [5]. In the past, information about occupants' interactions with systems was based on sporadic visits to households and rough estimates of thermal preferences of occupants.

The increasing deployment of intelligent metering systems in buildings and district systems creates a vast amount of building energy use and occupant-related information. Following the Third Energy Package in the Electricity [13] and Gas Directive [14] issued by European Commission in 2006, European countries plan to convert part of their legacy meter stock to smart by 2020 with a focus on electricity. According to the projections, by 2020, it is expected that almost 72% of European consumers will have a smart meter for electricity and about 40% will have one for gas [15]. The enormous amount of information and data opens up endless opportunities for researchers and engineers to study building dynamics and performance at a large scale. In combination with weather data and cross-sectional data, they can be utilized to develop more accurate prediction models and detailed analyses on the drivers of building energy consumption [16]. Smart meter data can also help developing and applying control strategies to improve building energy performance and efficiency [17]. Therefore, they can be utilized to decrease uncertainty related to building energy performance and occupant behavior and provide detailed information on energy monitoring.

National building databases and registers can support housing stock energy analysis, by providing information about building typologies and construction characteristics. These databases are usually created with regards to building regulations and schemes. In some cases, information from building owners via questionnaires has also been collected. Building information can be updated by local authorities and by citizens. However, occupants' interventions on the building fabric (i.e. energy renovation measures) are not regularly reported to building databases. Therefore, there is a significant gap between the data that has been registered and the real energy performance of the building.

This study aims at utilizing a big urban dataset, consisting of smart meter data from more than 14,000 households in a Danish city, to estimate temperature setpoints and thermal transmittances on building level. In addition, actual weather data, as well as data collected from a national building register and a geographic information system (GIS) have been utilized. A heat balance approach is implemented to the measured energy data of one year applying linear regression analysis to extract parameters that represent the whole heating season and the total building envelope. This approach has been inspired by the degree-day theory and aims at providing a new useful tool for utilities and researchers to extract building and thermal comfort-related characteristics at urban scale based on smart meter data. The data used allows us to capture the full range of heterogeneous behavior among people, through their temperature preferences. The estimation of people's variation enables the development of customized solutions and messages for them. The estimated thermal transmittance of the building envelope indicates the refurbishment state of the building and thus, provides more accurate insights into the building stock. The generated results -in the form of distributions-can be used to improve urban building energy models for the Scandinavian housing stock.

The rest of the article is organized as follows. In section 2, related works and methods to predict room temperature setpoints are summarized. In Section 3, we present and apply the heat balance model to the smart meter dataset. In Section 4, the dataset is presented and basic information about the examined housing stock is described. In Section 5, the results are compared and validated with previous findings and relevant literature. The applicability of the methods with regards to the considerations made and the data used is discussed in Section 6. Section 7 summarizes the research findings.

2. Background

To evaluate the potential impact of different energy retrofitting scenarios in urban areas, bottom-up urban building energy models (UBEM) have been introduced over the past years. UBEMs have the potential to become key planning tools for utilities, municipalities and urban planners [18]. A key input of UBEM models are building characteristics of a given building stock from thermal envelope properties to usage patterns including the number of occupants, equipment loads and schedules as well as thermostat settings. Some of those information may be derived from census data. However, there is generally a surprising lack of data available related to the thermal performance of buildings. A useful source of information can be derived from individual building energy audits [19]. In Ref. [19], the authors used the Monte Carlo method and created a physics-based housing stock model for energy performance prediction, where inputs were probability distributions based on an Energy Performance Certification national database. Another source are nationwide building databases which include information such as floor areas, construction materials, age of construction, etc. Nevertheless, these databases may have flaws or may not be updated frequently enough. Therefore, there is high uncertainty related to input parameters of UBEMs.

Several studies have been conducted on district or urban scale making use of statistical models and data mining techniques in order to extract hidden useful knowledge from building-related data, as well as to forecast energy consumption. The authors of [20] presented a data-driven approach to modeling end user consumption based on data from 6500 buildings in Cambridge, Massachusetts, using linear regression analysis and Gaussian process regression. In Ref. [21], electric energy data of thousands of buildings were investigated to extract specific features based on socio-economic information. In Ref. [17], a data mining method was proposed to analyze building-related data in order to establish building energy demand predictive models and examine the influence of occupant behavior on energy consumption. Older studies had also made use of regression analysis based on billing data to determine household energy. A study by Ref. [22] used monthly energy billing data to decompose energy use to weather and non-weather dependent elements, as well as explain anomalies in energy use of some households.

Determining the internal temperatures or temperature setpoints has been of particular interest, especially in residential buildings in mostly heating dominated climate since the main source of building energy demand is driven by heating which in term directly depends on the temperature difference between inside and outside. Temperature setpoints and heating duration may differentiate across dwellings based on their preferred thermal comfort range, which affect the resulting internal temperatures. Nevertheless, many top-down urban scale models assume the same constant temperature setpoints for the whole building stock, while the rest calculate internal temperatures as a function of building envelope, occupancy and systems [23].

Most of the existing literature puts emphasis on predicting internal temperatures or measuring household room temperatures at district scale based on temperature recordings [24]. For example, the authors in Ref. [25] collected temperature and humidity data from 1604 study dwellings in order to determine the effect of dwelling and household characteristics on indoor temperature variation. The median