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# Urban energy flux: Spatiotemporal fluctuations of building energy consumption and human mobility-driven prediction

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## HIGHLIGHTS

- Over 8,000,000 urban individual positional records for a full year were examined.
- Distribution predictability of over 600,000 urban electricity meters was determined.
- There is a spatiotemporal dependency between urban human mobility and energy use.
- Human mobility-driven spatiotemporal predictive approach for energy is proposed.
- A new perspective on how urban energy needs to be measured, managed and distributed.

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## ABSTRACT

Urbanization is causing a significant increase in the amount, diversity, and complexity of human activities, all of which have a substantial impact on energy consumption. Current approaches to predicting energy demand at different spatiotemporal levels are functions of the characteristics of either individual buildings or cities and their occupancy levels, or are data-driven, typically taking the form of sensor-based modeling. Nevertheless, accounting for both the spatial and temporal effects of heterogeneous human behavior patterns on buildings' energy use at the city level remains a challenge. In this paper, we examine the temporal manifestation of the fluctuations of energy use in urban buildings driven by spatial mobility patterns of the population. We then present an urban-level spatiotemporal approach for predicting buildings' energy demand. Using a full year of individual positional records from an online social networking platform (Twitter), we introduce a multivariate autoregressive model in reduced principle component analysis space to create monthly predictions of residential building electricity demand generated across 801 spatial divisions that account for 68% of the electricity used by buildings in the City of Chicago, through a spatial autoregressive model. This model represents an important step forward, incorporating the spatiotemporal energy use fluctuations of urban population activities to create more reliable predictions of demand in future cities.

## 1. Introduction

High levels of uncertainty about future energy demands impose limits on the continuing growth of cities worldwide. Urban areas, which have become the most complex built environments in human history, are rapidly expanding in terms of both their size and population [1]. However, subsequent additions to the amount and complexity of daily activities of urban populations may not be able to be sustained without an accompanying substantial increase in their energy infrastructure. Urban areas are now responsible for up to 80% of the world's total energy consumption [2,3] and the corresponding risks involved in supplying, or failing to supply, sufficient energy resources are inevitable. In particular, urban buildings are determined as the largest energy consuming sector in the economy [4]. Having a clear understanding of the space-time distributions of urban building energy demand [5–7] is thus clearly of paramount importance for both planners and city managers. Models of urban energy demand often tend to focus on quantifiable factors that influence the demand such as technological, socioeconomic, and those related to the infrastructure. Many models neglect the inclusion of human behavior which can be equally impactful [5,6], and adds to model uncertainty [8]. Today, with the advancement of technology, quantifying people's activities and behavior is increasingly possible in many ways [9–12]. Human behavior towards energy consumption is relatively well studied at

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the building level [13,14]. However, the significance of human behavior on buildings' energy consumption at the urban-level is an important aspect of urban energy demand modeling that is scarcely studied. Despite the profound impact that this aspect brings on spatiotemporal distribution of energy demand and the calls by researchers for incorporating the effects in demand estimations [15,16], such measures are currently missing from the literature. We need to be able to reliably estimate how much energy will be needed at particular times and locations across a range of urban buildings. Enhancing our ability to understand and manage short and long term urban energy resources is essential if our cities are to continue to thrive and develop into smarter built environments capable of accommodating the growth of technology and the corresponding fluctuating activity patterns of the urban population. Here, we examine the temporal manifestation of the fluctuations of building energy use driven by the spatial mobility patterns exhibited by a city's population as an indicator for human activities, and we introduce a spatiotemporal approach for predicting building energy demand in urban areas.

## 2. Related work

Current approaches to predicting urban building energy consumption at different spatial levels are functions of the characteristics of buildings [17–19], urban information [5,6,20], or rely on sensor-based data-driven approaches [13]. As the effects of rapid increases in complexity and human activities in cities are amplified [21], understanding and managing the end use patterns of energy demand in spatiotemporal dimensions [5], taking into account the uncertainties of human behavior becomes more imperative.

At the city scale, Chaudhary introduced a Bayesian regression model to estimate energy intensity distributions using floor area estimates for various building usages in London [20]. At the neighborhood level, Mikkola and Lund [6] incorporated information on building types, their load profiles, their share of floor area, energy intensity and electricity demand, as well as population density, and city area into their power demand predictive model. At the block (zip code) level, Howard et al.'s [17] energy prediction model is primarily based on building functions in different locations within New York City. Others have proposed spatiotemporal models for building energy demand patterns of power and temperature, taking into account the variability of energy services across residential, commercial, and industrial buildings at the neighborhood and city district levels [5]. In particular, Zhu et al. [7] proposed a time-for-space substitutional model, which evaluates the variations of residential buildings' energy consumption in China driven by seasonality, climate, and socioeconomic factors. Spatiotemporal energy demand models have further been used to examine the potential for renewable energy investments, by capturing the interplay between power demand and renewable sources at multiple spatial scales, taking into account land use and socioeconomic factors [22].

At the building level, these efforts have tended to focus on data-driven methods and sensor-based energy modelling approaches. For example, Jain et al. [23] introduced a sensor-based forecasting model for residential buildings' energy consumption in New York City, using inputs of electricity consumption at different spatiotemporal granularities supplemented with hourly outdoor temperature data. Sensor-based approaches have enabled models of energy consumption to effectively incorporate the behavioral impacts from the human activity patterns at the building level [14]. However, a thorough review of the literature in this area has uncovered no studies exploring the predictability of urban scale energy consumption that incorporate the spatiotemporal effects arising from fluctuations in the activity patterns of the populations at the urban level. In their studies of nationally representative samples, Huebner et al. [24,25] examined the significance of several variables (i.e., building factors, socio-demographics, appliances, and behavior) in residential building energy consumption and found that those variables that are directly driven by people's activities exhibit the strongest predictive power. Urban population activities are a major source of change affecting future demand and thus serve as the foundation of our spatiotemporal estimations of energy use towards more reliable predictions.

Researchers have not found it easy to study the dynamics of individual activities at different spatial and temporal resolutions because the only data available was from self-reported surveys, monthly bills, and conceptual frameworks to assist effective decision making. Thanks to recent advances in technology, more powerful computers, and the advent of online social networks, urban population data at high spatiotemporal resolutions is now plentiful. The use of humans as sensors has made city-wide human mobility data available [26] through mobile phone signals that incorporate Global Positioning System (GPS) data [10,26,27], smart card commuting data [28], and location-embedded information from online social networks [9,11,29–31], all of which can be applied to provide information on the mobility behavior of urban populations. The human mobility patterns that are now visible to researchers reveal important information about the way citizens interact with their surroundings as they go about their daily lives.

As individuals move around their urban environment, they drive the energy consumption associated with their location-based activities in different buildings at particular times. The essential challenge facing academic researchers is thus to find a way to anticipate future changes in human activities (human mobility) that will enable them to make reliable predictions of future urban energy demand. A growing body of research has explored the predictability of human mobility [31–35], and new models are continually being proposed that provide more reliable predictions of energy consumption [6,18,23,36,37]. Studies that have focused primarily on predicting human mobility [33,34,38,39] and building human mobility-based predictive models [12] have taken a number of different approaches. Although up to 93% predictability has been achieved for the movements of individuals [38,39], changes in their predictability can arise due to unforeseen circumstances such as natural disasters [35]. McInerney et al. [33] examined the boundaries of human mobility predictability to anticipate breaks from routine using a Bayesian model, while others analysed the travel patterns of up to 500,000 individuals using Markov chain based models to predict their visited locations, achieving an 88% theoretical maximum predictability [34], and introduced a mobility model for predicting individuals' locations using point of interest (POI) information [31]. Several studies of human mobility behavior have adopted a network perspective to predict the future of such networks as well as the proximity of individuals within the networks, showing great precision in anticipating future mobility topology [32]. Predictive models of human mobility have been extensively applied in recent years across applications such as traffic and travel demand predictions [40,41], human activity predictions [12], next place locations [42], epidemics and the spread of viruses [43–45], air pollution [46,47], and transport energy consumption [47,48].

In order to assess the energy use attributable to individuals' urban mobility and employ human mobility as a predictor of future energy consumption, this study focused on the spatiotemporal predictability of energy consumption driven by intra-urban human mobility behavior of the returners population [49] in the City of Chicago. This population has shown to be most representative of the spatial distribution of energy use in urban settings and dominate the spatial dependency between human mobility and energy use compared to their counterpart population (i.e., explorers). We