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# Estimation and projection of institutional building electricity consumption

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ABSTRACT

This study provides understanding of the influence of outside temperature on intuitional buildings in an urban landscape. We derive heating and cooling degree days for each of the buildings by identifying an appropriate choice of balance point temperatures and perform multiple linear regression seasonally to characterize the temperature-electricity use relations.

Our study reveals considerable differences in temperature-electricity relationships based on building use and characteristics. In addition to outside temperature, the weekday effect has large influences on electricity consumption of buildings. Summer months have greater influence of outside temperature on electricity consumption followed by transition months and winter as an increase in one cooling degree day (CDD) increases daily electricity consumption by 0.124 kW/m2 whereas during winter, one heating degree day (HDD) increases daily electricity consumption by 0.025 kW/m2 and by 0.099 kW/m2 during transition months. We apply two kinds of models to project electricity demand for projected temperature profiles in 2030. Both cases strongly suggest higher electricity demand not just in summer months but also during transition periods in spring and fall. Overall, electricity demand increases by 0.95% under a low emission scenario (RCP 4.5) and 2.03% under a high emission scenario (RCP 8.5), which is likely to put immense pressure on the United States electric grid system and an overall increase in the energy cost by 2030.

## 1. Introduction

### 1.1. Buildings and energy use

In 2010, the buildings sector accounted for approximately 32% of energy use worldwide and 8.8 Gt of $CO_2$ emissions (19%) including direct and indirect emissions [1]. Per capita energy consumption by buildings has increased to improve comfort levels and with extension of human activities [2]. By mid-century, urbanization and improvements in the wealth, lifestyles and access to modern energy services are expected to double the energy demand and increase $CO_2$ emissions by 50–150% [1]. The increase in building energy consumption raises concerns for the exhaustion of nonrenewable energy sources, accumulation of greenhouse gases in the atmosphere, and impacts on local air quality [1].

In the United States, residential and commercial building energy consumption alone account for 41% of total energy consumption [102]. With global warming and associated changes in the frequency of heat waves and cold spells [3], building energy consumption is expected to rise, especially during summer to cool buildings [4–9] as well as for heating during winter [10]. To counteract adverse impacts of rising energy demand and carbon emissions of buildings, energy efficiency can be improved by altering building characteristics [11–16] and by implementing behavioral and lifestyle changes [17–21].

Technical approaches to improving building energy performance include those targeted towards building equipment [22], refurbishment and retrofitting [23], operation and maintenance [24], and building designs such as building orientation [25,26], shape [27], and building envelope/shell [28–34]. Among these approaches are the development of new smart materials such as thermochromic windows [35–39], passive heating and cooling mechanisms [40–45], shading and glazing [46–51], green walls and

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roofs [52–59] and a host of other sustainable building approaches [34,60–62].

Among the social variables affecting building energy performance are occupant behavior [63–66], norms and expectations for indoor environmental conditions [67], and occupant characteristics such as household size and income. Changing norms, lifestyles and behaviors may reduce energy demand in developed countries by up to 20% in the short term and by up to 50% by mid-century [1]. Climate, technological, and behavioral determinants of building energy consumption are closely intertwined. For example, in the United States, as climate changes, electricity demand shifts from space heating to space cooling as a growing share of the populations is migrating to the warmer regions of the country [68,69].

Studies performed in cities with different climatic conditions [103,8] depict unique electricity-temperature relations for the assemblage of buildings found in those cities. The fact that the electricity-temperature relationship differs across buildings by their use, building shell, age, and heating and cooling sources altogether has not yet been fully incorporated into such studies. To begin addressing urban electricity use in buildings across temperature ranges and for different building characteristics and uses, we focus in this paper on institutional energy use. Specifically, our case study is for data from a university, which consists of a diverse assemblage of residential housing, office buildings, sports facilities and more, much of which is akin to buildings found in office parks and hospitals, for example, and can be considered as a microcosm of the city itself.

A better understanding of the electricity-temperature relationships for an assemblage of buildings of different types and uses can help owners and operators refine institutional energy demand and the energy contracts into which they enter, thus reducing their electricity bills. It can also guide efficiency improvements towards lower energy use and carbon emissions. With our study, we contribute to the knowledge on building energy consumption at scales larger than an individual building but smaller than the city itself, and for buildings that have a distinct workday effect.

### 1.2. Electricity consumption and outdoor temperature

The relationship between electricity consumption and outdoor temperature is typically studied in terms of heating degree day (HDD) and cooling degree day (CDD).

Most studies assume 65° F (18.3 °C) as the balance point temperature and calculate HDD and CDD based on that balance point [70–79]. Some researchers, however, have used different balance points depending on climatic regions or the economic sector for which the measure is applied [6,80–84]. However, even within a climate regime or a particular sector the temperature electricity demand is non-linear and depends on several factors such building characteristics and behavioral variables, which makes the use of a single, uniform balance point problematic for the assessment of temperature-energy use relationships for buildings.

Fazeli et al. [85] discuss a range of methods to determine balance point temperatures. These methods include those that deduce balance point temperatures by

a) assuming a linear relationship between temperature and energy consumption [86,87];
b) exploring non-linear relationships between these variables [88–92];
c) quantifying the relationships via non-parametric approaches [8,88,93,94].

Non-parametric approaches are based on the notion of smooth transitions between heating and cooling degree days in response to outside temperature variations. In addition to balance point temperatures, the temperature-energy use relationship is dependent upon building characteristics and use. As a consequence, applying one balance point for all the buildings with different uses on a campus or other institution, and more so for a city as a whole, is difficult to justify on grounds other than analytical convenience.

The following section describes the methodology to find site- and building-specific balance point temperatures. These balance point temperatures are then used to define HDD and CDD on which we base our study of temperature-electricity relationships and projections of future electricity demand. Section 3 closes with a summary and conclusions.

## 2. Methodology and results

### 2.1. Data processing

For our analysis we draw on electricity use data for 26 buildings at the Northeastern University Boston (Massachusetts, USA) campus. The datasets consist of electricity use (in kW) reported in 15-min increments for the years 2013–2014. These data are aggregated, by building, to calculate daily electricity use, and normalized by the total space available in each building. For the (rare) cases of missing values of daily electricity consumption we assume average electricity consumption of the particular day on the week before and after. Outside temperature data (dry bulb thermometer readings) comes in hourly increments from NOAA's Quality Controlled Local Climatological Data (http://www.ncdc.noaa.gov/orders/qclcd/) for Logan Airport, which we aggregated into mean daily temperature. Data processing and Analysis is performed using R program [95].

### 2.2. Building characteristics

We account for building characteristics such as building use, age of the building, and building shell types. The building use is categorized into four classes: 1) athletic facility, 2) classroom and administrative or combination of both, 3) administrative only, and 4) residence facility. Similarly, the ages of buildings are classified into three classes based on the built year: prior to 1950, 1950–2000, and 2000-present. Newer buildings have better insulation and efficiency. Heights vary from 3 to 22 stories.

Building shells are distinguished into three types: 1) brick, 2) concrete or precast masonry, and 3) metal and/or glass. In our case, brick buildings are mostly built before the year 2000 whereas metal/glass and concrete buildings are recently built, which in turn affects the building performance with improved and smart lightning fixtures and equipment. These buildings are closely spaced together in the urban landscape. As a consequence, shading effects from vegetation are almost negligible. These buildings are continuously conditioned and in most cases the windows cannot be opened, minimizing natural ventilation.

### 2.3. Balance point temperatures

Despite the fact that non-linear relationships between electricity consumption and temperature have long been established in the literature as the norm, the default assumption of a 65° F balance point temperature still dominates. To avoid errors in energy use estimation and projection that are caused when sticking to that default, we use a Logistic Smooth Transition Model (LSTR), adopted from Moral-Carcedo and Vicens-Otero [94], to determine the balance point temperature of individual buildings. Towards that end, we first carry out the following two steps: