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Impacts of climate change on energy consumption and peak demand in buildings: A detailed regional approach

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A B S T R A C T

This paper presents the results of numerous commercial and residential building simulations, with the purpose of examining the impact of climate change on peak and annual building energy consumption over the portion of the EIC (Eastern Interconnection) located in the United States. The climate change scenario considered includes changes in mean climate characteristics as well as changes in the frequency and duration of intense weather events. Simulations were performed using the BEND (Building ENergy Demand) model which is a detailed building analysis platform utilizing EnergyPlus™ as the simulation engine. Over 26,000 building configurations of different types, sizes, vintages, and characteristics representing the population of buildings within the EIC, are modeled across the three EIC time zones using the future climate from 100 target region locations, resulting in nearly 180,000 spatially relevant simulated demand profiles for three years selected to be representative of the general climate trend over the century. This approach provides a heretofore unprecedented level of specificity across multiple spectrums including spatial, temporal, and building characteristics. This capability enables the ability to perform detailed hourly impact studies of building adaptation and mitigation strategies on energy use and electricity peak demand within the context of the entire grid and economy.

1. Introduction

Building energy demand will change in response to future climate change, with cooling and heating demand generally going in opposite directions. Net increases or decreases largely depend on a region's cooling or heating demand dominance. Much of the literature on building energy demand modeling is oriented toward simply forecasting future demand or increasing energy efficiency. While it may address the impact of weather or climate sensitivity of demand or the impact of current climate on demand, it does not address the impact of future climate change (e.g., [24,37,38,50,55,56]). The extant literature projecting the effects of climate change on future building energy overwhelmingly has emphasized changes in overall annual energy consumption. Most analyses of the impacts of climate change on building energy demand distinguish between heating, cooling, and other end uses (e.g. [13]), but nearly all the existing literature discusses annual energy consumption, with only a few taking on the question of peak demand (for a nice review see Ref. [26] and specific papers [12,27,32]). However, peak demand is a critical element in the long-term planning for energy system capacity which for developed countries generally consists of electricity (the mix and spatial distribution of generation technologies, transmission, and distribution) and natural gas (production, transmission, distribution, and storage).

In most prior analyses, climate change has been expressed as changes in annual or monthly HDD (heating degree-days) and CDD (cooling degree-days) (generally using 65 °F/18.3 C) (see for example Ref. [4] and the survey of approaches in Ref. [20]) instead of the true building balance point or simulation approach (see however, Refs. [2,6,15,19,20,41]). Energy consumption is generally correlated with changes in HDD or CDD in the same periodicity (i.e., monthly or annual). Methodological approaches include multiple regression (e.g., [1,19,29,33,39,40]), simulation of individual buildings (e.g., [51]), and combining the two approaches (e.g., [52]). These analyses conclude that the impact of climate change is generally benign or at least not seriously deleterious as demonstrated by the following results:

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- Annual cooling energy consumption (almost always electricity) is likely to increase by a few percent,
- Heating energy consumption (by a variety of fuels) to decrease by a few percent, and
- Net total energy consumption to decrease by a lesser percentage in colder regions and increase in warmer regions.

Generally there is a note that cooling demand increases strongly in most regions, but the consequences for utility investment are not pursued. Some analyses have relied on detailed building models (see, for example, Refs. [7,17,23,43]) but, to date, no climate analysis has attempted to take into account the great diversity of buildings that actually would be affected by climate change. Instead, these papers have derived their conclusions concerning future energy consumption based on the energy response of only one or two building types, which is assumed to be representative of the entire building stock (e.g., [10,23,28,30,42,57]). One interesting exception that uses a group of buildings for forecasting, but for planning rather than forecasting with climate change, is Ref. [5]. How would the energy forecast answers change if the diversity of building types was taken into account directly, and in particular, how would peak loads be affected? These are the primary questions we address in this paper.

This paper presents the results of a comprehensive commercial and residential building simulation study, with the purpose of examining the impact of climate change on peak and annual building energy consumption over the portion of the Eastern Interconnection located in the United States. The climate change scenario considered (IPCC (Intergovernmental Panel on Climate Change)) A2 scenario as downscaled from the CASCaDE dataset—[9] has changes in mean climate characteristics as well as changes in the frequency and duration of intense weather events. This investigation examines building energy demand for three annual periods − 2004, 2052, and 2089. These years were chosen because they are representative of the overall climate trend in the CASCaDE A2 dataset. Simulations were performed using the BEND (Building ENergy Demand) model which is a detailed building analysis platform utilizing EnergyPlus as the simulation engine. EnergyPlus is a well known and highly validated model that is the industry standard. EnergyPlus has been validated in numerous tests from ASHRAE, ANSI, and IEA (for a complete listing of EnergyPlus testing and validation please visit: http://apps1.eere.energy.gov/buildings/energyplus/energyplus_testing.cfm).

BEND was developed in collaboration with the PRIMA (Platform for Regional Integrated Modeling and Analysis), a modeling framework designed to simulate the complex interactions among climate, energy, water, and land at decision-relevant spatial scales, which will be briefly discussed in Section 3. Over 26,000 building configurations of different types, sizes, vintages, and, characteristics which represent the population of buildings within the EIC (Eastern Interconnection), are modeled across the three time zones using the climate from 100 locations within the target region resulting in nearly 180,000 spatially relevant simulated demand profiles for each of the three selected years. In this study, the building stock characteristics are held constant based on the 2005 building stock in order to isolate and present results that highlight the impact of the climate signal on commercial and residential energy demand. Results of this analysis compare well with other analyses at their finest level of specificity. For example, some studies offer a high degree of variation within building types but have limited spatial variation and are not focused on climate change [5,43] while others offer wider spatial and temporal coverage yet lack detailed the detail simulation necessary to explore full impacts of climate change on building energy consumption [3,13]. This approach, however, provides a heretofore unprecedented level of specificity across multiple spectrums including:

- Spatial—Modeling geographic areas down to a one-eighth degree grid with the ability to aggregate up to any larger geographic area
- Temporal—annual, monthly, weekly, hourly, and sub-hourly modeling are possible
- Building Type—an array of building types possible; five residential and eleven commercial were used for this analysis.
- Building Vintage—multiple vintage classes possible for each type of building; seven categories used here.
- Building Size—limitless building size capability; six size bins were used.

This capability enables the ability to perform detailed hourly impact studies of building adaptation and mitigation strategies on energy use and electricity peak demand within the context of the entire grid and economy.

2. Models and methods

2.1. The BEND model

The Building ENergy Demand (BEND) model simulates climate-dependent hourly building energy demands for populations of buildings at various spatial scales with resolution as fine as a one-eighth degree grid and an ability to aggregate up to any size geographic area including counties, states, utility control area, and census regions. BEND combines DOE's EnergyPlus™ [46] model of individual building energy use with a geospatial analysis of regional climate, population, building types, and technologies to provide this scale-flexible characterization of regional building energy demand.

EnergyPlus is a highly detailed building thermal load simulation program that relies on detailed user inputs. EnergyPlus calculates heating and cooling loads, and energy consumption, using sophisticated calculations of heat gain and heat loss including transient heat conduction though building envelop elements. It also accounts for heat and mass transfer that impact sensible and latent thermal loads due to ventilation and infiltration. Additionally, the model has detailed calculations of heat transfer to or from the ground and comprehensive models of solar gain through the fenestration and opaque envelop components.

The BEND model is applied by developing a "population" of statistically representative buildings (see Section 5) for a geographic region (see Section 4) based on data from the Commercial Building Energy Consumption Survey [47] and the Residential Energy Consumption Survey [49]. Starting estimates for the number of each type of representative building are typically modified through a calibration exercise whereby actual historical weather is used to simulate energy consumption for the building population, which is compared to actual energy consumption for the same time period. The calibrated model can then be used to project energy consumption under specific climate and technology scenarios. BEND estimates of future building energy demand can then be used by other models in the PRIMA framework as described in the next section.

In addition to the statistically representative building population and flexible spatial scale just described, BEND also provides an ability to resolve the temporal character of building power demands. This capability is critical for understanding the way that electricity generation capacity requirements will need to change in the future and how a changing climate may influence the evolution of electricity system planning and operation. Finally, the richness of

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