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Assessing regional differences in lighting heat replacement effects in residential buildings across the United States

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HIGHLIGHTS

- Replacing inefficient lamps affects heating and cooling demands of a building.
- We assess regional differences of this effect at 105 cities in the U.S.
- The effect size depends on regional factors such as climate and fuel mix.
- The effect can undermine up to 40% of originally intended primary energy savings.
- The overall effect is at most 1% of total energy consumption by a house.

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ABSTRACT

Lighting accounts for 19% of total U.S. electricity consumption and 6% of carbon dioxide equivalent (CO_2e) emissions. Existing technologies, such as compact fluorescent lamps and light emitting diodes, can substitute low-efficiency technologies such as incandescent lamps, while saving energy and reducing energy bills to consumers. For that reason, lighting efficiency goals have been emphasized in U.S. energy efficiency policies. However, incandescent bulbs release up to 95% of input energy as heat, impacting the overall building energy consumption: replacing them increases demands for heating service that needs to be provided by the heating systems and decreases demands for cooling service that needs to be provided by the cooling systems. This work investigates the net energy consumption, CO_2e emissions, and savings in energy bills for single-family detached houses across the U.S. as one adopts more efficient lighting systems. In some regions, these heating and cooling effects from more efficient lighting can undermine up to 40% of originally intended primary energy savings, erode anticipated carbon savings completely, or lead to 30% less household monetary savings than intended. The size of the effect depends on regional factors such as climate, technologies used for heating and cooling, electricity fuel mix, emissions factors, and electricity prices. However, we also find that for moderate lighting efficiency interventions, the overall effect is small in magnitude, corresponding at most to 1% of either total emissions or of energy consumption by a house.

1. Introduction

In order to reduce emissions, improve energy security and avoid building as much additional electricity generation infrastructure, the U.S. has been fostering improvements in energy efficiency. In particular, energy efficient lighting has been promoted in many energy efficiency programs by utilities [1]. Switching from low efficiency lighting technologies, such as incandescent light bulbs, to compact fluorescent lamps (CFL) or light emitting diodes (LED) can provide the same level of illumination while consuming less power and thus reducing lighting electricity bills to consumers. The potential for reductions in energy consumption, in greenhouse gases emissions, and in criteria air pollutant emissions is large, as lighting accounts for 19% of U.S. electricity consumption [2] and 6% of CO_2 equivalent emissions [3]. We focus on the residential sector, where lighting accounts for 13% of total residential electricity consumption and 9% of total residential primary energy consumption in 2011 [4].

In many assessments of energy and cost savings from lighting retrofits, modelers use engineering analyses comparing lighting systems before and after an energy efficiency measure is

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implemented, assuming all other energy demands are held constant [5–8]. However, the substitution of incandescent light bulbs (where about 95% of the electricity is released as heat) with more efficient alternatives, such as compact fluorescent lamps or light emitting diodes, will lead to additional heating and reduced cooling energy consumption, which is generally called a ‘‘*heat replacement effect*’’ or HRE [9]. This HRE can be interpreted as a component of the *rebound effects*, i.e., the percent of energy or carbon dioxide emissions savings that were not achieved due to behavioral or technical reasons. In this work, we assess the magnitude of HRE across the United States, changes in household energy bills, and associated indirect carbon emissions for single-family detached buildings across 105 cities in the contiguous U.S. when incandescent light are switched to more efficient alternatives.

HRE has been studied through experiments using physical test chambers equipped with instruments measuring actual heat transfer [10–12]. These experiments, mainly designed for the benefit of building engineers, can estimate the lighting heat gain parameters for the experimental setup as a function of detailed parameters such as luminaire type, room air temperature, or airflow rate, types of information which are only available at a specific building level.

HRE has recently become a more prominent subject of policy discussion: in the UK, the Department of Environment, Food, and Rural Affairs (DEFRA) assessed the impact of HRE on energy consumption, consumer energy bills, and carbon savings in the UK residential sector [13]. DEFRA found that 24–26% of total anticipated light energy savings would be lost due to HRE. In the United States, most of the analysis and discussion has focused on commercial buildings [14,15]. These studies found no significant net gains or losses at a national level in primary energy (or source energy) use or energy expenditures for heating, ventilation, and air conditioning (HVAC). Hopkins et al. [16] provided a simple order-of-magnitude analysis of HRE of a residential lighting retrofit as a part of their report on a simulation tool developed to estimate nationwide residential energy use based on a nationally representative set of single-family residential buildings. Hopkins et al. report that for each unit of site energy savings due to lighting retrofits, there will be an additional 7% site energy savings from reduced use of AC, while 40% will be lost to satisfy additional heating demand on site (i.e. resulting in only 0.67 (=1 + 0.07 − 0.40) net units of energy being saved). Overall, the authors report that the net primary energy savings resulting from each unit of site energy saving is 0.95.

2. Materials and methods

2.1. Data

We use EnergyPlus 7.2 version for our analysis. EnergyPlus is a comprehensive building energy simulation program developed by U.S. DOE. It runs building energy simulations based on a formatted description of a building. Users create the description file by specifying fields predefined in EnergyPlus, which correspond to detailed components of a building (e.g. building dimensions, structure of heating/cooling systems, wall/window characteristics). EnergyPlus outputs site/source energy consumption categorized by end use and fuel type.

We adopt building prototypes created by the Pacific Northwest National Laboratory (PNNL) as an input to our analysis [17]. The prototypes originally developed by PNNL characterize both single-family detached houses and multi-family low-rise apartment buildings in 109 U.S. cities. Our study focuses solely on single-family detached houses, as they account for the majority (about 75%) of total residential electricity consumption in the United States [18]. Thus, we simulate the prototypes for single-family detached houses corresponding to the 105 cities in the contiguous U.S.

The prototypes represent buildings compliant with IECC of 2006, 2009, or 2012 – thus representing recently constructed residential buildings. New single-family houses built since 2006 in the U.S., which are covered by the PNNL prototypes, represent about 8% of residential building stock [19]. The IECC is developed by the International Code Council and adopted by most state or local governments as a basis for their building energy efficiency requirements. We use the prototypes complying with IECC 2009 since as of 2012 it is the baseline code most widely adopted by states for their building energy codes, having been adopted by 30 states [20].

The PNNL prototypes differ only in their U-factors and SHGC (Solar Heat Gain Coefficient) values for windows and *R*-values for exterior materials, which vary by climate zone to be in compliance with the IECC requirements. An *R*-value is a measure of thermal resistance and represents a reciprocal of how much heat energy is transferred per unit area of a material when a unit temperature difference is applied across it, measured in m^2 °C/W or ft^2 °F h/Btu. As such, a higher *R*-value means better insulation capability. The *U*-factor is the inverse of *R*-value and measures thermal transmittance.

The PNNL single-family house prototypes have two stories, an attic, two doors on the south and north sides, and a window on all four sides of each floor. Four foundation types are modeled (slab, crawlspace, unheated and heated basement), as well as four heating systems (gas/oil furnaces, electric resistance, and heat pump), resulting in sixteen combinations. The floor area is 224 m^2 (=2411 ft^2). The window-to-wall ratio is 15%. Thermostat settings are assumed to be 72 °F for heating and 75 °F for cooling.

Houses with *slab foundation* and *gas heating* are used as a base-case in our analysis, since they are the largest group among the residential building stock. The 2009 Residential Energy Consumption Survey (RECS) microdata—designed to be nationally representative—shows that among all the 7803 single-family house observations, those with *slab foundation* and *gas heating systems* take 14% [18]. In the sensitivity analysis we will assess the impact of having different types of heating system or foundation. In Table S1 in Section SI 5 of the Supplemental Information (SI), we show the proportion of buildings with each type of heating equipment and foundation among the 7803 single-family houses.

Weather data for the typical meteorological year for each of the 105 cities was retrieved from the U.S. DOE's Energy Efficiency and Renewable Energy (EERE) website [21]. We used the TMY3 data set, which is derived from the period 1991–2005 and contains hourly values of solar radiation and other meteorological data. Average electricity prices for each state and natural gas price for residential consumers for year 2010 were collected from U.S. Energy Information Agency (EIA) electricity data website [22,23]. Average carbon emission factors are from U.S. Environmental Protection Agency (EPA)'s eGRID database, and primary energy conversion factors for each state were adopted from Deru and Torcellini [24] (in SI, Section SI 4, we test the assumptions for emissions factors using marginal emissions factors instead). Building occupancy is characterized in EnergyPlus by defining two inputs: household size and daily occupancy profile. We assume a household size of three people, and the default occupancy schedule is as in PNNL prototypes (see SI, Fig. S11 for more detail).

2.2. Simulation scenarios

We assume a baseline lighting demand scenario and an efficiency scenario. The baseline scenario represents average lighting energy consumption of a single-family detached house meeting IECC 2009. We calibrate this profile by using lighting energy consumption from the 2010 U.S. lighting market characterization produced by Navigant Consulting for the DOE [2]. Based on that report, installed bulbs in single-family residential buildings are 68% incandescent, 24% CFL, and 8% linear fluorescent lamp. This