Applied Energy 141 (2015) 12–18

Contents lists available at ScienceDirect

Applied Energy

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

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.

ARTICLE INFO

Article history:
Received 14 June 2014
Received in revised form 18 November 2014
Accepted 19 November 2014
Available online 24 December 2014

Keywords:
Heat replacement effect
Energy efficient lighting
Building energy simulation
Rebound effects

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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http://dx.doi.org/10.1016/j.apenergy.2014.11.031
0306-2619/

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 differs from the lighting requirement of IECC 2009, which requires at least 50% of the lamps to be high-efficacy. This share distribution in 2010 is converted to average interior illuminance of 276 lux and lighting power density (LPD) of 12.2 W/m^2. The diurnal lighting usage schedule is adopted from the Building America Simulation Protocol [25] and scaled to match the average daily hours of use from the Navigant report of 1.45 h per lamp (see SI, Fig. S12 for more detail on lighting profiles).

The efficiency scenario complies with the lighting requirement of IECC 2012, which requires residential buildings to have at least 75% of the lamps being high-efficacy [26]. IECC 2012 was selected because this code is growingly being adopted by states. Building on the baseline assumption on shares above, we assume 25% incandescent, 67% CFL, and 8% linear fluorescent lamps, which corresponds to average LPDs of 7.4 W/m^2. Indoor illuminance level and hours of use are kept unchanged across scenarios, i.e., we do not account for rebound effects resulting from using efficient lamps for more hours (see Azevedo et al. [27,28] for a taxonomy on rebound effects). More detailed assumptions are given in Section SI 6.

3. Results

We compare a *baseline* scenario and an *efficiency* scenario for single-family detached houses with slab foundation and gas furnace in 105 cities around the contiguous U.S.

We compute the size of HRE as follows:

$$HRE\ (\%) = \frac{\{[C_{baseline} - C_{noHRE}] - [C_{baseline} - C_{HRE}]\}}{[C_{baseline} - C_{noHRE}]} \times 100\% = \frac{[C_{HRE} - C_{noHRE}]}{[C_{baseline} - C_{noHRE}]} \times 100\%, \quad (1)$$

where *C* can either represent primary energy consumptions, CO_2e emissions, or energy bills. Thus, an HRE of 20% in primary energy savings, for example, means that out of 100 units of anticipated primary energy savings, only 80 units of savings are actually achieved once HRE is taken into account. In this way, HRE can be interpreted as a technical *rebound effect*. A detailed explanation of this term is provided in Section SI 1. Additional details on methods and assumptions are provided in Section 2.

Fig. 1 shows total annual average primary energy (i.e. source energy) consumption (Fig. 1a), CO_2e emissions (Fig. 1b), and household energy expenditures (Fig. 1c) at the baseline scenario for single-family detached houses with slab foundation and gas furnace in each of the 105 cities. Fig. S3 in Section SI 3 of the SI presents a map for annual average site energy consumption for all end-uses. *CO_2e emissions* (metric tonCO_2e per year) account for both direct and indirect emissions of CO_2, CH_4, and N_2O for natural gas and electricity consumption for all end-uses. For the global warming potential of the gases, we used values released by IPCC AR5 for 100 years of lifetime. *Total energy expenditure* is the total annual energy bills for both natural gas and electricity for all end-uses using state level residential prices for electricity and natural gas. We use 2010 average state level retail residential electricity prices as reported by the Energy Information Administration, and an assumed natural gas retail price of $11.4 per thousand cubic feet. All prices and costs are in 2010 dollar. In the sensitivity analysis we assess the importance of these assumptions on our results.

In the baseline scenario, across the 105 cities, a detached house can consume between 10 and 25 GJ of primary energy annually for lighting, while they all consume identical site energy (5.2 GJ = 1.5 MW h) for lighting. This variation in primary energy consumption derives from differences in the electricity

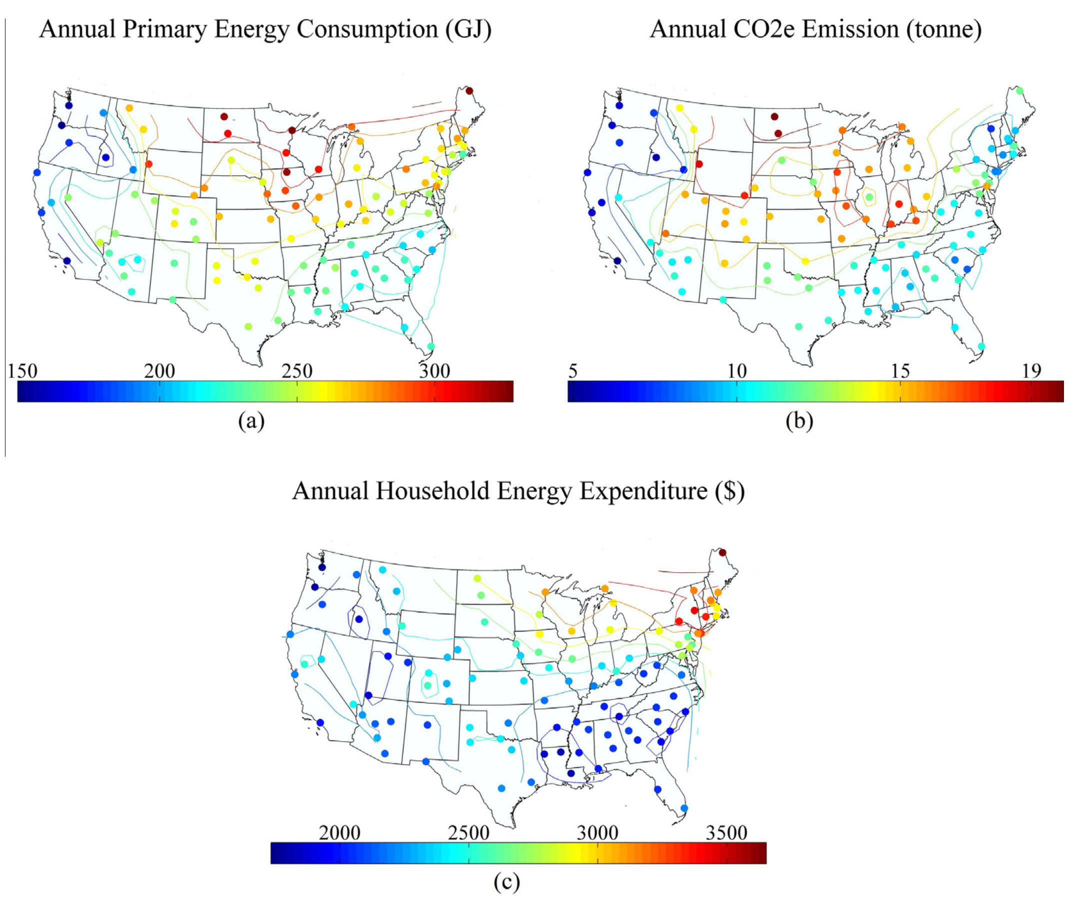

Fig. 1. Total baseline (a) primary energy consumption, (b) CO_2e emissions and (c) household energy expenditures (natural gas and electricity) for single-family detached houses with slab foundation and gas furnace in each of the 105 cities.

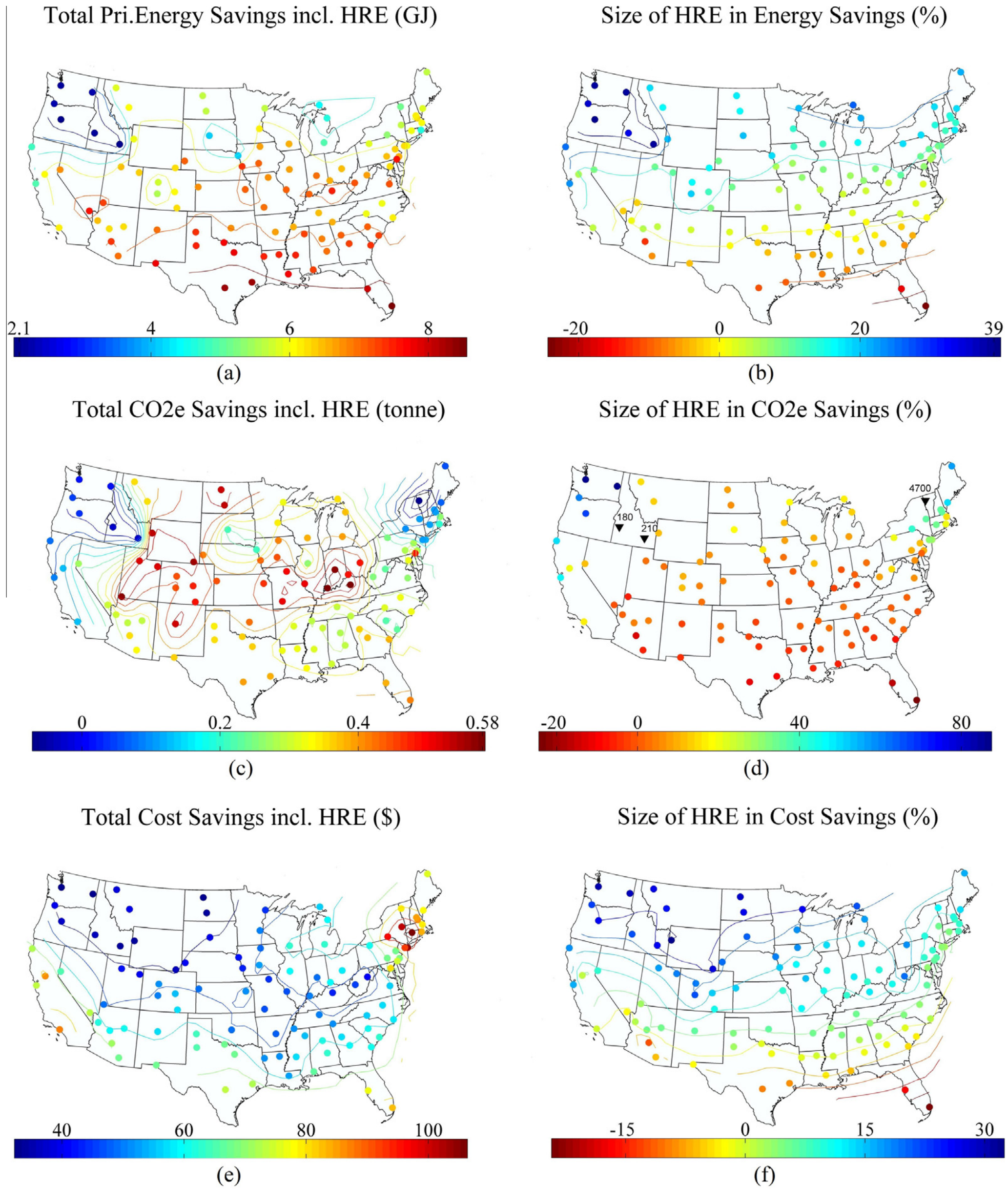

Fig. 2. Total savings resulting from the retrofit with HRE accounted for (left column), and corresponding size of HRE (percent of total savings that are not achieved because of HRE) (right). (a) Primary energy savings when HRE is accounted for, in GJ per year; (b) size of HRE in terms of primary energy savings; (c) CO_2e emissions saved annually when HRE is accounted for, in kg of CO_2e; (d) size of HRE in term of CO_2e emissions savings; (e) reduction in energy bills (electricity and natural gas) achieved annually after HRE is accounted for, in 2010 USD per year; (f) size of HRE in energy cost savings. Contour lines for (d) are not presented since the values of the three cities marked with "▼" are very different from those of other locations, leading to a misleading interpolation.

generation mix in each region, and associated differences in efficiency. Total annual primary energy use (including water heating and appliances) range from 150 to 330 GJ per household (Fig. 1a). Total annual CO_2e emissions from electricity and natural gas consumption per household range from 5 to 20 ton CO_2e (Fig. 1b). Finally, total annual spending on energy (gas and electricity) ranges from $1700 to $3600 (Fig. 1c).

In SI, Section SI 2, we show percent savings, without HRE accounted for, of primary energy consumption, CO_2e emissions, and household energy expenditures for single-family detached houses with slab foundation and gas furnace in each of the 105 cities. A first key conclusion is derived from such assessment: lighting interventions that are aiming at compliance with IECC 2012 can lead at most to a 4% reduction at a building level in total household primary energy consumption, total CO_2e emissions, or energy expenditures. The magnitude is reasonable considering that lighting consumes at most 9% of total residential primary energy use [4]. In our simulation results, this ratio at a building level ranges from 5% to 13% depending on the location of buildings. It is noteworthy that even when HRE for lighting is large, we can anticipate that the effects in overall household energy consumption, emissions or expenditures will be small.

Fig. 2 highlights the changes in the results when we account for HRE. Fig. 2a, c, and e shows total savings of annual primary energy, CO_2e emissions and energy expenditures between the baseline and efficiency scenario once HRE is taken into account.

Fig. 2b, d and f shows the size of HRE in primary energy savings, CO_2e emissions savings and annual cost savings when HRE is accounted for. As defined in Eq. (1), *negative* numbers in these figures mean that there are *more* savings than anticipated, while *positive* values mean that some of the savings are *eroded* due to HRE.

3.1. Primary energy savings

HRE does not always lead to reduction in energy savings. In the Southern U.S., for example, switching from more efficient lighting systems lowers the need for AC during the summer months. This reduction exceeds the increase in heating demand during the relatively short winter season, leading to about 22% more energy savings than what is anticipated when HRE is not taken into account (Fig. 2b).

Conversely, most of northern cities experience final energy savings smaller than what would be predicted if HRE is not taken into account. In those cities, the increase in energy consumption for heating due to HRE outweighs the relatively small decrease in demand for cooling.

Furthermore, in some states such as Washington, Idaho, and Oregon, their large proportion of power provided by hydroelectric generators leads to low primary energy conversion factors, making their final primary energy savings lower than other states [24]. The size of HRE in primary energy savings in these states can be as high as 40% (dark blue[1] dots in Fig. 2b), meaning that among 100 units of primary energy savings expected from a more efficient lighting system, only 60 will be achieved.

In contrast, houses in Florida can achieve up to 20% more primary energy savings than expected because the cooling energy service can be lowered (dark red dot in Fig. 2b). When the absolute HRE size is compared with total baseline primary energy consumption, the largest penalty on the intended energy savings is observed in Seattle, WA: under our baseline assumptions, total energy use was 155 GJ and the efficient lighting system, without accounting for HRE, is expected to save 3.6 GJ; the size of rebound due to HRE amounts to 1.4 GJ, or 0.9% of total baseline energy consumption.

3.2. CO_2e emissions savings

CO_2 equivalent emission savings are mostly determined by emission factors from the electric grid. We adopted state-level average carbon emission factors from U.S. EPA's eGRID database [29]. In two states with substantially low emission factors for electricity, Idaho (0.13 lb/kW h) and Vermont (0.006 lb/kW h), a lighting retrofit results in larger emissions of CO_2e than the baseline emissions, thus having a HRE size higher than 100%. Since the sizes of HRE in the two states significantly out-lie the rest of the cities, we mark them in Fig. 2d with "▼" and corresponding percentage values next to the marks. Burlington, VT exhibits a tremendous rebound in emission savings: the city *increases* its CO_2e emissions by forty-seven times compared with what it intend to save as it switches to more efficient lights. This is because any forms of electricity savings in this state yields almost no CO_2e reduction due to its near-zero emission factor for the electricity grid, while the emission from increased natural gas use for space heating easily exceeds the small reduction. Two other northwestern states (Washington and Oregon) and Maine, which have very low grid emission factors for electricity, have hardly any emission savings from improving lighting efficiency. On the other hand, in Lexington, KY and Evansville, IN (dark red dots in Fig. 2c), we observe the largest emission savings out of the 105 cities considered, as these states have one of the largest grid emission factors for electricity in the country. The percentage of total baseline CO_2e emissions that are negatively affected by HRE is largest in Arcata, CA, which is 1.3%. The city has the sixth lowest total emission and the lowest cooling demand among the 105 cities at the baseline.

3.3. Energy expenditures

Buildings located in southern states save more when HRE is accounted for than when they are not (i.e. negative HRE size), but the situation is opposite in most other states. For example, a household in Jackson Hole, Wyoming would expect to save $50 a year from the efficient lighting system but HRE reduces the savings by $16 (31% less, shown as a dark blue dot in Fig. 2f), while a household in Florida saves $83 a year, which is 24% more than what is anticipated without considering HRE (=$66). States with higher electricity price (such as California and the New England region) benefit more from lighting retrofits and see annual energy expenditure savings of up to $110 per year.

4. Sensitivity analysis

Throughout the analysis, we took the strategy to pursue several simplifying modeling assumptions. Indeed, there is a large uncertainty concerning carbon emissions factors one should use in these sorts of assessments, types of efficiency retrofits a household could do, influence of the heating and cooling equipment types, types of housing foundations, change in electricity and natural gas retail prices over time, change in occupancy, etc. To understand the impacts of the assumptions used in the building models on heat replacement effects, a series of sensitivity analyses are conducted. The assumptions tested are: (1) heating equipment and building foundation type, (2) carbon emissions factors for electricity, (3) building orientation, (4) efficiency value of heating/cooling equipment, (5) wall insulation level (*R*-values), (6) occupancy schedule, (7) lighting consumption schedule, and (8) energy prices.

The findings presented so far are limited to houses with gas furnaces and concrete slab foundations. In SI, Fig. S4, we compare primary energy consumption for several types of heating systems and building foundations for Bismarck, North Dakota: the city has one of the largest temperature ranges over the course of a year amongst the 105 U.S. cities studied, and so has both substantial heating and cooling demands. Not surprisingly, heating systems powered by electricity consume much more primary energy. The HRE size for electrically heated houses is larger than the alternatives, but foundation types do not affect the total energy consumption in a notable manner. Depending on the heating equipment type, HRE size in Bismarck, North Dakota, ranges from 16% (for natural gas powered heating) to 48% (for electricity based heating).

Grid emission factor for electricity in each state will naturally affect total CO_2e emission from a household and consequent size of HRE. Moreover, for each emission factor value, the size of HRE will also vary depending on which fuel (mainly electricity or natural gas) a building primarily uses for heating. For Bismarck, ND, we assessed the sensitivity of HRE size in CO_2e emissions savings with respect to emission factors for a wide range of value, assuming scenarios of either electric or natural gas heating, which is also presented in SI materials, Section SI 4. The size of HRE is sensitive to grid emission factors only in gas-heated buildings. For buildings with electric heating, both increase and decrease in household energy demand resulting from a lighting retrofit are from electricity, and the resulting size of CO_2e emission rebound due to HRE are simply proportional to total intended emission savings. On the other hand, when a building is heated mainly by natural gas, and the emission factor for electricity is low, additional

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

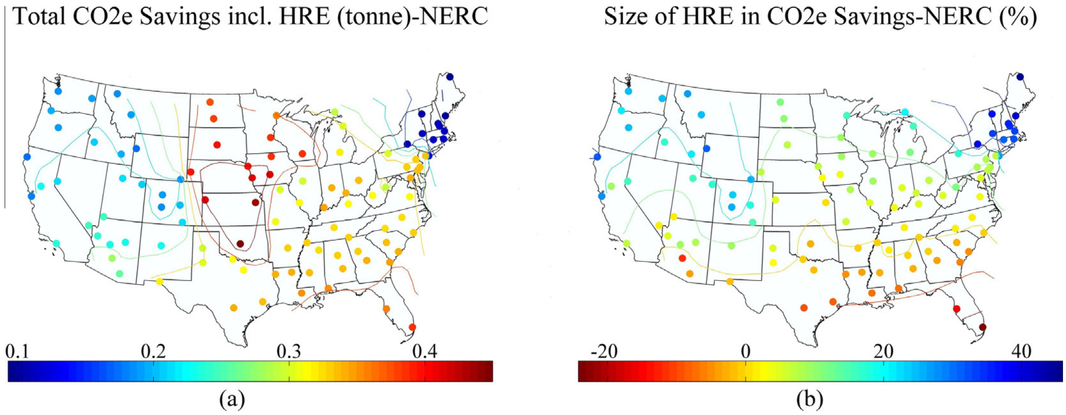

Fig. 3. Annual CO_2e emission savings based on NERC region-level emission factors. These maps are analogous to Fig. 2c and d, which were based on state-level emission factors.

emissions from heating energy use become relatively large compared to a decrease due to electricity savings.

Our analysis so far makes use of state-level electricity emission factors based on eGRID 2012 data. We test now how the analysis changes depending on which set of emission factors we adopt. Instead of state-level data, here we adopt NERC (North American Electric Reliability Corporation) region-level emission factors from the same database. Since each NERC region includes multiple states, using the NERC values acts as taking spatial averages across states in each region. Because of this averaging effect, extreme values are removed, and Fig. 3a now has a lot narrower range of values than Fig. 2c. In Fig. 3b, we do not see cities with the size of HRE larger than 100% (which was the case in Fig. 2d for Vermont and Idaho). Caribou, ME becomes a city with the largest size of HRE (46%). This comparison suggests that relying on data at a different regional scale may lead policy makers to aim at lower priority targets. For example, our analysis based on state emission factors indicates that either Kentucky or Indiana is the state with the largest carbon savings while the result in Fig. 3 shows it will instead be Oklahoma.

We also show in Section SI 4 of the SI how our results will change at each location if one uses marginal emission factors (MEF) instead of average emission factors. We adopt time-of-day average annual MEFs for each NERC region from Siler-Evans et al. [30]. As mentioned in that work, the Southwest Power Pool (SPP) region has an average emission factor (760 kg/MW h) significantly higher than MEFs (around 560 kg/MW h) because of large amount of coal used for its base load. Other than SPP, most regions have MEFs similar to or higher than average emission factors, resulting in larger emission savings from a lighting retrofit. MEFs from Siler-Evans et al. are only for CO_2 instead of CO_2e, which does not change the result significantly.

The SI also presents a sensitivity analysis on energy price changes. The result is more sensitive to electricity rate changes than to natural gas price changes because, among a household's overall energy expenditure savings caused by a lighting retrofit, electricity bill savings are a larger part than natural gas bill savings. We observe that a 20% increase (decrease) in electricity rate brings about up to 30% increase (decrease) in overall energy cost savings. An increase (decrease) in natural gas price by 20% causes up to 10% decrease (increase) in overall savings.

Our analysis so far is based on a lighting retrofit using only CFLs. Replacing incandescent bulbs with LED bulbs instead of CFLs will also affect the result, which is shown in Section SI 4 of the SI for Bismarck, ND. When we assume a typical LED bulb in the market, about 17% larger primary energy saving is achieved than the case where CFLs are replacing incandescent bulbs. However, the size of HRE, which is about −16% in the city, is not affected significantly because the rebound due to additional heating also increases.

The result is sensitive to efficiency rates of heating/cooling equipment as expected. These rates directly scale the site energy consumption used for heating and cooling, thus affecting the size of HRE directly. Building orientation, insulation level (*R*-values), occupancy schedule, and lighting consumption schedule did not substantially change the relative size of HRE. These analyses are all shown in SI (Fig. SI10).

5. Conclusions and policy implications

In this work, we investigate the heat replacement effect of switching to more efficient lighting system on net primary energy consumption, CO_2e emissions, and savings in energy bills for single-family detached houses across the U.S.

Almost all cities achieve positive savings in all three aspects from the simulated lighting retrofit scenario when we account for heat replacement effects. However, in a few states, where the emission factors for electricity generation are very low (WA, ID, OR, and VT), the overall emissions associated with the building may not decrease as expected or actually increase as a result of the lighting efficiency measures. This suggests that as the U.S. electricity grid becomes less carbon intensive, these indirect effects associated with changes in heating and cooling demands may actually become more important.

Among the assumptions tested for sensitivity analyses, main heating fuel type and efficiency rate of the heating/cooling equipment are the factors that have significant effects on the size of HRE. This is because using electricity as a main heating fuel incurs a larger HRE rebound because of its larger primary energy conversion rate than natural gas. Also, the efficiency rates of equipment directly determine how much energy has to be spent to compensate the heat loss from switching to efficient lighting. Thus, building codes and energy efficiency measures that coupled lighting and heating and cooling equipment simultaneously are key to avoid large heat replacement effects.

In addition, energy prices and emissions factors are also crucial factors directly influencing the size of HRE in energy cost savings and emissions savings respectively. The size of HRE is more sensitive to changes in electricity rate.

Finally, we also find that for moderate lighting efficiency interventions, the overall effect is small in magnitude, corresponding at most to around 1% of either total emissions or of energy consumption by a house.

Acknowledgements

This work was supported by the center for Climate and Energy Decision Making (SES-0949710), through a cooperative agreement between the National Science Foundation and Carnegie Mellon University. The authors would also like to acknowledge the Carnegie Mellon Electricity Industry Center (CEIC), and the feedback and comments from two anonymous reviewers.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.apenergy.2014.11.031.

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