Analysis of Heat Replacement Effect (HRE) in the U.S. residential buildings*

Jihoon Min and **Ines Azevedo**
Carnegie Mellon University,
5000 Forbes Ave, Pittsburgh, PA 15213
minjihoon@cmu.edu, iazevedo@cmu.edu

(1) Overview

Most estimates for energy and cost savings from lighting retrofits have been made simply based on engineering analyses of lighting systems before and after a retrofit, assuming all other energy demands are held constant. While this may provide just enough information in the lighting system level, what we care more about from a policy standpoint is how much resource a certain intervention can save as a whole. The simple comparison between different lighting systems clearly overlooks interactions between lighting and heating/cooling systems in residential buildings. Only 5% of electric energy that a 60W light-bulb consumes is converted into usable light, while the rest is emitted as heat. When a household substitutes incandescent light bulbs with efficient lights, such as CFLs or LEDs, significant internal heat gains are lost. This in turn calls for additional heating energy consumption during heating seasons compensating the lost heat. During cooling seasons, the opposite happens, and lighting retrofits will reduce cooling demands as the internal heat gains are replaced. Because of this heat replacement effect (HRE), energy and cost saving estimates due to lighting retrofits tend to be inaccurate when the analysis focuses only on lighting system performances. In this study, we delve into more realistic residential lighting energy use scenarios and more comprehensive results including the HRE's implications on household energy expenditure and carbon emission at an identical single-family detached building across 105 cities throughout the U.S. We also look into sensitivity analyses with respect to factors that are considered influential for building energy consumption such as insulation, house size, orientation, heater/AC efficiency, and occupancy.

(2) Methods

This study relies on building energy simulations using EnergyPlus 7.2. The simulations are based on residential building prototypes created by the Pacific Northwest National Laboratory (PNNL). There are three subgroups in these PNNL prototypes depending on which version of International Energy Conservation Code (IECC) they are compliant to (i.e. 2006, 2009, or 2012). As of now, since the IECC 2009 is the baseline code most widely adopted by states for their building energy codes, the simulations are based on the PNNL prototypes complying with the IECC 2009.

In this study, we compare two scenarios. The baseline scenario is set up based on a recent report on U.S. lighting market characterization (Navigant Consulting, 2010). According to the report, as of 2010, 68% of all lamps installed in an average single-family detached house are incandescent, 24% are CFLs, and 8% are linear fluorescent lamps, from which we could derive that the average interior illuminance of a single-family detached house is 276 lumen/m^2 (=26 foot-candles). We compare this baseline with the 2012 IECC scenario (i.e. 25% incandescent, 67% CFLs, and 8% linear fluorescent lamps). We assume the illuminance level and hours of use are kept unchanged between inefficient and efficient lighting scenarios. The 2012 IECC requires that for residential buildings at least 75% of the lamps in permanent light fixtures must be high-efficacy (raised from 50% requirement in the 2009 IECC), which does not provide guidelines on illuminance.[1] The lighting usage schedule is adopted from Building America Simulation Protocol (Hendron and Engebrecht, 2010) and scaled to match the average daily hours of use from the Navigant report, which is 1.45 hour for each lamp. These assumptions give average lighting power densities (LPD) of 12.2 and 7.4 W/m^2 for the baseline and the 2012 IECC scenario respectively. These LPD values and the daily schedule are used as inputs to EnergyPlus for simulations.

A round of simulations can be run for each of all 16 combinations of main foundation and heating equipment types. However, considering the space limitation and the high percentage of gas heating/slab foundation houses, we only present results for this type of buildings, while providing sensitivity analyses for other foundation and heating types. To observe impacts from other crucial factors affecting the HRE in a residential building, an additional series of sensitivity analyses are performed. The factors we test are 1) efficiency value of heating/cooling equipment, 2) size, 3) orientation, 4) occupancy schedule, and 5) insulation level (R-values). The results are summarized in three different ways to better visualize the impacts of the HRE: primary energy consumption, household energy expenditure, and carbon emission.

(3) Results

Figure 1 summarizes the impacts of the HRE on three aspects in 105 U.S cities per year: primary energy consumption, CO$_2$ equivalent emission, and household energy expenditure. The first colunm is for total absolute savings while the second one shows percentage of savings that are lost because of the HRE.

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* Work in progress

[1] High-efficacy fixture is defined as compact fluorescent lamps; T8 or smaller-diameter linear fluorescent lamps; or lamps with a minimum efficacy of 40 lumens/W for <15W, 50 lumens/W for 16-40W, and 60 lumens/W for >40W lamps.

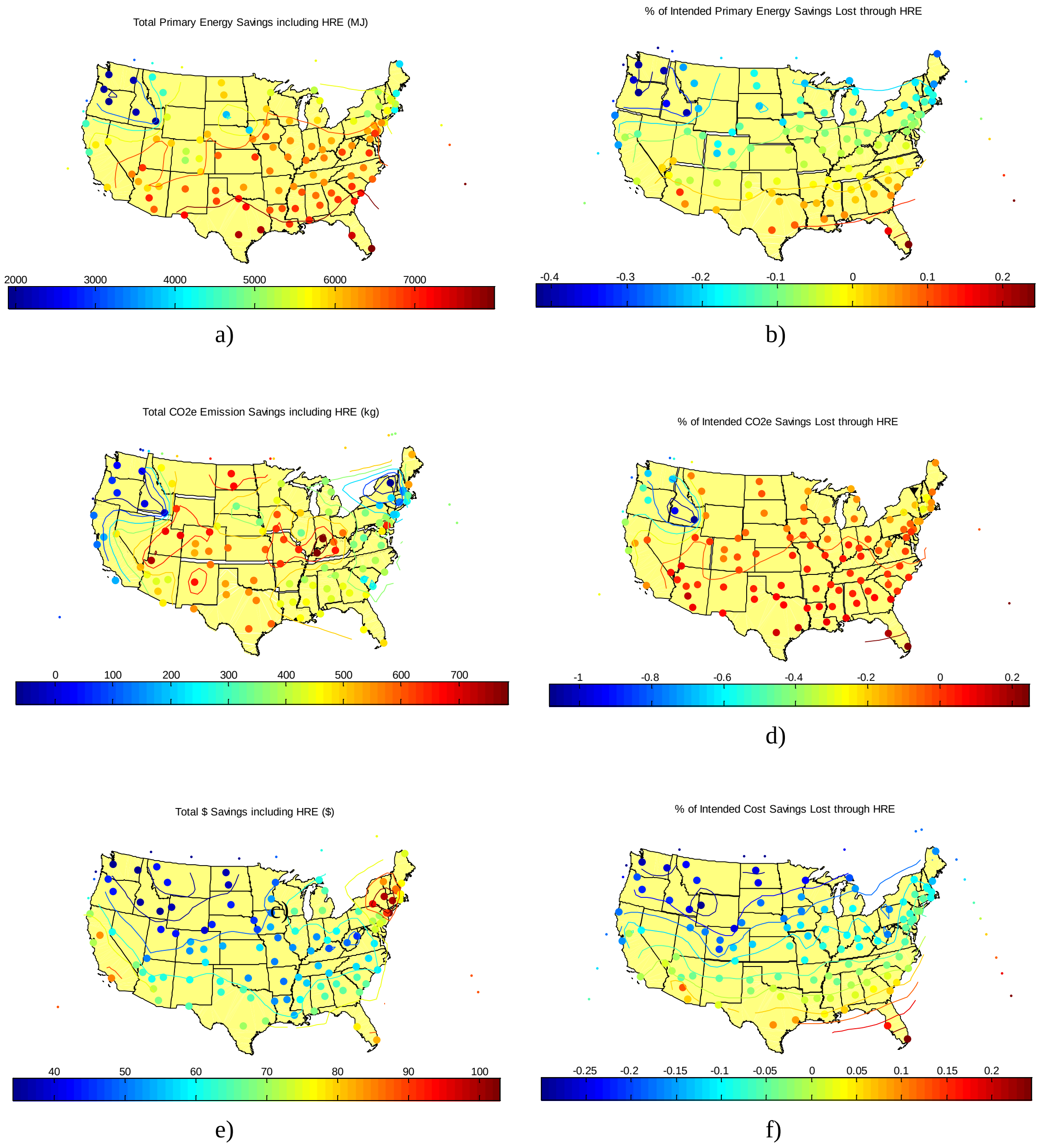

Figure 1. Size of HRE across the U.S. (a) Primary energy savings are low in states of WA, ID, and OR because of large percentage of hydropower in their fuel mixes. Other states follow primarily the climate pattern in the region. (b) The loss (negative HRE) can be as big as -40% of total lighting energy saved in those three states. (c) Total CO_2 equivalent emission savings are mostly determined by emission factors for delivered electricity and climate patterns. (d) Most dots red/orange dots suggest that there are almost no influence of HRE as emission savings from cooling load reduction are canceled out by extra emissions from larger heating demands. (e) Regions (CA and New England region) with higher electricity price save up to around $90 or more per year. (f) Most cities in southern states save more than what they can expect from lighting electricity savings, but all other states do not save as much as what they expect (shown as negative numbers or bluer dots).

(4) Conclusions

Even though many cities lost part of expected savings because of HRE, we find that almost all cities achieve positive savings in all three aspects of primary energy, energy expenditure, and CO_2 equivalent emission from the simulated lighting retrofit scenario. Only a few states with substantially low emission factors for electricity generation (WA, ID, OR, and VT) will not save any or even throw out more carbon emission as a result of switching lights. Policy makers in these regions need to take this finding into account when they promote energy efficient lighting and well recognize what kind of goals they are trying to reach through the measure. Among the tested factors for sensitivity analyses, efficiency rate of the heating/cooling equipment is the factor that has the biggest effect on the size of HRE predictably, since it directly determines how much energy has to be spent to compensate the loss of heat from lighting.

References

Hendron, R. and C. Engebrecht (2010). "Building America House Simulation Protocols", National Renewable Energy Laboratory.

Navigant Consulting (2010). "U.S. Lighting Market Characterization", EERE Building Technologies Program. U.S. Department of Energy.