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Urban Heat Island Impact on State Residential Energy Cost and CO_2 Emissions in the United States.

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Urban heat island (UHI) is a climate effect that magnifies air temperature in cities. In the US it affects over 80% of the population and in general is considered an adverse phenomenon with externalities ranging from increased air pollution to higher energy demand and deteriorated human comfort. Therefore, UHI and its mitigation strategies have been studied extensively to focus on hot summer months and demand for cooling energy. However, current approaches fail to recognize that for regions in cold climates UHI may be a positive phenomenon with benefits from decreased heating energy demand exceeding downsides of higher cooling energy demand. Here, for the period of 12 years we analyze for 48 US states the cost that UHI imposes on the $120B residential market with CO_2 emissions that exceed 550M tons each year. While for states situated in warm climates UHI significantly increases the energy bill, due to varying heating and cooling costs and emissions associated with generation of energy, for some regions located in cold climates, UHI significantly reduces energy demand and carbon emissions. This information will help legislators and policy makers understand better energy demand of buildings and subsequently reduce their carbon footprint at city and state levels.

Keywords: Residential Energy Consumption, Carbon Footprint, Climate Change, Urban Heat Island, Carbon Emissions, Energy Expenditure.

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Abbreviations:

C_C = Cooling Cost ($/kWh)

CDD = Annual Cooling Degree Days

CDD_m = Monthly Cooling Degree Days

CDD_{UHI} = Annual Urban Heat Island (UHI) influenced CDD

C_E = Cooling CO2 emissions (kg/kWh)

C_i = Carbon Emissions (kg) to generate kWh of energy using fuel source i

CO_2 = Carbon Dioxide

E_c= Energy cooling (kWh/year)

E_c^{UHI}= Energy cooling with UHI (kWh/year)

E_h = Energy heating (kWh/year)

E_h^{UHI} = Energy heating with UHI (kWh/year)

EIA = Energy Information Administration

$f()$ = empirical function to convert T to HDD

$g()$ = empirical function to convert T to CDD

GHG = Greenhouse Gas

h = average household size

H_C = Heating Cost ($/kWh)

HDD = Annual Heating Degree Days

HDD_m = Monthly Heating Degree Days

HDD_{UHI} = Annual Urban Heat Island (UHI) influenced HDD

H_E = Heating CO_2 emissions (kg/kWh)

r = Heating sources ratio: Natural Gas (g), Oil (o), Electricity (e), Propane (p)

m_c = household cooling gradient (kWh/ CDD)

m_h = household heating gradient (kWh/ HDD)

P = Population

P_h= number of households

P_h^{urban} = urban number of households

P_h^{rural} = urban number of households

P_i^y = average price of fuel source i ($/kWh)

r_{urban} = urban population proportion

r_{rural} = rural population proportion

S_i = Energy production/delivery ratio for source i

T_j^m = average temperature for month j

T_m = average monthly temperature

UHI = Urban Heat Island

$UHI\ Cost$ = UHI influenced cost in state-wide residential energy per year

$UHI\ CO_2$ = UHI influenced state-wide residential energy carbon emissions per year

1. Introduction

The empirical link between greenhouse gas (GHG) emissions and global warming is evident (Edenhofer et al., 2014; Pichler et al., 2017). The climate is changing at the pace that is correlated to the rate at which fossil fuels are burnt to meet the energy demand fostered by the global economic growth (Bloomer et al., 2009). In recent years, global leaders and legislators have come to recognize the perils of climate change and under the United Nations Framework Convention on Climate Change, in 2016 the Paris Climate Agreement was established with the long-term goal of reducing GHG emissions and keeping the global temperature rise below 2°C above pre-industrial levels. However, in 2017 US federal government announced that it will cease its participation in the global climate change mitigation efforts captured in the charters of the Paris Accord. Moreover, in 2018 under the Section 201 of the Trade Act, the federal government has imposed new tariffs on solar energy imports, which is likely to discourage renewable energy growth in the US. To oppose those decisions of the federal government that aim to discourage the regulations, which would encourage nationwide reduction of GHG, many business, cities and some states across the US have voluntarily come together to declare the *"We are still in"* and *"America's Pledge"* coalitions that will continue to support the climate action plan to meet the Paris Climate Agreement. Although, US Climate Alliance of this kind has the potential to mitigate the effects of climate change, majority of the US nation continues to be under no official obligation to reduce carbon emissions and improve energy efficiency. This poses a great environmental threat to the US and rest of the world for two reasons: first the effectiveness of energy policies is much higher when compliance is mandatory as opposed to

voluntary (Martin and Saikawa, 2017; Pichler et al., 2017) and second, US has the second largest CO_2 emissions in the world. Unequivocally, establishment of mandatory regulations is a portion of the challenge to achieve goals of the Paris Agreement; however, the other important portion of the challenge is selection of the sector and approach that would offer the greatest opportunity for economic and environmental changes rather than be solely a climate mitigation solution (Edenhofer et al., 2014; Rabe, 2004).

According to the US Energy Information Administration (EIA), accounting for 40% of total domestic energy consumption buildings are the single most energy consuming source of infrastructure in the US and thus have been the primary focus of energy policies (Pérez-Lombard et al., 2008). Space heating and cooling is estimated to contribute to about 20-25% of total energy consumption (Ürge-Vorsatz et al., 2015), which for the US residential stock of about 113 million units translates to about 10% of the total domestic energy consumption. Globally, the impact of the residential sector is even more significant – it is estimated that its contribution to total energy consumption is 27%, which translates to 17% of CO_2 emissions (Nejat et al., 2015). One of the main factors that influences energy consumption of residential buildings is outdoor air temperature (Abdolhosseini Qomi et al., 2016). That temperature depends on both regional and local climates. With wind, cloud coverage and seasonality, the former is considered an uncontrollable variable (Rizwan et al., 2008). The latter one, however, is influenced by the humankind and shaped through urban growth (Li et al., 2017; Oke, 1973). This is because urbanization changes the structure of natural land by replacing open areas and vegetation with various forms of infrastructure. Buildings and pavements are arranged in different geometrical layouts (Ramamurthy and Bou-Zeid, 2017; Sobstyl et al., 2018) and use different types of materials (Norton et al., 2015), both of which are known to influence the amount of solar radiation that is stored during the day and its release rate at nighttime. In addition to storage and release of radiant energy, ventilation (Mirzaei, 2015), indoor temperatures (Mirzaei et al., 2015) and anthropogenic heat (Flanner, 2009), all have been listed as factors that lead to thermal changes in the environment causing formations of UHIs. Although, there is no general consensus on the magnitude of local temperature changes with different studies estimating its values to be (i) (Santamouris, 2001) 5-15ºC, (ii) (Oke, 1973) 1-8ºC, (iii) (Sobstyl et al., 2018) 1.4-4.2ºC at nighttime, (iv) (Ramamurthy and Bou-Zeid, 2017) 1ºC, (v) (Zhao et al., 2014) 3ºC for daytime, it has been estimated that average UHI causes air temperature to intensify by 1-3ºC in the US (U.S.

Environmental Protection Agency, 2008) and 1.72ºC globally (Estrada et al., 2017). These higher temperatures, in general, necessitate higher energy demand, which translates to economic and environmental losses for cities worldwide (Estrada et al., 2017; Pérez-Lombard et al., 2008). Beyond increased energy usage, UHI has been found to create externalities in the forms of increased air pollution (Mohajerani et al., 2017; Rizwan et al., 2008) and deteriorated human comfort (Rosso et al., 2018), which during extreme heatwaves has been attributed to augmented mortality rates (Medina-Ramón and Schwartz, 2007). Moreover, with global climate change patterns (Meinshausen et al., 2009) and urban growth (Grimm et al., 2008), future impacts of UHI are expected to intensify (Estrada et al., 2017). Because of that, UHI mitigation strategies and techniques—traditionally to include tree and vegetation (Rizwan et al., 2008) cover and reflective pavements (Mohajerani et al., 2017)—have been studied extensively with their importance expected to grow in the future (Huang and Lu, 2017). Reflective materials, cool and green roofs and cool pavements have proved to be successful in diminishing negative UHI effects (Akbari et al., 2016; U.S. Environmental Protection Agency, 2008). Most of the UHI studies have been focused on quantifying the impact on the demand for cooling energy during hot summer months (Mohajerani et al., 2017; Pérez-Lombard et al., 2008; Rizwan et al., 2008), leaving the topic about the influence of UHI on the annual heating and cooling energy sectors in the need of further investigation. Energy modeling of buildings and numerical simulation have been used to provide comprehensive assessment of UHI mitigation tactics on the building's energy demand. Reductions of outdoor temperate of 1ºC during peak time cooling energy demand could reduce energy consumption by as much 6% (Kikegawa et al., 2003). However, during cold winter months, heating energy may be halved in urban areas when compared to their rural surrounding due to UHI effect (Santamouris et al., 2001). It is important to note that while reducing UHI in areas with high cooling energy demand is beneficial for the economy and environment, in regions with high heating and low cooling energy demands, alleviating UHI is likely to increase overall energy costs and pollution. Therefore, in order understand the impact that UHI has on energy consumption, annual heating and cooling energies, rather than just solely summer or winter months, must be considered. The outcomes of such studies suggest that in the presence of UHI, the combined annual heating and cooling energy may decrease (Magli et al., 2015). However, more regional energy modeling studies are needed to evaluate the impact of UHI effect and its countermeasures on the energy consumption of the entire state or country.

Building energy modeling techniques for regional or national studies for residential energy consumption can be divided into two types (Swan and Ugursal, 2009): (1) top-down and (2) bottom-up. Top down models rely on historical aggregate energy consumption data and generally are considered to be simplistic with small number of input variables providing average estimates of the energy consumption. As such, they lack the ability to account for new stock of buildings, any advances in building energy technology or identifying areas for improvements. However, it is their simplicity and availability of data that makes them an attractive choice for many national building energy modeling studies. The second category, bottom-up models are known for their high level of detail and ability to identify areas for improvements and measure their future impact; however, this comes at the price of increased complexity and necessity for more input data, which oftentimes requires energy bill data that generally is limited to the local scale. As such, bottom-up models work best for studies that aim to identify specific areas for improvements and quantify predictions for future energy consumption.

2. Methods

In this work, to quantify annual UHI costs, we utilize a regression statistical bottom-up approach to perform a 12-year financial and environmental analysis of UHI for 48 US states (due to lack of data Hawaii and Alaska excluded) using annual household space heating and cooling energy consumption data combined with air temperature values, state prices for heating and cooling energy sources and carbon emissions associated with production of specific types of energy. Due to limited availability of heating and cooling energy consumption data in the US for the commercial sector, our study is focused only on the residential stock of buildings.

2.1. Residential Space Heating and Cooling Residential Consumption.

In order to understand the economic and environmental consequences that UHI effect has on the residential space heating and cooling energy consumption of US states, we begin by establishing a regression model for the outdoor air temperature and household space heating and cooling energy consumption. To obtain building energy consumption, we resort to the EIA's database—available to the public use—residential energy consumption surveys that were created

using bottom-up modeling approaches. Although, the most recent energy survey was created for year 2015, its geographical resolution is too low for the purposes of our study – it divides the US into 4 regions. Therefore, we utilize the most recent version of the energy consumption, which offers the resolution at the state level. The earliest available dataset that offers that, is 2009 Residential Energy Consumption Survey Data (U.S. Energy Information Administration, 2009). Using previously established regression models (Swan and Ugursal, 2009), we investigate the correlation between average annual household heating and cooling energy and annual heating and cooling degree days.

2.2. Degree Days.

Degree days are a common metric used in the energy industry for calculating the effect that outdoor air temperature has on building's heating and cooling energy consumption. They are divided into two categories: Heating Degree Days (HDD) and Cooling Degree Days (CDD). HDD measure for how many days and how many degrees the air temperature was below a reference temperature, in this case (and typically) 65 °F. On the other hand, CDD measure the number of degrees above that reference value. Regional monthly or annual degree days can be obtained directly from the National Oceanic and Atmospheric Administration (NOAA) (National Centers for Environmental Information, 2009). However, to be able to understand the influence that local temperature variations (i.e. UHI) have on energy consumption, we must employ the correlation between temperature and degree days. We find that the concept of degree days can be generalized to the set of equations based on the correlation between historical average monthly temperatures, T_m and the number of HDD_m and CDD_m with the data obtained from NOAA/NCDC Climate Division for the period between 2005 and 2016. They can be modeled using the following equations:

$$HDD_m = \begin{cases} -29.54 \times T_m + 1941 & , T_m \leq 60°F \\ 1.43 \times 10^{25} \times T_m^{-12.85} & , T_m > 60°F \end{cases} \quad (1)$$

$$CDD_m = \begin{cases} 29.58 \times T_m - 1905 & , T_m \geq 70°F \\ 1.07 \times 10^{-18} \times T_m^{10.96} & , T_m < 70°F \end{cases} \quad (2)$$

2.3. Relationship between energy consumption and degree days.

Energy responsiveness of buildings due to changes in outdoor temperature is dependent on multiple factors, such as thermal comfort of residents, efficiency of the buildings, which measures how much energy is lost through building's envelope, size of the building, number of household members, or presence and type (i.e. central, window) of air conditioning. However, their contribution to the overall building energy consumption varies significantly and the outdoor temperature is considered to be the driving factor (Abdolhosseini Qomi et al., 2016; Swan and Ugursal, 2009). Therefore, using just a single input of outdoor temperature it should be possible to predict the space heating and cooling energy consumption of residential buildings. The correlations obtained using eqs.1-2 allow us to confirm that notion, that changing temperature (i.e. due to global warming or UHI) affects the number of degree days, which are directly related to state-wide annual residential heating and cooling energy consumption. More specifically, we find that using a linear regression model, it is possible to correlate annual state residential heating energy consumption with annual HDD, which is captured with the heating energy response of a residential buildings, m_h, equal to 2.20 kWh per HDD [95% CI: 2.05, 2.35] (fig.1a). Similarly, annual state residential cooling energy consumption scales linearly with the annual CDD, which is captured with the cooling energy response of a residential building, m_c, equal to 1.80 kWh per CDD [95% CI: 1.62, 1.98] (fig.1b). While neither of these correlations offers a robust relationship that would predict accurately heat or cooling energy demand with just a single input of temperature or degree days, they both offer meaningful, statistically significant—with coefficients of correlation, R^2 equal to 0.66 and 0.73 for heating and cooling energies, respectively— positive correlations, which we can utilize to estimate values for heating and cooling energy consumptions.

2.4. Energy Expenditure.

To estimate residential space heating and cooling costs, we resort to EIA's annual average retail residential user prices for non-renewable energy fuels used in the US. Using EIA's guidance for residential fuel sources, we limited electricity, natural gas, propane, and heating oil as the only heating source fuels. Due to availability of data, we assume that fractions of the

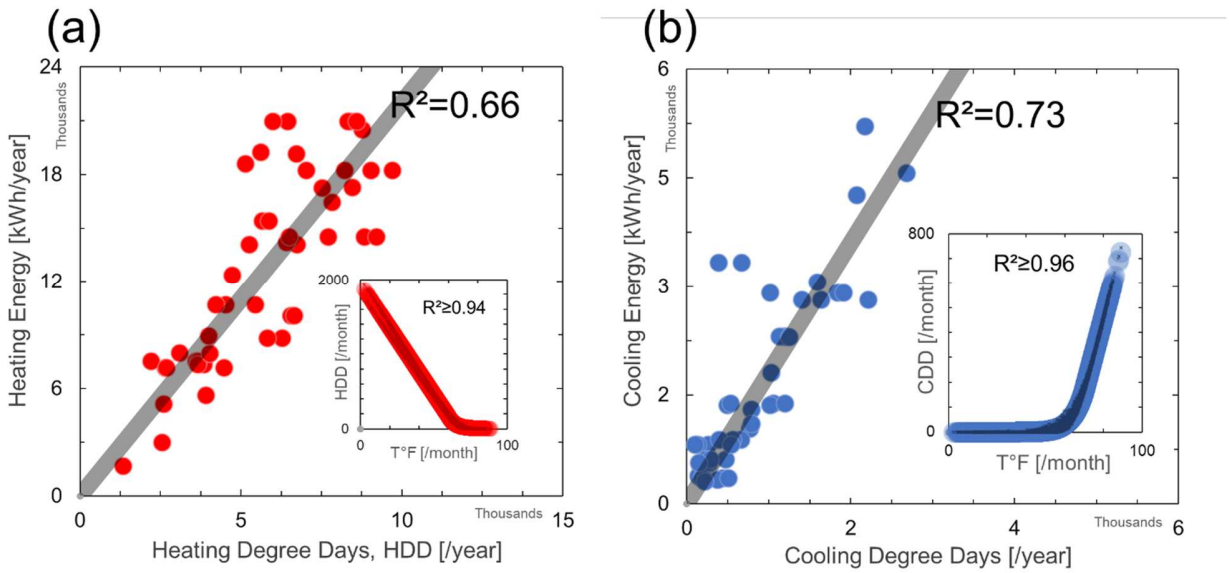

Figure 1: Residential Household Heating and Cooling Energy Consumption

(a) linear relationship between annual heating energy consumption and HDD. The inlet shows the fitting model between monthly HDD and temperature (b) linear relationship between annual cooling energy consumption and CDD. The inlet shows the fitting model between monthly CDD and temperature. Monthly Degree Days and Temperature for 2005-2016 were obtained from NOAA/NCDC Climate Division.

heating fuel sources remain unchanged for each of the states within the boundaries of these energy regions: west, midwest, northeast, south. Due to lack of prices, we disregarded wood and due to their minimal contribution, we did not include kerosene or any of the renewable sources. For space cooling, we assumed that all energy is supplied with electricity (due to their minimal contribution renewable resources were ignored). Lastly, any variables that could influence energy responsiveness of buildings to changes to outdoor air temperature remain constant over the time. Electricity and natural gas prices are annual residential averages for each state. For heating oil and propane, we used weekly prices, which we converted to annual averages. For states with missing values, we used (when available) regional or national averages.

2.5. Carbon Dioxide (CO_2) Emissions.

Space heating and cooling in residential buildings requires a mixture of various energy sources. While on-site energy usage is an important measure in evaluating performance of a building and understanding its sustainability rank, it is not representative of how much energy must be generated to deliver each unit of energy to a building. Therefore, to account for any losses and inefficiencies during the production and delivery processes of energy, we adopted a source energy measure (S_i) from Energy Star Portfolio Manager Technical Reference ("Source Energy. Energy Star Portfolio Manager Technical Reference," 2013), which traces the on-site energy back to its raw fuel input, thereby enabling a complete thermodynamics assessment. For US buildings, to deliver a single unit of energy on-site the following ratios of fuels need to be produced: electricity (3.14), natural gas (1.05), heating oil (1.01), and propane (1.01). To exemplify this implies that on-average for each 1 kWh of end-use electricity, 3.14 kWh must be generated. One or even 5% fuel losses may seem insignificant when compared to 3.14 ratio for electricity. Although, these statistics are appropriately reflected in higher electricity prices when compared to other fuels—which on average are 2-2.5 higher— we want to establish how they affect the amount of carbon dioxide generated to supply residential space heating and cooling energy across the US. The next step is to quantify the amount of CO_2 for each kWh of energy (C_i). To quantify CO_2 emissions associated with heating and cooling energy consumption, we obtain national source values for raw fuels used in electricity generation by year while disregarding any renewable resources. For residential energy production in the US, there are only three non-renewable fuels that contribute to most electricity generation (used for space heating and cooling), while for space heating there are four sources. For natural gas (0.18 kg per kWh), heating oil (0.25 kg per kWh), propane (0.22 kg per kWh) emission levels are assumed to be constant for the 12-year period. However, for electricity we utilize net generation energy sources (coal, hydroelectric conventional, natural gas, nuclear, other, other biomass, other gases, petroleum, wood and wood derived fuels, geothermal, pumped storage, thermal and wind) used for annual total electric power industry production also obtained from EIA. Based on the ratio of different sources, we obtain average CO_2 kg per kWh of electricity for each state for each year.

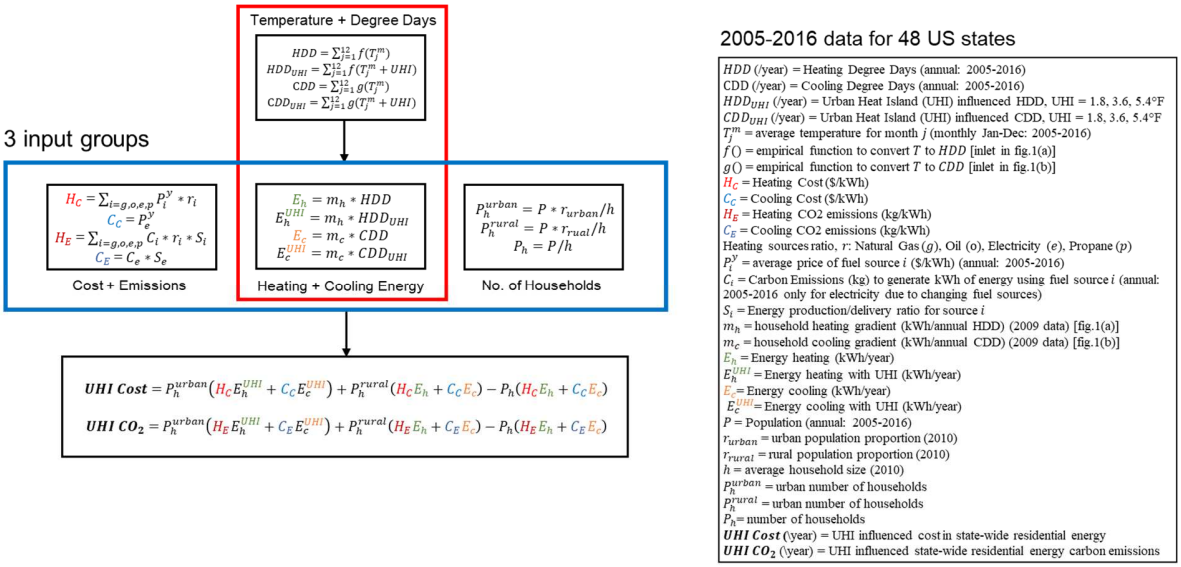

Fig.2. UHI Costs + Emissions Flowchart

Visual representation of the methodology employed to calculate annual UHI state residential heating and cooling energy cost and carbon emissions.

2.6. UHI impact on energy consumption.

We utilized preceding steps to establish methodology that we adopted to quantify the impact that UHI has on residential space heating and cooling energy consumption. The flowchart of this methodology is depicted in fig.2. To derive the equation for state-wide environmental and energy costs associated with the of impact of UHI three inputs are necessary: (1) residential heating and cooling energy consumption per building for temperatures with and without UHI (fig.1), (2) heating and cooling costs and emission levels and (3) the number of households in each state. While, EIA provides total state energy expenditure values in conjunction with the household ones, but they come with an error imposed by the averaging approach used for low population states. To depress this error, we use population and average household size data (U.S. Census Bureau, 2005; US Census Bureau, 2010) to estimate the total, as well as the urban number of households in each state. We convert estimated values of population for each year between 2005-2016, to urban (P_h^{urban}) and rural (P_h^{rural}) number of households by multiplying population values by appropriate urban/rural ratio and dividing it by an average household size

(US Census Bureau, 2010). With three inputs obtained in such way we were able to quantify for annual UHI influenced heating and cooling costs ($UHI\ Cost$) and CO_2 emissions ($UHI\ CO_2$) for 48 individual US states using the following equations (see fig.2):

$$UHI\ Cost = P_h^{urban}(H_C E_h^{UHI} + C_C E_c^{UHI}) + P_h^{rural}(H_C E_h + C_C E_c) - P_h(H_C E_h + C_C E_c) \quad (3)$$

where, H_C stands for heating cost, E_h^{UHI} is UHI influenced heating energy, C_C is cooling cost, E_C^{UHI} is UHI influenced cooling energy, P_h is state's household population, E_h is the heating energy and E_C is the cooling energy.

$$UHI\ CO_2 = P_h^{urban}(H_E E_h^{UHI} + C_E E_c^{UHI}) + P_h^{rural}(H_E E_h + C_E E_c) - P_h(H_E E_h + C_E E_c) \quad (4)$$

where, H_E stands for heating CO_2 emissions, C_E is cooling CO_2 emissions.

3. Results

Using average monthly air temperature values for each state, we calculated the annual number of degree days for temperatures with no UHI effect, as well as three increments of UHI (1°C (1.8°F), 2°C (3.6°F) and 3°C (5.4°F)). To understand what the absolute state-wide residential energy cost without UHI effect is, we combined annual energy prices with modeled heating and cooling energy usage (fig.1) to obtain average heating and cooling residential energy cost per year (averages for years 2005-2016) for each of the US states (fig. 3a). For UHI calculations, we assume the UHI effect to be 2°C (3.6°F). Although we restrict our calculations to that average UHI of 2°C, we find that the impact on cost and CO_2 of the other two increments of UHI equal to 1°C (1.8°F) and 3°C (5.4°F) that prevail in the US (U.S. Environmental Protection Agency, 2008), are linearly correlated with each other (see inlets in fig. 3a and fig. 3b). This shows that regardless of the magnitude of UHI, for state-wide residential sector in the

US, we can generalize the UHI influence to be either positive or negative. Moreover, we find that increasing UHI temperature by 1°C, on

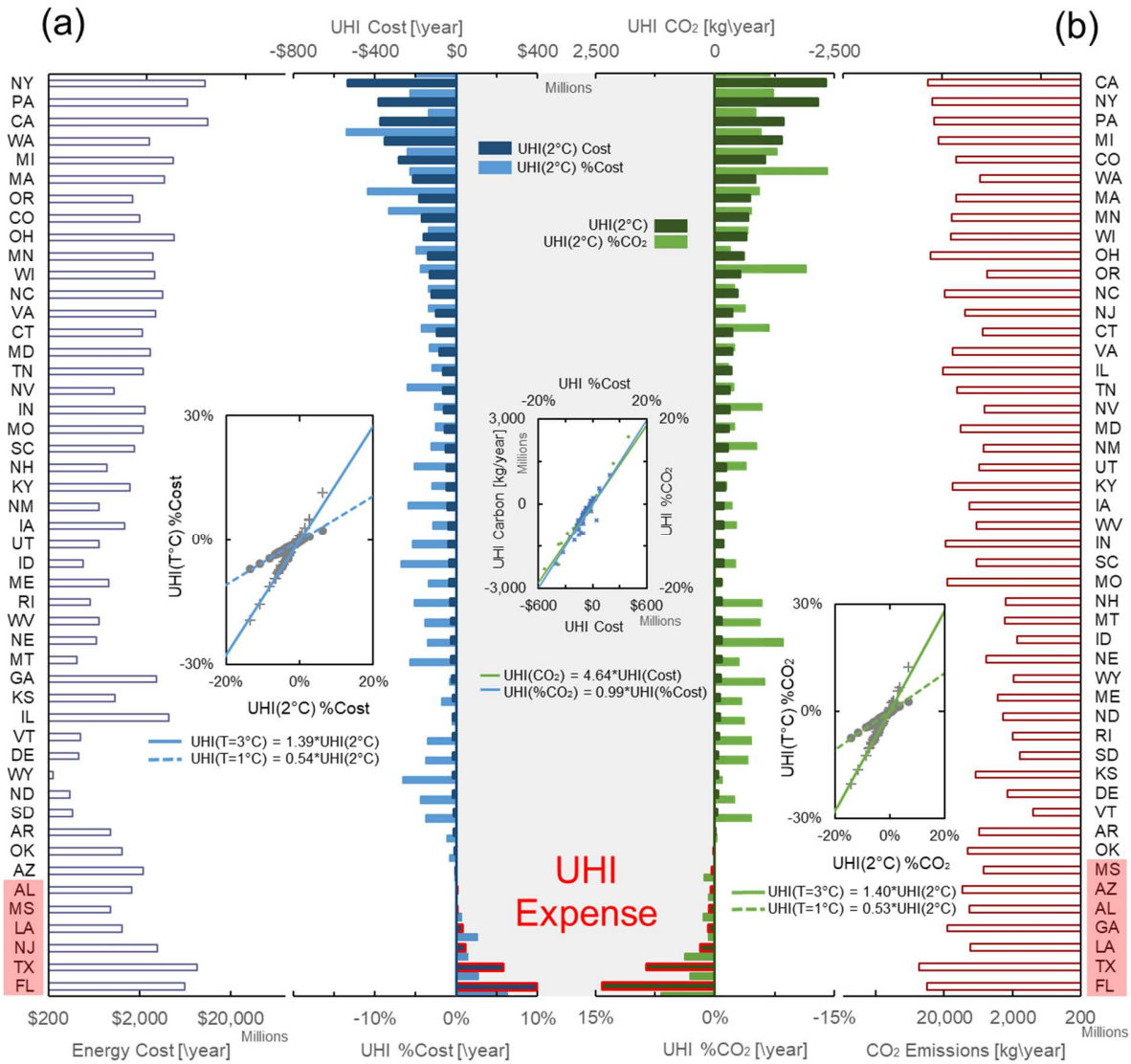

Fig.3. Residential heating and cooling energy cost and CO_2 emissions for 48 US states.

(a) on the left average annual non-UHI heating and cooling cost and on the right UHI=2°C annual cost and % differences relative to non-UHI total cost. The inlet shows linear relationships between different magnitude UHI % cost differences. (b) on the right average annual non-UHI heating and cooling CO_2 emissions on the right UHI=2°C annual CO_2 and % emissions differences relative to non-UHI emissions. The inlet shows linear relationships between different magnitude UHI % CO_2 emissions differences. The middle inlet figure represents linear scaling between UHI cost and CO_2 emissions.

average intensifies UHI percentage energy costs by 40%, while reduction of 1°C translates to UHI percentage energy cost reduction by 46%. Moreover, we identified UHI influenced excess total and percentage costs and savings (UHI expenses) relative to the total residential heating and cooling energy expenditure. We categorized US states in terms of their UHI saving potential starting with regions where UHI of 2°C leads to the greatest absolute residential energy cost savings. It is worth noting that while absolute savings for a given state may appear large and significant when compared to the other states, the percentage UHI expense may act as a more appropriate metric for a evaluating the UHI impact on the residential space heating and cooling as it conveys more information about the distribution of energy expenditure within a state.

Energy cost is one of the metrics of evaluating the impact of UHI on the residential sector. However, because heating fuel sources are different to the fuel sources needed for cooling energy, higher energy cost does not necessarily imply a proportional change in the levels of emitted carbon dioxide. This is mainly due to the fact that while energy prices fluctuate, the emissions associated with a particular source of fuel remain the same. Therefore, for as long as the efficiency of energy generation and its delivery do not change, while its supply prices do, it is expected that CO_2 emissions will not explicitly follow the pattern of UHI energy costs. This indeed is depicted by the middle inlet in fig.3, which shows the slight disparity between UHI carbon emissions and UHI cost. Further, the variation in heating and cooling fuel sources across different states reflects in the order of states with the highest UHI CO_2 emission savings (fig.3b), which differs from the order of UHI energy cost savings. However, a linear regression fitting model shows that for the US states, on average the UHI cost translates to 4.64 times higher emissions of carbon dioxide. This means that knowledge of UHI cost allows one to identify associated UHI CO_2 emissions and vice versa. In other words, knowing UHI impact on state's residential energy bill allows us to approximate alteration in state's residential carbon emissions.

The most critical and perhaps impactful part of this analysis, however, is obtained from the visual depiction of the UHI cost and CO_2 analyses captured in fig. 4, which show the varying effects of UHI across the US. The maps provide visual representation of parts of the US that are most negatively affected by UHI = 2°C (red color states) as well as those where UHI has positive effects (green color states) and areas where UHI has marginal impact on the annual residential energy cost and emissions (yellow color states). Since there is a linear relationship between

different magnitudes of UHI (inlets in fig.3), with appropriate outdoor air temperature measurements for cities across a given region, the state-wide results can easily be transformed to more accurate values.

4. Discussion

UHI intensifies air temperature regardless of the season. Therefore, increase in cooling energy would correspond to decrease in heating energy for states that experience months with temperatures below 65°F. In fact, more than 80% of US states are located in areas with significant space heating energy bills suggesting that depending on energy fuels, UHI could have a positive impact—the reduction in annual resdiential energy bill cost and carbon emissions—on the overall energy consumption of the residential sector. Higher contribution of heating over cooling to the UHI energy bill occurs because energy response of buildings to changes in temperature is about 20% higher for heating than it is cooling, as depicted by fig.1. This can be explained by the fact that while most heating systems are centralized, air conditioning systems for many US households are usually restricted to bedrooms and living spaces.

We compared impacts of 1°C and 3°C UHIs with the reference base UHI equal to 2°C. As it is depicted in fig.3 various magnitudes of UHI are correlated in a linear fashion, where 1°C UHI depresses and 3°C UHI intensifies the percentage effect on residential state heating and cooling cost and carbon emissions of UHI = 2°C by factors of approximately 50% in both instances. In the context of this study, heating and cooling energy costs at the household level are affected mainly by regional variations in energy prices and emission levels by various types of heating and cooling energy generation sources. However, at the state level variations in energy cost and emissions are predominantly driven by population density. This is reflected in non-UHI resdiential energy cost and CO_2 emissions among the US states, where the highly populated states such as New York, California, or Texas, each year spend four times more than the US average, which translates to about $10B on residential heating and cooling and about 40M metric tons of CO_2 emissions each year (see fig.3). While total energy costs and emissions for the residential sector are important metrics to consider, they alone should not be regarded as the prioritizing factor for UHI mitigation strategies. By incorporating changing HDD and CDD due to various levels of UHI, we found that regional climate has a great influence on the percentage

change in UHI driven cost and emissions levels, where states with high $HDD:CDD$ ratio, such as Washington, Oregon or Colorado

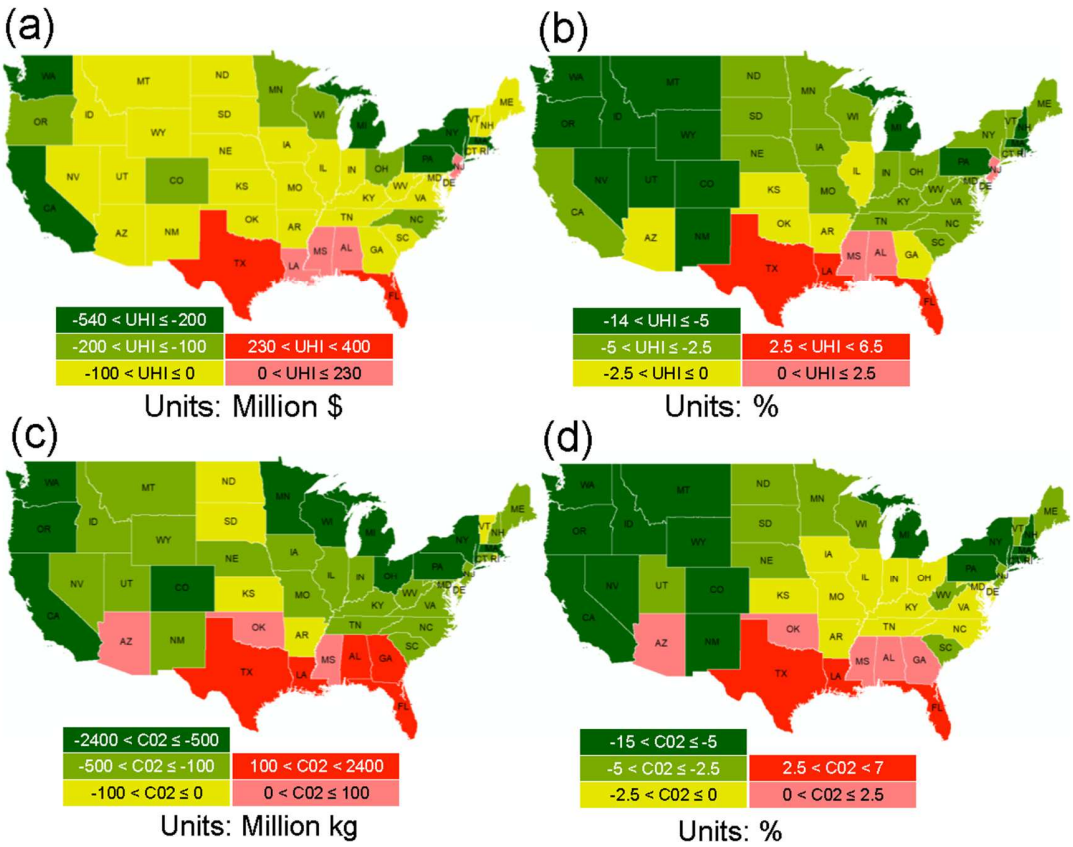

Fig.4. UHI Impact US Map.

12-year average annual state residential heating and cooling expenditure (a-b) and CO_2 emissions (c-d) for UHI=2°C.

experience between 9-12% reduction in the overall residential heating and cooling energy bill with UHI = 2°C.

To account for climate and energy price calculations, we analyzed data for a 12-year period between 2005-2016 and extracted averages. We argue that the impact of UHI should not be generalized as having solely negative impact on the environment and cost of energy. This is because it is an outcome of three variables: (1) climate, which constitutes HDD and CDD, (2) energy prices, (3) types of fuels used for heating and cooling. Using annual averages, we found that there are only several states across the US that experience negative effects of UHI in terms of residential energy consumption. While for most US states UHI has marginal impact on energy

costs and emissions (less than 5%), there are few states where UHI imposes a strenuous impact on the residential market energy and there are some where UHI offers a major benefit. For cities in the parts of the US that experience winter seasons, UHI may have a positive impact on residential buildings, as exemplified for UHI = 2°C in figs. 3-4. At the local level, a typical average household could save between $75-150 on their annual energy bill, while at the same time making contribution to reduction of carbon emissions of about 400-500kg, which approximately is equivalent to emissions produced by a 30mpg vehicle that has travelled 1750 miles. While these values may seem insignificant, in highly populated states such as New York, Illinois or Massachusetts they translate to UHI offering a substantial reduction in economic and environmental burdens with over $200M and as much $500M in annual heating savings and reduction of approximately 2M tons in CO_2 emissions. However, for states located in warm southern parts of the US, regions with high ratio of $CDD{:}HDD$ would on average increase annual energy bill by about $50-100, while creating an addition of about 300-600 kg to carbon emissions from a single household. For highly populated states such as Texas or Florida, these values translate the UHI equal 2°C to contribution of approximately $400M and 2M tons of CO_2 in additional energy costs and emissions. It is important to emphasize that while these values account for fluctuating climate and seasonality changes averaged out for a 12-year period, these values are still state-wide averages. However, due to linear relationship between different magnitudes of UHI it is possible to enhance them with local air temperature measurements for cities. This is especially relevant for states like California or Nevada whose boundaries extend across different climates with mountain and dessert regions that impose large errors in average temperature values.

This UHI analysis has been focused on the current state of the US stock of residential buildings, which neglects building and neighborhood designs as the potential mitigation strategies for ameliorating energy bill and carbon emissions. However, if we take into consideration changes in population that are expected to occur by 2030 (U.S. Census Bureau, 2005), we can prioritize states for UHI controls and regulations based on their expected growth of urban number of households. Shown in fig. 5, we find that for most states we should expect at least 100,000 of new residences to be built in urban areas, but for the few extreme cases, states such as Arizona, Texas, California and Florida, we can expect to see an urban household increase

in excess of 1 million. Consequently, these are the states that should examine sustainable building design measures to reduce the environmental impact of residential buildings.

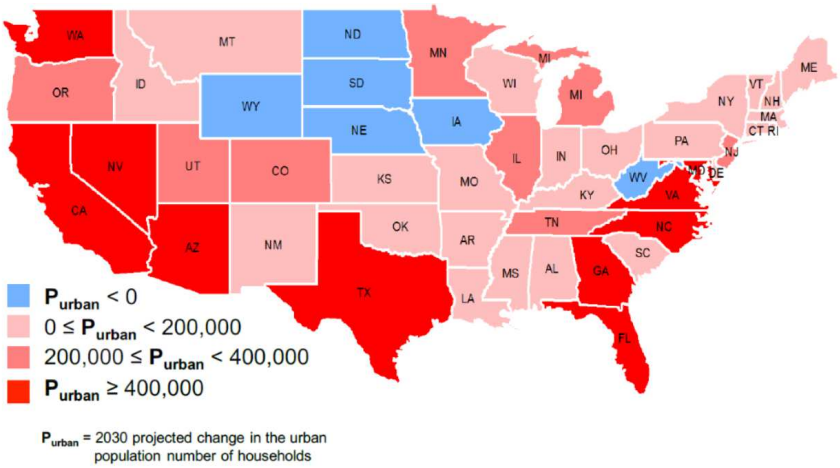

Fig.5. Urban Household Growth Projections in the US.

Projections of changes in the number of urban households between 2010 and 2030 visualized as a map categorized into four groups with blue color being representative of expected decline in the urban population number of household, P_{urban}, while three different shades of red showing projections for increase in P_{urban}.

5. Conclusion

In this study, we demonstrated that costs of UHI are closely related to regional temperature variations, which can shift financial and environmental costs from positive to negative, and vice versa. By quantifying environmental impact that UHI-imposed temperature changes have on energy consumptions in residential buildings, we are in a unique position to help cities and states tackle climate change with executable and concrete measures. Projection of financial benefits and carbon emission reductions appeal not only to legislators and policy makers, but also to voters and private investors who recognize the value in sustainable design. When linked with urban population changes this analysis can be applied to prioritizing energy policies and regulations for UHI controls. Current cities where UHI has negative effects should seek to utilize sustainability retrofitting strategies (Akbari et al., 2016) such as green and cool

roofs, or reflective pavements, while future cities should focus their efforts on minimizing the envelope structure of buildings and considering non-regular layouts for streets. On the other hand, cities that seek to maximize benefits of UHI through lowered heating energy demand should concentrate on forming high density building clusters arranged on a regular grid (Sobstyl et al., 2018). As a result, controlling UHI becomes a method for partially managing space heating and cooling energy consumption and a tool for helping cities, states and countries achieve their greenhouse gas emissions reduction goals. States of Florida and Texas are currently the most negatively influenced by UHI states in the US and in consideration of their future population growth, they should be prioritized for any future environmental building energy regulations and UHI mitigation strategies. They should also consider adopting street layouts and sky view factors that minimize UHI in their future urban expansion. We are confident that the negative impacts of UHI from the residential sector outlined in this study, will translate directly in the form of intensified energy bills among the commercial sector, which contributes to about 10% of the US total energy consumption (Ürge-Vorsatz et al., 2015). However, before making any policy recommendations for states with high ratio of $HDD{:}CDD$, where for the residential sector UHI has positive effects on energy costs and CO_2 emissions, we strongly recommend investigating impacts of UHI on the commercial sector, which has much higher cooling costs relative to heating expenditure when compared to residential buildings. Above all, urban planners and legislators should not neglect common UHI mitigation techniques simply because UHI significantly lowers the energy bill. UHI mitigation techniques that increase green space in cities have the potential to reduce the severity of summer heatwaves (Zhao et al., 2018), as well as improve comfort, health and safety of local communities (Branas et al., 2018), which are benefits that extend far beyond the monetary energy savings. Therefore, we believe that UHI mitigation techniques should always be incorporated into planning methods for optimizing UHI in cities.

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