Minimizing heatwave risk through an equitable distribution of solar panels

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1. Introduction

Climate change will increase the frequency and severity of extreme heat events and, due to the Urban Heat Island (UHI) effect, urban centers are more susceptible to heat waves and heat stress [1, 2]. The Union of Concerned Scientists estimates that the number of days above 32 °C in the Midwest will increase five-fold by midcentury unless action is taken to reduce carbon emissions and slow climate change [2]. The lack of strong federal climate policies leaves individual states and institutions responsible for acting on climate change. Illinois passed the Climate and Equitable Jobs Act (CEJA) in 2021 which established strong climate goals and programs for the state, including subsidies for rooftop solar panels [3]. This case study investigates the optimal distribution of rooftop solar panels that minimizes heat wave risk for the City of Chicago.

We chose Chicago as the focus of this work for two reasons. First, Chicago was the epicenter of a deadly heat wave in 1995; one of the deadliest heat waves in United States history. Over 700 people died in this heat wave [4]. Further, the death toll from this heat wave was exacerbated by a combination of social factors including income, isolation, and crime rates [4]. As a result of this heat wave, Chicago officials recognized the need to prepare for future heat waves. This work proposes rooftop solar panels as a possible mitigation strategy. Second, the State of Illinois has programs such as Solar for All and Illinois Shines that aim to provide greater access to clean energy for low-income populations [5]. Thus, the resources to increase rooftop solar penetration already exist but lack guidance based on heat wave risk.

Illinois Solar for All and Illinois Shines are two programs strengthened by the 2021 CEJA bill [3, 5]. These policies intend to expand the rooftop solar capacity in Illinois by providing incentives or subsidies for solar installation, with specific allocations for low-income communities. Rooftop solar panels help reduce the percentage of household income spent on energy costs, known as the energy burden, through net-metering policies that pay consumers for excess energy generation [6]. This reduction of energy burden improves resilience to heat waves by increasing access to air-conditioning for low-income households during high-demand times when electricity is most expensive. However, a high penetration of intermittent renewables, such as solar panels, increases price volatility and the energy burden for consumers without solar installations [7, 8]. This is called the "paradox of renewable energy policy" and highlights the need for efficient prioritization of at-risk areas [9]. Therefore, the purpose of this study is to identify areas with the highest heat wave risk so they may be prioritized by programs like Solar for All and Illinois Shines.

In order to identify high-priority areas, we curated economic and demographic data for Chicago, along with satellite data from the National Solar Radiation Database (NSRDB) published by the National Renewable Energy Laboratory (NREL). We identified regions of similar risk and suitability for solar panels with a hierarchical clustering algorithm. Section 3 discusses details of the data selection and processing, section 4 presents the results of the clustering algorithm, and section 5 develops a descriptive typology based on the clustered areas.

2. Literature Review

The UHI effect, where urban areas tend to be warmer than their surroundings, is among the most well studied phenomena, often using remote sensing technology and land surface temperature data [10, 11]. Some studies evaluated UHI intensity for particular cities by incorporating data about urban features such as albedo, building height, and vegetation [12, 13] along with urbanization trends [14]. Other work in the literature examined UHI along a socio-economic axis. Chakraborty et al. [15] used satellite and census data for multiple cities and found that UHI disproportionately affects low-income residents in most places, including Chicago, and suggest that UHI mitigation should benefit demographic groups that experience greater UHI intensity. Hsu et al. [16] also found that race and income level were correlated with greater UHI intensity.

Strategies to mitigate UHI typically interrupt the heat storage process that drives UHI, where low albedo surfaces such as pavement and rooftops absorb and trap heat. Green roofs are a popular method to reduce UHI by reducing heat storage and increasing the energy from latent heat rather than sensible heat [17]. Similar to green roofs, several studies determined that increasing the urban tree canopy is an effective way to reduce UHI by reducing heat storage in surfaces, but also by providing shade [18–22]. "Cool" roofs reduce UHI by increasing the albedo of rooftop surfaces and decreasing the amount of radiation that gets absorbed [17, 18, 23]. Lastly, rooftop solar panels are also found to, counter-intuitively, mitigate UHI effects at night due to boundary layer structure and by reducing energy requirements for cooling [23–25]. However, the primary function of solar panels is to improve adaptive capacity by generating energy for cooling [24].

As with UHI intensity, the literature also indicates that UHI mitigation efforts disproportionately benefit wealthier residents. McDonald et al. reported that high-income areas had nearly twice the tree canopy of neighboring low-income regions [20]. Further, efforts to mitigate UHI with vegetation may lead to gentrification, thereby excluding the intended beneficiaries [15]. Solar panel adoption has also developed along socio-economic lines. Vaishnav et al. [26] showed that subsidies for rooftop solar panels favored the affluent. Reames et al. [27] identified that the greatest solar panel penetration was found in areas with the greatest income, although it remained quite low compared with other cities. The researchers also indicate that lack of information contributes to these disparities [26, 27]. Illinois' Solar for All campaign sought to prioritize low-income areas using a tool called the Environmental Justice Screening Tool (EJSCREEN) from the Environmental Protection Agency (EPA) [28]. Another tool that identifies climate justice areas is the Climate and Energy Justice Screening Tool (CEJST) [29]. However, neither of these tools incorporate temperature data nor UHI effects, thereby limiting their effectiveness at targeting areas facing heat wave risk.

In the present work, we use the hazard-exposure-vulnerability framework for risk established by International Panel on Climate Change (IPCC) in 2018 [30]. This framework is useful for understanding the different factors that contribute to risk. Hazards are the climate events that can produce adverse outcomes. Examples include flooding, hurricanes, and heat waves. Our work focuses on the latter. Exposure implies the presence of people. People are not at risk from a hazard if they are not present. Regions with different population densities have different levels of exposure. Further, cities have a higher exposure to heat waves due to UHI. Lastly, vulnerability describes susceptibility and adaptive capacity to particular hazards. This includes socio-economic factors such as race, income, and age. Adaptive capacity reduces exposure or vulnerabilities while mitigation efforts minimize the hazard itself.

As identified earlier, lower income is associated with greater UHI and therefore both a greater exposure to heat waves with less adaptive capacity. However, income is one of many factors that contribute to heat wave risk. Maragno et al. [31] mapped heat stress risk by adapting the hazard-exposure-vulnerability framework and included age as a demographic vulnerability along with landuse for different types of buildings. There are other socioeconomic factors that contribute to heat wave risk, such as crime rate, educational attainment, access to cooling centers, and housing characteristics [4, 32] that Maragno et al. do not include.

Several works mapped regions with the highest UHI [10], identified disparities in UHI [15] and its mitigation [20, 27]. At least one study applied the hazard-exposure-vulnerability framework in a heat wave risk assessment [31]. However, there is no existing literature that prescribes a methodology for efficient allocation of rooftop solar panels. The present work fills that gap by collecting satellite and socio-economic data to identify areas of high heat wave risk that accounts for disparities in exposure and adaptive capacity.

3. Methods and Data

In this section we review the data we collected for the City of Chicago and the methods we used to cluster Chicago's census tracts into priority areas for solar panel distribution. We used the hazard-exposure-vulnerability framework asserted by the IPCC to categorize the datasets used in this work [30, 33].

3.1. Hazard

Hazards are the climate-related events the may lead to adverse outcomes for people, such as losses of life, function, property, infrastructure, and resources [30]. In this work, we focus on the risk of heat stress and the potential for heat-related deaths, for which temperature is the primary hazard. We gathered hourly temperature data for each community area in Chicago for the years 2000 to 2020 using the NSRDB [34]. In order to capture the temperature difference among Chicago's community areas during heatwaves, we set a temperature threshold of 32°C and filtered out the data below this threshold. We defined a heatwave temperature anomaly,

$$H_a = T_{ca} - T_{city}, \tag{1}$$

where T_{ca} is the temperature of the community area and T_{city} is the mean temperature of the city (i.e. the mean of all community areas), in celsius. We then took the mean of the hourly H_a to use in our clustering algorithm. Figure 3.1 shows the variations in temperature during heatwaves in Chicago.

Table 1. Summary of curated data for the city of Chicago

Dataset	Risk Aspect Aspect	Spatial Resolution	Factor	Source
Temperature	Hazard	Community Area	Aggravating	[34]
Population density	Exposure	Census tract	Aggravating	[35]
Percent tree canopy	Vulnerability	Census tract	Mitigating	[36]
Energy burden	Vulnerability	Census tract	Aggravating	[29]
Age	Vulnerability	Census Tract	Aggravating	[35]
Cooling centers	Vulnerability	Community Area	Mitigating	[35]
Social network	Vulnerability	Community Area	Mitigating	[35]
Crime rate	Vulnerability	Community Area	Aggravating	[35]
Percent qualified roof area	Vulnerability	Census Tract	Mitigating	[37]

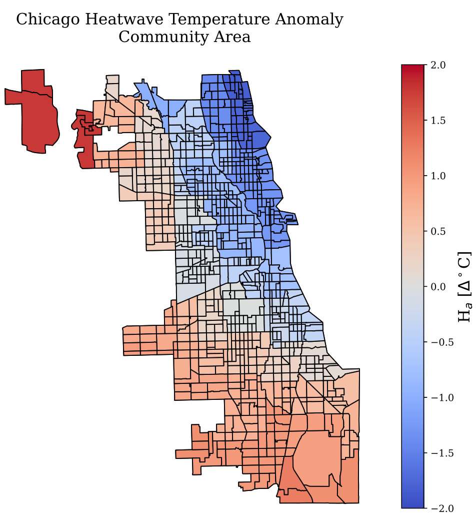

Figure 1. The temperature variations among community areas in Chicago during heatwaves. Higher values indicate warmer temperatures than the city mean temperature and lower values indicate cooler temperatures.

A positive H_a indicates regions that experience higher temperatures during heatwaves and a negative H_a indicates regions with lower heatwave temperatures, with respect to the citywide average temperature. The region near O'Hare International Airport experiences the highest temperatures, nearly 2°C above the citywide average. The temperature anomalies are further adjusted by subtracting the minimum temperature difference such that the coolest area of the city has an $\bar{H}_a$ value of zero and other values indicate the temperature above this minimum value. This is done to ensure good behavior from the clustering process.

3.2. Exposure

Exposure is the presence of people or important assets in places that could be adversely affected by climate hazards [30].

3.3. Vulnerability

Vulnerabilities are the factors that predispose certain groups or areas to adverse outcomes. We consider several physical and social vulnerabilities. Studies that mapped heat stress and heatwave risk tend to focus on weather effects (hazards) alone [2, 11, 38, 39]. One study incorporated a hazard-exposure-vulnerability framework by treating land use and building purpose as proxies for exposure and vulnerability, along with population age [31]. Conversely, studies that map the disparities in solar panel distribution do so along a social axis, without climate differences.

3.3.1. Energy Burden Energy burden is the ratio of household energy costs to household income. We created a map of energy burden in Chicago using data from CEJST [29]. Energy burden affects access to electricity, especially during heatwaves when demand and cost of electricity are highest. Rooftop solar panels can reduce energy costs and therefore improve access to cooling during heatwaves. Figure 3.3.1 shows the distribution of energy burden throughout Chicago.

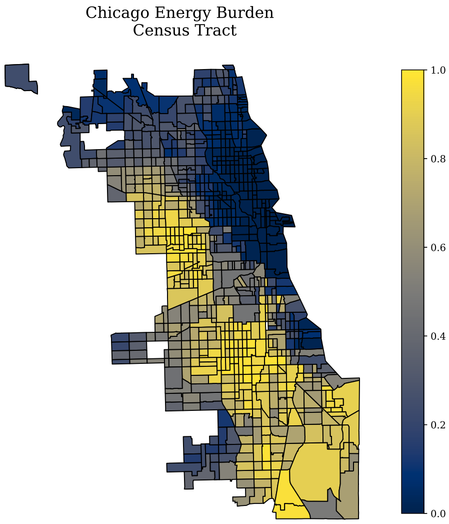

Figure 2. Energy burden throughout Chicago as a percentile. A region in the zeroth percentile has the least energy burden and a region in the 100th percentile has more energy burden than any other region.

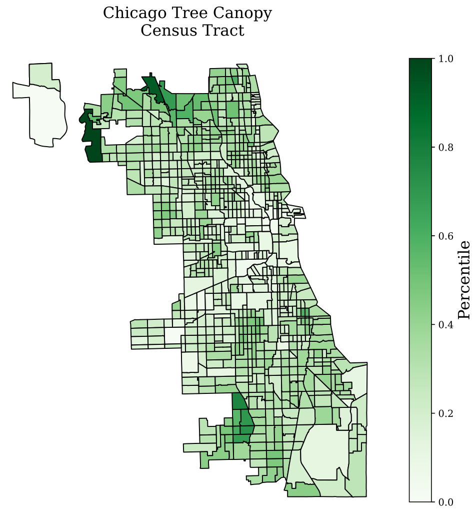

Figure 3. Distribution of trees in Chicago by percentile. A region in the zeroth percentile has the least tree canopy and a region in the 100th percentile has more tree cover than any other region.

3.3.2. Tree Canopy Urban tree cover effectively mitigate land surface temperatures in cities [19, 20, 22]. Tree canopy reduces temperature by preventing ground heat storage through shade and encouraging evapotranspiration [20]. Thus, areas with greater tree cover are less vulnerable heatwaves. Figure 3.3.2 shows the distribution of trees in Chicago from the Morton Arboretum Tree Census [36].

4. Results

5. Discussion

6. Conclusion

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