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Energy efficiency vs resiliency to extreme heat and power outages: The role of evolving building energy codes

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ABSTRACT

Environmental issues, costs, and limited energy supply, among other concerns have been driving the efforts toward more energy efficient buildings over the last four decades. Hence, energy efficiency is not only well-established within the building design and construction industries, but is also an active field of research. Many countries have state-mandated building energy codes that are becoming more stringent with time. Therefore, the building stock in many regions is becoming more efficient. With the observed increase in frequency and intensity of hot weather events in urban areas around the world and research that suggests a more extreme future, the resiliency of the built environment to heat has become a major concern for planners and policymakers. Therefore, it is important to understand how the evolution of energy codes affects the resiliency of buildings to heat. In this study, we used whole-building energy simulations to investigate the performance of high-rise residential apartment buildings under a three-day power outage scenario coinciding with a three-day heat wave. We modeled buildings compliant with consecutive versions of two building energy codes and standards commonly used in the U.S. to investigate the effect of building code on resiliency in all distinct climate zones within the country. The results suggest that in most climates, indoor conditions exceed critical thresholds during the modeled scenario. Moreover, we observed a synergy between energy efficiency and resiliency to heat in warmer climates. However, in heating-dominated climates, newer codes can potentially have an adverse effect on heat resiliency of buildings.

1. Introduction

Buildings are large contributors to global energy consumption. For example, according to [16]; buildings in the U.S. are responsible for more than 40% of the country's total energy consumption. Therefore, over the last 50 years, there have been continuous efforts to reduce the energy consumption of buildings. This encompasses low-cost and simple retrofits done by individual homeowners to reduce their utility bills as well as nationwide implementation of more stringent building energy codes. In the U.S, the concept of a nationwide building energy efficiency program was first discussed in the 1950s, when the Housing and Home Finance Agency established the residential efficiency standards. In early 1970s, commercial building energy codes were developed by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) as a response to a major blackout in New York [1]. Currently, ASHRAE Standard 90.1 (first published in 1976) and the International Energy Conservation Code (IECC) are the two leading building energy codes and standards used in the U.S [1]. There is a consensus about the effectiveness of these codes in reducing building energy demands. For example, considering ASHRAE90.1, according to [49] and [22]; the estimated average site EUI of 2013 compliant high-rise apartment buildings—the archetype used in this study—is nearly 20% less than that of the 2004 code. Nevertheless, different states and regions comply with different versions of ASHRAE 90.1 and IECC [18]. For example, as of July 2017, the state of New Mexico's residential building standard complies with IECC 2009 while those in Oregon comply with IECC 2015. California has its own code (Title-24) which is more stringent than the current version of IECC 2015, and Mississippi has no state-level residential code [6].

In addition to these enforced building codes, there are rating systems and certification programs that surpass many state-mandated codes. Examples include but are not limited to the Leadership in Energy and Environmental Design (LEED), ENERGY STAR, Passivehaus standard, and Living Building Challenge Net-Zero Energy certificate [41]. Despite the vast differences in these codes and certification schemes, they all have one common feature: each version is more stringent than the previous one. In addition, states are shifting toward more recent versions of the codes [18]. Hence, it can be inferred that in general, the

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building stock of U.S. (along with most other countries) is moving towards higher energy efficiency.

According to [28]; most of the U.S. population spends more than 80% of its time indoors. As a result, the indoor conditions that residents are exposed to can have a significant impact on their mental and physical health as well as their quality of life. Thermal discomfort is among the most important factors affecting occupants' health in indoor environments. Despite the limited research on direct health implications of indoor environments [27], there are numerous studies on health implications of exposure to heat in general. As reported by Ref. [26]; high temperatures can cause heat stroke, heat exhaustion, heat syncope, and heat cramps. In addition, survivors can suffer from permanent damage to organ systems [15], severe functional impairment [14], and increased risk of early mortality [51]. Because of the longer periods people spend indoors a large portion of heat-related mortality and morbidity during heat waves occurs inside buildings. A well-known example is the 2003 heat wave in France, during which 74% of mortalities happened indoors [10]. Hence, considering the observed (and predicted) increase in intensity and frequency of heat waves in many regions around the world [5], it is crucial that buildings have the ability to maintain safe thermal conditions during extreme events.

In general, buildings that have mechanical air conditioning (AC) are expected to be able to maintain thermal comfort during current and future heat events [44]. Hence, research has been mostly focused on scenarios where AC is required but not available. This can be a power outage in conditioned buildings or an unexpectedly hot summer weather episode in colder climates where buildings do not have AC. To address this [46], proposed the term “passive survivability” as the ability of buildings to maintain thermal comfort during temporary loss of mechanical cooling. Since energy consumption and passive survivability of a building are both functions of its design and physical attributes [46], there could be synergies or tradeoffs between them. As a result, several studies have explored these interactions [29]. measured the indoor temperature of 268 non-conditioned houses in Leicester, UK and reported that houses with cavity wall insulation (that are more energy efficient) were in general warmer in summer than those without it. Also, their data suggest that in general, older and less efficient homes were cooler than new constructions [7]. expanded this study to the whole country and reported similar results. The EnergyPlus simulations of [31] highlighted the adverse effects of internal wall insulation on passive survivability of buildings in London, UK. In a similar study on the same city [38], reported that “too much insulation” can cause summertime overheating in dwellings [43]. ran validated simulations of a net-zero super-insulated building and reported that without mitigation strategies (e.g. proper ventilation) the indoor temperature will exceed thermal comfort thresholds 30% of the time [12]. used TRNSYS simulations to investigate the overheating risk of added insulation in free-running buildings in Portugal. Their results suggest that without proper ventilation and solar radiation control, buildings with increased insulation tend to be warmer [30]. used measurements and EnergyPlus simulations to study summertime overheating in social housing buildings in London, UK. They investigated multiple building properties and reported that in general, increased insulation and air-tightness exacerbate the problem of summertime overheating in these buildings [35]. used computer simulations of five archetype buildings based on several energy codes in London and Edinburgh and reported that building codes with increased insulation levels and air-tightness can potentially result in summertime overheating in urban areas. There are also studies that suggest Passivehaus buildings have a higher potential for summertime overheating than typical buildings in Montreal, CA [47], Coventry, UK [45], Limbus, Slovenia [34], and London, UK [32] [4]. investigated a three-day power outage in two archetype residential buildings representing “old” and “new” constructions in two U.S. cities with hot climates: Phoenix, AZ, and Houston, TX. Their findings highlight a synergy between energy efficiency measures (such as insulation and air-tightness) and passive survivability. In another study conducted for warmer climates [36], found that newer buildings with higher insulation levels outperform older constructions during power failure scenarios in Phoenix, AZ, and Los Angeles, CA. Studies that consider the ENERGY STAR rating system in Australia [3,42,53] suggest that synergies and tradeoffs between energy efficiency rating and passive survivability are a function of climate. These studies show that in cooling-dominated cities of Australia such as Darwin, buildings with a higher ENERGY STAR ratings perform better. However, cities with colder climate, e.g. Brisbane, Australia, show the same trend as the above-mentioned European studies. An important consideration in interpreting the findings of all these studies is the condition under which trade-offs or synergies between energy efficiency elements and passive survivability are identified. For example, as reported by Ref. [34]; proper ventilation and shading can avoid the adverse effects from the extra insulation in Passivehauses. In other words, higher insulation and air-tightness alone do not dictate less passive survivability. Instead, their undesirable effects depend on climate, occupant behavior (e.g. window operation), and existence of other passive strategies such as thermal mass.

The U.S. comprises a large variety of climates with urban areas predicted to become warmer due to climate change [5,20] and urban heat island intensification [20]. In addition, data from the US Department of Energy shows that between 2000 and 2015, 402 outage events were reported that lasted more than 12 h and affected more than 100,000 costumers (DOE, 2017a). Therefore, despite being a developed country, the risk of man-made or naturally caused power outages in U.S. are not trivial. Moreover, the construction practices used in this country over the last several decades mainly involved lightweight wood-frame or steel-frame buildings with minimum regards for passive ventilation strategies which heavily rely on AC to maintain thermal comfort [2]. Therefore, in this work, we consider buildings compliant with consecutive versions of ASHRAE standard 90.1 as well as the IECC code and use whole-building energy simulations to compare the passive survivability of buildings under a three-day power outage coincident with a heat wave. The focus is to explore how building codes in the U.S. are evolving in terms of passive survivability. In addition, understanding the passive survivability of buildings compliant with different versions of the code can show a general picture of the heat resiliency of the U.S. building stock.

2. Methods

To study the effect of energy code evolution on passive survivability of buildings, we conducted energy simulations of buildings compliant with different versions of ASHRAE 90.1 and IECC under a three-day power outage scenario coinciding with a hot weather event in 15 distinct US climates categorized by ASHRAE. Post-processing the output data resulted in metrics that enabled us to compare different code versions.

2.1. EnergyPlus

Developed and funded by U.S. Department of Energy (DOE), EnergyPlus is a highly validated whole-building simulation engine widely used by researchers to conduct building energy analysis [13]. In addition, most studies in the literature that included free-running (i.e. no AC) simulation of buildings use EnergyPlus. Therefore, EnergyPlus was selected as the simulation tool of this study.

2.2. The archetype building

In general, there is a relationship between vulnerability to heat and socio-economic status. People of lower socio-economic status have fewer resources to cope with heat. Hence, as reported by Refs. [24] and [21]; income is a significant explanatory variable in different models of heat-related mortality in U.S. cities. Therefore, overheating in