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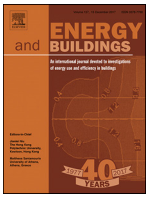

Combining carbon mitigation and climate adaptation goals for buildings exposed to hurricane risks

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ABSTRACT

As climate risks increase, there is a challenge of combining the goals of carbon mitigation and climate adaptation into building designs. These two goals are often misaligned because adaptation measures use additional materials and equipment, which can increase greenhouse gas (GHG) emissions. This phenomenon means that building design involves tradeoffs between enhanced structural resilience and reduced GHG emissions. This paper seeks to identify the optimal investment allocation mechanisms between carbon mitigation and climate adaptation measures for the design of buildings in hurricane-prone regions. A dynamic decision-making model is developed to maximize individual investors' expected payoffs over a building's lifetime. The model is based on the damage evaluation of non-stationary hurricane occurrence and building emission performance under different mitigation scenarios. The results reveal a transition from long-advocated low-carbon investments to risk-oriented portfolios for building retrofits. A case study on Anne Arundel County, MD, for which a "60-40" resilience/abatement portfolio is recommended, shows the value of enhancing structural resilience. Discretion on the accuracy of insurance premium discounts is needed to support risk mitigation efforts. Meanwhile, subsidies for emission abatements are recommended to accommodate existing emission trading schemes and building property values.

1. Introduction

Historically, sustainable building policies have focused almost exclusively on greenhouse gas (GHG) mitigation [1]. Emissions trading schemes at national and regional levels were formed as instruments of climate policy, controlling global warming by creating economic incentives for achieving GHG reductions [2]. These schemes are economically efficient in an environment where projects can achieve stable revenues with the presence of carbon price signals. However, they are suspected to be less attractive in geographic areas at risk of experiencing catastrophic events such as hurricanes and floods [3]. These events result in significant costs, including restoration of damaged local buildings and indirect costs, such as the loss of business revenue and economic growth in impacted areas. To minimize the future costs of structural failures, project proponents have been advised to pay extra up-front costs to enhance structural resilience and to prepare, absorb, recover from and adapt to natural disasters [4].

Much of the early work on resilient building structures focused on design with an emphasis on soil-foundation-structure building envelope systems to improve performance in disasters (e.g., for a new development to be built in a hurricane-prone area) [5–8]. Traditional design practices involve slab-on-grade construction, which is susceptible to hurricanes. Recently, many modular building systems have been proposed to reduce the risk of hurricane damages. As an example, such system could involve the use of precast concrete elements combined with light-frame wood sub-systems, and provide occupants shelter in the basement [9]. Resilience studies have recently been extended to focus on the performance of a group of buildings that have functional interdependence [10–12]. Relevant studies have sought to optimize the overall performance of multiple buildings exposed to a spectrum of natural disasters that can be matched to community resilience goals. Therefore, they consider resilient interdependent infrastructure system a necessary component of resilient communities.

With some exceptions, enhancing structural resilience inevitably aggravates global warming, as it not only requires additional construction materials and installation activities, but it also tightens budgets for emission abatements. The costs of strengthening measures, depending on construction specifications and the

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availability of materials, ranges from 5% to 10% of the total property value [13]. This cost makes project proponents with limited leveraging abilities tighten their expenditures on emission abatement measures, such as envelope insulation, daylight control, and window upgrades. Meanwhile, additional construction materials and activities are required to improve building element capacities to withstand natural disasters. For example, more resilient buildings are now constructed on modified, elevated foundations, and materials are stronger and more resistant to mold and hurricane straps [3]. These retrofitted elements emit GHGs throughout their production, transportation and installation and thus become additional emission sources that are not a factor in non-retrofit cases [14].

Therefore, methods of properly addressing climate risks depend on investment decisions that trade off, at least implicitly, emission abatement (slowing down global warming) for resilience management (adapting to global warming). As a traditional solution, adopting emission abatement measures can reduce energy costs and generate revenues from carbon offset sales. Kneifel [15] showed that these measures can limit energy use in new commercial buildings by 20–30% on average [15]. Life-cycle costs, the sum of all recurring and one-time costs over the full life span, can be reduced by 3% on average, and can reach over 6% for some building types and locations [15,37]. However, these reductions can be interrupted due to structural failures resulting from disasters, rendering abatement investments less attractive. As global temperatures continue to increase and more areas are subjected to severe natural disasters, the vast majority of property and wealth is now at risk of significant damage. UNISDR (2012) reported that the annual loss accumulated by infrastructure failures amounted to roughly $55 billion in the United States [16]. This number is expected to increase due to the combined effects of climate change and an increase in coastal inventories of assets [17]. These expected damages highlight the need to improve resilience to sustain building operations and to accelerate post-disaster recovery. According to ULI [18] studies on the South Florida Resort, the use of hurricane resilience measures can lower annual expected damages by an estimated $500,000, thus significantly reducing annual operation expenses [18]. Robati et al. [36] showed that an appropriate selecting of construction forms and type of concrete can save up to 7% of the cost of material consumption, 5% of the total energy consumption expense, and 5% of the CO_2 emissions of the building across all five major cities in Australia [36]. Other relevant studies also highlighted the economic and environmental benefits achieved by using resilient construction system and structural materials [38,39]. These findings imply resilience management as an important addition to traditional low-carbon development pathways, and if it is properly managed in conjunction with emission abatements, it can lead more sustainable and resilient communities.

This paper attempts to identify the optimal investment allocation between carbon mitigation and climate adaptation measures for the design of buildings in hurricane-prone regions. A dynamic decision-making model is developed to maximize individual investors' expected payoffs over a building's lifetime. The model is based upon a damage evaluation of non-stationary hurricane occurrence and carbon emission from building operation under different mitigation scenarios. Optimal investment allocation is determined by characterizing individual investment behaviors towards emission abatements and hurricane mitigation. This paper supports the following outcomes: (*i*) the development of a hybridized decision model that facilitates a balance between resilience and sustainability objectives, (*ii*) the ability to reflect resilience goals in building design, construction and maintenance, and (*iii*) the model's application to a selected county to demonstrate its capacity to manage a broad range of building cases, and to determine policy implications for a county's environmental and economic sustainability.

2. Model design

Carbon mitigation and climate adaptation are two approaches available to project proponents in the design of sustainable buildings. Carbon mitigation is often achieved by implementing energy-efficient technologies to reduce electricity and natural gas use during building operation. Climate adaptation is often achieved by reinforcing a building's structure, allowing it to better defend against catastrophic events, such as hurricanes. Both approaches involve an additional upfront technology investment, while also offering financial benefits owing to reduced expenditures dedicated to energy usage and structural restoration.

Emission abatement measures generate financial benefits mainly through voluntary carbon trading markets. The markets encourage the participation of entities that are not mandated to reduce carbon emissions (e.g. building sector). Certified carbon offsets can be traded in the compliance schemes and counted toward compliance goals in the sectors that are mandated to reduce emissions. For the example of building sector herein, the markets enforce emission thresholds for individual buildings, referred to as performance baselines. According to the definition by the United Nations Framework Convention on Climate Change, performance baselines are emission thresholds that surpass the 80th percentile of comparable peers [19]. Comparable peers include project activities undertaken in the previous five years in similar social, economic, environmental and technological contexts. The difference between the baseline emission amount and the actual building emission amount can be traded in markets as carbon offsets. The prices of carbon offsets are determined by auction, and vary among projects and offset providers. Revenues from carbon offset sales are earned on an annual basis and often last over the remaining building years.

Adaptation measures strengthen building structures and help to reduce property damages during catastrophic events. Catastrophic events exacerbated by climate change include hurricanes, floods, droughts, forest fires, etc. [43]. This study restricts attention to hurricanes for illustration purposes. The probability and intensity of hurricane winds are expected to increase in a changing climate [42]. Using hurricane mitigation measures in buildings can reduce the chance and severity of damages, thus reducing restoration costs. Expected cost savings are dependent on many factors, such as building values, hurricane intensity levels, damage severity levels, and recovery periods. This information is assumed to be known by individual project proponents amidst the uncertainty surrounding hurricane occurrence.

In this context, the goal of a project proponent is to maximize expected payoffs by determining investment allocation between emission abatement and hurricane mitigation. As shown in Fig. 1, each project proponent is modeled as a forward-looking decision maker whose decision involves balancing current sacrifice against future benefits. The project proponent is a potential participant in voluntary carbon trading markets, and has perfect information on any technologies applicable to his/her building to reduce energy consumption or to enhance structural strength. Restricted by a fixed annual budget, he/she aims to allocate the budget in a way that would achieve maximum lifetime payoffs. He/she is given the right to adjust allocation practices on an annual basis as changes in the market environments and climate risks are observed. Each project proponent makes decisions independently, and the performance of a single building has no effect on the performance of another building during hurricane events. The result of this model is a dynamic investment allocation between emission abatement and hurricane mitigation measures throughout a building's lifetime.