




Navigating the Green Transition During the Pandemic Equitably: A New Perspective on Technological Resilience Among Boston Neighborhoods Facing the Shock

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Abstract. Cities, public authorities, and private organizations respond to climate change with various green policies and strategies to enhance community resilience. However, these community-level transition processes are complex and require deliberate and collective planning. Under this context, the purpose of this study is to understand the energy actions taken at the local level, as well as to analyze the differences between the neighborhoods' green energy transitions in terms of their socio-economic aspects, using a big data perspective. The paper is addressing the following question: what was the role that the pandemic played in accelerating or slowing Boston's green investments, and to what extent do different racial and socioeconomic groups invest in green technologies during this period? The study aims to answer these research questions using the City of Boston as a case study to reveal different neighborhoods' paths in achieving the transformation of city ecosystems towards green neutrality. Next, the theoretical framework builds the linkages among the city's measures, climate actions proposed by the City of Boston, and their associated contexts and outcomes in shaping new policy and planning models for higher 'green' performance. Following the understanding of the actions, the neighborhoods' socio-economic and building permit data were assessed to understand whether economic disparities exacerbated during the pandemic have affected neighborhoods' performance in green transition. This method is applied in a comparative study of its 23 neighborhoods, using a dataset provided by Boston Area Research Initiative (BARI). Intriguingly, the paper's findings show that racial differences within the city have no significant impact on tech-related expenditures. There is a clear negative correlation between poverty rate and investment, which indicates the reverse relationship between these socio-economic factors. The study concludes that city authorities will need to address the challenges of each community achieving green transition with more targeted programs based on its needs.

Keywords: Technological resilience · Big data analytics · Covid-19 Pandemic · Green transition · Urban innovation · Climate change · Socioeconomic analysis · LEED

1 Introduction and Context

1.1 General Observations

The sustainable city discourse is becoming ubiquitous and highlights the need for a long-term strategic approach to create a regional context in which sustainable development is increasingly becoming the norm [1]. Wheeler identified sustainability “as requiring a holistic, long-term planning approach, as well as certain general policy directions such as compact urban form, reductions in automobile use, protection of ecosystems, and improved equity” [2]. By the end of the 20th century, “sustainable city” initiatives began to emerge in different parts of the world [2]. Then, the arrival of “resilience” as a new concept of urban policy and a buzzword has reformulated the imperatives of sustainability in the context of the environmental crisis [3, 4]. The current resilient sustainable discourse reflects that the city can and should be green but it needs significant innovations [5]. The discourse of sustainable and resilient cities showed that cities are the current major challenge facing sustainable development - this is mainly due to an ever-increasing population density and high energy consumption. But, at the moment, there is a shift from understanding cities as environmental problems towards cities being understood as the solution to environmental problems on a global scale [6]. Urban sustainability has guided the development in urban and metropolitan areas around the globe in lowering their carbon footprints and reducing greenhouse gas emissions by targeting resource and energy consumption in the construction, operation, and maintenance of the urban built environment [7]. However, the complex environment that characterizes cities, and especially metropolitans, makes the transition towards sustainability more challenging. The mounting climate pressures have compelled cities and planners to seek more green and innovative alternatives to steer cities and their inhabitants towards sustainable pathways [8].

The rapid growth of energy use has caused concerns regarding the supply, the collapse of energy resources, and the severe environmental impacts [9]. The global contributions from buildings towards energy consumption have steadily increased [10]. Around the world, buildings consume 38% of the world’s resources, generate 40% of the waste in landfill sites, and emit 28% of the greenhouse gases produced on the planet [11]. Moreover, according to the US Green Building Council, buildings in the United States account for 36% of total energy, use 65% of electricity consumption, and almost 40% of global energy-related CO₂ [<https://www.usgbc.org/press/benefits-of-green-building>]. For this, reducing energy use includes the goal of reducing the electricity needed while obtaining the same or nearly the same results from the building’s systems. Improving the energy consumption in buildings is a prime objective to reduce human impacts on the environment at the national and international levels.

Despite all the big pronouncements and pledges of the city authorities to become greener, the pandemic has shown us a bitter reality; the world is still very dependent on

fossil fuels [12]. Cities are far behind reaching their targets of achieving 100% use of clean energy. In this difficult equation, addressing the existing vulnerabilities, economic disparities, and race inequalities will be key for the cities to become leaders in creating a sustainable future for their residents. The current study works towards this direction, aiming to reveal a variety of inequities in how residents of different neighborhoods and racial and socioeconomic groups have been able to achieve a green transition before and during the pandemic. It uses the City of Boston dataset on building permits to test the hypothesis within the city's neighborhoods that vulnerable communities' socioeconomic context affects neighborhoods' capabilities to achieve green transition. In this line of reasoning, the research tries to conceptualize pillars of measures based on socioeconomic factors and neighborhood physical formation to understand which factors are most relevant to the pandemic shock absorption thus the resilience of the system.

In order to fully weigh the benefits of innovative neighborhoods as a way to achieve a green transition, we begin by identifying the city planning initiatives and discussing the city's climate actions. There are already citywide initiatives to finance energy efficiency in municipal buildings, for example, the Renew Boston Trust. Nevertheless, we seek to evaluate private buildings' implications for deep energy building retrofits, the installation of rooftop solar energy, and the procurement of zero-carbon electricity. The paper uses LEED's green building system assessment standards as a proxy for investigating tech-related permits. The following section provides a brief overview of Boston's climate action plans and policies. In the remaining part of the paper, 23 neighborhoods within the City of Boston will be evaluated on the basis of their characteristics and their adoption of green technology. We conclude by discussing the results of the study, to provide a sense of the extent to which Boston is considering the advancement of reducing the amount of CO₂ emissions that is emitted from buildings.

1.2 Research Questions, Goals, and Hypothesis

During the last months, we have seen energy prices being dramatically surging as countries and households confront shortages of oil, gas, and coal. In this period, the neighborhoods of Boston need to look at some of the major factors behind the energy crunch, from the role of green policies to the historical housing discrimination affecting homeownership in the city. In this context, the discussion concerning urban informatics around the potential pitfalls of the field that could harbor its overall success in improving cities for the user. One of the biggest concerns is the lack of interconnectivity between studies in different cities of similar types. This seems like a big, missed opportunity as it could expose important relationships in the way cities function. Another, perhaps even larger challenge, is maintaining an even level of funding amongst cities for urban informatics, an issue which is not easily solved. Larger cities will have bigger budgets for this manner of project by default, meaning that cities without funding get left behind when it comes to the data analysis of the city. Although data mining and analysis in the urban environment has grown exponentially in recent decades, the organization and execution of how we interact with this data and use it for the public good are still in need of advancement.

This paper aims to lead the policymakers to pay more profound attention to the neighborhood level to enhance the community level and form a much more robust network to face shocks and stresses. Resilience strategies stem from the technological

advancement of communities. Green technologies are knowledge-based assets; thus, local investments could lead the neighborhood to significant developments. Moreover, the current energy crisis has revealed the importance of creating self-sufficient communities that can long-term produce the energy they use. This type of open systems, which will allow the regeneration of the energy in buildings, will affect the sustainability of Boston's neighborhoods.

Through our research, we address the following questions: RQ1: what was the role that the pandemic played in accelerating or slowing Boston's green investments? RQ2: To what extent do different racial and socioeconomic groups invest in green technologies during this period? These questions address the ways the pandemic affected the neighborhoods' investments in green technologies as well as the ways that different racial and socioeconomic groups have been investing in green technologies before and during this recent healthcare crisis. We aim to approach our research as a critical point where we are collecting, analyzing, and visualizing big data which will allow us to understand neighborhoods' dynamics and constraints in green transition.

As urban problems continue to emerge, more data analysis is needed to support continued efforts. Cities are living laboratories and have certainly shifted because of the COVID-19 pandemic, so research should attempt to keep up with the latest changes. The recent unrest in cities and local governments necessitates research and expertise, especially since cities were almost breeding grounds for the pandemic. In order to understand cities, and reverse current inequalities, researchers must alter perspectives at the city level, such as health crises, and provide equal opportunities to all populations, which will certainly require more robust technologies, data, and instruments. We hypothesize that vulnerable communities' socioeconomic context affects neighborhoods' capabilities to achieve green transition.

In the end, if the green transition is reliant on public policy or government intervention, there will need to be a transfer of knowledge and associated advocacy to promote change at the neighborhood level. However, awareness of a problem does not necessarily bring a response that will follow suit, and though data can identify relationships, patterns, or problems, it does not always have the power to create change. Translating the findings of the current and similar studies into tangible policy will be the most ambitious goal and challenging aspect of our future work in big data analytics.

The paper sets out the study as follows:

Section 1 presents the topic of green transition and green neutrality as a way to enhance community resilience during the pandemic. It also introduces the two main research questions. The answer to these questions will provide support to city authorities to improve the current programs and policies they propose to enhance green neutrality at the local, neighborhood scale. Section 2 provides an overview of other studies, previous research attempts and measurement tools in the discourse of big data analytics and urban informatics to identify city areas with better performance in carbon neutrality. Section 3 introduces the socio-economic context of the City of Boston, which is used as a case study and provides significant considerations regarding previous strategies and climate actions in support of its green neutrality. It also analyzes significant constraints for Boston's neighborhoods to achieve high performance towards that goal and attempts at exploring correlations between 'green' neighborhood performance and socio-economic context.

Section 4 contains a big data-driven analysis of city investments in building permits related to green transition, which was used as the main method to provide insights into how different neighborhoods are incorporating green technologies. Section 5 contains the findings with a summary of the range of factors that affect neighborhoods' performance, while Sect. 6 provides conclusions and recommendations for further study.

2 Literature Review

2.1 Building a Framework for Measuring Green Transition Based on Other Case Studies and Toolkits

Buildings contribute to 38% of carbon emissions which highlights the need for green buildings [11]. Therefore, over the past two decades, the green building movement started to emerge and new councils for green building were established. The US Green Building Council defined a green building as they “are designed, constructed, and operated to boost environmental, economic, health, and productivity performance over that of conventional building.” [13]. As a result, green buildings have become a promising pathway for the nation's sustainable development. New assessment systems developed around the world. For example, the US Green Building Council (USGBC) developed its green building rating system, which is Leadership in Energy & Environmental Design (LEED). Similarly, the Building Research Establishment Environmental Assessment Method (BREEAM) in the UK, and the Green Star in Australia. Among those, the US was one of the most developed areas in green building projects [14]. For instance, Austin, Texas, is best known for its efforts in green building [15]. It won an award at the first UN conference on sustainable development in Rio de Janeiro in 1992. Subsequently, local residential green building movements rapidly emerged in many American cities such as Denver, Colorado; Kitsap County, Washington; Clark County, Washington; the Baltimore Suburban Builders Association; and the EarthCraft Houses Program in Atlanta. Besides USGBC, the US has a wide range of green building local organizations that took part in the green building movement. For example, the National Association of Homebuilders issued guidance on how to create a green building program in the local area [16]. Additionally, local and state governments have been highly involved and promoting green building. In 1998, Boulder, Colorado stood up and passed an ordinance requiring specific measures with respect to green building. Moreover, Pennsylvania, for example, made significant efforts to promote green building. It established the Governor's Green Government Council (GGGC) in part to address the implementation of green building principles in the state. The country even made it feasible for everyone and all organizations to be up to date regarding everything related to green buildings in the US through the Environmental Building News - a monthly newsletter published by BuildingGreen.

However, investments in green buildings have been very limited. For example, only US\$148 billion of the total US\$5.6 trillion investment in buildings are allocated to green buildings [11]. Moreover, Debrah et al. revealed the gap in green finance in green buildings in the research area [17]. They pointed out that although the US is dominant in the green investments debate [18], it has very limited academic research on this topic. Their review of the research area worldwide on green investments in buildings shows that “GF-in-GBs [Green Finance in Green Buildings] research has been around for about

only a decade now, although both the green finance and green building research fields in general were born in the 1970s". This underpins the crucial need for more studies on green building investments.

For this, this study examines the econometrics capturing patterns of a US city's performance in supporting green building projects. We assess Boston's neighborhood growth and 'green' investment through the volume and profile of building permits. We focus on the spreading supply of GHG-free electricity in the City of Boston. We evaluate the number of investments that go to green transition, assess the number of buildings' tech-related projects such as rooftop solar energy in different neighborhoods and assess the potential of the city's neighborhoods in adopting low- and zero-GHG fuels to reduce emissions and adapt other green technologies. Our central argument is that innovation is one of the main drivers to post-carbon transition at the neighborhood level. Innovation is at the heart of the transition to a cleaner global environment. However, "it is still insufficient to address the environmental challenges facing the planet today" [19]. There are some barriers that could limit the green transition such as a lack of public acceptance of new technologies, financial barriers, and innovation capacities [19], and there is evidence to suggest that the pace of green innovation has slowed in recent years. This suggests that major barriers remain and need to be lifted to accelerate the transition.

2.2 Technological Resilience as a Factor of Neighborhoods Green Transition Before and During the Pandemic

Technological resilience is a factor of regional resilience that relies on the capacity of a city or region to capture technological changes over time. Balland et al., proposed four pillars to identify this concept in a regional realm [20]. Although our research deals with similar attributes, we aim to extend this understanding to a local level, where communities have their own evolutionary paths to fulfill transition goals requirements, and local units have their own structural identities based on path dependency. In other words, we are translating the effort of technological resilience conceptualization in regional economic geography into a tangible measurable analysis to generate local maps and models. According to the mentioned reference, looking at two semitransces aspects: first, evolutionary development path: could be addressed in a way to reveal the crisis effect on the evolution of a city utilizing the neighborhoods as cells of the system. The shock due to the pandemic, stated earlier, changed the course of the investment pattern, and emerged a new ornament that creates a local definition of evolutionary development. In this research, we rely on these attributes benefiting from a before/during shock classification.

Second, Path dependency: as explained by scholars there is a strong relationship in the legacy of the history of local units and the current status of the resources. In this research, we brought the structural properties of the neighborhood into the investigation in a way to address the racial configuration and physical characteristics of the neighborhood. Nevertheless, there is a tendency in the literature claiming path dependency is an issue for looking at the emerging characteristics of the local units.

In this research, we are looking at the mentioned identities under the lens of big data to examine historically claimed status about racial disparities and physical configuration.

3 The Case Study of Boston

3.1 Assessing Boston as a Case Study Towards a Net Zero Carbon, Equitable and Resilient Built Environment

Boston is an East Coast city with 23 neighborhoods (Fig. 1). Boston is experiencing increasing sea levels and a range of climatic issues, including flooding, storm surge, and extreme temperatures. Historically, Boston expanded by landfill projects which created new neighborhoods and almost doubled the city’s area. Thus, the City of Boston now deals with a vulnerable position on reclaimed land. If sea levels continue to rise in the Boston area, the Climate Ready Boston initiative predicts that by 2070, upward of 90,000 residents in the city will be at severe risk, with billions of dollars of infrastructure, property, and business loss [21, 22]. Future sea level rise and temperature change depend on how much the world is able to cut carbon emissions. Nevertheless, water is not the only risk, extreme temperatures and heat waves put Boston under threats for public health, especially for vulnerable communities. Sasaki analyzed that by 2070s, the annual losses from flooding could cost up to \$1.4 billion, and the exposure to flooding could

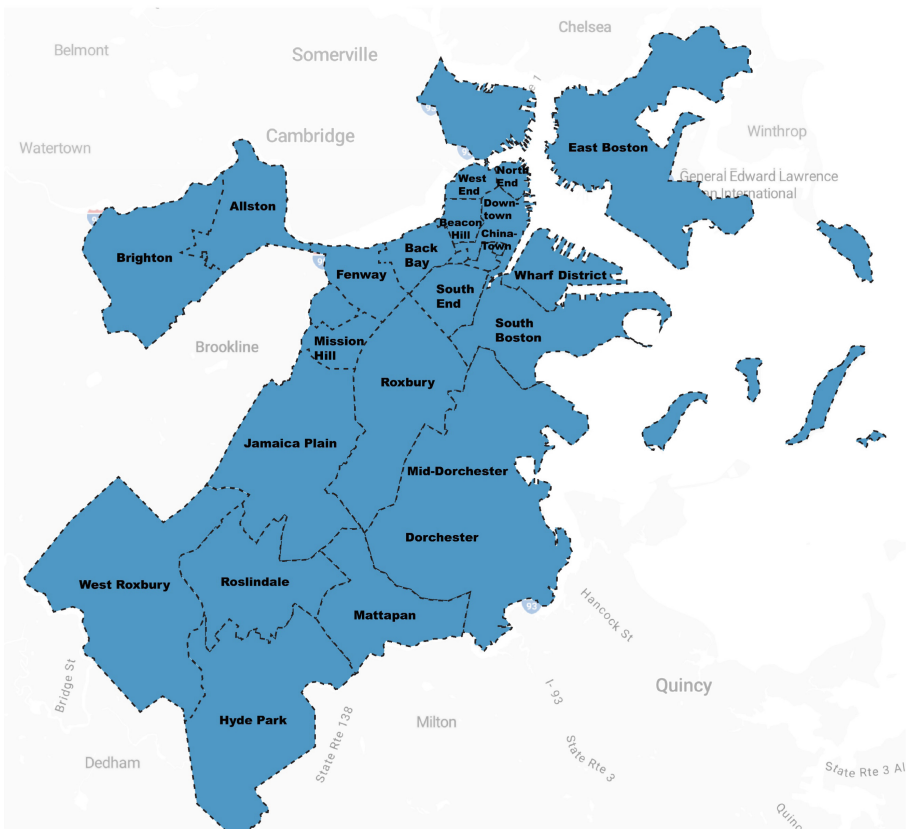


Fig. 1. Boston’s Neighborhoods

include 14% of Boston's population (88,000 people), 10% of the city's K-12 schools, 32 MBTA stations, 240 essential public facilities (law enforcement stations, fire stations, and EMS), and sections of many evacuation routes [23]. On the other hand, extreme heat will increase mortality rates [23].

3.2 Previous Strategies and Climate Plans in Boston to Understand Green Transition

Boston's journey toward resilience planning and climate action has been comprehensive since the start of the twenty-first century [24]. In 2000, Boston joined the Cities for Climate Protection Campaign of ICLEI—Local Governments for Sustainability. Through this campaign, Boston pledged to step up for increasing energy efficiency and reducing greenhouse gas emissions. Moreover, Mayor Menino decided to develop and implement a local action plan to fight against greenhouse gas and air pollution emissions. Five years later, Boston adopted the U.S. Mayor Climate Protection Agreement and joined the target of reducing carbon emissions to below 1990 levels [25]. In 2007, the city of Boston released its first citywide climate action plan. Boston's former mayor, Thomas Menino, issued an executive order in 2007 on climate change that set an ambitious goal for the city to reduce its GHG emissions by 80% by 2050. In 2008, Massachusetts enacted a law that required “the Department of Environmental Protection to establish targets for GHG emissions reductions below 1990 levels between 10–25% by 2020 and 80% by 2050” [26]. Since then, the city has adopted long-term climate goals such as waste reduction, transportation and mobility, mitigation, and adaptation. The City of Boston started to integrate the community in the action plans and thus in March 2009, Mayor Thomas M. Menino formed the Boston Climate Action Leadership Committee and Community Advisory Committee. The aim of the committee is to propose recommendations to the Mayor and set the goals and objectives that Boston should follow in order to confront the risks of climate change. Hence, over a year, community leaders came together to develop recommendations on buildings, transportation, and adaptation. In 2010, the committee proposed Sparking Boston's Climate Revolution report [27]. This report was fruitful and rich of recommendations to tackle climate change.

Along with Mayor Menino aiming to bring all levels of community together, the Green Ribbon Commission was launched [28]. The commission was a way to engage the city's business and civic leaders for the same goal. It aims at designing and implementing the City's climate adaptation and mitigation strategy. In 2011, Boston set carbon reduction goals of 25% by 2020 and 80% by 2050 below 2005 levels. Later, Mayor Martin J. Walsh announced that Boston joins the C40 Cities Climate Leadership Group (C40). In 2015, the City of Boston joined the Carbon Neutral Cities Alliance (CNCA) with cities from all over the world. Each city has committed to save the planet and mitigate global warming. A year later, the Mayor launched Climate Ready Boston [29]. It is “an initiative to plan for how the city will continue to thrive while adapting to long-term climate change. It has three main components: climate project consensus (completed by the Boston Research Advisory Group), vulnerability assessment, and resilience initiatives”. In 2017, Mayor Walsh announced Boston's goal of carbon neutrality by 2050—an ambitious yet necessary commitment to meet the urgency of the climate challenge [30]. In Imagine Boston 2030, the city's long-term strategic plan, also sets an interim carbon

reduction goal of 50% by 2030. Carbon neutrality goal means that Boston is fulfilling the commitment to the Paris Climate Agreement and leading efforts to keep global warming under 1.5 degrees Celsius. By 2017, the City of Boston reduced emissions from municipal buildings and fleets by more than 40% below 2005 levels. Based on the progress Boston expects to make in energy efficiency and renewable energy, this Plan increases the reduction goal for municipal operations from 50% to 60% by 2030.

Boston's most recent climate action plan, released in 2019, sets the stage for Boston's transition to carbon neutrality and describes the roadmap for the next five years [31]. The 2019 Climate Action Plan (CAP) focuses on strategies to accelerate emissions reductions from three work areas: buildings, transportation, and energy supply. We focus in our study on Boston's buildings as buildings account for over 70% of greenhouse gas emissions in Boston [32]. Boston's two main targets for building are adopting a zero net carbon standard for new constructions by 2030 and retrofitting and electrifying at least 80% of existing buildings over the next 30 years. Adopting a zero net carbon standard by 2030 would cut 17% of cumulative emissions from new construction to 2050; adoption by 2023 would cut another 17% [31]. According to the city, reaching carbon neutrality is possible if effective legislation is enacted and implemented in a timely manner. On the other hand, four out of five existing buildings in Boston will need deep energy retrofitting and moving to fossil-fuel-free heating and hot water systems in order to reach carbon neutrality by 2050. Existing building energy retrofitting can lead to reducing the city emissions by up to 40%. The City of Boston requires residential buildings that are 20,000 ft² or larger (excluding parking) or have 15 or more units to reduce their building emissions and to begin reporting their energy use in 2022. By doing this, owners and tenants would become more aware of their energy use and costs, and greenhouse gas emissions. They would be able to compare them to similar size buildings and give opportunities to reduce the energy consumption. The City of Boston suggested that deep energy retrofits should happen by 1) Upgrading mechanical systems, lighting systems, and appliances; 2) Insulating walls, roofs, crawlspaces, and foundations; 3) Upgrading HVAC and plumbing; 4) Replacing windows; 5) Air sealing; 6) Installing renewable energy systems where possible.

Moreover, the city suggested converting fossil fuel systems to electric equivalents. With deep energy retrofits and electrification, existing buildings can become carbon neutral. There are existing state incentives, such as Mass Save, that help residents upgrade their energy efficiency and it offers a wide range of services, and incentives. In addition to Mass Save, there are over 14 units that were implemented by E+ Green Building Program launched by the City of Boston in order to regenerate multi-unit residential buildings and bring energy and environmentally positive homes to Boston's neighborhoods. To reach carbon neutrality, the city will need to implement deep energy retrofits and electrification by 2050. Businesses, residents, and the city should invest more in solar panels on building rooftops and other green technologies to have more energy-efficient buildings. In the end, communities will benefit environmentally, socially, and economically, since these investments will also spur innovation and job creation.

In the next section, there is a data analysis of the city's investments in technological projects that will help the city and each neighborhood to make a successful transition to being a green city. Throughout the section, we get a glimpse of how different neighborhoods are adopting green technologies.

Boston's Demographics

Boston was ranked 19th in terms of segregation in 2019. By 2020, the city's dissimilarity index between black and white residents is 68.8, which implies that more than 68.8% of whites would have to move to a different neighborhood so that blacks and whites are equally distributed across all neighborhoods. As compared to 2010, this was an increase from the 60% index of dissimilarity [33].

There are several articles discussing Home Owners Loan Corporation (HOLC) "redlining" maps (Fig. 2) and how in the long run it still affects the trajectories of urban neighborhoods and more specifically the structure of segregation and economic inequality [34, 35]. Areas that were labeled hazardous or "redlined" by lending institutions, were denied access to capital investments, which could improve the housing and economic opportunity of residents. In spite of the fact that redlining occurred throughout the country, racial segregation in Boston was particularly egregious. In addition to

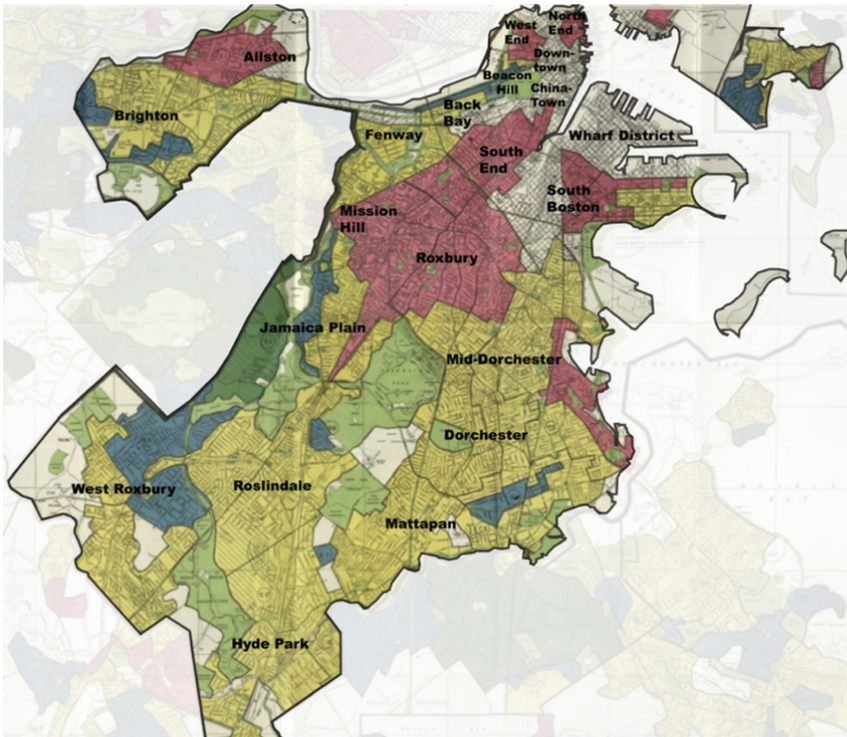


Fig. 2. Boston's Redlining Map. Source [33].

redlining, the federal government funded 25 public housing projects in the Boston area, all of which were racially segregated by race [33].

It is likely that the long history of racial disparities in the US has affected the neighborhood’s ability to make the transition towards a green economy, which we are exploring in this study.

4 Scope, Methods and Data Collection

The study uses big data analysis as a crucial method to detect patterns and correlations related to neighborhood inequalities in green transition. Furthermore, it explores new opportunities that can be derived from such analyses. The research methodology is structured to assess the prioritization of each neighborhood’s investment before and during COVID-19 pandemic shock in the City of Boston and to find out the most relevant variables for this prioritization. We tested our hypothesis on vulnerable and prospered neighborhoods’ behavior against acute shocks. The methodology of this research relies on exploring a significant number of observations in the City of Boston to see if COVID-19 pandemic changed the investment priorities among the city’s 23 neighborhoods. This could shed light on the inclusiveness issue in transition during shocks. Thus, to answer the research questions stated earlier, we used the Boston Permits dataset published by Boston Area Research Initiative (BARI) to capture neighborhoods’ tendency to invest in technological-related projects prior to and during the pandemic shock. When this study was conducted, the data was only available up until March of 2021. Due to this and in order to create two equal subsets of observations, we selected the period 23rd March 2019–2020 as the pre-pandemic and the period 24th March 2020–2021 as the pandemic period.

The following step was to transform the dataset from addresses and ZIP codes to the 23 neighborhoods defined by the City of Boston for easier interpretation. The dataset contained 435k observations for all recorded permits which were filtered and then summed to the neighborhood level. As the permits were related to different aspects of buildings, we ran a text analysis algorithm using solar energy and LEEDs’ certificate-related keywords (Table 1) to find tech-related projects in order to be aligned with our questions regarding green transition.

Table 1. Keywords used for supporting the dataset based on LEED measurements.

solar	Voltage	low emitting
Energy	Recycle	Thermal comfort
Tech	waste management	innovation
panel	Environmental	refrigerant
renewable	green power	cooling tower

This step revealed a total of 299 building permits aimed at decreasing energy consumption by using technology. Among the keywords listed in the energy section of the

LEED, we identified a corpus of 15 keywords that are repeated several times and identified as important to the research question and topic of this paper (Table 1). We analyzed the green transition across Boston’s neighborhoods before and after COVID-19 pandemic based on these keywords. Then we used the IQR technique and removed outliers due to the high data variance within a neighborhood.

After sorting the observations, and creating two time periods, we conducted three parts of analysis based on this data. The first part started by creating a frequency table to compare the number of all permit requests for each period to the number of permits for tech-related projects. To compare these numbers, we compute the proportion of each category (all permits issued and technology-related permits) for each period (Eqs. 1&2). Then, in order to determine the trend of permits issuance, we calculated the change rate of each category (Eq. 3). If the results show a positive sign that indicates that technological projects were less impacted by the shock than the other categories, while the negative sign describes that in these areas technologically related projects were heavily affected by the shock.

$$A = \frac{\sum X_A}{\sum (X_A - a)} \tag{1}$$

$$T = \frac{\sum X_T}{\sum (X_T - a)} \tag{2}$$

$$M = A - T \tag{3}$$

where

- A is the change rate in the number of all issued permits
- T is the change rate in all tech-related permits
- X_A is the number of all issued permits
- a is the change in pre- and during-pandemic
- X_T is the number of all tech-related permits
- M Proposed technological resilience measure

After the first part of the analysis was completed, the next step was to quantify the investment per neighborhood in both periods and compare the two to find a specific flow. As a way of making a fair comparison between neighborhoods, we calculated a fixed amount of USD (100 dollars) per house.

The third part was to measure and determine which possible variables influence the investment in these periods. We explored a mathematical model to work on the context-based indicators to find an appropriate regression line. After combining socioeconomic factors of Boston neighborhoods retrieved from Census.gov & Analyze Boston platform (the City of Boston’s open data hub to find facts, figures, and maps related to lives within the city), we decided to elaborate on three pillars. Social factors include age, race, and educational degree. The next pillar is dedicated to exploring the economics of people, such as median income, and poverty rate. The last pillar of the data set investigates the physical properties such as the ratio of vacant houses, poverty rate per neighborhood, and race proportion. After that, we ran a multivariate regression (MVR) in which we had a dependent variable of 100 USD invested in tech-related per house in each neighborhood and the variables mentioned earlier as independent variables. After running the model, residual analyses and ANOVA explain the model fitness and quality of selected variables.

5 Research Findings and Discussion

Based on the analysis of the patterns of permits issued by the city of Boston over the past decade, it appears that the number of permits issued by the city in 2020 has shown a dramatic decline (see Fig. 3). Subsequently, the technology-related domain has also been impacted, but the rate of this change has been quite slow. This 2019–2020 period can be compared to the Covid-19 pandemic. A major objective of this study is to identify the trend distribution and the possible factors that impact this distribution at the neighborhood level, and then to draw a different line between the general permit rate and the technology-related ones to determine if there are specific factors that influence these two patterns differently.

The first finding shows that the number of the total permissions for the period of one year before and the number for the one-year period during the pandemic differ by 46%. In this dataset, there are 50k records for 2019–2020 and 27k for 2020–2021. The second finding reinforces the first by estimating a similar proportion; in the first period, 8116 tech-related projects were recorded, while in the second period, 4679 were found. Table 2 illustrates a comparison of the change rate among Boston neighborhoods in the two periods. On average, the number of projects set up dropped by almost half. Its standard deviation is 0.09, which indicates that all neighborhoods had a declining trend. However, we could later determine what was driving that in each neighborhood. The range is vast, from 23% for the downtown neighborhood to 62% for Chinatown and the financial district. When we examine the frequency of the technological project, we observe a higher variance that could translate to a gap between areas of Boston, and we introduce this as the first step in technological resilience explorative research. The average change in technological projects is 41% less than the prior year, which is lower than the drop rate in the total projects. The standard deviation was 0.2 and the range is from 0.01 in Hyde Park to 0.94 in South End, showing a 0 to almost 100% spectrum. We then proposed a technological resilience measure (See Table 2 & Fig. 4) by subtracting the change rate of technological projects frequency from drop rates in all issued permits frequency.

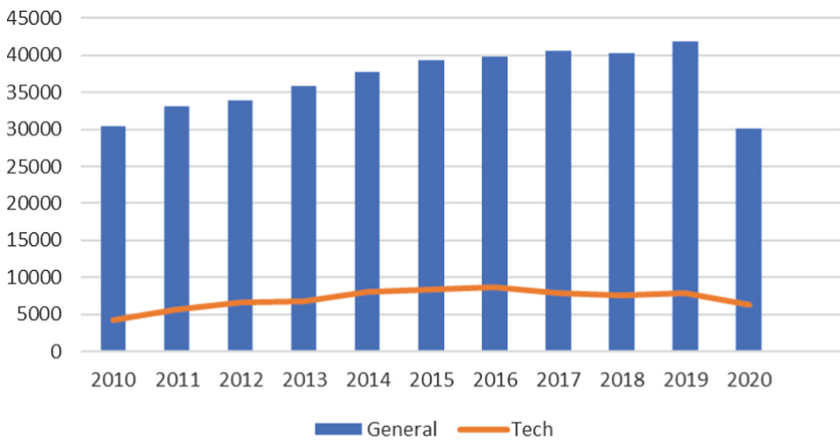


Fig. 3. Number of permits issued by the City of Boston from 2010 to 2020.

Table 2. Boston's Neighborhoods and tech-related building permits change pre and during the pandemic.

Neighbourhood	Number of all projects			Number of Tech-related projects			Proposed Technological Resiliency Measure
	Pre-pandemic	During Pandemic	Change rate	Pre-pandemic	During pandemic	Change Rate	
1 Allston	836	477	0.43	118	91	0.23	0.2
2 Back Bay	3354	1486	0.56	798	321	0.6	-0.04
3 Beacon Hill	976	409	0.58	210	88	0.58	0
4 Brighton	1776	1039	0.41	262	152	0.42	-0.01
5 Charlestown	1522	753	0.51	151	76	0.5	0.01
6 Chinatown	1114	418	0.62	228	91	0.6	0.02
7 Dorchester	5446	3301	0.39	761	528	0.31	0.08
8 Downtown	844	647	0.23	214	167	0.22	0.01
9 East Boston	2416	1341	0.44	390	209	0.46	-0.02
10 Fen-way_Kenmore	3117	1580	0.49	812	383	0.53	-0.04
11 Hyde Park	1636	1157	0.29	269	249	0.07	0.22
12 Jamaica Plain	2404	1196	0.5	317	157	0.5	0
13 Mattapan	1416	912	0.36	244	223	0.09	0.27
14 Mid_dorchester	1144	635	0.44	171	113	0.34	0.1
15 Mission Hill	528	300	0.43	102	50	0.51	-0.08
16 North End	398	203	0.49	59	25	0.58	-0.09
17 Roslindale	1946	1069	0.45	242	125	0.48	-0.03
18 Roxbury	3258	1971	0.4	470	307	0.35	0.05
19 South Boston	3752	2065	0.45	652	386	0.41	0.04
20 South End	67	35	0.48	18	1	0.94	-0.46
21 West End	1815	771	0.58	481	218	0.55	0.03
22 West Roxbury	1854	1147	0.38	177	143	0.19	0.19
23 Wharf District	1527	561	0.63	390	148	0.62	0.01

Interestingly, we can observe a polarization of values with negative and positive values. There was a more significant trend in technology-related projects than in the rest of categories. The frequency of 12 neighborhood tech projects did not decrease as significantly as the rest of neighborhoods. The resilience measure we proposed showed negative values in 8 neighborhoods (Fig. 5), but they are relatively minor when compared with the negative rate in South End, which is -0.46 . Beacon Hill, Jamaica Plain, and the

Wharf District, however showed no signs of any deterioration or improvement during the pandemic.

Having said that, South End, North End, Mission Hill, Fenway-Kenmore, Back Bay, Roslindale, East Boston, and Brighton hold a negative value, sorted in ascending order. As mentioned before, since the decrease rate in tech-related projects is higher than other categories, this indicates that technological domains were more valuable during the shock. Alternatively, we have a list of neighborhoods, including Mattapan, Hyde Park, Allston, West Roxbury, Dorchester, mid-Dorchester, Roxbury, South Boston, China Town, Downtown, and Charlestown showing a positive value. This group of neighborhoods was more resilient to the pandemic shock in a way that minimized the stagnation that would have affected their technological behavior.



Fig. 4. Technological Resilience Measure.

After describing the first layer of this analysis, we created the measure of the amount of investment per house unit based on the number of occupied houses. As discussed earlier in the methodology, a 100 USD per house unit was selected. Table 3 indicates the rate of investment evolution on tech-related projects before and during the pandemic.

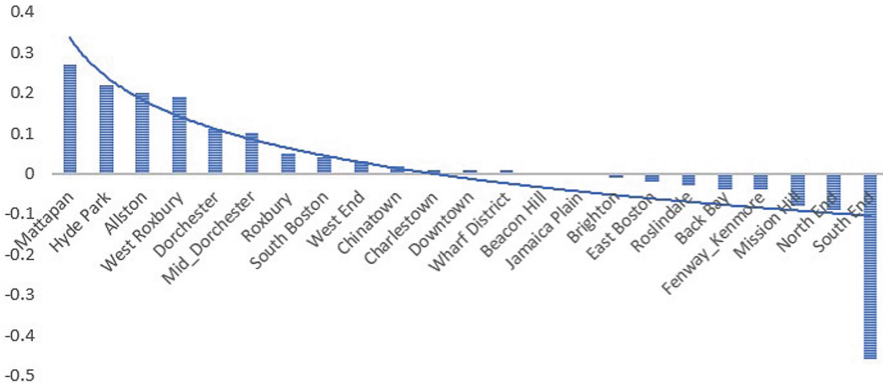


Fig. 5. Technological Resilience Measure

Results show two neighborhoods with higher investments, Mattapan, and Allston, 8 and 4% increase, respectively. In the other 21 neighborhoods, however, the situation is different (see Fig. 6). As a result of the pandemic, the budget was reduced by 3 to 100% through different neighborhoods compared to the pre-pandemic year. West Roxbury, Mid-Dorchester, and Hyde Park showed around roughly 5% reduction of investment. South End, Wharf District, and Chinatown show the lowest expenses compared to the rest of the neighborhoods with 100, 68, and 62% decline, respectively.

Before the pandemic, we see that Wharf District, Chinatown, West End, Fenway Kenmore, and Back Bay were the neighborhoods with the highest investment, while during the pandemic, few changes in this order are observed. West End becomes the neighborhood with the highest number of green tech investments, followed by Wharf District, Fenway Kenmore, Chinatown, and Back Bay. However, the declines in preferences for investment in technology projects has varied among different groups of neighbourhoods and it could be interpreted due to context-specific factors that we will be explaining in the following paragraphs.

First, we retrieved the City of Boston maps based on some socio-economic factors and aligned them to our work (Figs. 7, 8, 9, 10, 11 and 12) to see any spatial concentration and to try to see if these factors could be the reasons behind our results. Surprisingly, Fig. 9 shows how the highest “vacant unit ratio” neighborhoods are concentrated in the Boston center area. Figure 8 shows the poverty rate and that Fenway, Kenmore, Mission Hills, Roxbury, and Dorchester are the highest in Boston. Then, we focused on a number of variables that could have an impact on the neighbourhoods’ investments. The variables that are included in the analysis are vacant units’ ratio, white people’s ratio, median age, master’s degree ratio, graduation ratio per capita, income, poverty rate, population, and the number of families.

All in all, running an iterative multivariate regression helps interpret Table 3, which describes why investment criteria vary among neighborhoods. Table 4 is a merged index that shows how the model works by comparing the so-called “100 USD per House” expenditure on tech-related projects.

Table 3. Investments in tech-related projects in Boston’s neighborhoods and their change rate.

	Neighbourhood	Pre-pandemic 100 USD per House	During-pandemic 100 USD per House	Change rate
1	Allston	0.95	0.99	0.04
2	Back Bay	8.69	5.28	-0.39
3	Beacon Hill	5.24	2.59	-0.51
4	Brighton	1.02	0.85	-0.17
5	Charlestown	1.25	0.64	-0.49
6	Chinatown	14.34	5.4	-0.62
7	Dorchester	1.58	1.48	-0.06
8	Downtown	6.37	3.74	-0.41
9	East Boston	2.06	1.13	-0.45
10	Fenway_Kenmore	11.81	5.59	-0.53
11	Hyde Park	2.4	2.27	-0.05
12	Jamaica Plain	1.35	0.92	-0.32
13	Mattapan	2.55	2.76	0.08
14	Mid_dorchester	1.11	1.07	-0.04
15	Mission Hill	1.87	0.83	-0.56
16	North End	0.67	0.27	-0.6
17	Roslindale	2.07	0.92	-0.56
18	Roxbury	1.8	1.49	-0.17
19	South Boston	5.83	3.54	-0.39
20	South End	0.14	0	-1
21	West End	13.24	9.23	-0.3
22	West Roxbury	1.15	1.12	-0.03
23	Wharf District	24.92	7.85	-0.68

In the pre-pandemic period, the multivariate regression (MVR) model held an 82% R-squared which we can interpret as a relatively significant number of observations explained by this model. Considering that the significance F in the pre-pandemic period is 0.001, we are able to consider the model relevant to the proposed hypothesis. In this way, we are able to establish a meaningful relationship between the technological expenditure and the three pillars of indicators. The most significant coefficient is for the “vacant unit ratio” which is 81.755, which explains how neighborhoods with a larger ratio of isolated buildings have the propensity to invest in tech-related projects. There is a negative 27,150 correlation between poverty rate and investment, which indicates the reverse relationship between these socio-economic factors. While the number of families and median age have relevant P-values, the coefficients are relatively small. The model for pre-pandemic period is as follows:

$$Y = 81.755(\text{vacant units ratio}) + 0.6613(\text{median age}) - 27.65(\text{poverty rate}) - 0.003(\text{no. of families})$$

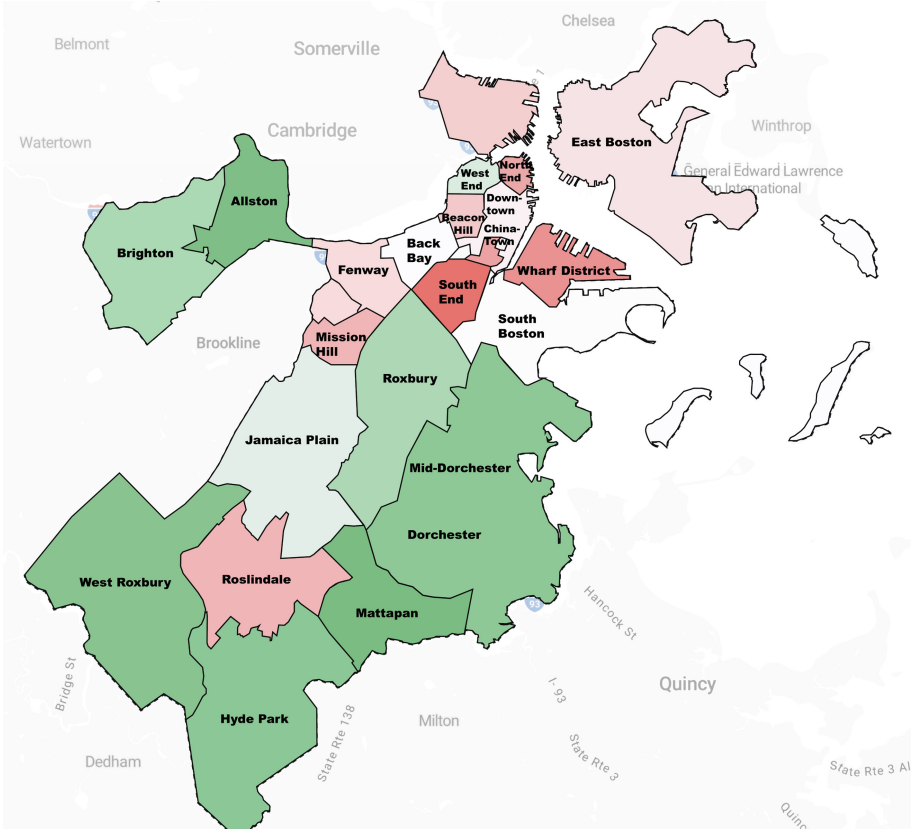


Fig. 6. Boston's Neighborhoods and Change Rate in Green Tech related investment

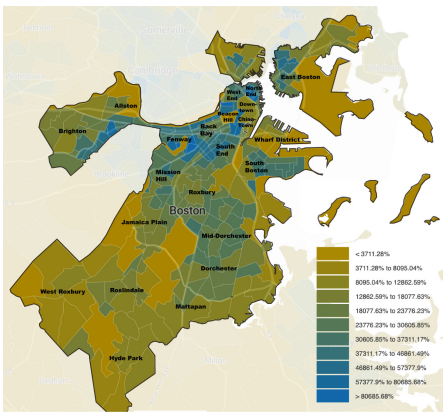


Fig. 7. Population Density

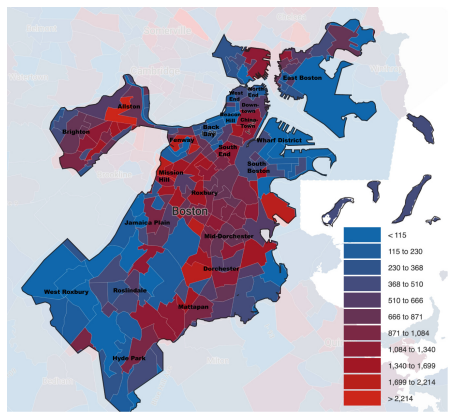


Fig. 8. Population in Poverty

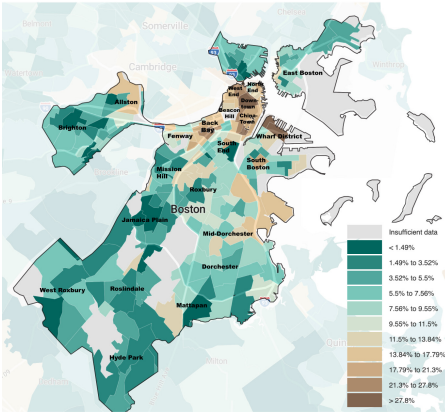


Fig. 9. Vacant Units

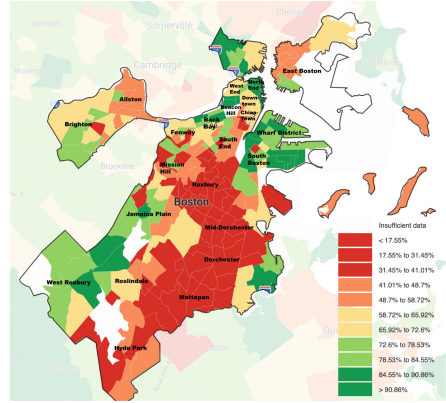


Fig. 10. White population

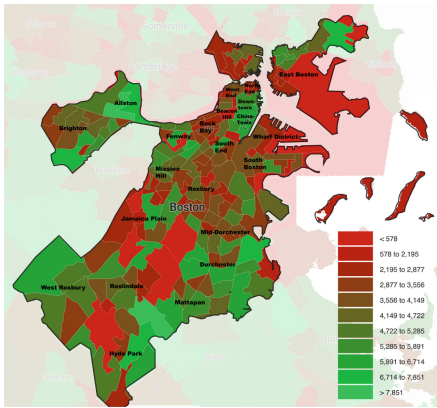


Fig. 11. Number of Families

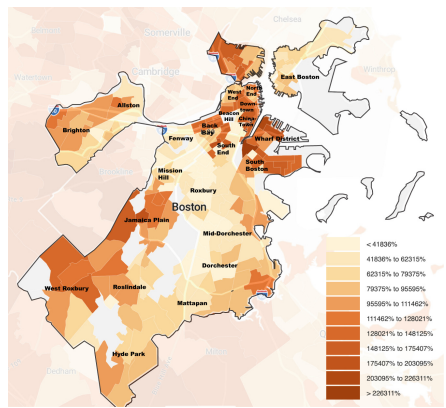


Fig. 12. Median Household Income

Next, we explore the post-pandemic period. We see that the R-squared and significance F are 67% and 0.033, respectively. On the one hand, we could observe the same model and relatively slight discrepancies in p-values, but the coefficients are formed differently. It is essential to shedding light on the proportion of coefficient formations in pre-pandemic and post-pandemic periods. For example, the falloff is more significant in the “Poverty rate” from -27.65 to -6.52 . Decreasing the share of the poverty-related recession could pave the way for new research on neighborhood clustering topics for understanding community-level programs that rendered this amount of resiliency. The model for during-pandemic period is as follows:

$$Y = 32.13(\text{vacant units ratio}) + 0.377(\text{median age}) - 6.526(\text{poverty rate}) - 0.001(\text{no. of families})$$

In the last step, we look at the variables of MVR under the lens of transmutation in investment between pre-pandemic and post-pandemic to find out the most influencing

Table 4. Regression Coefficients and P-values

	Pre-pandemic		During-pandemic		Change	
R Square	0.826146821		0.679134786		0.763318434	
Significance F	0.001086511		0.033345573		0.006418594	
	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>	<i>Coefficients</i>	<i>P-value</i>
Vacant Units Ratio	81.7552	0.0016*	32.1304	0.0157*	43.7726	0.0135*
White Ratio	-7.8836	0.1864	-4.0397	0.2241	-6.3106	0.1570
Median age	0.6613	0.0445*	0.3774	0.0398*	0.1683	0.0407*
Master’s degree ratio	-3.2727	0.5350	0.5240	0.8582	0.8115	0.8242
Graduate ratio	-12.6381	0.2671	-1.6336	0.7931	-11.3157	0.1963
Per capita Income	0.000003	0.9593	-0.000005	0.8903	0.000027	0.5980
Poverty rate	-27.6500	0.0490*	-6.5263	0.0466*	-17.5702	0.0406*
Population	0.0006	0.0088*	0.0002	0.0458*	0.0003	0.0401*
Number of Family	-0.0031	0.0046*	-0.0012	0.0319	-0.0016	0.0352**

variable in this before-after regression. At first glance, the same variables are considered significant but looking more in detail, we observed a more significant opposing footprint of poverty rate compared to post-pandemic analysis. Furthermore, we find out the “vacant unit ratio” is the most significant factor here, followed by the same pattern of median age & poverty rate. The change model is as follows:

$$Y = 43.772(\text{vacant units ratio}) + 0.168(\text{median age}) - 17.57(\text{poverty rate}) - 0.001(\text{no. of families})$$

While all neighbourhoods across Boston have dealt with navigating the challenges of the healthcare crisis, we clearly see that there are inequities in how different neighbourhoods were able to achieve their green transition vision. Our model suggests that city authorities will need to address the challenges of low-income communities achieving green transition with more targeted programs.

6 Conclusion

First, we observed clustering phenomena by neighborhood’s tendency on tech-related project continuation trend versus the permission of the general project requests among 23 Bostonian neighborhoods. This finding could reveal the disparity among districts in the same city regarding green transition. We tested this finding in the spatial context to perform an illustration of technological resilience mapping for policymakers.

Second, for neighborhood groups, we suggested a measure of “100 USD per unit of housing” spent on tech-related projects. In this way, we captured neighborhoods’ size,

population, and housing density patterns to find a uniform measure in comparing them. After drawing districts' behavior diagrams and their pre/post-pandemic observations, we noticed a pattern of transition among them; this leads us to conduct a model for this phenomenon. Finally, to allocate scalable weight to each independent factor, we ran an MVR model and discussed the findings above. Suggesting a model despite results guides us to characterize groups of variables; these suggested pillars of ingredients offer a perspective to qualitative research plans for conducting surveys within the suggested neighborhoods to enhance the pillars. We believe there is more room for investigating community-level priorities and opportunities due to the diversity of Boston. Exercising shock heat maps, known as resilience mapping, is a novel perspective in urban studies investigating the flexibility of communities facing acute turbulence.

Third, the final maps are created to call for more attention on structurally weak neighborhoods by policymakers and the communities to think again. The acute shock of the Pandemic enhanced the transition in structural change level. This phenomenon addresses the socioeconomic disparity at the local level. As a team of researchers, we believe the so-called post-carbon transition could be implemented locally. While this micro-scale is obliged to follow global programming structures, the ability to reveal inclusive shifts is a nexus between actors and places. Finally, we suggest spatial network analysis approach for the next steps of this research question on technological resilience assessment by benefiting from a relatively long panel data analysis of neighborhood behavior [36]. In this paper, we suggested an MVR Model test and demonstrated the hypothesis on the lack of inclusiveness of transition based on the spatial disparity between Bostonian neighborhoods. In this way, there were limitations on expanding the pillars to more flexible measures at the neighborhood level, which one can suggest as a novel perspective in big data for urban research.

7 Limitations of the Study

Surprisingly, looking at the model and pillars of the suggested variable, we could conclude that race, despite of long history of being addressed as a discrimination factor, has no significant effect on this transition model. However, one could claim "poverty rate" and "white race ratio" have a collateral relationship; we could not find any in this paper. Racial disparity is known as a risk factor in most American resilience plans. However, in the technological resilience domain, this could be addressed differently due to the reasonably uniform access to federal and local government funds on tech-related projects in the housing field. Although the highest R-squared is below 85%, this range's consistency allows us to generalize these findings as a call to map the city based on more research-based factors. Enduring a most significant variable pattern with expenditure (specifically on tech-related) layers on a dashboard could lead the policymakers to design an appropriate real-time and place-based plan for communities to prioritize actions.

Even if the differences in green technology investment didn't translate to ethnic and racial differences in our model. We understand that looking only on the white population ratio is a starting point for our study. In a future study, it would worth it focusing more on different ethnicities and races to explore how these can explain the neighbourhoods' tendency to invest in tech-related projects and ability to deal with green transition.

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Data Availability. <https://dataverse.harvard.edu>.

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