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Downscaling of the emissions related to energy usage in buildings

High spatial resolution to evaluate future decarbonization policies in the City of Boston

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Abstract

Large cities are responsible for considerable quantities of greenhouse gases and air pollutants released in the atmosphere. In particular, the City of Boston attributes 71% of the total community-wide greenhouse gases emissions to buildings energy activity. Thus, urban buildings greenhouse gases and air pollutants emissions modeling is essential for such large cities, and it is usually performed in literature via bottom-up approaches. However, these methods involve the gathering of significant amount of data, which is often limited by the availability of detailed information. This paper proposes an innovative downscaling methodology to estimate the city's buildings-specific energy consumption and related emissions at high spatial resolution; these estimates originate from national surveys and local data, and narrow down to the building level. The results are also forecasted in future scenarios of space heating electrification in buildings, covering the next 30 years, and visualized in 100 m x 100 m spatial cells grids to evaluate their efficacy on the city. The presented electrification measures allow significant emissions reductions and would considerably improve the city's air quality. Nevertheless, the carbon neutrality goal by 2050 might need additional policy implementation to be achieved, such as the electrification of water heating systems. The results are scrutinized and possible solutions that would lead to decarbonization are discussed. In addition, the methodology presented in this study can be applied to other cities, as it is only limited by the level of accuracy of the available data.

Keywords climate; downscaling; buildings; emissions; electrification

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1 Introduction

Global energy consumption has rapidly increased over the last decades, along with population growth and technological development. As global warming effects are becoming increasingly visible and undeniable, with extreme weather events and ruined ecosystems, energy consumption behavior inevitably needs to be modified. Climate change mitigation and adaptation require new methodologies to be experimented and implemented in urban greenhouse gases and pollutants modeling.

The United States of America are the second largest emitter of greenhouse gases (5.79 million kton in 2018) and one of the largest emitters per capita (17.74 ton/person in 2018) [1]. In 2017 the country withdrew its participation in the Paris Agreement, which unified two years before the European Union and 190 states towards climate change mitigation, adaptation and finance [2]; fortunately, in January 2021 the country announced the intention to bring back its contribution to the agreement [3]. Nevertheless, internal states have continued ever since to formulate independent policy plans and strategies to reach carbon neutrality by setting ambitious goals.

In particular, the State of Massachusetts has instituted the Clean Energy and Climate Plan for 2030 (2030 CECP) to reach 45% reduction in emissions as compared to 1990 baseline. This plan also describes the policies, strategies and actions that will increasingly lead the state to carbon neutrality according to the 2050 Decarbonization Roadmap [4]. This latter presents ambitious reactions to climate change mitigation to achieve Net Zero carbon emissions by 2050 [5]. It combines an effective series of strategies to reduce emissions, such as clean energy transition away from fossil fuels in buildings, vehicles and other end uses, increased energy efficiency, zero and low-carbon energy production, and carbon sequestration.

The City of Boston, the capital of Massachusetts, has actively responded to climate change by instituting city-wide climate action plans; in addition, it is part of the C40 cities initiative to act faster than the Paris Agreement [6]. The 2019 Climate Action Plan (CAP) leads the city towards carbon neutrality by 2050, and to 60% reduction in emissions by 2030 [7]. The plan is collected under 18 strategies, such as set specific net-zero standards for buildings, implementing biking and walking infrastructure, developing a building emissions performance standard, transportation demand management, zero-emissions vehicle deployment, clean energy investments, and energy efficiency improvement. According to the plan, the city is also intended to substitute coal and oil with natural gas and, finally, renewables; furthermore, Boston is committed to the Zero Waste initiative [8] to significantly reduce the city's waste production, and instead increase its recycling and reusing activity, improved also thanks also to the use of anaerobic digestors.

Boston's buildings account for 71% of the total community greenhouse gases emissions and represent the greatest opportunity to decarbonization. In order to reach the target, new constructions are needed to be built zero net carbon (ZNC) by 2030, and electrification and retrofitting strategies are essential for at least 80% of the existing buildings until 2050 [7]. Furthermore, to establish whether if a decarbonization pathway could be suitable to the city and which tools, actions and strategies this would implicate, it is relevant to model the current energy status of the city. In particular, energy consumption and related emissions modeling at the building level may be crucial. Usually in literature, two existing methods are adopted for this purpose: the bottom-up and top-down modeling approaches.

The bottom-up approach involves starting from a high level of detail to produce estimates on broader scales, both spatial and temporal. On the other hand, the top-down (or downscaling) procedure follows the opposite pathway, where coarser resolutions are managed to produce estimates at finer extent. Each of these methods has positive and negative aspects, and one could be favorable or not depending on the case study.

The aim of this study is to downscale the national and state greenhouse gases and pollutants emissions related to buildings' energy use to the Boston's buildings level to evaluate the effect of policies and climate change mitigation measures on each building of the city. In particular, the emissions estimates are produced for every commercial and residential building of Boston to reflect the current scenario and future electrification pathways.

The buildings' emissions estimates are represented in a 100 m x 100 m cells grid and large emitters are highlighted in the corresponding area of the city. Furthermore, detailed information on buildings, such as use class, building type, area and vintage, are preserved and are combined with the emission estimates. The current status of the buildings fleet is analyzed and future electrification measures are applied. The forecasted emissions are analyzed and questions on the feasibility of decarbonization by 2050 are discussed, together with possible further actions that may be necessary to reach the established target.

The results presented in this study can be useful for policymakers to support urban greenhouse gases modeling and air quality control. They also allow to locate with high spatial accuracy major contributors of emissions, in order to address proper decarbonization policies and to evaluate their efficacy. This work also highlights the need of active participation of multiple measures that synergistically contribute to achieve the set climate mitigation goals of the city.

2 Literature review

Urban greenhouse gases emissions modeling is often developed in literature via bottom-up or top-down approaches. The first involves the gathering of detailed data at finer spatial or temporal scale to constitute the final coarser scale, while the latter follows the opposite direction, ending in fine resolution. Both methodologies are reliable and well-established in literature, but their differences permit to choose one over the other depending on the case and on the available information or data.

Gurney et al. [9] applied the two methods to four US urban areas to estimate spatiotemporal urban fossil fuel carbon dioxide ($FFCO_2$) fluxes; the study highlighted that the difference between the two approaches was significant especially when estimating on-road $FFCO_2$ emissions and point sources. In fact, downscaling approaches to estimate emissions of greenhouse gases (GHG) and pollutants are effective at large scales, such as global or national scales, with relatively little effort, but the spatial proxies that they use can fail in certain applications; on the other hand, bottom-up approaches can be more accurate at finer spatial scales but require a large amount of data to be gathered and processed. Furthermore, the study revealed that an agreement between the two approaches can be found at 25 km^2 to 100 km^2 of spatial scale, and that this decreases for smaller emitting grid cells and increases for larger values.

Bottom-up approaches have been widely used in literature, due to their high yield at fine scales; however, as previously mentioned, data gathering is essential. The study conducted by Gately et al. [10] estimated on-road carbon dioxide emissions via a bottom-up approach, providing an on-road emission inventory product for the State of Massachusetts based on traffic data from the Highway Performance Monitoring System (HPMS). The CO_2 emission estimates were obtained on a 1 km grid for the years 1980-2008, combining average daily traffic volumes with the distribution of vehicle miles traveled of different vehicle types. The results were compared to the estimates produced by the Emissions Database for Global Atmospheric Research (EDGAR), the Vulcan Product and the Federal Highway Administration (FHWA). It was found that EDGAR estimates exceeded FHWA by 22.8% on average; furthermore, the HPMS model had a difference on agreement of 5% with Vulcan. However, the discrepancies may be influenced by a different fuel economy chosen for the vehicles over those years, or by the decision of using road density rather than traffic volume to account for emissions. The study also found that vehicle emissions per mile are directly correlated with population densities for values lower than 2000 persons per km^2, while they are negatively related for above values.

Many studies of the topic agree that there is still a significant lack of available information and of important and detailed data to be used for the purpose of accurate emissions modeling using bottom-up approaches. In fact, Quéré and Levasseur [11] highlighted the difference of both approaches for smart cities pollutants and GHG measurements. They found that traditional inventories lack of important and accurate data, such as the total amount of fuel used within cities. Thus, they highlighted a new top-down method, based on existing literature, such as the INFLUX project in

Indianapolis or a similar project in Paris, to “combine GHG sensor networks with atmospheric inverse modelling coupled with meteorological and chemical transport models” [11]. Furthermore, a new technology has been applied in Paris, the Greenhouse gas Laser Imaging Tomography Experiment (GreenLITE).

Moreover, top-down approaches are less sensitive to detailed data gathering and can result in fine resolution estimates. Indeed, Alam et al. [12] estimated road transport emissions in the Greater Dublin Area by downscaling national emissions to the street level. They applied two methods, one based on the road density and the other based on traffic volume data. Their estimates were developed by the Computer Programme for calculating Emissions from Road Traffic (COPERT) software and the national fleet was divided by vehicle categories and by fuel type, engine size and Euro emission technologies. The modelled traffic volume data were collected and used, together with geographical data from GIS (Geographical Information System). The emissions were assigned at the street level following the two methods, which were also compared against each other in a 0.5 x 0.5 km^2 grid cell. The study found that at a finer scale, emission distribution based on traffic volume was more appropriate, while the density-based distribution is suitable for urban area rather than suburban or rural areas since it is indifferent to low and high traffic zones.

Much literature focuses on estimating emissions from roads and vehicles, such as the study conducted by Mateo Pla et al. [13] for the city of Valencia. Their work developed a novel bottom-up approach based on Vehicle Kilometers Travelled (VKT) methods recognized by the Intergovernmental Panel on Climate Change (IPCC); their model could be applied to other cities. Indeed, road traffic emissions are significant, especially for large cities, but it is also important for a city like Boston to control energy consumption and emissions from buildings since they account for the majority of the total community greenhouse emissions, as previously described [7].

Detailed building-level energy consumption estimates are more frequently performed via bottom-up approaches in literature. For example, Davila et al. [14] investigated the generation and execution of a citywide urban building energy model (UBEM) for the city of Boston, based on official GIS datasets and a custom building-archetype library. The model was first built into the Rhinoceros 3D CAD environment and afterwards completed by EnergyPlus simulation program. Where data were not available, such as occupant behaviors, a stochastic approach has been used. The model was successful, demonstrating how it may influence local planning and energy policy decisions. However, the authors highlight that there is still a need of further access to detailed information necessary for an accurate model and of faster data conversion and mapping procedures.

Detailed energy use data and other important buildings information were made available for the Carbon Free Boston report, commissioned by the City of Boston. In fact, this study, performed by Hatchadorian et al. [15], evaluated the influence of different policies to reduce energy usage, increase electrification and design performance targets across the city of Boston. They grouped buildings depending on use classes and vintages, and they used a building energy modeling (BEM); their model is built on detailed building-level analysis since they received metered data from the City of Boston and from the operating providers of energy for the city. They found that the decarbonization target of the city necessarily requires a large percentage of buildings to be electrified and retrofitted. However, detailed open-to-public data is difficult to be found or is simply lacking. Thus, the bottom-up approach reveals its limitations in modeling buildings when relying on open data.

The solution could be found in the downscaling method. For example, San José et al. [16] modeled energy consumption of real buildings in the city of Madrid, under present and future climatic conditions through downscaling of regional, urban and computational fluid dynamics meteorological models to reflect the effects on buildings on a 50 meters scale. They found how significantly climate change will impact future energy demand of buildings, with both space heating and cooling expected to increase over a 90 years' time frame. However, in literature there is no record of a comprehensive and detailed downscaling of the energy consumption data and related emissions to the building level.

The aim of this study is to estimate greenhouse gases and air pollutants emissions at the building level for the city of Boston to properly address and evaluate climate change mitigation strategies. The chosen methodology is based on the downscaling procedure, which involves starting at broader spatial scale to allocate estimates at finer local scale.

3 Research material and methods

The main methodology for estimating emissions this study is based on is the top-down approach. In particular, proportional downscaling is preferred as it assumes that the bigger unit and the smaller unit proceed at the same growth rate, especially if changes are small or not enough information is available [19]. Current emissions and energy consumption rates are obtained from a proportional downscaling of national buildings estimates and are subsequently adjusted for the community of Boston based on the actual and most recent data available for this latter. The resulting estimates are forecasted in the future three decades via proportional downscaling of the scenario-related results that the GLIMPSE/GCAM-USA model produced for the State of Massachusetts; it has been assumed that the same growth rates for the state and the city would apply.

The GLIMPSE (GCAM-based Long-term Interactive Multi-Pollutant Scenario Evaluator) decision support tool, developed by the U.S. Environmental Protection Agency (EPA), allows to compute the efficacy of different policies and factors on national-, regional- and state-level air quality management, which is directly reflected on energy systems, agriculture, land use and atmosphere evolutions [20]. The tool, based on the pre-existing GCAM-USA (Global Change Assessment Model for the United Stated of America) integrated assessment model, generated a wide prospective of air quality in future scenarios at national and state level, influenced by different technologies and sectors.

In particular, for the purpose of this study, different building energy system technologies for both commercial and residential sectors for the state of Massachusetts have been computed by the tool to reflect two scenarios: Business As Usual (BAU) and Building Electrification in 2025, 2030 and 2035. The BAU scenario assumes that no policy is implemented, and the same regulations and restrictions that the State is applying see no development in the future; on the other hand, the electrification scenarios state that the sales share of electrified space heating technologies in buildings should achieve 100% by 2025/2030/2050. Furthermore, the projections start in year 2010 and end in 2050 with a 5-year interval increment. The tool modeled space heating electrification technologies as a balanced mix between heat pumps and electric furnaces in commercial buildings throughout the years, while it expected heat pumps to gradually substitute the other technologies, even electric boilers, in households.

Current community-wide and local governmental energy consumption data were first collected from sources open to the public and then forecasted accordingly to the GLIMPSE model, via proportional downscaling (section 3.1). Subsequently, detailed information of the Boston's buildings fleet, such as living area, parcel number, use class, vintage, and building type, was first collected from publicly available sources, arranged in a comprehensive inventory (section 3.2.1); thus, national energy consumption surveys were utilized to produce approximative energy usage estimates for each building, based on its specific characteristic (section 3.2.2). Afterwards, each building energy data was adjusted for and allocated to the community or institution of Boston based on the total community-wide and local governmental energy consumption data previously obtained (section 3.2.3). Lastly, greenhouse gases and pollutants emissions derived from the estimated energy usage for each building have been forecasted according to the GLIMPSE model based on the predicted activity in the modeled scenarios (section 3.2.4). An exhaustive schematic of the downscaling methodology developed in this study can be found in Figure 1, which presents also the combination between national and state-level data with city-level information that allowed to estimate and forecast Boston's building-by-building energy consumptions and related emissions.

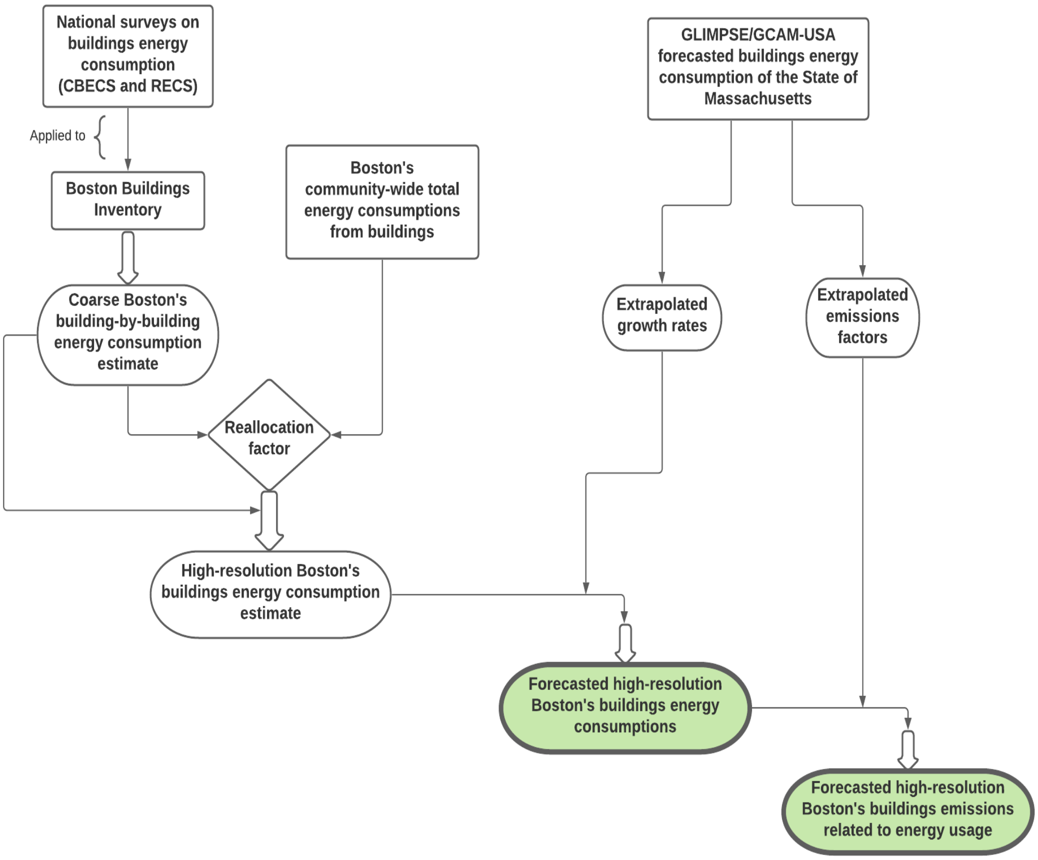

Figure 1 Downscaling methodology to estimate and forecast Boston's buildings energy consumptions and related emissions.

3.1 Greenhouse gases emissions from Boston's buildings fleet

The procedure to estimate building-level energy consumptions started at local scale, with the collection of current data related to the city of Boston. The Boston's government publishes every year the greenhouse gas emissions inventory for the city, divided into local government and community-wide operations, and open to the public [21]. The annual emissions are collected from year 2005 to 2018, and the database is the result of direct data extrapolation and estimates, ranging from city records, utility company reports and information from state and federal agencies.

The community greenhouse gas emissions inventory follows the Global Protocol for Community-Scale Greenhouse Gas Emissions Inventories (GPC), as stated by the Global Covenant of Mayors (GCoM) signed by the city in 2015 [22]. The protocol, developed by the World Resources Institute, C40 Cities, and ICLEI Local Governments for Sustainability, helps cities to monitor their greenhouse gases emissions to support and address standards, actions and targets to tackle climate change [23]. The inventory categorizes annual emissions based on the end-use sector (small residential, large residential/commercial/industrial, transportation, and waste) and source (electricity, natural gas, fuel oil, steam, and vehicle fuels).

Emissions are collected as Scope 1 or Scope 2: the first are directly emitted by the city's facilities, vehicles or other equipment through the burning of natural gas, fuel oil or vehicle fuels; the latter are indirect emissions released by facilities owned and operated by external parties, to produce electricity and steam that the City uses [22] (Figure 2). The emissions are calculated as the product between the activity data, obtained from a range of city records or energy providers information, and the emissions factor relative to the specific source or fuel.

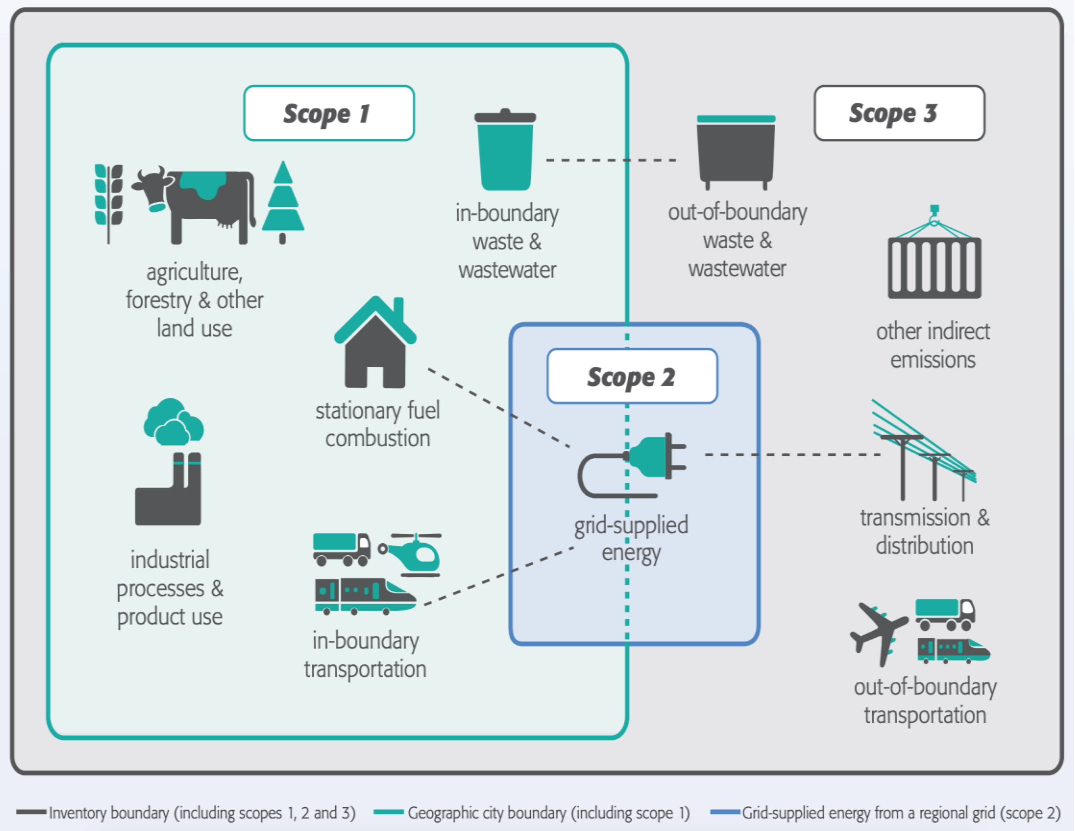

Figure 2 Greenhouse gas emissions inventory scope and boundaries definitions [21].

For the purpose of this study, the small residential category is considered as solely residential, and the large residential/commercial/industrial group as purely commercial; in fact, large residential are aggregated to the latter category only relatively to their natural gas consumption, since the energy provider did not account separately for it, so that there is no certainty on the quantity attributable directly to them. Transportation and waste are outside of this study's scope since not directly related to buildings activity. Industrial buildings are left out of the analysis since their energy consumption profile is more difficult to be accurately modeled, due to their differentiation of activity depending on the product the industry focuses on [24]. Steam and, in general, Scope 2 emissions are not included in the analysis since they involve more problematic modeling due to their dependance on various factors that are outside the city's boundary, for which insufficient data is provided.

The Local Government Operations inventory follows the global protocol for local governments operation developed by ICLEI Local Governments for Sustainability [22]; it reports greenhouse gases emissions produced by the public sector of the city, divided by department (Fire, Police, Public Schools, etc..), sector (buildings, streetlights, and vehicles), fuel (electricity, natural gas, fuel oil, steam, and vehicle fuels) and year. As for the community-wide inventory, only Scope 1 emissions were taken into consideration in this study, as directly related to buildings activity. Thus, all departments' emissions from buildings due to the use of natural gas and fuel oil were summed to form a comprehensive public sector, which has been grouped under the commercial category.

The forecasting methodology was based on a proportional downscaling from the GLIMPSE/GCAM-USA modeling results for Massachusetts' residential and commercial buildings. The results for year 2018, which corresponds to the most recent greenhouse gases emissions records for the community and the public buildings of Boston, were obtained via linear interpolation between the 2015 and 2020 results that the tool produced. Thus, year 2018 represented the baseline and forecasting began in 2020 until 2050 with a 5-year interval increment.

The GLIMPSE/GCAM-USA tool modeled energy consumptions of buildings for the commercial and residential sectors divided by fuel and based on the technology used. In addition, it denoted different sub-sectors as contributors in the final energy usage of a building. In fact, commercial buildings' consumptions come from cooking, cooling, heating, hot water, lighting, office, refrigeration, ventilation and other; every sub-sector is assigned with specific technologies, such as electric stoves, electric heat pump, gas furnace, or gas water heater. On the other hand, residential consumptions are produced by cooking, clothes dryers and washers, cooling, computers, dishwashers, freezers and refrigerators, hot water, lighting, television, and other. Their relative subsector is assigned to the corresponding technology as well.

The community-wide and local governmental greenhouse gas emissions obtained from the inventory have been first converted to energy consumptions, dividing these by the specific greenhouse gases emission factor that the EPA attributes to each fuel [25]. In fact, the emission factor for a fuel represents the amount of CO_2 equivalent emitted for each unit of energy consumed by an energy technology. Emissions are counted in kilograms of equivalent CO_2 that three harmful greenhouse gases represent: carbon dioxide (CO_2) with a Global Warming Potential (GWP) of 1, methane (CH_4) with a GWP of 25, and nitrous oxide (N_2O) with a GWP of 298. The Global Warming Potential is a measure that allows to compare different pollutants and indicates the amount of energy the emissions of 1 ton of a gas will absorb over a given period of time (100 years in this case) as compared with the emissions of 1 ton of carbon dioxide [26].

The emission factor for electricity is the most problematic to be measured due to the heterogeneous nature of electricity production; however, EPA attributes electricity factors to the regional grid, which in the case of Boston is the New England grid. Furthermore, the inventory does not report the type of fuel oil that emissions refer to; thus, Distillate Fuel Oil n.2 has been taken as suitable to the case, since it is merely a heating oil [27], and the city's usage of fuel oil is entirely attributable to heating purposes.

The community-wide and local governmental greenhouse gases emissions obtained for year 2018, aggregated by fuel and sector as previously described, have been forecasted via proportional downscaling of the State's projections from GLIMPSE/GCAM-USA results for each of these. Thus, the same growth rate that the tool modeled year by year for a specific sector, fuel and technology of Massachusetts has been applied to the City of Boston. For a given fuel (electricity, natural gas or fuel oil), the growth factor of the future year with respect to the starting year 2018 is obtained as follows:

$$Growth\ Factor_n = \frac{EC_n\ (EJ)}{EC_{2018}\ (EJ)} \qquad (1)$$

where n is the future year (2020, 2025, 2030, ..., 2050), and EC_n and EC_{2018} are respectively the energy consumptions for the given fuel in the future year n and in 2018 that the tool generated for the State under a specific scenario.

The State of Massachusetts' energy consumption predominantly relies on natural gas (0.466 EJ in 2019), electricity (0.345 EJ in 2019), and distillate fuel oil (0.163 EJ in 2019) [28]. Overall, renewable net electricity generation in the State accounted for 23% of the total in 2019, where solar power is the largest contributor, followed by hydropower, wind and biomass. Bioenergy use is only limited to the conversion of municipal solid waste and landfill gas; furthermore, the State has entirely phased-out from coal.

Moreover, the majority of Massachusetts' households still use predominantly fossil fuels for heating purposes, ranking the State higher than the U.S. average: more than half use natural gas, one in four fuel oil, and only one in six use electric heat. In fact, the mild summers and the cold winters have a significant impact on the heating consumption behavior of the population, which is most densely located near the Boston area. The chosen proportional downscaling methodologies assume that the State and the city proceed at the same decarbonization rate; as a matter of fact, they both share a decarbonization goal for 2050, which is the net-zero emissions target, and they share similar energy consumption behavior.

The stationary energy uses are responsible for 70% of total greenhouse gases emission of the entire city in 2018 (4.5 million ton CO_2e), where 51% (3.2 million ton CO_2e) is generated by commercial, industrial and large residential buildings, and the remaining 19% (1.2 million ton CO_2e) is emitted by small residential buildings [29]. Figure 3 shows the prevailing reliance of most of the city's buildings on electricity and natural gas for covering their energy demand, although new efficient equipment, such as heating pumps, have decreased the overall emissions during the last decade. In addition, the slow phasing out of fuel oil dependance has left space to natural gas acceleration as substitute for mainly heating purposes.

Natural gas has been preferred over refined oils or other gaseous fuels over the last years due to its significant lower environmental impact, together with lower and competitive costs and flexibility. Nevertheless, its deployment arises environmental threats related to methane leaks from the infrastructure. However, fuel oil has been kept as a back-up or demand-peaking fuel especially in large commercial and industrial buildings thanks to its ease of long-term storage capability [15].

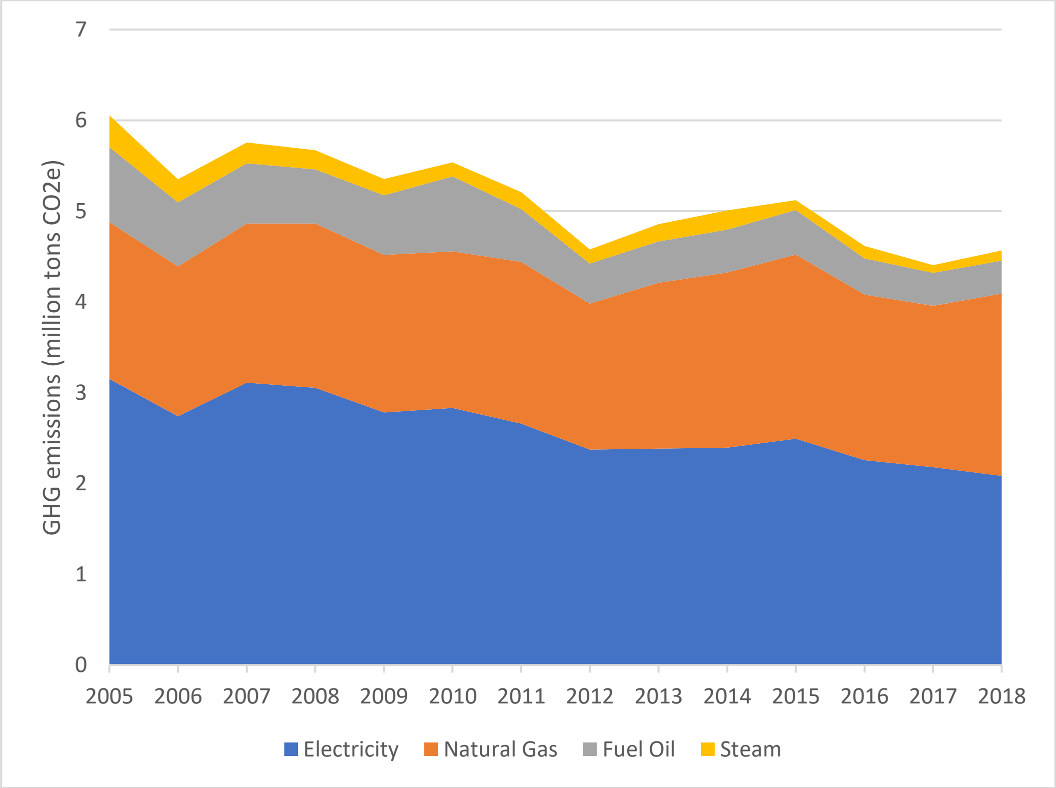

Figure 3 City-wide greenhouse gases emissions from buildings in 2005-2018 by fuel [21].

Electricity covers an important part of buildings demand, even though the electric grid of Boston is not already fully or significantly renewable; thus, the electricity usage could not currently guarantee net-zero emissions, since the electricity generation plants are still dependent on fossil fuels. In fact, electricity generation relies on a mix of natural gas, nuclear, coal, hydroelectric and other renewable sources, accounting for 21% of Massachusetts's total greenhouse gases emissions [22].

Steam is generated in dedicated plants and distributed throughout the city for heating purposes [22]. In addition, coal has been completely phased out by 2017 in Massachusetts, even if less than 0.1% of the State's households still relies on coal as primary heating fuel [28]; thus, the city does not recall any use of coal. The city's biomass use is only limited to conversion of solid waste to electricity in power plants [22], so greenhouse gases emissions related to biomass burning are included in the emissions factor for electricity. However, the state-level scenarios from GLIMPSE/GCAM-USA accounted for biomass use in buildings for heating purposes, which does not reflect the city's pattern; thus, biomass consumptions have been equally divided and added to the other three sources of energy, as if other heating technologies, such as electric, natural gas and fuel oil furnaces, had the same probability of substituting biomass furnaces.

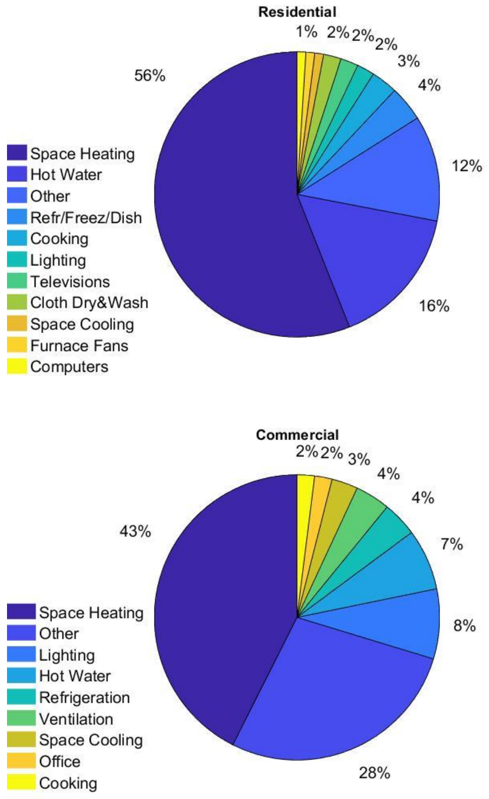

Figure 4 Residential and commercial buildings energy usage by technology share in 2018.

Space heating consumption takes the largest portion of energy use in buildings. It has been estimated that the average annual energy consumption for space heating in residential houses is 59% of the total household's in Massachusetts, which is a higher portion than the national estimate (41% in the U.S.) [30], due to the cooler climate region; moreover, commercial buildings space heating accounts for about 36% of their energy use [31]. The GLIMPSE/GCAM-USA tool estimated energy consumptions from commercial and residential buildings for Massachusetts divided by fuel and by technology used, based on current and accurate data. The shares that each technology records as contribution to the total energy use has been calculated from the tool results; thus, the same portions have been applied to the status of the City of Boston and proportionally forecasted according to the growth rates of the State.

The technological share status of buildings energy consumption of the city is presented in Figure 4. The tool estimated that the shares of space heating energy usage out of the total energy consumptions are 56% in residential and 43% in commercial buildings. Together, space heating and hot water usage take 72% of annual energy consumption in households, while cooling is less energy-consuming thanks both to the cold climate region in which Boston is located, with relatively mild summers and cold winters, and to the usage of electric cooling equipment. On the other hand, although commercial buildings are used to gas cooling during summers, space cooling takes only 3% of their energy use, while space heating and hot water altogether occupy 50% of the total. In fact, most of the remaining commercial buildings activity relies on electrical equipment, such as lighting, refrigeration, and ventilation.

The largest portion of energy usage in buildings is dedicated to space heating, which mostly relies on fossil fuels, such as natural gas and fuel oil. In addition, buildings are the most carbon-intensive sector in Boston [29]. Thus, the electrification of space heating technologies would accommodate a significant part of energy consumptions of the entire city.

3.2 Estimating and forecasting Boston's building-by-building greenhouse gases and air pollutant emissions

In order to accurately estimate building-level energy consumptions and related emissions, the complete database of buildings in Boston has been first collected; thus, national energy consumption surveys were downscaled and adjusted according to the local community-wide and institutional results previously obtained. The Boston's government updates every year the Boston Buildings Inventory, an open-to-public database that collects information on every building of the city [32]. The inventory is updated to fiscal year 2019 and is the result of the collection of different databases, such as Tax Assessor Data, Building Footprints and BERDO.

In particular, the BERDO (Building Energy Reporting Disclosure Ordinance) dataset collects high-detailed consumption information for buildings which, however, result in less than 2 thousand footprints registered [33]. In fact, the ordinance targets all non-residential buildings greater than 35 thousand square feet, residential buildings that are 35 thousand square feet or larger or have 35 or more units, and any parcel with multiple buildings that sum to 100 thousand square feet or 100 units; furthermore, it requires them to report their annual energy and water use to the city, starting in 2017 and continuing every year.

In total, the inventory provided 98931 buildings with detailed information, including building typology, use class, year built, living area, number of floors, number of units, and address. Furthermore, some buildings reported their heating system type and the total site energy with the corresponding percentages attributed to electricity and gas uses; however, only a significantly small part of the population reported this data, which was impossible to be effectively used for the purpose of this study. Thus, more accurate building-by-building energy consumption estimates were performed via a downscaling approach of national surveys, which started with a meticulous building classification as presented in the following section.

3.2.1 Boston buildings classification

To correctly estimate energy consumption of Boston's buildings, it was first essential to determine their typology, since different characteristics and end-uses correspond to various energy usage behaviors. The Boston Buildings Inventory reported the property code, which uniquely identifies an assessor name of a property [34]. This information was used to classify buildings and to attribute them to the correct end-use sector, residential or commercial.

In addition, the assessor name corresponding to unique property codes was crossed and compared with the definitions adopted by the U.S. Energy Information Administration (EIA) for the classification of commercial buildings in the United States [35]; in fact, commercial buildings in the inventory often lacked of proper classification, but this allowed to precisely determine the building typology and type for every record belonging to the commercial sector. On the other hand, the building type and typology reported in the inventory for residential buildings corresponded to unique assessor names, which allowed a more direct and simple identification. With these data organized, each building was assigned to the proper end-use sector, residential or commercial, and classified to the correct building type. Nevertheless, some property codes or assessor names were controversial since could not find a match with the EIA building type definitions, while others reported wrong assessor names corresponding to a single property code; thus, these have been classified according to the possible best fit.

In addition, other categories needed to be adjusted: public and quasi-public buildings fall under the commercial category, according to EIA's classification; industrial buildings were left out of the analysis, as well as vacant buildings or blank data. Furthermore, buildings without living area reported, or with single digit living area were neglected. In fact, the analysis could not have been performed without information on living area, and it was not possible to extrapolate this from other data, such as land area, although this latter was reported; in total, more than 14 thousand records were left out of the analysis due to lack of this data.

Table 1 Boston buildings classification under analysis, based on the Boston Buildings Inventory.

	Building type	**Number of buildings**
Commercial	Public Assembly	255
	Public Order & Safety	49
	Lodging	104
	Other	1401
	Office	1505
	Health Care - Inpatient	92
	Health Care - Outpatient	11
	Mercantile - Enclosed and Strip Malls	6
	Mercantile - Retail Other Than Mall	1165
	Food Service	303
	Education	501
	Food Sales	29
	Warehouse and Storage	772
	Religious Worship	166
	Service	124
Residential	Single-Family	30601
	Multi-Family	45236
	Mixed-Use	1674

Moreover, some properties did not report their number of floors, and these were assumed to consist of one floor only; in fact, due to the relatively low difference between EUI for one floor and for bigger floors, this should have a small impact on estimates. Finally, mixed-use buildings were assumed to dedicate half of their living area for commercial purposes and half for residential purposes, since the exact space share was not specified.

The total population of buildings that was analyzed is presented and classified in Table 1. In total, 83994 buildings formed the population under analysis, 6483 of which were commercial (including 2307 public) and 77511 were residential (including 1674 mixed-use). The population of buildings has been organized in an inventory, preserving their useful information; in addition, every record has been provided with its relative estimated energy consumption and greenhouse gases and air pollutant emissions, as presented in the following section. The comprehensive classification of buildings, where property codes and assessor names were directly attributed to building typology, can be found in Appendix 1.

3.2.2 Boston buildings energy consumption estimate

The energy-related consumptions and emissions for the identified population of buildings has been estimated based on the energy use intensities (EUI) provided by EIA's consumption surveys for the commercial and residential sectors, the Commercial Buildings Energy Consumption Survey (CBECS), and the Residential Energy Consumption Survey (RECS). These surveys are the result of national samples collecting information of the stock of commercial and residential buildings in the United States, including their energy-related characteristics and energy usage data. For the purpose of this study, the most recently published surveys were utilized, which are 2012 CBECS [31] and 2015 RECS [30]. In particular, tables E4 and E7 from 2012 CBECS were used to estimate respectively commercial electricity and natural gas consumptions, while tables CE1.2 and CE4.2 from 2015 RECS for residential consumptions.

3.2.2.1 Commercial buildings energy consumption estimate

The CBECS identifies multiple categories and factors that have influence on commercial buildings energy consumptions. In this study, six categories were selected, as the most compatible with the extent of the available data: building floorspace, principal building activity, year of construction, census region and division, climate region and number of floors. Two categories, census region and climate region, were fixed to, respectively, "New England" and "cold", while the remaining four were linked to an embedded "IF" statement which assigned the right EUI depending on the belonging characteristic of the building.

The six EUIs provided by the survey, one for each category, were aggregated into a single EUI for each building; different weights were attributed to the six EUIs, depending on the influence that the representing category could have on the population of buildings. Walker [36] attributed more importance on the building type, with half of the weight, and adjusted the other five categories' weights based on the assumed impacts on energy intensity. The weighted average resulted in a single EUI, which was multiplied by the living area of the building to provide the total energy consumption value of the building for each fuel type as follows:

$$\begin{aligned} C_{el} = A_{living} \times \big[&\left(EUI_{sq}^{el} \times 0.12\right) + \left(EUI_{t}^{el} \times 0.5\right) \\ &+ \left(EUI_{v}^{el} \times 0.12\right) + \left(EUI_{r}^{el} \times 0.07\right) \\ &+ \left(EUI_{c}^{el} \times 0.07\right) + \left(EUI_{fl}^{el} \times 0.12\right) \big] \end{aligned} \tag{2}$$

$$\begin{aligned} C_{ng} = A_{living} \times \big[&\left(EUI_{sq}^{ng} \times 0.12\right) + \left(EUI_{t}^{ng} \times 0.5\right) \\ &+ \left(EUI_{v}^{ng} \times 0.12\right) + \left(EUI_{r}^{ng} \times 0.07\right) \\ &+ \left(EUI_{c}^{ng} \times 0.07\right) + \left(EUI_{fl}^{ng} \times 0.12\right) \big] \end{aligned} \tag{3}$$

where C_{el} and C_{ng} (kWh) are respectively the total electricity and natural gas consumptions per building, A_{living} (m^2) is the building living area, and EUI_{sq}, $EUI_t, EUI_v, EUI_r, EUI_c, EUI_{fl}$ $(\frac{kWh}{m^2})$ are the energy use intensities for electricity (el) and natural gas (ng) related to building floorspace (sq), principal building activity (t), year of construction (v), census region and division (r), climate region (c) and number of floors (fl).

Fuel oil consumption of commercial buildings has not been accounted for in this study. In fact, these buildings are more likely to use fuel oil as a back-up or demand-peaking fuel [15]; furthermore, fuel oil furnaces are already being substituted with natural gas furnaces in the city. Thus, commercial fuel oil consumption has been considered negligible.

3.2.2.2 Residential buildings energy consumption estimate

The RECS provided EUIs related to the total site energy consumption (Table CE1.2 [30]) and reported the annual site energy consumption from different sources of energy, divided by end-use (Table CE4.2 [30]). Furthermore, it identifies multiple categories and factors that influence residential buildings consumptions; six of these were chosen as the most relevant and compatible with the data available for this study: census division (New England), census urban classification, climate region (cold), housing unit type, year of construction, and total square footage.

In order to extrapolate the category specific consumption for electricity, natural gas and fuel oil usage, first the total site energy consumption has been calculated from the EUIs presented in Table CE1.2 of the survey. An "IF" statement allowed to assign the right EUI based on the characteristic of the building that fell under the right category. As for commercial buildings, the six EUIs were collected into a single one, giving them different weights on the basis of the potential influence a category could have on a residential building energy consumption. Walker [36] attributed half of the importance on the number of units and adjusted the remaining weights for the other categories. The resulted weighted EUI was finally multiplied by the living area of the building to obtain the total energy consumption of the buildings, as follows:

$$\begin{aligned} C_{tot} = A_{living} \times [\ & (EUI_{sq}^{tot} \times 0.12) + (EUI_{nu}^{tot} \times 0.5) \\ + \ & (EUI_{v}^{tot} \times 0.12) + (EUI_{r}^{tot} \times 0.07) \\ + \ & (EUI_{c}^{tot} \times 0.07) + (EUI_{ur}^{tot} \times 0.12)\ ] \end{aligned} \tag{4}$$

where C_{tot} is the Total Site Energy Consumption (kWh) , A_{living} (m^2) is the building living area, and EUI_{sq}^{tot}, $EUI_{t}^{tot}, EUI_{v}^{tot}, EUI_{r}^{tot}, EUI_{c}^{tot}, EUI_{fl}^{tot}$ ($\frac{kWh}{m^2}$) are the energy use intensities related to building floorspace (sq), number of units (nu), year of construction (v), census division (r), climate region (c) and census urban classification (ur).

The calculated total site energy consumption was then divided into electricity, natural gas and fuel oil consumption. Each consumption factor related to these fuels was obtained and calculated from Table CE4.2 of the survey; again, an "IF" statement allowed to assign the right factor based on the characteristic of the building. Furthermore, the same weights of equation 4 have been applied to these factors. Thus, the weighted average of the collected factors was multiplied by the previously obtained total site energy consumption as follows:

$$\begin{aligned} C_{el} = C_{tot} \times \ & [(F_{sq}^{el} \times 0.12) + (F_{nu}^{el} \times 0.5) + (F_{v}^{el} \times 0.12) \\ & + (F_{r}^{el} \times 0.07) + (F_{c}^{el} \times 0.07) + (F_{ur}^{el} \times 0.12)] \end{aligned} \tag{5}$$

$$\begin{aligned} C_{ng} = C_{tot} \times \ & [(F_{sq}^{ng} \times 0.12) + (F_{nu}^{ng} \times 0.5) + (F_{v}^{ng} \times 0.12) \\ & + (F_{r}^{ng} \times 0.07) + (F_{c}^{ng} \times 0.07) + (F_{ur}^{ng} \times 0.12)] \end{aligned} \tag{6}$$

$$\begin{aligned} C_{fo} = C_{tot} \times \ & [(F_{sq}^{fo} \times 0.12) + (F_{nu}^{fo} \times 0.5) + (F_{v}^{fo} \times 0.12) \\ & + (F_{r}^{fo} \times 0.07) + (F_{c}^{fo} \times 0.07) + (F_{ur}^{fo} \times 0.12)] \end{aligned} \tag{7}$$

where C_{el} , C_{ng} , and C_{fo} are respectively the total electricity, natural gas and fuel oil consumptions (kWh), C_{tot} is the Total Site Energy Consumption (kWh), and F_{sq}, F_{nu}, F_v, F_r, F_c, F_{ur} are the fractions of electricity (el), natural gas (ng) and fuel oil (fo) usage related to building floorspace (sq), number of units (nu), year of construction (v), census division (r), climate region (c) and census urban classification (ur).

3.2.2.3 Mixed-use and public buildings energy consumption estimate

As previously mentioned, mixed-used buildings were assumed to dedicate half of their living area to residential purposes and the other half to commercial, since no detailed information on the distribution of the mixed-space was reported in the inventory. Thus, half of the living area was used to estimate the commercial consumptions, following the procedure for commercial buildings illustrated in section 3.2.2.1; the other half was inserted in the equations for residential consumption estimation, presented in section 3.2.2.2.

Public buildings are aggregated in the commercial category according to the EIA's commercial buildings classification; their building type, assessor name and property code were useful for this purpose. Thus, their energy consumption estimation followed the procedure presented in section 3.2.2.1.

3.2.3 Energy consumption adjustment

The energy consumption estimates for commercial and residential buildings in Boston were based on a top-down approach that originated from surveys conducted at the United States national level, which reported a latest version dated 2012 (CBECS) and 2015 (RECS). In order to adjust both the spatial scale to the city level and the temporal scale to a more recent one, each evaluation has been corrected of a factor that relates these with the calculated community and institutional energy consumption data of the City of Boston in 2018 (section 3.1). In fact, the total GHG emissions in 2018 from residential, commercial and public sectors were aggregated and converted into energy consumptions given the emission factor of each fuel or source of energy (electricity, natural gas and fuel oil). These totals were divided by the respective calculated totals of the estimated population of buildings, aggregated in residential, commercial and public sectors, and divided by fuel, to obtain the factor of reallocation as follows:

$$RF_{commercial}^{el,ng} = \frac{Etot_{commercial}^{el,ng}}{Ctot_{commercial}^{el,ng}} \tag{8}$$

$$RF_{residential}^{el,ng,fo} = \frac{Etot_{residential}^{el,ng,fo}}{Ctot_{residential}^{el,ng,fo}} \tag{9}$$

$$RF_{public}^{el,ng} = \frac{Etot_{public}^{el,ng}}{Ctot_{public}^{el,ng}} \tag{10}$$

where $RF^{el,ng,fo}$is the reallocation factor, $Etot^{el,ng}$ is the calculated energy consumptions from the greenhouse gases emissions inventory for community and institutional buildings, and $Ctot^{el,ng}$ is the sum of all the building-by-building energy consumption estimate, respectively from for electricity (el), natural gas (ng) and fuel oil (fo) consumptions. Finally, each building energy consumption estimate has been multiplied by this factor, to be spatially and temporally reallocated.

3.2.4 Emissions estimate

The resulted energy consumption estimate for each building in Boston was converted into emissions of different harmful air pollutants. The consumptions for heating and cooling purposes were first obtained from the calculated fractions of these with respect to the total consumptions of the commercial and residential buildings at the state level, generated by the GLIMPSE/GCAM-USA tool for 2018. Thus, the same fractions were applied to the City of Boston's buildings, assuming neglectable differences between the State's and the city's heating and cooling behaviors in buildings.

The tool also provided a technology-specific emission factor for each fuel and pollutant. In fact, the GLIMPSE tool modeled future emissions and health impacts from a range of hazardous air pollutants: ozone precursor gases, such as carbon monoxide (CO), nitrogen oxides (NO_x), and non-methane volatile organic compounds (NMVOC); acidifying gases, such as ammonia (NH_3), nitrogen oxides (NOx), and sulfur dioxide (SO_2); primary particulates, such as fine particulate matter (PM_{10} and $PM_{2.5}$) and carbonaceous speciation, such as black carbon (BC) and organic carbon (OC); greenhouse gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ozone (O_3) and water vapor (H_2O), all computed under CO_2 in correlation with their respective global warming potential. The emissions factors that the tool provided for these air pollutants are collected in Table 2.

Table 2 Pollutants emissions factors from GLIMPSE/GCAM-USA, related to space heating and cooling fossil fuels technologies in buildings.

	COMMERCIAL		RESIDENTIAL		
	Natural Gas Heating	Natural Gas Cooling	Natural Gas Heating	Fuel Oil Heating	
BC	0.000439	0.000439	0.0000443	0.00247	(g/kWh)
CO	0.146	0.146	0.0688	0.0446	(g/kWh)
NH3	0.00100	0.00100	0.0325	0.00889	(g/kWh)
NMVOC	0.0112	0.0112	0.00943	0.00634	(g/kWh)
NOx	0.175	0.175	0.166	0.160	(g/kWh)
OC	0.00364	0.00364	0.000371	0.00190	(g/kWh)
PM10	0.00860	0.0086	0.000893	0.0212	(g/kWh)
PM2.5	0.00731	0.00731	0.000738	0.0190	(g/kWh)
SO2	0.00308	0.00308	0.00103	0.378	(g/kWh)
CO2	0.184	0.184	0.184	0.259	(kg/kWh)

Air pollutants are strictly related to the combustion of fossil fuels and are harmful for both human health and the environment, as their cause a severe variety of respiratory illnesses and other health problems. Carbon monoxide, nitrogen oxides and non-methane volatile organic compounds are involved in a series of chemical reactions that produce ozone; this is normally present in the stratosphere, where it filters dangerous sun's ultraviolet radiation, but ground levels of it attack lungs tissues when inhaled [37]. Furthermore, carbon monoxide inhalation at high concentration causes deficit of oxygen in human tissues and blood, known as hypoxia, which causes confusion, unconsciousness and death [38]. Ammonia, nitrogen oxides and sulfur dioxides cause respiratory illness, smog and acid rains, which destroy ecosystems and vegetation [39]. Particulate matter is the result of chemical reaction between other pollutants, such as carbonaceous speciation, and its fine inhalable particles affect the respiratory system and cause smog [40].

Greenhouse gases are severely dangerous for the environment, as they are the precursors of global warming, which leads to irreversible impacts on the natural habitats. They trap the heat in the atmosphere, causing increased temperatures that lead to imbalances in ecosystems and in weather, resulting in destroyed habitats and extreme climate events. The primary greenhouse gas released in the atmosphere due to human activity is carbon dioxide [41].

3.4 ArcGIS modeling

The detailed energy consumptions and emissions estimate for each building in the City of Boston has been inserted and computed in ArcGIS software, to produce a long-term emission map under different scenarios. This software uses a geographic information system (GIS) to interactively create queries and maps, in Earth-based, spatial-temporal references [37]. The buildings inventory with the calculated energy consumptions and related emissions has been matched with the Boston's buildings shapefile to produce a detailed emissions map for the city.

The City of Boston's government provided an online, open-to-public 2D shapefile of all buildings in the city, for a total of over 121 thousand records [38]. To assign a shape polygon to each building of the emission estimates inventory, this latter was joined with the city shapefile based on the parcel number of the building. However, the polygons reported insufficient or wrong parcel numbers for a significant part of the records; thus, the Boston buildings emissions estimate file was crossed and separately matched also with the Live Street Address Management (SAM) inventory [39], which provided the required information along with addresses, zip code and building ID. The joining procedure was based on the parcel number, which attributed to the missing records the building ID; this latter was finally used as joining base to merge the estimate file with the city shapefile, together into a single one.

Nevertheless, the joining procedure left out of the analysis over 3 thousand buildings which could not find a match neither with the Boston buildings or with the SAM shapefiles, leaving over 39 thousand shapes without consumption and emissions information. The explanation for a large number of buildings included in the shapefile (over 121 thousand) but not in the original Boston buildings inventory (over 98 thousand) may lie in the inclusion of double or multiple polygons for a single parcel and of garages or similar structures that are not properly considered buildings in the inventory. Furthermore, this study neglected industrial buildings, which, however, do not cover a major part of the city. In total, over 80 thousand buildings constituted the population under analysis, for which energy consumptions and air pollutants emissions were computed in ArcGIS software.

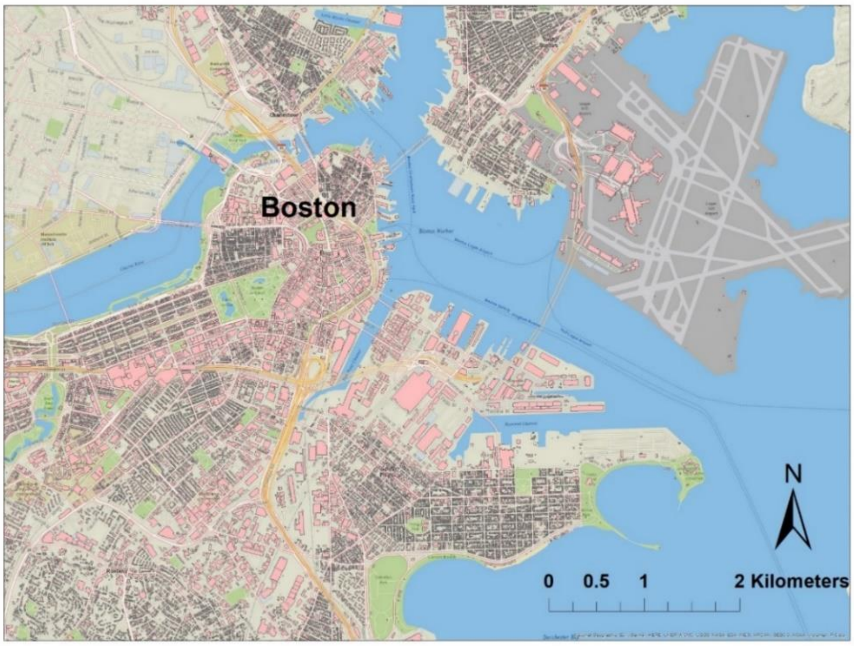

Figure 5 The City of Boston's buildings as polygonal shapes.

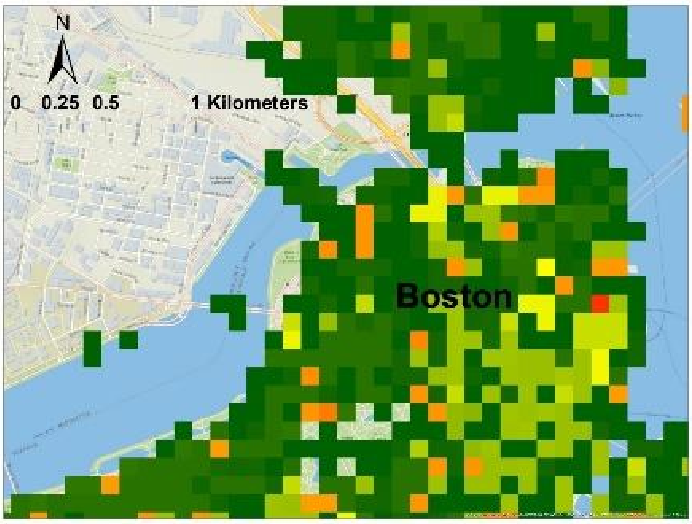

Figure 6 The City of Boston's buildings raster with 100 m x 100 m cells grid: focus on the city center.

3.5 Data sources and errors

The estimates for the population of buildings under analysis are inevitably affected by a possible variety of errors. These might reflect in temporal scales, since data gathered refer to different years, or in spatial scales, since a mix of national and local data was used. The comprehensive data sources used in this study, along with their description, is presented in Table 3.

Table 3 Data sources, description and publishing date.

Dataset	Source	Description	Date
Greenhouse Gas Emissions	City of Boston – Analyze Boston [21]	Annual greenhouse gas emissions inventory (community-wide and local government operations)	09/2020
Boston Buildings Inventory	City of Boston – Analyze Boston [32]	Annually updated inventory of all buildings with individual characteristics	05/2020
Property Assessment	City of Boston [34]	Property, parcel, ownership and value information of all type and classifications of buildings	04/2020
CBECS - Building Type Definitions	U.S. EIA [35]	Commercial building classification according to the principal activity	-
Table E4 and E7 – 2012 CBECS	U.S. EIA [31]	Electricity and natural gas consumption intensities by end use for commercial buildings based on national surveys	2016
Table CE1.2 and CE4.2 – 2015 RECS	U.S. EIA [30]	Summary consumption and expenditures and End-use consumption by fuel in the Northeast for residential buildings based on national surveys	2018
Boston Buildings	City of Boston - BostonMaps Open Data [43]	Shapefile of all Boston's buildings	12/2020
Live Street Address Management (SAM) Addresses	City of Boston - BostonMaps Open Data [44]	Inventory of addresses and parcel numbers of all Boston's buildings	4/2021

The data collected in the Boston Buildings Inventory is dated to fiscal year 2019 and the number of buildings might not match with, for example, the Boston Buildings shapefile, dated 2020. In fact, it could be possible that new buildings were built, or others were left without occupancy; if this is the case, the energy consumption adjustment that was based on the complete sum of energy usage of the reported buildings might not be complete. Nevertheless, a presumably a significant small variation may occur in such cases, without a considerable effect on the produced estimates.

On the other hand, the necessary assumptions and simplifications made in the classification procedure of the buildings, described in section 3.2.1 could represent the most relevant source of error; in fact, some buildings may have been aggregated under the wrong typology, and be attributed with higher or lower consumptions. This could be the case of tax-exempt properties, which are all classified by the inventory under the same category regardless the end use of the building; for example, hospitals and universities match different energy uses but belong to the same class. Furthermore, mixed-use buildings were insufficiently described and did not provide the exact partition of floor area to the proper end-use; thus, they were assumed equally partitioned between residential and commercial uses, which could not always be the case. However, the lack of detailed data and the incomplete classification of potentially useful information might have resulted in inevitable errors.

In addition, the community greenhouse gases emissions inventory aggregated large residential and industrial buildings under the commercial sector, and only small residential buildings form the residential sector. Since the exact classification was not available, this insufficiency could generate imprecisions in the estimates. In fact, the inclusion of industrial buildings in the commercial category might negatively influence estimates, as they register different energy uses.

Moreover, buildings stock is predicted to face a square footage increase of 15% by 2050, where multifamily buildings see the largest growth [15] . However, this study presents forecasting results based on the growth factors the GLIMPSE/GCAM-USA tool modelled for the State of Massachusetts; in fact, the estimate procedure was simplified by embracing this assumption although this may not entirely reflect the city growth. Nevertheless, such increase could be considered negligible as compared to the total buildings stock foot area and estimate should not be affected by large errors. Furthermore, the carbon footprints of the city would still be predominant and need to be properly addressed even if the new buildings fleet was net zero emissions.

Moreover, energy consumption forecasted estimates have been adjusted for biomass; in fact, the State of Massachusetts' buildings reported biomass usage in buildings, while the City of Boston's biomass use is limited on waste-to-electricity generation [22]. Thus, the State bioenergy consumptions have been equally added to the other three energy sources (electricity, natural gas and fuel oil) as if they had the same probability of replacing it with corresponding technologies; however, this might not be the case, so small errors may be related to this division.

In addition, the energy consumption estimates for commercial and residential sectors are based on weighted averages of factors or energy intensity unit correlated to the building characteristics; however, there is no evidence in literature of the reliability of these weights, so their value has been attributed based on the available data for this study and on the match that could have possibly reflected the case. Finally, the population of buildings under analysis reflects the majority of Boston's fleet, but not entirely; in fact, many buildings were left out due to insufficient reported data. Furthermore, the unexpected failing in matching the collected inventory with the geographical shapefile for ArcGIS further diminished the buildings fleet. Thus, the final results could be influenced by small errors.

4 Results and discussion

The proportional downscaling of the emissions forecasted by GLIMPSE allowed to obtain a comprehensive inventory for Boston's buildings fleet in future scenarios. The resulting greenhouse gases emitted by the entire fleet of Boston's buildings, divided in commercial and residential sectors, are presented in section 4.1. Moreover, the downscaling of national energy consumption data, coordinated with proportional downscaling of the tool's results, produced a detailed inventory for each building of Boston, where every record reported building information, energy usage and emissions from space heating and cooling technologies. Greenhouse gas and air pollutant emissions from space heating and cooling usage in these buildings are presented and discussed in section 4.2.

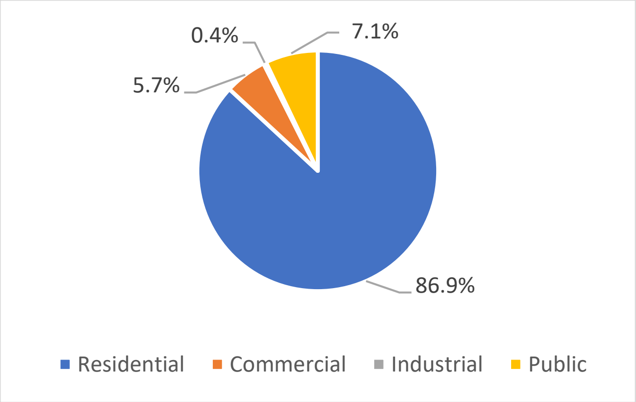

Figure 7 Use class in total occupied Boston's buildings.

The analysis of the Boston Buildings Inventory revealed that the total square footage of buildings is almost evenly owned by both commercial and residential sectors, but the latest class dominates the city occupancy by 86.9% (Figure 7). In addition, the predominant occupation of residential buildings is more densely concentrated in western and southern areas, as Figure 8 shows in a 100 m x 100 m cells grid. Moreover, the majority of households was built before 1980 and only a few were more recently constructed (Figure 9). On the other hand, commercial and public buildings are most densely located in the city center, where the newest vintages are also recorded.

Overall, the mean and median vintages of Boston's buildings are respectively 1923 and 1911. Old buildings are typically characterized by thinner walls and windows that considerably decrease the insulation of the structure, and by inefficient equipment that increases the overall consumption and emissions of the site [15]. On the other hand, recent buildings are constructed according to energy performance standards, which guarantee better insulation and efficiency. In addition, retrofitting strategies, such as improving the insulation of the building, or substituting old equipment with new and more efficient ones, significantly improves the performance of the site.

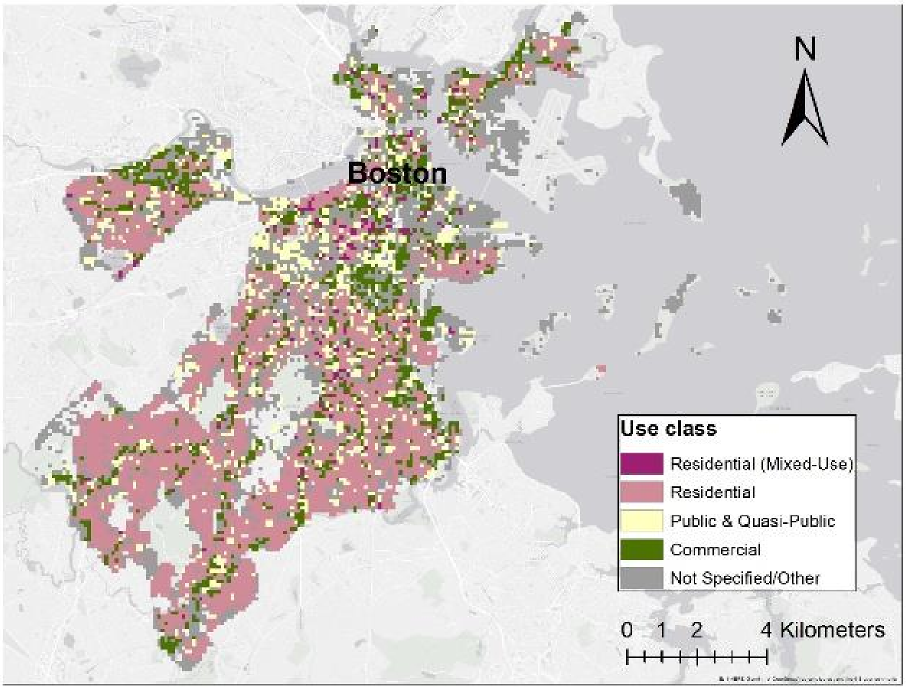

Figure 8 Use class distribution in the population of Boston's buildings under analysis.

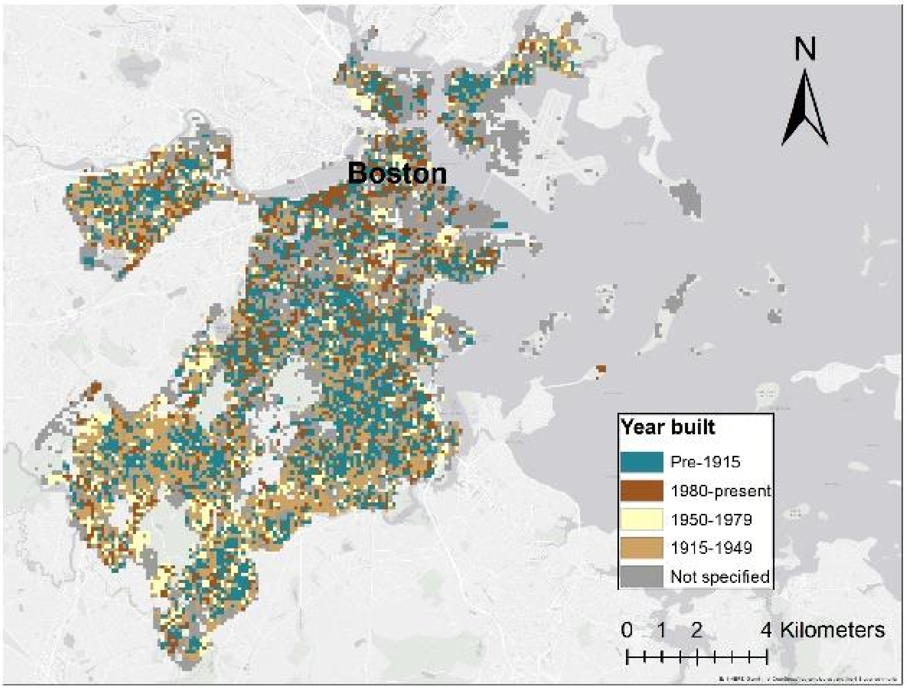

Figure 9 Year-built distribution in the population of Boston's buildings under analysis.

The City of Boston is characterized by the contrast between historical buildings and new and modern architectural structures; the buildings fleet also includes tall skyscrapers that were more recently built. The city's buildings are the result of the construction boom after the World War II and the new century. In fact, the mix of buildings vintages and styles makes the city unique.

In addition, multifamily and single-family households dominate the city's fleet and currently, the majority of these use hot-water-based and forced-air heating systems, and only a few already use heat pumps or electric boilers. Thus, the electrification of space heating would accommodate the largest portion of buildings, and it would be beneficial for the entire city. Nevertheless, commercial buildings host activities that require much more energy than residential buildings; in fact, these register significantly higher emissions intensities. In particular, hospitals and restaurants are the most energy intensive type of building and they might register intensities even 5 times higher than offices [31], constituting a potentially challenge to full electrification.

4.1 Forecasted greenhouse gases emissions from Boston's buildings fleet

The greenhouse gas emissions inventory provided the most recent information for the City of Boston's buildings activity related to electricity, natural gas and fuel oil usage. The total greenhouse gases emissions released by commercial, institutional and residential buildings were forecasted according to the results that the GLIMPSE model generated for the state of Massachusetts; the projections start in 2020 and end in 2050 with 5-years increment interval. Furthermore, the forecasted emissions reflect the BAU scenario, where current policies will be constant throughout the years without implementation, and the 2025/2030/2035 Electrification scenarios, where the sales share of electrified space heating technologies in buildings will achieve 100% by 2025/2030/2050 respectively.

The city's Climate Action Plan intention to replace fuel oil in buildings heating systems has allowed a decrease in its consumption by more than half since 2005, resulting in 20 thousand households having replaced it with natural gas or electric systems [7]. Together with fuel oil usage reduction and natural gas adoption, the last 8 years from 2010 to 2018 have registered a constant decrease in electricity consumption. This can be directly attributable to new and highly efficient equipment being installed. Moreover, natural gas deployment covers a central role in decarbonization measures that the city is intended to follow in the future.

As a matter of fact, current policies favor natural gas over electric technologies (Figure 10 and Figure 11). However, future scenarios of building space heating electrification forecast an increase in electricity consumption in 2050 by around 33% in commercial buildings (34% in 2025, 33% in 2030 and 31% in 2035 Electrification scenarios) and by around 35% in residential buildings (36% in 2025, 35% in 2030 and 33% in 2035 Electrification scenarios) with respect to the BAU scenario (Figure 11).

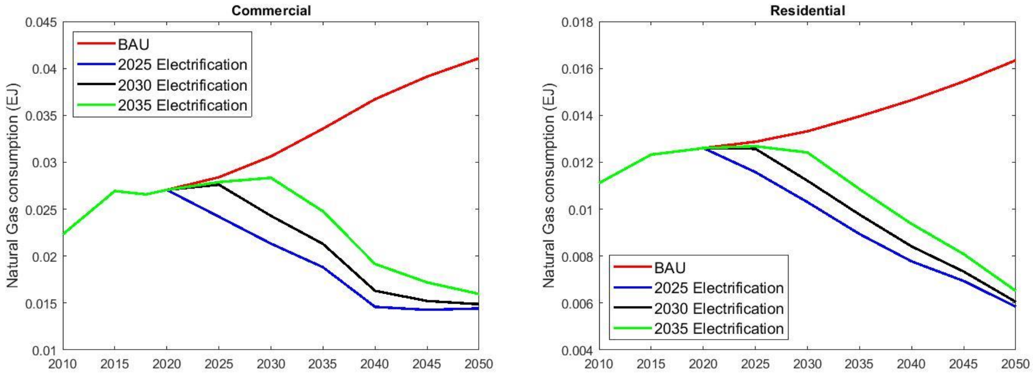

Figure 10 Natural gas consumption (EJ) of Boston's community buildings (commercial and residential). Projections accordingly to the BAU and 2025/2030/2035 electrification scenarios.

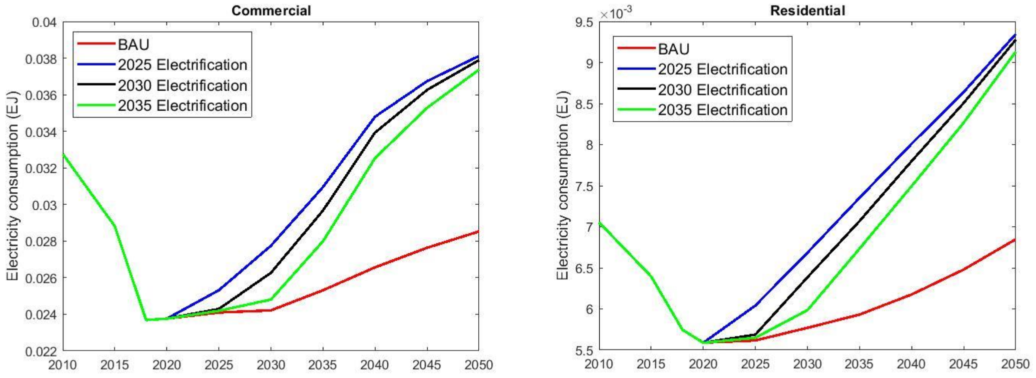

Figure 11 Electricity consumption (EJ) of Boston's community buildings (commercial and residential). Projections accordingly to the BAU and 2025/2030/2035 electrification scenarios.

However, space heating electrification of the entire building fleet of the city, excluding only industrial buildings, would require larger supply of electricity, and would inevitably shift the electricity peak demand, in magnitude and temporally. Walker [36] estimated that the electrification of space and water heating in Boston's commercial and residential buildings would cause an 87% increase in peak demand, and would shift in season from June to January, and in day from 2:00 PM to 7:00 AM. This would require proper infrastructure and organization in the generation plants to support this shift and increase.

In order to provide the grid with the stability and sufficient supply that it needs, organized infrastructure and new strategies must be adopted. A solution could be found in microgrids, defined as local energy grids with control capability [40]. In fact, these can both operate autonomously, covering the end-use demand directly near the source, and in synergy with the traditional grid, supplying energy to it. Furthermore, during instabilities or crisis in the grid they can break off and work independently as “islands” and during peak loads they reduce the load, preventing the failure of the grid [41]; their energy is constantly provided by local generators, storages (such as batteries) or renewables (such as solar power).

However, microgrids still need to store their electrical surplus with batteries, as well as renewable power does. In fact, the variable and unpredictable nature of renewable energy resources, such as solar or wind power, has necessity of energy storages to constantly cover the demand. However, energy storages need much space to be installed, which may not always be available, and, depending on their technology, the sustainability of their materials is still under discussion. For example, batteries are convenient, reliable and efficient, but their widespread adoption arises important questions regarding the toxicity and availability of their production materials, their considerable life-cycle emissions, and their unproper and unregulated disposal and recycling at the end of their use [42].

In addition, over the last 8 years period Boston’s buildings released lower amounts of greenhouse gases in the atmosphere (Figure 12); this recent trend is the result of fuel oil usage being substituted by natural gas deployment, and new efficient technological equipment being installed. However, the business-as-usual scenario clarifies how current policies, along with high energy intensities and growth rates, could only culminate in even higher emissions in 2050 than 2010 levels, especially concerning the commercial sector. In fact, this would reach almost 2.2 million tons of CO_2 equivalent released in 2050. On the other hand, the 2025 Electrification scenario allows a greenhouse gases emissions reduction of 65% from natural gas consumption and of 77% from fuel oil usage in from commercial buildings as compared with the BAU predictions for the same year. Residential buildings would reach a peak of almost 0.9 million tons of CO_2 equivalent in 2050 under the BAU scenario; however, electrification scenarios allow a 64% reduction in emissions from natural gas and a 68% reduction from fuel oil usages.

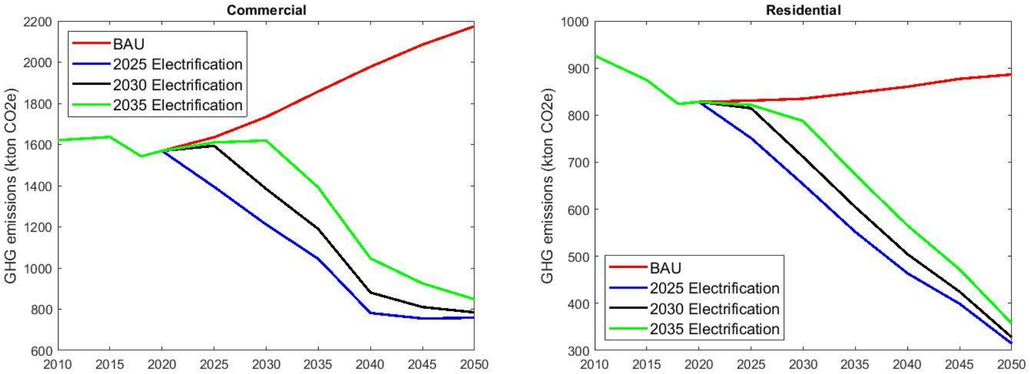

Figure 12 Forecasted greenhouse gases emissions (kton of CO2e) from natural gas and fuel oil use in Boston’s buildings.

Overall, space heating in 2018 takes 43% of the total commercial buildings' energy consumption and it accounts for 66.5% of their natural gas consumption. Furthermore, residential buildings address 55% of their total consumption to heating purposes; in particular, space heating accounts for 67.6% of natural gas usage and 82% of fuel oil's. Under the BAU scenario, both commercial and residential space heating consumption shares undergo a slow decreasing trend until 2050, reaching the lowest value of 42% for the former and of 52% for the latter (Figure 13).

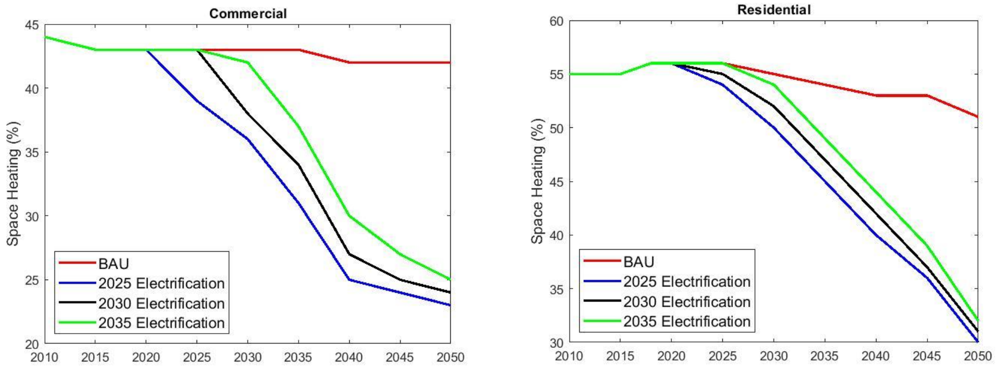

Figure 13 Forecasted space heating consumptions in Boston's buildings as percentage of total energy consumptions. Projections according to BAU and 2025/2030/2035 Electrification scenarios.

Nevertheless, the electrification scenarios show promising results, but the fastest implementation of policies allows to achieve higher decarbonization rates. In fact, the 2025 electrification scenario allows deep decreases in space heating consumption share until 23% in commercial buildings and 30% in households (Figure 14). Furthermore, electrification scenarios would modify the share balance in energy consumption; in particular, households would increase their hot water heating consumption shares from 18% to 27%, which would still be the second bigger portion. The reason behind this is attributable to new and more efficient electrical equipment being installed for space heating purposes, decreasing its consumptions; on the other hand, domestic hot water would still be left covered by older and fossil-fuel based systems.

Water heating and cooking in residential buildings still rely on fossil fuels, while the other technologies are almost entirely electric. Thus, with residential water still heated by natural gas, accounting for 27% of the building's consumption, carbon neutrality might not be achieved by 2050 since there would still be greenhouse gases emissions released by these, even though fuel oil usage would decrease to nearly zero. In fact, the electrification of hot water systems, or alternative carbon-free solutions, must be investigated. Nevertheless, scenarios of electrification can find a suitable place in decarbonization pathways only if the sustainable and carbon-free nature of the entire electric generation system of the city will be ensured. Thus, it is strongly advisable to reinforce renewable generation of the city's energy system.

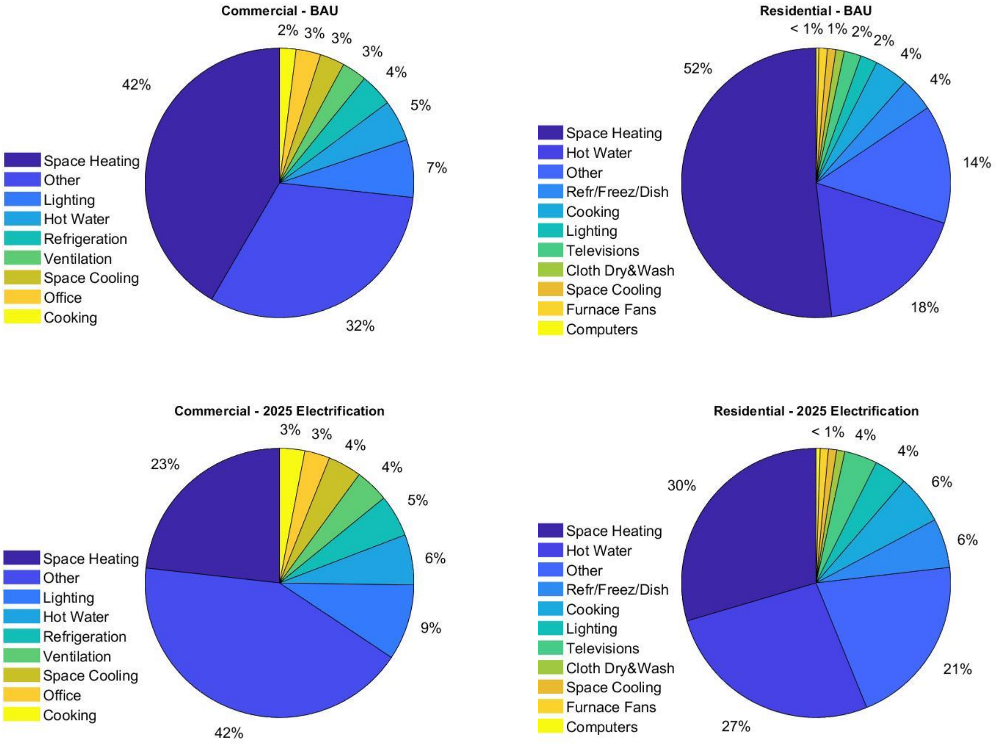

Figure 14 Commercial (left) and residential (right) buildings energy usage by technology sector in 2050 under BAU and 2025 Electrification scenarios.

The 2025 Electrification scenario could be considered the most ambitious, since it would leave only 4 years left to achieve the electrification goal in commercial and residential buildings; however, under this policy, the best results in terms of carbon emissions reduction are obtained, as compared to the other two electrification scenarios. Furthermore, the faster actions are directed to climate change mitigation, the better is for the environment since the point of no return is near. Nevertheless, the electrification of the entire buildings fleet of the city would increase the burden on the grid, which will require new adaptation with proper infrastructure.

Another solution to unburden the grid could lie in the deployment of alternative and sustainable fuels to replace nonrenewable energy in boilers. In fact, these latter could operate with a mix of natural gas and biomethane, or of hydrogen and biomethane, or with pure hydrogen. However, biofuels and biogas have a variety of positive aspects, such as sustainability since they are part of a circular economy where waste and carbon captured become a new usable product, but they are subjected to blending limits since cannot be used neat; thus, they could not entirely substitute fossil fuels.

On the other hand, hydrogen is a prominent fuel with remarkable combustion properties and efficiencies that result in zero carbon emissions. Nevertheless, its use in buildings still needs to be further explored, as its absence of odor and ignition flame, and its high inflammability could constitute a risk [48]. Furthermore, its high combustion temperatures need to be controlled to avoid the formation of nitrogen oxides.

4.2 Estimated emissions from Boston’s buildings space heating and cooling technologies

The aim of this study was to estimate future greenhouse gases and air pollutants emissions from the City of Boston’s commercial and residential buildings, at a high-resolution scale under decarbonization measures. The entire population of buildings was collected, analyzed and classified; in total, 80 thousand buildings were selected for this study. The resulting inventory contains detailed information for every record, such as street address, ward, year built, living area, building type, end use, energy consumption, and pollutants emissions.

Each building’s fossil fuels consumption has been estimated via a downscaling procedure of the national surveys for commercial and residential buildings energy usage developed by the U.S. Energy Information Administration. These estimates have been further allocated to the city through an additional adjustment based on the current consumptions of the community and local governmental buildings. In addition, future emissions from space heating and cooling systems have been estimated until 2050 under decarbonization pathways via proportional downscaling of the projections that the GLIMPSE tool generated for the state of Massachusetts. The results have been incorporated in the buildings inventory for every record and computed with ArcGIS in 100 m x 100 m grid cells; the maps were obtained for every pollutant in the chosen future years under the BAU and electrification scenarios.

A comprehensive and detailed inventory of pollutant emissions maps could have a significant contribution in policymaking. In fact, they allow to foresee the effects of measures and actions with high spatial accuracy and in the proper temporal scale. Moreover, they facilitate the identification of possible areas of the city where emissions are mostly concentrated in, in order to formulate targeted climate action measures by precinct, ward or neighborhood; in fact, they preserve all buildings characteristics information and they maintain track of each record’s contribution in terms of energy usage and related emissions.

Greenhouse gases are formed during the combustion of fossil fuels, such as coal, refined liquids and natural gas; they are mostly composed of carbon dioxide, which is also the largest pollutant released in the atmosphere by the human activity. Greenhouse gases emissions from heating and cooling systems in Boston’s buildings would register values of more than 2500 ton of CO_2 for a significant part of the city if current policies are applied until 2050 (Figure 15). In particular, the tallest building of the city, which is the 62-floor John Hancock Tower, registers the highest value of 4937 ton of CO_2. On the other hand, the same building with space heating electrification emits 1040 ton of CO_2, a 79% lower value. In fact, the promptness with which 100% of electric space heating technologies sales share is reached reveals its importance in the 2025 electrification scenario, where the most promising results reside in as compared with the other two electrification scenarios, which share similar conditions.

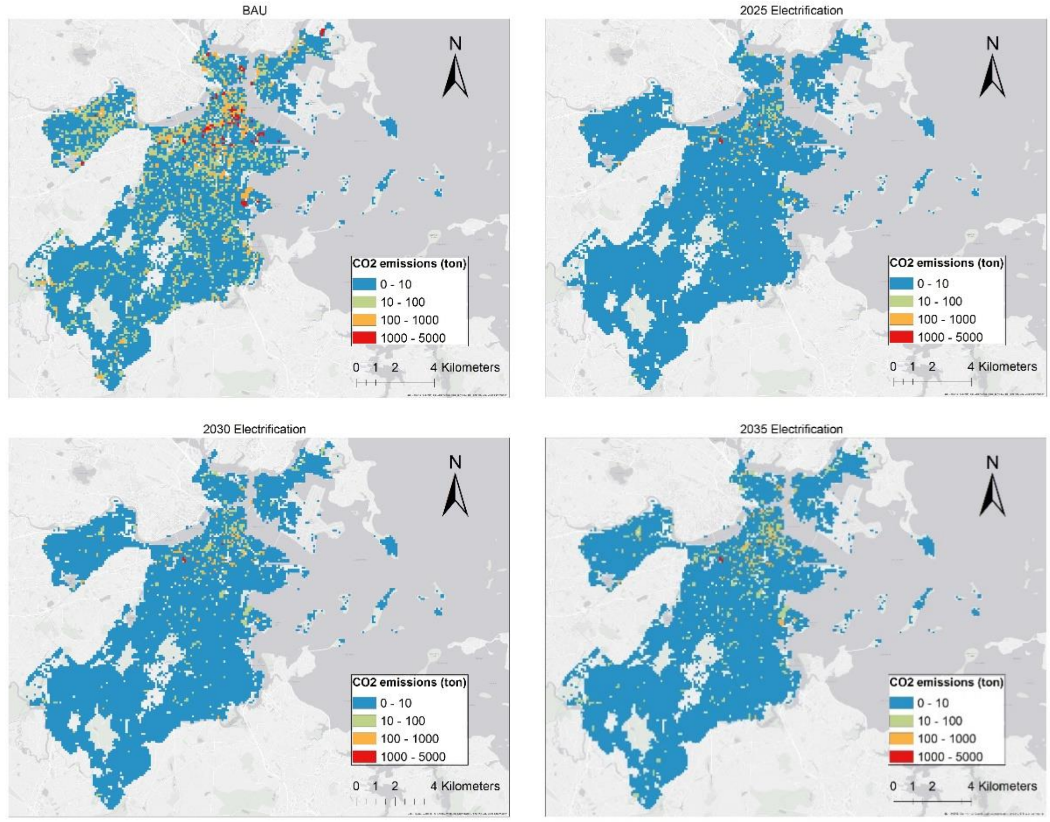

Figure 15 Greenhouse gases emissions (ton of CO_2) in fossil fuel-based heating and cooling systems of Boston's buildings; predictions for year 2050 under BAU and 2025/2030/2035 electrification scenarios.

In addition to increased energy consumption, business-as-usual measures would result in higher emissions intensities as well. In fact, in 2050 the greenhouse gases emissions intensity, measured as kilograms of CO_2 per square meter of building living area, related to heating and cooling systems usage are predicted to register the highest value of 80 $\text{kg}_{CO2}/\text{m}^2$ and an overall mean of 7.96 $\text{kg}_{CO2}/\text{m}^2$. Furthermore, as Figure 16 presents, discrepancies between commercial and residential energy activities are highlighted: a larger density of high values can be directly attributed to the city center, where most of the commercial buildings are located, while lower intensities are located in suburban areas, where residential buildings prevail.

Nevertheless, the electrification scenarios forecast both low emissions and low emissions intensities throughout the city. As a matter of fact, in 2050 the greenhouse gases emissions intensity related to heating and cooling systems usage will register values well below 20 $\text{kg}_{CO2}/\text{m}^2$ for the majority of buildings. In particular, the 2035 electrification scenario registers a maximum value of 28 kg_{CO2}/m^2 and a mean of 1.1 kg_{CO2}/m^2, the 2030 electrification scenario a maximum of 26 kg_{CO2}/m^2 and a mean of 0.73 kg_{CO2}/m^2, and the 2025 electrification scenario a maximum of 25 kg_{CO2}/m^2 and a mean of 0.58 kg_{CO2}/m^2.

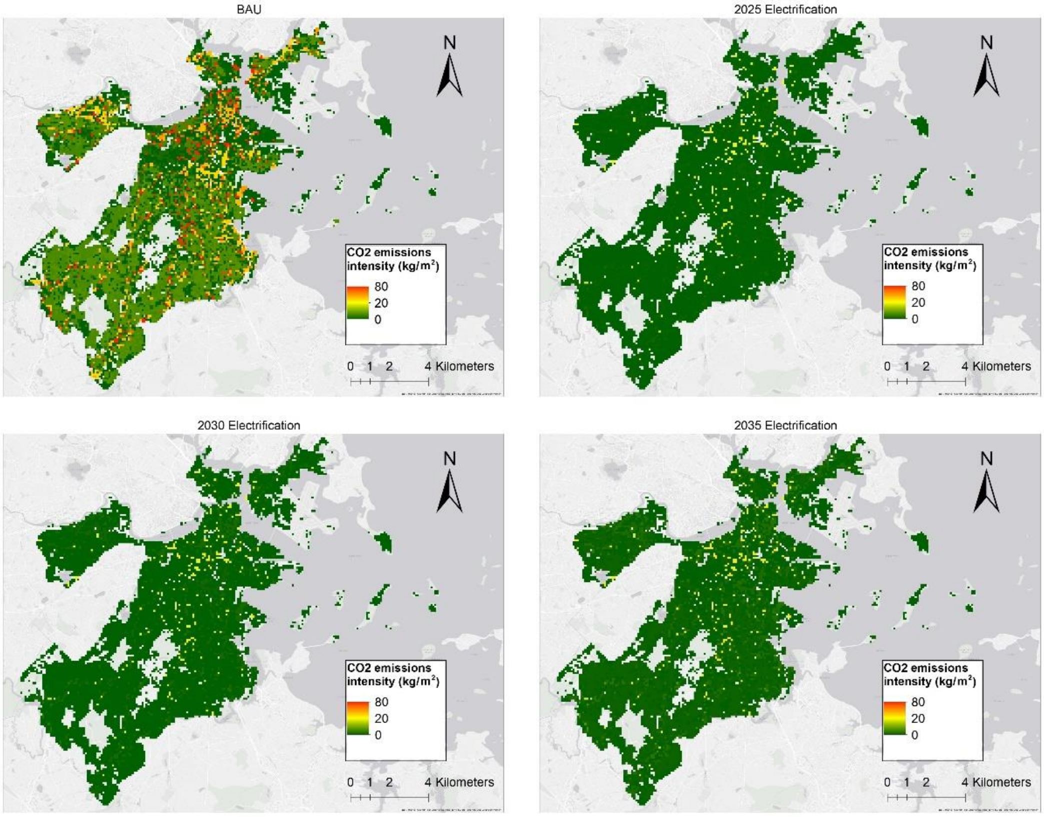

Figure 16 Greenhouse gases emissions intensity (kg $_{CO_2}/m^2$) in fossil fuel-based Boston's buildings; predictions for year 2050 under BAU and 2025/2030/2035 electrification scenarios.

The City of Boston's government introduced, along with BERDO [33], new building performance standards (BPS), which set CO_2 equivalent emissions intensities on a descendant trend throughout the near-future years, to culminate with 2050 carbon neutrality [41]. The results obtained in this study imply that, even in the best electrification scenario, many buildings could not be able to meet the carbon neutrality target set by the standards for 2050, meaning that electrification of space heating only may not be enough. In fact, cooling systems in commercial activities would still rely on natural gas, although this use represents 4% of the fuel consumption in 2050; the remaining would still be dedicated to hot water systems, contributing to taking the distances from carbon neutrality.

Nevertheless, energy intensity is not only the result of specific needs that a certain type of building, such as hospitals, could have with respect to other less intensive. Indeed, it is strictly related to occupants' behavior, which significantly affects the building consumption profile. Its modeling and predictability are currently object of research, also due to the temperature increase that climate change will cause in the near future. In fact, climate change will affect heating and cooling loads and in a sustainable scenario occupants would be required to modify their energy usage behavior, supported also by high efficiency equipment and clean energy transition.

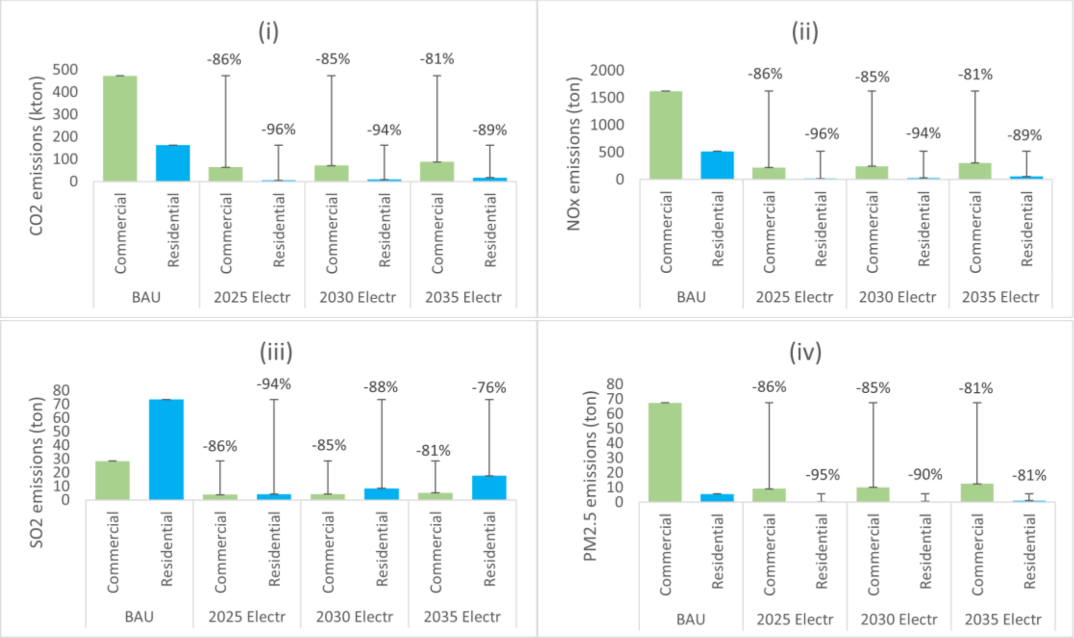

Figure 17 Boston's buildings emissions from fossil fuel-based heating and cooling systems in 2050 of greenhouse gases (i), nitrogen oxides (ii), sulfur dioxide (iii), and particulate matter 2.5 (iv) in 2025/2030/2035 Electrification scenarios as in percentage change with respect to the BAU scenario.

Although carbon neutrality in buildings energy performance standards may need further efforts, the electrification of space heating would allow important pollutants emissions reduction in buildings in 30 years, which would significantly improve the air quality of the city. The highest decrease, with respect to the business-as-usual scenario, is recorded in the 2025 Electrification scenario. In particular, households see the highest reduction of 96% less greenhouse gases and nitrogen oxides emitted in 2050, while commercial buildings will release 86% less of the same pollutants (Figure 17).

Overall, commercial buildings are responsible for larger amounts of pollutant released in the atmosphere, due to their higher energy consumption intensity. However, sulfur dioxide is mostly related to residential activity; in fact, 70 tons of SO_2 will be attributed to households' usage in 2050, and almost 30 tons to commercial activity, according to the BAU scenario. The reason behind this gap is that sulfur dioxide emissions are mostly attributable to fuel oil burning, which is predominantly used by residential buildings. However, the fuel oil switching policy measure that is already being in use in the city allows significant SO_2 emissions reduction even in the BAU scenario; as a matter of fact, 2035 electrification scenario forecasts the lowest emissions reduction for sulfur dioxide, corresponding to a 76% decrease for residential buildings (Figure 18).

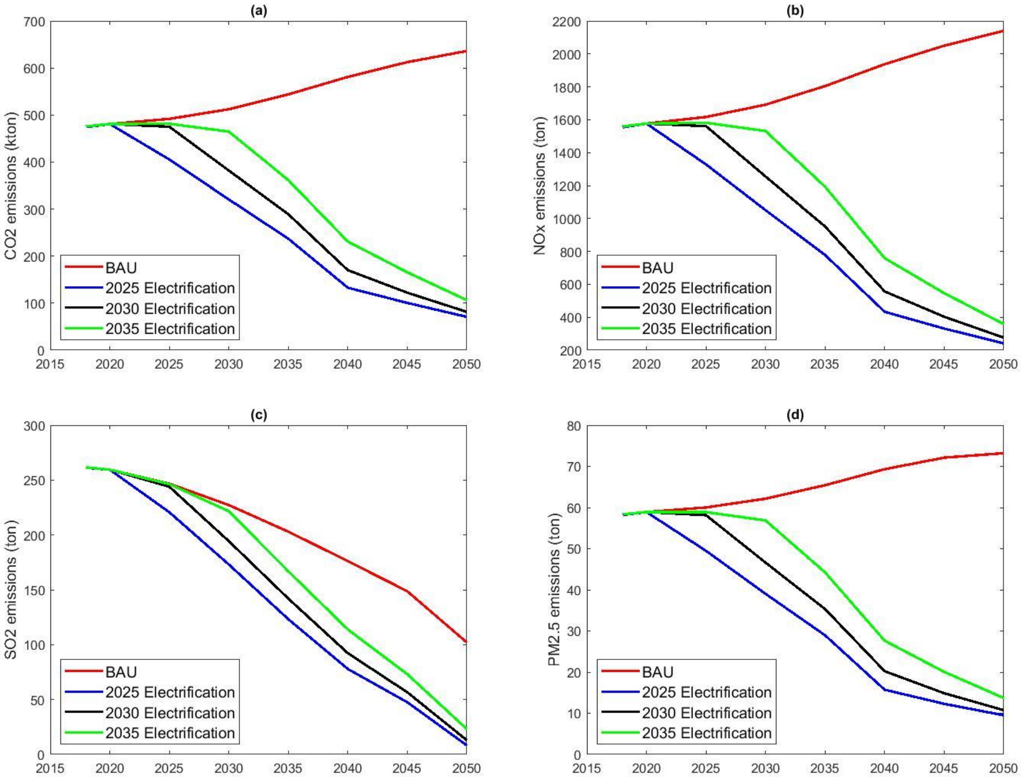

Figure 18 Boston's buildings air pollutants emissions related to fossil fuel-based heating and cooling systems use forecasted in BAU, and 2025/2030/2035 Electrification scenarios. Projections for greenhouse gases (a), nitrogen oxides (b), sulfur dioxide (c), and particulate matter 2.5 (d) emissions.

Although fuel oil switching measures are currently allowing the city to significantly reduce their sulfur dioxide emissions, these would still be widespread throughout the city in the business-as-usual scenario. As a matter of fact, Figure 19 highlights their significant reduction in 2050 according to the 2025 Electrification scenario as compared with the BAU scenario. Nevertheless, the map shows how sulfur dioxide would be spread in an extended area of the city, corresponding both to commercial and residential buildings, where no further policies are applied in the future. In contrast, another pollutant, the particulate matter 2.5, would achieve higher peaks of emissions as compared to sulfur dioxide, but its spread would be mostly concentrated in the commercial area of the city, where higher values can also be attributed to. Overall, the electrification scenario allows the city to significantly improve its air quality; in fact, the highest portion of buildings would limit their emissions below 0.5 kg of both pollutants, although peaks would still be registered by the city center, that is mostly by commercial buildings.

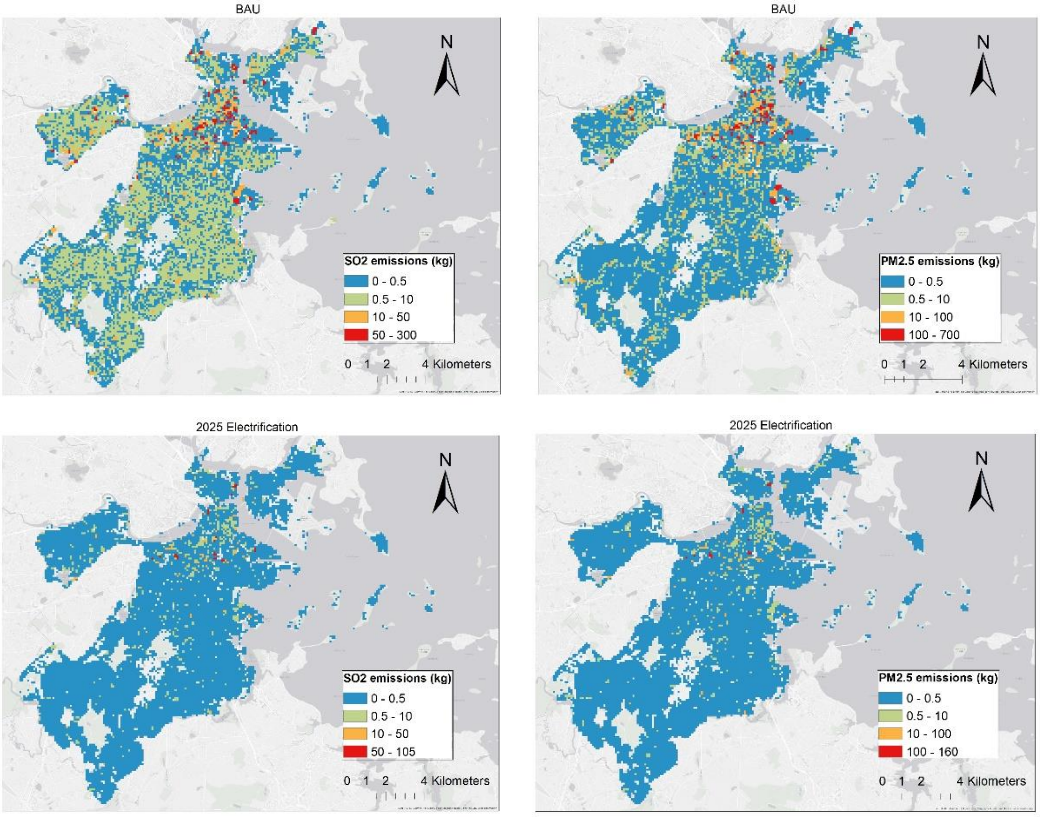

Figure 19 Sulfur dioxide (left) and Particulate Matter 2.5 (right) emissions (kg) in fossil fuel-based heating and cooling systems of Boston's buildings; predictions for year 2050 under BAU and 2025 electrification scenarios.

Fuel oil switching measures imply deployment of natural gas as combustion fuel, which, however, is not carbon-free. In fact, air pollutants such as carbon monoxide and nitrogen oxides are released during the combustion of both fuels in similar quantities. If the same policies would be applied until 2050, the city would still register high levels of NOx in its atmosphere. Figure 20 shows that in the business-as-usual scenario for year 2050 nitrogen oxides emissions would be the contribution of both commercial and residential buildings activities; in fact, this pollutant would be widespread in the city, but higher values would still be related to commercial activities, with peaks of almost 17 tons of NOx.

On the other hand, in the electrification scenarios the predicted emissions are more than 4 times lower and peaks of more than 1 ton would still be registered, especially due to the commercial cooling activity, but most of the city would contain its annual emissions well below 10 kg of NOx. Furthermore, the fastest implementation of electrification policies would allow to achieve lower emissions and better air quality since the 2025 Electrification scenario still presents the highest emissions reduction.

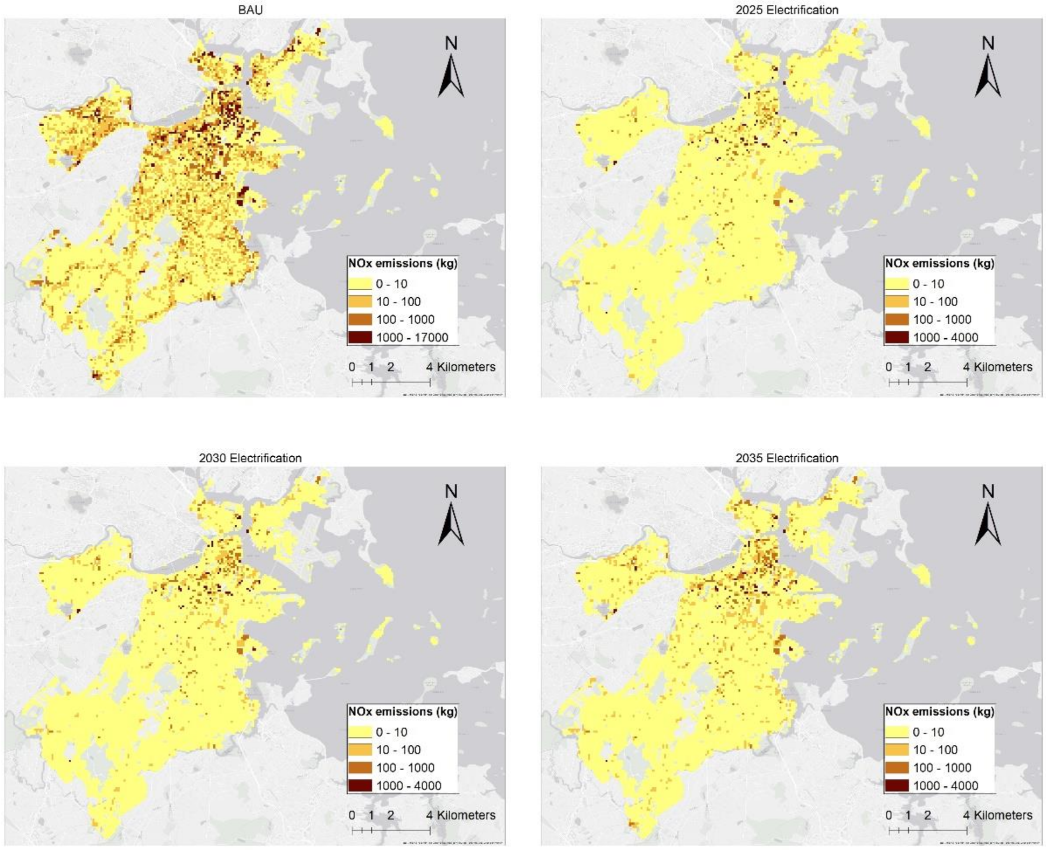

Figure 20 Nitrogen oxides (NOx) emissions (kg) in fossil fuel-based heating and cooling systems of Boston's buildings; predictions for year 2050 under BAU and 2025/2030/2035 electrification scenarios.

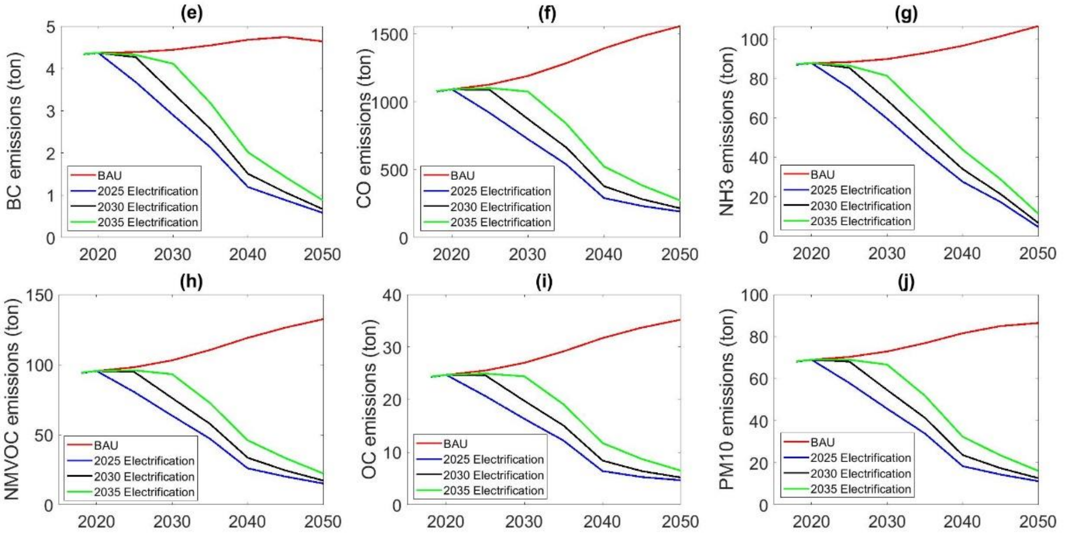

Figure 21 Forecasted Boston's buildings air pollutants emissions related to fossil fuel-based heating and cooling systems use. Emissions from black carbon (e), carbon monoxide (f), ammonia (g), non-methane volatile organic compounds (h), organic carbon (i), and particulate matter 10 (j).

A similar trend also characterizes carbon monoxide emissions which, as previously mentioned, are related to natural gas combustion. In fact, the business-as-usual scenario depicts an increasing curve until 1500 ton in 2050 emitted by the entire fleet of buildings (Figure 21), with commercial activity being the major contributor. In addition, commercial buildings natural gas usage is related to the largest emissions of non-methane volatile organic compounds and organic carbon, as in comparison with the residential one; as a matter of fact, their curve is particularly similar. On the contrary, households are responsible for 20-times higher ammonia emissions, due to their natural gas and fuel oil boilers; in fact, space heating electrification would significantly remove NH_3 pollution, reaching 4.8 tons in 2025 electrification scenario (6.9 tons in 2030 electrification scenario and 11.5 tons in 2035 electrification scenarios). Moreover, fuel oil switching measures allow considerable reduction of black carbon and particulate matter 10 emissions.

The City of Boston has actively responded to the climate emergency by setting goals, measures and ordinances that are constantly under revision as the situation evolves. In fact, in 2013 the city enacted the Building Energy Reporting and Disclosure Ordinance (BERDO) that requires all non-residential buildings greater than 35 thousand square feet, residential buildings that are 35 thousand square feet or larger or have 35 or more units, and any parcel with multiple buildings that sum to 100 thousand square feet or 100 units to report their annual energy and water use to the city [33]. Currently, as part of the 2019 CAP updates [7], the city is intended to extend the ordinance to smaller buildings, setting the threshold to 20 thousand square feet or larger, or to 15 or more units [42]. The new threshold enlargement could contribute to identify large emitters, but carbon neutrality needs deep efforts from all the city to be achieved. Thus, it is advisable to comprehend all Boston's buildings in this ordinance.

Furthermore, the city is intended to develop carbon targets for existing large buildings, formulated under emissions performance standards. These set a threshold for carbon intensity (as kg_{CO2}/ft^2) of large buildings depending on their typology [41]; the limit decreases every 4 years to reach 50% reduction in 2030 and finally 100% reduction in 2050, as compared with 2005 levels. The results presented in this study suggest that such emission performance standards could be achieved by the city; in fact, a reduction of 40% in carbon emissions intensity of commercial buildings' heating and cooling systems is registered in 2030 under the 2025 electrification scenario, with respect to the 2018 estimated levels. However, such reduction decreases as slower the electrification is achieved: the 2030 electrification scenario predicts a 23% reduction, while the 2035 electrification scenario only a 1% reduction.

Nevertheless, limiting carbon targets for commercial buildings only might not be enough, especially if considering the high usage of fossil fuels in households related to space and water heating. In fact, the results presented in this study indicate that tempestive intervention is essential and that limiting electrification to space heating might not allow to achieve the decarbonization targets, even though it would substantially decrease carbon footprints of buildings. Thus, the decarbonization of other technologies in buildings must be addressed and investigated.

For example, decentralized systems such as microgrids, could be favorable as discussed in the previous section. These should involve renewable technologies that could be solar panels to cover the electricity demand of the building and solar collectors that could supply hot water. In fact, the city registers medium solar irradiation [51] that constitute a good opportunity for solar power technologies; however, the peculiar skyline of the city with a mix of high-, mid- and low-rise buildings could lead to shading effects that must be properly addressed.

In addition, climate change leads to increased temperatures, which will inevitably affect cooling or heating loads. In fact, cooling loads may increase in summer or could shift even to spring and the grid with its infrastructure must be prepared. However, in a renewable grid this would not mean increased greenhouse gases emissions, since the new demands will occur during high availability of renewable energy, which could be mid-day or summer and spring [51].

The results presented in this study suggest that hot water systems decarbonization is needed to achieve the 2050 target, as this technology still represent an important share of fossil fuels consumption in buildings. An integrative solution to decarbonize both space and water heating could lie on district heating; this allows to create a grid of centrally produced clean energy that is supplied directly to customers belonging to the same neighborhood or area. Although district heating is already in use in Boston with cogeneration plants (CHP), a new and more complete system could be needed in the near future. In fact, thermal storages might be used to cover loads during times of insufficient supply; furthermore, the electricity produced in these plants could be distributed to microgrids that operate, for example, with heat pumps.

This study presented a model for estimating emissions from buildings at high-resolution scale starting from national and state data. Usually in literature, such level of detail is obtained via bottom-up approaches that, however, require large amounts of data to be gathered. On the other hand, the presented downscaling procedure allowed to achieve valuable estimates from relatively low amount of data collected. Nevertheless, the results are affected by errors that, for the major part, could be solved if a more comprehensive inventory have been provided by the city.

The model allows to evaluate decarbonization policies and their efficacy in the long term for every building of Boston, and it could be adapted to other cities. As fighting climate change is becoming an increasing priority, the model presented in this study contributes to analyze solutions to enhance buildings resilience under future climatic conditions.

5 Conclusions

This study presented a comprehensive and innovative downscaling procedure to estimate high-resolution city-level greenhouse gases and air pollutant emissions from buildings energy consumption activity under current policies and future decarbonization pathways. The national- and state-level energy usage data were allocated to the City of Boston based on the status of the city and on future scenarios reflecting decarbonization measures that the State of Massachusetts is intended to enact. The energy-related emissions from every building of Boston have been estimated to evaluate the effect of policies and climate change mitigation measures on high resolution scale.

The buildings' greenhouse gases and air pollutants emissions from space heating and cooling technologies in buildings were represented in a 100 m x 100 m cells grid. Furthermore, detailed buildings information, such as use class, building type, area and vintage, are available for every record and are combined with the emission estimates. The forecasted emissions reflect the business-as-usual scenario and three space heating electrification pathways that the GLIMPSE/GCAM-USA tool modeled for the state of Massachusetts; the same growth factors were applied to the city.

The study shows the efficacy of electrification of space heating technologies in buildings to significantly reduce their annual carbon footprints. The presented decarbonization measures will allow commercial and residential buildings to address their energy consumptions share to space heating respectively by 23% and 30% according to the more tempestive scenario, with respect to the current status of 43% and 55%. Moreover, in the 2025 electrification scenario households would see the highest reduction of 96% less CO_2 and NO_x emitted by heating and cooling systems in 2050, while commercial buildings will release 86% less of the same pollutants, as compared with the business-as-usual scenario.

Nevertheless, the proposed electrification scenarios would modify the balance in energy consumption shares; in particular, residential buildings would increase their water heating consumption shares from 18% to 27%, as compared to the total. This would still result in space heating systems ranking as the first bigger portion of households' energy consumption. Furthermore, in 2050 it is forecasted an increase in electricity consumption of 33% in commercial buildings and of 35% in residential buildings with respect to the BAU scenario. In fact, business-as-usual policies involve fuel oil switching measures in buildings, in favor of natural gas; the rapid deployment of this latter is expected to contribute to significant amount of greenhouse gases emitted in the atmosphere in the coming years, exceeding 2010 levels.

The results obtained with the proposed model highlight the importance of tempestive actions to see consistent results by 2050. In fact, the highest emissions reduction from space heating systems in buildings is obtained in the 2025 electrification scenario, which prospects 100% electric space heating technologies sales share achieved by 2025. However, this is also the promptest scenario that will leave only 4 years to complete actions that lead to electrification. Thus, the remaining two electrification scenarios contribute to expand the temporal scale of possible actions and their results, which are still promising, could be considered highly feasible. However, the proposed results are highly dependent on the future energy mix that will satisfy the electricity generation of the city, which has been forecasted by the tool for the purpose of this study.

The downscaling procedure followed in this study allowed to convey to building-level estimates obtained as manipulation of national surveys and state forecasting results. The results could be confidently interpreted as satisfactorily reliable, although inevitable errors might affect these; in fact, errors are mainly due to open but scrupulous interpretation of missing data that, if were available, would have simplified the procedure and would have significantly increased the reliability of the model. For example, reported heating system fuels in buildings would have allowed the analysis to be performed more precisely. Thus, in the interest of the scientific community, it is advisable to increase the level of detail in such data sources.

The work remarked how the electrification of space heating technologies in buildings would lead to effective emissions reduction, but it would still leave water heating systems covered by fossil fuels. In fact, water heating would still rank as the second-highest share of energy consumption in buildings; thus, it would still constitute a possible source of pollutants emissions, if not decarbonized. As a matter of fact, the City of Boston’s decarbonization target by 2050 would not be achieved with space heating only, but it would require all buildings technologies to be emissions-free. However, the electrification of all these components impacts grid and its stability since it would cause higher and shifted peaks in demand. Thus, to preserve the grid integrity alternative and complementary solutions should be evaluated.

New electric technologies involve highly efficient both equipment, such as heat pumps, and buildings; in fact, buildings retrofits play an important role in decarbonization pathways, as they must be ensured as efficient as possibly achievable. However, the increase in electricity demand that building electrification would inevitably cause should not impact the grid stability. In fact, proper infrastructure and transmission systems should be ensured, and solutions to unburden the grid, are advisable for the city.

The city could be organized into microgrids to independently provide the required energy supply, whenever covering of periods of insufficient power from the stressed grid is needed. Furthermore, microgrids could be complemented by district heating, which ensures higher efficiencies. District heating is already being used in the city, but it could be implemented with new equipment, increasingly powered by renewable energy sources. Furthermore, until the electric generation of the city is not completely “green”, alternative fuels could be employed. For example, hydrogen is a sustainable solution for boilers, although its application in buildings is still being investigated.

The results presented in this study can be usefully relevant in policymaking to support urban greenhouse gases modeling and air quality control. In fact, the emissions maps allow to identify the efficacy of climate change measures in a high-resolution spatial scale and in an extended temporal scale. In addition, the downscaling procedure proposed in this work can be applied to every city and it is only limited by the amount of data and information available for this purpose.

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Appendix

Appendix 1 (1/3) Classification of Boston’s buildings under analysis

	Building type	Building typology	Assessor name	Property code
Commercial	Public Assembly	Convention/Assembly	Arena Ice Skating, Arena Roller Skating, Athletic Facility, Auditorium/Sport Center, Bowling Alley, Hotel/Convention Center, Movie Theater, Museum/Gallery, Night Club, Race Track, Recreation Building, Restaurant/Lounge, Restaurant/Service, Stage Theater, Charitable Organization, Library	326-329, 360-362, 364, 365, 367, 370-372, 376, 377, 905, 941, 947, 978, 988
	Public Order & Safety	Fire/ Police	Fire Station, Police Station, Correctional Building	972, 974, 975
	Lodging	Hotel	Hotel/Lodging, Inn/Resort/B&B, Motel, Nursing Home, Rectory/Convent	300-302, 304, 971
	Other	Medical/Lab/Production, Garage	Air Freight Terminal, Laboratory, Parking Garage, Parking Lot, Pay Parking Lot, Subterranean Garage, U.S. Government, Science Lab, Other Exempt Bldg	31, 116, 119, 306, 336-339, 387, 395, 900, 943, 955, 961, 985
	Office	Office	Bank Building, Funeral Home, Medical Office, Office, Office 1-2 Story, Office 3-9 Story, Office Building, Postal Service, Private City Club, Retail Use, Social Club, Training Facility, Activity/Social Center, Administrative Building, Armory, Boston Redeveloping Authority, Cemetary, City of Boston, Commonwealth of Mass, Gov’t Office Building, Medical Office, Office/Administrative Building,	303, 340-348, 350, 351, 353, 355, 369, 901-903, 906-908, 914, 924, 925, 945, 952, 954, 965, 973, 982, 983

			Religious Organization, Boston Housing Authority, Exempt 121A Property	
	Health Care - Inpatient	Medical/Lab/Production	Hospital	305, 958, 979
	Health Care - Outpatient	Medical/Lab/Production	Medical Clinic, Veterinary Hospital	307, 309, 953
	Mercantile - Enclosed and Strip Malls	Retail	Shopping Center	323
	Mercantile - Retail Other Than Mall	Retail	Boat House/Marina, Health Club, Retail Store, Retail/Office, Retail/Wholesale/Service, Service Plaza Retail, Showroom, Tennis/Racquet Club	310, 311, 319-323, 325, 330-335, 357, 374, 375, 384
	Food Service	Restaurant	Bar/Tavern/Pub, Fast Food Restaurant, Restaurant/Lounge, Restaurant/Service	326-329, 361
	Education	School	Day Care Use, School, Classroom, College, Private School	117, 352, 378, 904, 942, 976, 977
	Food Sales	Supermarket	Supermarket	324
	Warehouse and Storage	Warehouse	Ancillary Storage, Cold Storage Warehouse, Lumber Yard Storage, Repair Garage, Self-Storage Warehouse, Truck Terminal, Warehouse, Storage Area, Maintenance/Service Area, Utility/Equipment Building	312-318, 332, 949, 957, 963, 968
	Religious Worship	Worship	Church, Synagogue	379, 970

	Service	Retail	Auto Supply/Service, Car Wash, Gas Station, Laundromat, Laundry Facility	310, 311, 331, 333, 335
Residential	Single-Family	Single-Family	Single Family Dwelling, Residential Condo, Condo Parking	-
	Multi-Family	Multi-Family (2,3, 4-6, 7-30, 31-99, and >=100 units)	Apartment, Apt 100+ Units, Apt 31-99 Units, Apt 4-6 Units, Apt 7-30 Units, Apt Subsidized Housing, Assisted Living/Elderly, Dormitory, Residence Hall, Residential Condo, Three-Family Dwelling, Two-Family Dwelling	-
	Mixed-Use	Residential (Mixed-Use)	Residential/Commercial Mixed-use	-