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An Assessment on New York City's Energy Efficient Retrofitting Policies

Master Thesis Research

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Executive Summary

Global carbon emissions have been increasing exponentially since the 20th century, and have been one of the main contributors to global warming (Goodwin, 2014). The building sector is directly responsible for 28% of direct energy-related CO_2 emissions, with a third of it coming from fossil fuel combustion in buildings (Abergel, 2017). New York City (NYC) has recently passed legislation to lower its carbon footprint, approving a progressive legislation in 2018, the so-called Green New Deal (York, 2020). This legislation encourages all large, existing buildings (25,000 square feet or more) to implement retrofit measures by imposing emission caps and carbon tax. It also aims to achieve a 40 percent reduction in GHG emissions from covered buildings by the end of 2030 and an 80 percent reduction in citywide emissions by the end of 2050 (City of New York, 2020). The aim of this research is to create an impact assessment of how sustainable legislations (i.e., carbon tax and greenhouse gas (GHG) emission cap) could affect future retrofit projects from the perspective of optimal energy retrofit measures. The NYCECC energy codes were used as a guideline for the energy retrofit measures chosen during the building optimization process. All NYC's boroughs were assigned a building design and the optimal ERM configuration for each borough was found. An economic analysis for all boroughs was designed to examine the impact that the optimal ERMs in combination with the carbon tax, have on the NYC's built environment. The results of this research found that the optimal ERMs could lead to an annual energy reduction of 17% for certain buildings, and a CO_2 equivalent emission reduction of 94% for the city of New York. Additionally, the results found that for New York City to achieve their 2030 energy emission goals, 43% of the current NYC built environment shall be retrofitted by 2030. Lastly, this research learned that should be included to the NYC Green New Deal to ensure compliance and encourage retrofitting in the built environment.

Keywords: New York City, Green New Deal, Retrofitting, Carbon Taxes, Energy Retrofit Measures (ERMs)

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Chapter 1

Introduction

Global carbon emissions have been increasing exponentially since the 20th century, and have been one of the main contributors to global warming (Goodwin, 2014). CO_2 emissions have increased by 90% since 1970, with industrial processes and fossil fuel combustion being responsible for two-thirds of that increase (Edenhofer, 2014). Cities are other major contributors to CO_2 emissions and this can be linked directly to the high concentration of commercial and residential buildings, which because of its human activity, have a much higher operational energy use from heating, cooling and lighting (Abergel, 2017). The building sector is directly responsible for 28% of direct energy-related CO_2 emissions, with a third of it coming from fossil fuel combustion in buildings (Abergel, 2017). Many countries, such as the US, have acknowledged that buildings have become one of their largest emitters, and have started taking actions to lower their carbon footprint. The United States Department of Energy partly funds six regional energy efficiency organizations that work on accelerating and promoting energy efficiency techniques in commercial and industrial sectors (NEEP, 2020). These organizations have assisted US states on implementing carbon reduction goals for 2030 and 2050, with many cities projected to be carbon neutral by 2050 (NEEP, 2020). Every region has different strategies to achieve these goals, for example the northeast region has focused on improving building's energy efficiency, improving the grid's responsiveness to loads, and electrifying heating, cooling and hot-water systems (NEEP, 2020). However, for the Northeast region to achieve their goals, some challenges have to be overcome first. The lack of business and financial models for retrofit and electrification, has been a major obstacle for the private sector, as it has limited the knowledge over these technologies and has discouraged new development (Hopkins, 2017). Additionally, new state- and city-wide legislations have also influenced the private sector's future endeavors, since carbon taxing and stricter emission regulations are being implemented (Hopkins, 2017). For example, New York City (NYC) has recently passed legislation to lower its carbon footprint, approving a progressive legislation in 2018, the so-called Green New Deal (York, 2020). This legislation will mandate all existing large buildings to employ retrofit measures to increase energy efficiency and decrease their carbon footprint with the objective to reduce carbon emissions by 40% from a 2005 baseline by 2030 (York, 2020). The legislation also includes a carbon tax for every tone of carbon dioxide equivalent emitted that exceeds the maximum carbon emission allowed per year for a given building (Johnson, 2019). With the implementation of the Green New Deal and other sustainable legislation being passed state-wide in New York, carbon taxes have become one of the main concerns for building owners, as more than half of present high-rise buildings would be subjected to the carbon tax (Spivack, 2020). With stricter legislations becoming a norm, increasing research and broaden the knowledge of energy retrofit measures (ERM) will be an essential step forward to assist with the transition period the private sector will go through.

With the rapid increase of governmental support for energy efficiency in the last decade, multiple studies have been presented over how retrofit measures can reduce energy usage for buildings or houses. However, these studies have focused on the technical aspect of retrofit measures and how much energy these measures can save, yet they fall short on implementing a more detailed economic analysis, which could be used by stakeholders when planning on future projects. For example, a study has been performed on how heat pump technology can save energy for three different office buildings across different regions in Canada and has found that energy reduction is dependent on climate, building type and occupancy behavior (Chidiac, 2011). Although, (Chidiac, 2011) found improvements on the energy usage, it did not take into consideration on costs or local regulations. Similarly, (Huang, 2020) found that implementing the passive house standard (i.e., an international criterion for houses that have reached a certain level of quality, comfort and energy efficiency) to a high-rise building in northern china could have a 78.9% energy reduction. (Huang, 2020) performed an economic analysis which found that the project would have a payback period of 18.4 years, however this calculation was only based on initial investment and did not take into consideration any regulations or cap that could influence the feasibility of the project in the future. Furthermore, a study on San Francisco's office and retail buildings found that a 23-38% energy reduction can be reached when installing retrofit measures for lighting, heating, cooling, and air conditioning (HVAC) system and envelope (Chen, 2017). Similarly, to (Huang, 2020), a simple payback period was calculated for each retrofit measure individually, however it falls short of creating an economic analysis for the overall retrofit project. ERMs have been proven several times that their implementation can reduce energy usage dramatically, however, all of the studies have shown that there is a gap on implementing local legislations on their economic analysis. Hence, studying both the technical and economic aspects of a retrofit project simultaneously and implementing local regulations in the process, is vital to support government officials and stakeholders on their decision-making process for the future.

1.1 Problem Definition

With the implementation of the Green New Deal and other sustainable legislations being passed state-wide in New York, electrification and carbon taxes have become the main concerns for building owners. Understanding how these regulations influence the feasibility of retrofit projects and simultaneously analyzing which ERM performs the best will assist with the decision-making process of government officials and stakeholders. However, current New York building owners and investors have limited knowledge concerning retrofit technologies, since there have not been many retrofit studies based in NYC and energy auditing information has been behind, making it harder for stakeholders to invest in retrofit technologies (Hopkins, 2017). The lack of studies and research could also affect the Green New Deal, as NYC legislators have until 2023 to finalize its mechanisms and have allowed changes to occur if studies are performed until then (Arana, 2020).

The Green New Deal imposes a carbon tax and GHG emission cap that are meant to encourage building owners to invest on retrofit technologies. One of the strategies the Green New Deal has put in place is to encourage electrification and heat pump usage (York, 2020). By understanding the economic impact of how electrification and heat pumps effect the building's feasibility, would help lawmakers and companies to prepare for the future (Arana, 2020). Hence, it is necessary to have a clear understanding of how the Green New Deal policies could affect the NYC built environment both technically and economically.

1.2 Research Aim

There is a knowledge gap between the technical and economic steps when analyzing retrofit projects, as the economic analysis is overshadowed by the detailed technical analysis; hence, it falls short of providing an in-depth analysis on the project's feasibility. Additionally, studies neglect to include the consequences local laws and regulations have on the feasibility of retrofit projects. Therefore, the aim of this research is to create an impact assessment of how sustainable legislations (i.e., carbon tax and greenhouse gas (GHG) emission cap) could affect future retrofit projects from the perspective of optimal ERMs. The optimal ERMs are defined as the best configuration between a couple of retrofit measures, at which a trade-off is made between costs and CO_2 emission reduction. This research will take into consideration three different ERM's (lighting, HVAC and envelope) to recreate the private sector's decisions and understand how it will impact the built environment. The outcome of this research will demonstrate how these regulations are administered, alter the built environment, and the chosen ERM for a retrofit project.

1.3 Research Question

Based on the problem description, the following research question and sub-questions are introduced:

"To what extent will the policies of NYC's Green New Deal allow for the achievement of the deal's high energy efficient retrofitting targets from the perspective of optimal ERMs?"

In this instance, the policies analyzed will be the carbon tax and GHG emission cap imposed by the Green New Deal. The high energy efficient retrofit targets are goals that the NYC government intents for the city's build environment to achieve in the upcoming years.

1.3.1 Sub Questions

1. "How does the NYC government currently implement the Green New Deal policies towards achieving the higher energy efficient retrofitting targets?"

This sub-question clarifies what the Green New Deal policies are and explains how the NYC government plans to analyze and regulate the built environment when encouraging higher energy efficient buildings. The emphasis on electrification and heat pump usage set by the NYC's government and its auditing tactics are examined, indicating whether the NYC government's schemes fall-short of their targets.

2. "What is the optimal configuration of ERMs that can be applied in NYC based on the guidelines dictated by the Green New Deal?"

This information determines which ERMs would be the best suited, cost-effective and energy-efficient, for NYC's built environment based on the carbon taxes, GHG emission caps and other regulations imposed by the Green New Deal. This sub-question takes in mind that all five boroughs (The Bronx, Manhattan, Brooklyn, Queens and Staten Island) of NYC have different building structures and characteristics, however an overall ERM for NYC's built environment is determined.

3. "What will be the effect of the optimal configuration of ERMs on NYC's built environment in the following decades and will they be sufficient to achieve the Green New Deal's retrofitting targets?"

This sub-question utilizes the data from the aforementioned sub-questions and examines how they would impact NYC's built environment throughout the years. NYC's built environment is bounded by the five boroughs and is assumed that their characteristics will not change throughout the years. This information reveals the impact that the Green New Deal policies have on NYC's built environment and how the built environment will evolve in the following decades.

1.4 Relevance of the Research

The results can provide a basis for the NYC government and NYC's building sector to examine how the new regulations are being assessed and how they might influence the built environment. The implementation and impact of these regulations on the built environment have yet to be well documented. At the time of writing this research, only two studies on the NYC Green New Deal have been published, and they both focus on the enforcement and compliance to the law. This research went one step further, and analyzed how the regulations and the carbon taxes, will impact the NYC's built environment. The research indicates to what extend will these policies assist with lowering carbon emissions in NYC. Additionally, an optimal ERM configuration is proposed, which could assist the NYC government with electing which measures the city should encourage the private sector to invest in. Moreover, the NYC government has stated that the Green New Deal can be modified until 2023, therefore the outcomes of this research could help adjust NYC's current energy strategy. Lastly, the methods presented and the optimization results obtained can be a guide for future research that the NYC building sector or neighboring municipalities can utilize to assist with their carbon reduction strategies.

1.5 Outline

The remainder of this thesis is structures as follows. Chapter two introduces the theoretical framework which elaborates on the NYC policies and discusses the key technologies within this research. The next Chapter demonstrates the methodological approach performed in this research to answer the main research question. Chapter four includes the results for three main cases i) an assessment of the Green New Deal policies being implemented by the NYC government, ii) the optimal ERM configuration for NYC based on the guidelines imposed by the Green New Deal, and iii) an evaluation on the effect the optimal ERMs can have on NYC's built environment in the following decades. Thereafter, chapter five consists of discussing the results from chapter 4. At last, chapter six concludes the research and answers the research questions stated above.

Chapter 2

Literature Overview

This chapter contains three sections which are used as basis to the methodology chapter. Section 2.1 briefly explains the NYC sustainable targets and regulations that have been imposed in the last few years. The key technologies analyzed in this research are discussed in section 2.2, and are explored in further details individually. Finally, section 2.3 focuses on the optimization process used in this research: building structures, economic analysis and cost-development.

2.1 New York City Targets and Regulations

Legislation has become an imperative instrument to ensure environmental change in communities all over the world. It can include goals to which these communities aspire to reach or it can include regulations and taxations to encourage change (Wilkinson, 2016). Legislations are vital for governments to ensure their constituents take appropriate measures to achieve their targets, which is exactly what NYC's government aims to do. With the addition of multiple sustainable plans and laws being passed in recent years, OneNYC 2050 and NYC's Green New Deal, the NYC government has emphasized its commitment to fight global warming (Blasio, 2019). The OneNYC 2050 is a long-term strategic plan that aims to confront NYC's climate crisis. The OneNYC 2050 was created under Local Law 84 (LL84) of 2009, which requires "covered buildings" to benchmark their energy and water use every year and help to improve NYC's energy and water usage (Viverito, 2009). OneNYC 2050 also pursues to reach carbon neutrality by the year 2050, and encourages cuts in GHG emissions across all buildings (Blasio, 2019). On the other hand, the Green New Deal is a legislation that imposes stricter targets for the years 2030 and 2050. It mandates that all large, existing buildings (25,000 square feet or more) have to implement retrofit measures to ensure the total emissions from the built environment reduces by 10% by 2030 based on 2005's carbon emissions baseline (York, 2020). The Green New Deal also encourages the replacement of conventional heat and hot water systems in favor of efficient electric systems, which would assist in achieving the 2050 carbon neutral target (Blasio, 2019). Finally, the Green New Deal also bans the use of inefficient glass-walled buildings, encouraging the use of more energy efficient materials used on building facades (Blasio, 2019). These targets will ensure that the NYC government has a clear focus on the direction of the evolution of its built environment.

Targets are the first step to achieve change, although without the implementation of certain policies and taxations, the private sector would fall behind. Local and state-wide regulations are imperative to follow and acknowledge as they can influence product selection or overall cost estimates in the USA (Ben Arana, 2020). Regulations have become more important to developers in NYC, as new legislations have imposed GHG caps and carbon taxation. For example, NYC passed Local Law 97 (LL97) in 2019, which sets caps on GHG emissions for buildings in NYC. According to the LL97, every room in a building will have a maximum GHG emission limit based on the room's occupancy capabilities (Council Member Johnson, 2019). These caps will be implemented and lowered every five years starting from 2024 until 2050 (Council Member Johnson, 2019). The LL97 states that if a building exceeds its maximum annual emission limit, the owners will be charged $268/tCO2eq (Council Member Johnson, 2019). This emission charge has become a big concern for building developers and investors, as new designs and strategies would have to be taken to ensure their buildings do not exceed the annual emissions limit (Hopkins, 2017). Besides legislations, local building codes have to be considered, such as the 2020 Building Codes of New York State and city, which ensures all projects are being conducted safely. These policies incentivize the built environment to invest in higher energy efficient measures, which could lead the NYC government to achieve its 2030 and 2050's targets.

This research makes use of these policies in order to answer the research questions presented in chapter one. Additionally, a further analysis on these policies and how the NYC government is implementing and enforcing them is stated afterwards. Finally, these policies indicate which key technologies this research should focus on, which is described in more detail in the following sections.

2.2 Energy Efficient Measures

There are many different techniques to retrofit a building: optimizing building shape and form, refining building envelopes, enhancing efficiency, using alternative cooling and heating systems, and altering occupant's behavior and building operations (Harvey D. , 2009). However, these measures might influence different parts of the building, which could impact each measures' overall efficiency, therefore it is important to understand these measures in detail. The research will focus on three measures: building envelopes, HVAC systems and electrification, since these measures are being encouraged to be used by the Green New Deal. Building envelopes can be built with a range of materials that vary on quality and costs. Similarly, when looking at HVAC systems, there are several units and methods that can be used, from upgrading the boilers to installing heat pump units. Finally, electrification can be composed of different lightbulb options, more efficient housing appliances and control systems. In the following sections, energy efficiency, building envelopes, HVAC systems and electrification will be explained in more detail.

2.2.1 Energy Efficiency in Housing Complex

Maximizing the energy efficiency of a building is essential to lower its energy consumption and GHG emissions. Energy efficiency in a building can be improved by employing conventional measures to the constructional elements (building envelopes) and to operational systems (Heating, cooling, ventilation and hot water supply) (Diakaki, 2010). According to the Energy Information Administration, up to one-third of a typical apartment's heat loss is derived from the windows and doors (Carter, 2008). A quick fix is to install blinds or draperies to create a thermal barrier between the exterior and interior, however these barriers might limit the natural light during the day (Gloede, 2015). Replacing existing windows with low emissivity ones could cost 10-15% more than regular windows, but could reduce energy loss by 50% (U.S. Department of Energy, Window Types and Technologies, 2020). Poor insulation can also lead to heat loss in the building; therefore, installing insulation with higher thermal resistance will provide an effective resistance to the heat flow (U.S. Department of Energy, Insulation, 2020).

The effectiveness of the insulation is also dependent on the location of installation, as heat is often transferred through thermal bridging like: studs, joints and other building materials (U.S. Department of Energy, Insulation, 2020). The combination of these thermal bridges can lead to a building having a low Energy Star rating. This rating states that these buildings are performing worse than half of similar buildings nationwide, encouraging energy efficient retrofits to be implemented (Spivack, 2020). In NYC, large buildings (23,000 m^2 or more) were required to post the building's energy efficiency rating after October 2020, which led to half of the buildings getting a D Energy Star rating (Spivack, 2020).

2.2.2 Building Envelopes

Building envelopes are designed at an early stage and can greatly influence the energy performance of the building. Building envelope is the structural barrier between the outside and inside of the building; and is responsible for keeping the interior climate stable (Schenk, 2017). When retrofitting a building, some envelope structures can be modified, such as building structure, orientation, self-shading, height-to-floor-area ratios, window-to-wall area ratios, insulation levels and window properties (Harvey D. , 2009). Some of these elements are difficult to be altered for existing building structures or sometimes future projects, such as orientation. However, many of these elements can be improved effectively, which could reduce heating and cooling loads. Implementing high-performance thermal envelopes and passive heating can greatly reduce heating loads. Improving insulations in walls and ceilings, improving air tightness, and window and door properties, can be effective solutions to improve a building's efficiency.

In addition to lowering the heating load, improving building envelopes can reduce the cooling load as well. There are several ways to reduce cooling loads: orienting a building to reduce east-west sun exposure; utilizing neighboring buildings for self-shading; implementing fixed or adjustable shading; utilizing reflective materials; improving insulation; installing better performing windows; using thermal mass to reduce the interior's daytime temperature; making use of ventilation from outside to reduce the interior's nighttime temperature; and mounting efficient lighting and appliances (Harvey D. , 2009). Implementing these measures, singularly or in unison, can reduce cooling loads up to 50% compared to non-retrofit options; although this will all depend on the regional climate (Harvey D. , 2009).

2.2.3 HVAC systems

There are several passive and active ways to improve efficiency of HVAC systems in buildings. Implementing passive cooling techniques such as passive ventilation, evaporative cooling, desiccant dehumidification and Earth-pipe cooling, can reduce the cooling load, which in turn reduces the stress on the building's HVAC systems (Harvey D. , 2009). On the other hand, there are active techniques that can be used to increase efficiencies on heating and cooling equipment (furnaces and boilers, heat pumps, and air conditioners and chillers). In North America, old residential furnaces tend to have an efficiency between 60%-70%, while new equipment can have efficiencies between 78%-96%, offering substantial annual savings. Heat pump are the most promising solution though, as they can provide high COP performance (ratio between heat energy transferred to energy input) (Girard, 2015).

Heat pumps use the outside temperature to cool or heat the interior, which can be used both in winter and summer times (Hannah Licharz, 2020). As the COP increases a net savings in source energy can occur, especially when the energy source is provided by renewable energy (Girard, 2015). Regularly, heating and cooling circulate large volumes of warm and cool air throughout the building, but this air cannot be 100% reused, as it can be carrying contaminants. Therefore, fresh air has to be introduced to the system, after every cycle. Instead of introducing the fresh air in one place, utilizing displacement ventilation can reduce the HVAC systems energy use by 30%-70% (Harvey D. , 2009). Displacement ventilation introduces the fresh air in low speeds through many diffusers in the floor and sides, which rise to the top of the room as it is heated up by internal heat sources (residents and lighting) (Harvey D. , 2009). This allows the fresh air to be displaced throughout every room and heated up by other energy sources, which can save up to 40%-60% in cooling energy use (Harvey D. , 2009). Finally, introducing control systems that can test if all systems are functioning properly and efficiently, can save 15%-30% in energy use, with a payback period of 2 years (Claridge, 2001).

2.2.4 Electrification

Electrifying buildings is a way to shift the usage of fossil fuels for heating and cooling, to utilizing electricity to perform these tasks. NYC's goal is for all electrically powered buildings to be powered by renewable energy or other zero-carbon energy sources (Gerdes, 2020). Electrification can also increase flexibility when managing electric loads, foster economic development, improve air quality, and reduce electricity price fluctuation (Jeff Deason, 2018). Although, the biggest challenge is not for technical reasons, but economical, as fuel prices and capital costs are the main determinants when deciding on electrical or non-electrical options (Jeff Deason, 2018).

The most promising way to electrify heating and cooling systems, is to utilize heat pumps, as explained on section 3.3.2 (Ben Arana, 2020). Additionally, utilizing electrical stoves and ovens are important to electrify cooking units (Ben Arana, 2020). Improving lighting efficiency in a building can also be vital to reduce lighting energy use and there are three main strategies: efficient lighting systems, efficient lighting devices, and optimizing the daylighting intake. Replacing traditional incandescent to compact fluorescent lamps (CFLs) or light emitting diodes (LEDs), can lead to 25%-80% in energy reduction (Energy U. D., 2020). Efficient lighting systems can use separate controls for different zones in the building that can change independently according to the zones' light levels (Harvey D. , 2009). Lastly, optimizing daylighting intake yield up to 90% reduction on lighting energy use in rooms, when using fiber optics (Harvey D. , 2009).

2.3 Optimization

This section elaborates on the most common variables to optimize in the field of energy efficient retrofitting. The following definition of optimization is considered: an action of finding the most effective solution to a specific situation or resource (Optimization, 2021). There are a couple of key strategies for building design which are necessary to implement to achieve an optimal configuration. According to (Fullerton, 2016), there are three strategies to optimize a building design: use a modeling program, consider the needs of the project, understand the utility cost structure and total budget (Fullerton, 2016). The use of a modeling program ensures the possibility to correctly optimize a building system from an energy and utility bill perspective. Understanding the needs of a project is also critical to understand which systems and equipment should be considered that will provide the biggest efficiency and optimized performance. Finally, regarding the utility cost structure and total budget is an imperative strategy as it allows for a more accurate analysis of building performance and system selection. There are three optimization strategies used in this study: model optimization, building structure and orientation optimization, and optimizing cost-components. Considered strategies are presented in the next sections.

2.3.1 Optimization models

When analyzing optimal solutions for a retrofit project, a multi-objective optimization tool is often used. A multi-objective optimization is a vector of multi-criteria decision-making which uses mathematical optimization equations that include more than one objective function to be optimized simultaneously (Chang, 2015). Multi-objective optimizations are used for applications where one or more objectives might conflict with each other (Chang, 2015). There are various tools developed that advise building stakeholders with retrofitting decisions for energy savings. However, these tools are commonly focused on the technical feature of energy efficiency and lack details for the economic assessment (Chang, 2015). For example, TOBUS software, which was funded by the European Commission, provides an interactive tool for diagnosis and decision-making for retrofit in office buildings. It is comprised of seven modules which tackle different aspects of the retrofit assessment and incorporates investment costs (F. Flourentzou, 2002). It neglects to take into account future cash flows; however, which in turn decreases the feasibility of retrofit options that could significantly save energy in the future (Chang, 2015).

In addition to a multi-objective optimization tool, the assistance of building simulation software assists with the optimizing a retrofit project. There are various software programs that can perform this task, but few have been approved for governmental usage. According to NYC's energy conservation code (NYCECC), when conducting an energy analysis of a building, the software used must be EnergyPlus (NYCECC, 2020). EnergyPlus is a software that uses the energy management system data and includes an interface that converts the energy data into a useful format (Gürkan Kumbaroglu, 2012). This program ensures that building retrofit projects are modeled accurately under NYC's energy codes and standardizes the modeling approval process.

2.3.2 Optimizing building design and orientation

When attempting to optimize a building's design for retrofitting, several factors should be taken into consideration. The NYC government has created a guideline for optimizing high performance buildings, and came up with technical strategies to design and plan a building for new construction or retrofitting (Department of Design and Construction, 1999). According to the guidelines, the two main technical strategies to ensure maximal energy efficiency include optimizing site developments and energy use. This research will utilize these technical strategies when simulating NYC's built environment and optimal ERM configurations. The technical strategies for optimizing site developments are: analyze urban/historical context, general site layout, and improved environmental quality (Department of Design and Construction, 1999).

Analyze urban/historical context

It is necessary to analyze urban/historical context as it will respond to the cultural issues a project faces, such as: inventory infrastructure and utilities, identify construction constraints, and examine the neighborhood's architectural style

General site layout

Studying the general site layout is important as it defines the location of where the building mass should be situated, the architectural design and orientation the project should utilize, and sun and shading patterns the site might endure.

Improved environmental quality

Coordinating building envelope, windows, light intake and airflows are necessary to improve environmental quality of the project. Additionally, the guidelines also refer to optimizing the building's energy use. There are several ways to lower energy use in a retrofitting project, however the guidelines emphasize on seven main technical strategies, which are listed below (Department of Design and Construction, 1999):

Interior layout/spatial design

Interior layout/spatial design can reduce energy consumption and promote use of passive solar heating and cooling (see section 2.2.2). This strategy can do so by optimizing the HVAC system, and optimize natural ventilation and daylighting.

Optimizing the building envelope

Optimizing the building envelope can improve thermal and moisture control by appropriately assembling walls, roofs, and window materials (see section 2.2.2).

Controlling daylight and direct sun intake

It can alleviate charges during peak demand, since by optimizing sunlight intake, it reduces the interior lighting load and operating costs (see section 2.2.2).

Installing/upgrading electrical systems and equipment

Installing/upgrading electrical systems and equipment can increase the building's energy efficiency, leading to reduction in energy consumption and associated costs (see section 2.2.3).

Examine energy sources

The project might be connected and use different energy sources based on location or design, such as oil, natural gas, and electricity. The guidelines highlight that a project should primarily work on conservation techniques, and rely on fossil fuel technologies as a last resort.

Optimizing mechanical systems

Mechanical systems include boilers and chillers, which by distributing them accurately throughout the building, utilizing correct sizes and equipment, can lower the dependency on fossil fuels.

Managing the energy load

Continuous maintenance and calibration of the mechanical systems optimizes the life and performance of the systems, which minimizes the use of fossil fuels

These technical strategies included in NYC's high performance building optimization guideline have cost-components attributed to them, which this research takes into consideration. The costs related to these strategies and retrofitting projects in NYC are presented in the next section.

2.3.3 Optimizing cost-components and cost-development for retrofitting

Understanding the market behavior of the different retrofit measures could determine the future growth and direction of these measures in the USA. Analyzing these behaviors will set the ground work for the economic analysis in order to estimate the impact these measures could have on the future NYC's built environment. In order to create an accurate economic analysis, understanding the corresponding cost-components and cost-developments, for a retrofit project is necessary. For any retrofit project, the following cost-components should be taken into account during their lifecycle when performing an economic analysis (Sigrist, 2019):

Investment costs:

- Planning costs
- Permission procedures costs

Retrofit strategies costs:

- Installation cost
- Grid connection costs
- ERM costs

Operational and maintenance (O&M) costs:

- Energy price
  - Electricity
  - Gas
  - Oil
  - Steam
- Interest rate

Tariffs:

- Carbon tax

In the next sections, an elaboration on these components, and its corresponding cost-components and cost-developments is provided.

Fuel Prices

Apartment buildings usually consist of appliances and systems that utilize multiple fuel sources simultaneously. This can lead to the city having to ensure connectivity from certain fuel sources to desired buildings, which can lead to higher maintenance costs (Department of Design and Construction, 1999). Therefore, as stated aforehand, the NYC government decided that all buildings should be powered 100% by electricity by 2050. This target can lead to cost fluctuations for many fuel sources. There are three main fuel sources in NYC: oil, natural gas, and electricity (EIA, New York State Profile and Energy Estimates, 2018). The cost components for these fuel sources are shown in Table 1.

Table 1 Fuel Sources used in NYC and their cost components

Fuel Type	Cost	Unit
Oil	2	**$/gal**
Natural Gas	0.0089	**$/kBtu**
Electricity	0.040	**$/kWh**

Many experts are wary of the rapid push by the NYC government to electrify all buildings, as it could result in a sharp increase in electricity prices for the first few years, until the electricity grid is upgraded to comply with the increase in demand (Hopkins, 2017). The price of oil should remain similar to the average US interest rate for the near future, as oil prices are not decided by local governments (EIA, Oil and petroleum products explained , 2021). On the other hand, natural gas cost has been decreasing in the last decade, and reached a record low in 2020, however the World Bank predicts that with the increase for demand in the upcoming years, the price for natural gas may increase (MET, 2020).

Envelope

Retrofitting envelopes can lead to high energy savings, however it can be one of the most manually intensive retrofit measure, which could impact the overall costs (Hutchinson, 2012). As discussed in section 2.2, retrofitting envelopes can consist of multiple measures, however the four most common measures performed in the Northeast United States is to restore cladding, replace windows, roof upgrade and improve air sealing. All of these measures have different costs attributed to them, Table 2 their average costs in the USA (RSMeans, 2021), (Robinson, 2018), (Leo B, 2020), (Fixr, 2018).

Table 2 Envelope Retrofitting Measure Costs (USD) per Square Meter.

Envelope Retrofitting Measure	**Costs ($/ft^2)**	**Costs ($/m^2)**
Cladding (EIFS)[1]	6.86	73.84
Windows replacement[2]	29.29	315.27
Roof replacement[3]	10	107.64
Air sealing (Rigid foam)[4]	0.50	5.38

Sources: 1. (RSMeans, 2021)*, 2.* (Robinson, 2018)*, 3.* (Leo B, 2020)*, 4.* (Fixr, 2018)

When investigating the future costs of these measures, an expected rise in prices is found, which can be linked to an increase demand for envelope retrofitting materials (RICS, 2021). The cost for cladding has increased by an average of 8% in the last few years (RICS, 2021). On the other hand, the increase demand for window replacement, roof replacement and air sealing have not impacted their average costs as much, although future predictions indicate that these measures will increase in price in relation to the US real interest rate of 3.8% (Bank, 2018).

HVAC

HVAC systems are usually very costly and can vary on installation costs based on the building's original structure, as for example, converting central heating to localized heating could require additional constructional work and materials, which increases costs (Sigrist, 2019). There are multiple ERMs intended to improve HVAC efficiency, however the most commonly used measures in the northeast region of the USA are: steam system repair, central boilers, hydronic systems, heat pump systems, and VRF systems (Pesce, 2021). Table 3 illustrates the present-day average costs for these measures in the US.

Table 3 Present-day average costs for HVAC retrofitting measures

HVAC Retrofitting Measure	**Costs**	**Unit**	**Costs**	**Unit**
Steam system repair[1]	0.87	**$/ft^2**	9.36	**$/m^2**
New central boiler[1]	152,493	**$/building**	152,493	**$/building**
Hydronic system (steam to hydronic)[2]	733,153.56	**$/building**	733,153.56	**$/building**
Heat pump (steam to heat pump)[3]	11,102.88	**$/building**	11,102.88	**$/building**
VRF (steam to VRF)[4]	33,645.1	**$/building**	33,645.1	**$/building**

Sources: 1. (Pesce, 2021)*, 2.* (RSMeans, 2021)*, 3.* (HomeAdvisor, 2021)*, 4.* (IEA, 2020)

Future cost estimates vary between these measures, as some of these measures are becoming more frequently used, while some are vanishing slowly because of new regulations (EHPA, 2018). Steam system repairs and central boiler systems are not predicted to experience any drastic price variation throughout the years, and should just increase with the United States' real interest rate of 3.8% (IdealHeating, 2020). On the other hand, hydronic systems, heat pumps and VRF systems are expected to encounter a rise in demand, which could lead to reduction of installation costs, which could make up around 30% of total capital costs in heat pump systems (EHPA, 2018). Besides installation costs, operation and maintenance costs have to be taken into consideration as they could impact the payback period of the beforementioned measures. O&M costs consist of the cost for fuel to power these measures and a life expectancy of these measures is linked to calculate the frequency of replacement. Table 4 demonstrates the O&M costs for the HVAC retrofit measures and the corresponding life expectancy (RSMeans, 2021), (EIA, Oil and petroleum products explained , 2021), (U.S. Department of Energy, Calculate the True Cost of Steam, 2014).

Table 4 Operation and maintenance costs for HVAC retrofit measures

HVAC Retrofitting Measure (Fuel)	O&M Costs	Units	Life Expectancy (years)
Steam system repair (Oil)[1]	2	**$/gal**	10
New central boiler (Oil)[1]	2	**$/gal**	12.5
Hydronic system (Natural Gas)[2]	.0089	**$/kBtu**	20
Heat pump (Electricity)[2]	.040	**$/kWh**	15
VRF (steam to VRF)[3]	.040	**$/kWh**	10

Sources: 1. (EIA, Oil and petroleum products explained , 2021)*, 2.* (RSMeans, 2021)*, 3.* (U.S. Department of Energy, Calculate the True Cost of Steam, 2014)

Electrification

As mentioned in section 2.2.4, electrification can lead to energy savings; however, it could be the least costly option as some measures can be performed without the need of experts. As stated in section 2.2.4, heat pump is a common measure of an electrification retrofit measure, however this research attaches it to an HVAC measure. Additionally, to heat pumps, other electrification measures can be performed to achieve energy savings the northeast region of the United States, the most common measures used are: lighting replacements (common areas and apartment), refrigerator replacement and electric sub-metering (Pesce, 2021). The O&M costs are assumed to be the electricity usage cost. Additionally, for electricity sub-metering, a monthly operational cost of $4 per apartment unit is added for maintaining the equipment (Iannucci, 2014). The costs for these measures do not have any expected initial cost rise in the upcoming years (Pesce, 2021). Table 5 states the cost components for each measure and their corresponding life expectancy.

Table 5 Cost components for electrification retrofit measures and their corresponding life expectancies

Electrification Retrofitting Measure (Fuel)	Costs	Unit	Life Expectancy	Unit
Lighting replacement (Common area)[1]	0.21	**$/ft^2**	10,000-50,000	hours
Lighting replacement (Apartment area)[1]	0.39	**$/ft^2**	10,000-50,000	hours
Refrigerator replacement[2]	700	**$/refrigerator**	14	years
Electric sub-metering[3]	1000	**$/apartment unit**	10	years

Sources: 1. (Energy U. D., 2020)*, 2.* (Pesce, 2021)*, 3.* (Iannucci, 2014)

The policies discussed, the key technologies and the optimization variables are all used on chapter three, when conducting the methodological approach to answer the research questions.

2.4 Policy Compliance and Enforcement

Practically 80 percent of NYC's emissions are ascribed to buildings' energy use, which has caused the NYC government to pass legislations encouraging new sustainable technology and an unprecedented commitment to increase the sustainability of buildings (City of New York, 2020). As stated in section 2.1, LL97 was passed in 2019 by the NYC council as part of the Green New Deal. LL97 will further the target of achieving a 40 percent reduction in GHG emissions from covered buildings by the end of 2030 and an 80 percent reduction in citywide emissions by the end of 2050 (City of New York, 2020). For the city to achieve its targets, buildings have to follow multiple energy codes and regulations, and the government has to inspect its progress through reporting and auditing. The following sections will examine the ways the NYC government plans to enforce, report and encourage compliance of this new law.

2.4.1 NYC Energy Conservation Code

According to New York States Energy Law, the city of New York is authorized to enact its own energy code, as long as it is more stringent than the State level code (de Blasio, 2020). The New York City Energy Conservation Code (NYCECC) has been regulating the city's buildings since 2009 (de Blasio, 2020). The code has been updated throughout the years, but in 2020 it was updated to align with Mayor Bill de Blasio's OneNYC plan (see section 2.1), which demands for development and implementation of "world class green building and energy codes" (de Blasio, 2020). According to Local Law 85 of 2009, any revision to the NYCECC has to meet current requirements or be more stringent, as this will ensure NYC's commitment far into the future (de Blasio, 2020). There are several energy codes that residential and industrial buildings have to follow. However, this research will focus on four residential energy efficiency codes that the NYCECC mandates: insulation, air leakage, controls and lighting. These regulations are necessary to ensure that buildings are compliant to the NYC's energy codes and allows the city to standardize the built environment.

Insulation and Fenestration

According to NYCECC, a residential building's thermal envelope shall meet certain U-factors and R-values based on their climate zones. When computing the R-values, if insulation materials are installed in layers, such as framing cavity insulation or continuous insulation, the R-values for each material should be summed up. The insulation materials have to be installed in a way where the R-value mark is observable by inspectors. Fenestration U-values for windows, glass doors and skylight have to be determined the NFRC 100 (National Fenestration Rating Council) and labeled and certified by the manufacturer. By standardizing and labeling the R-values and U-values, the NYC government ensures that its built environment uses similar, energy efficient, materials.

Air leakage

The building's thermal envelope has to be constructed in a way where air leakage is limited, and the sealing method between different materials shall allow enough space for different expansion and contraction of the materials. Standardizing energy codes for air leakages and mandating inspections, encourages the built environment to follow the regulations, increasing overall compliance in NYC's built environment. An energy code present in the NYCECC related to air leakage states that a continuous air barrier has to be present in the building envelope, including exterior thermal envelopes, and breaks and joints have to be sealed off (NYCECC, 2020). Also, that insulation installed shall fill the cavity filled uniformly without leaving any substantial air gaps. To ensure compliance, a building official, and an approved third-party inspector, shall inspect all components and verify the building's compliance to the regulations (NYCECC, 2020). The inspectors shall perform tests for the building or individual dwelling units, and air leakage rate should not exceed more than three air changes per hour (volume of air added or moved from a space within one hour) (NYCECC, 2020). When buildings have more than seven dwelling units, a group of sample units (not more than seven) shall be chosen and the air leakage of each sample unit should not exceed more than 0.3 cubic feet per minute per square foot (NYCECC, 2020).

HVAC System Controls

NYCECC includes criteria for system controls for multiple areas of the building, this ensures buildings are subjected to a minimum amount of energy control and reporting. By creating a baseline for the built environment to follow, it ensures the NYC government that accurate energy reporting will be received to them. The NYCECC, states that at least one thermostat shall be provided for each separate heating and cooling system (NYCECC, 2020). A thermostat controlling the heating or cooling system has to be able to maintain different temperatures setpoints throughout the day, to ensure a constant room temperature (NYCECC, 2020). The thermostat should also be able to operate and maintain temperatures between 55°F (13°C) and 85°F (29°C) (NYCECC, 2020).

Lighting

Lighting systems are also listed in the NYCECC to ensure lighting quality in buildings and increase daylight intake. This ensures the government that the built environment is installing proper lighting, in a safe and efficient way. Creating certain codes ensures that the built environment complies to the government's energy targets. NYCECC states that not less than 90 percent of lighting fixtures installed permanently shall use lamps with an efficacy of 65 lumens per watt, or a 45 lumens per watt total luminaire efficacy (light output divided by the total power consumed). Additionally, every individual dwelling unit shall have their individual electric energy consumed report.

2.4.2 Compliance

The NYC Benchmarking Law passed in 2016 as Local Law 133, requires building owners to annually measure their energy and water consumption. The law standardizes the process by utilizing the Energy Star Portfolio Manager tool, which facilitates online submissions. The failure to submit leads to a financial penalty, creating an incentive for the built environment to comply. The data gathered increases transparency in annual energy and water usage, setting a foundation for building owners to improve the building's efficiency. The Energy Start tool also includes a rating which compares building's energy performance with similar buildings in similar climates. LL97 utilizes these ratings to calculate the GHG emission cap and visualize if the built environment is compliant. The energy ratings include both letters and numbers to illustrate the building's energy efficiency, which is shown below:

- A – score is equal to or greater than 85;
- B – score is equal to or greater than 70 but less than 85;
- C – score is equal to or greater than 55 but less than 70;
- D – score is less than 55;

- F – for buildings that didn’t submit required benchmarking information;
- N – for buildings exempted from benchmarking or not covered by the Energy Star program.

If a building fails to submit its energy and water usage in time, may result in a $500 initial penalty, which can reach $2000 per year of failure to submit. Additionally, if the building fails to display the Building Energy Efficiency Rating label, a $1250 fine can be given. Mandating energy labels to be displayed to costumers, allows the public to encourage the built environment to improve. Additionally, penalizing the built environment for non-compliance, also motivates change.

Additionally, GHG emission reporting was stablished by LL97, which states that all, covered buildings, have to report their annually GHG emission every year, starting on May 1, 2025. LL97 enforces GHG emission limits for a certain occupancy space group and the area of the unit. There are ten different occupancy groups (i.e. Assembly, Business, Factory, Residential, etc.), which are separated since they serve different functions and may be designed differently. Residential occupancy groups are divided in two types, R-1 and R-2. Group R-1 include temporary abodes, such as hotels, boarding houses, and college dormitories. Group R-2 includes buildings containing sleeping units of permanent resident purposes, such as apartment houses and apartment hotels. Emission limits for residential buildings (R-1 and R-2) for the calendar years 2024-2029, 2030-2034 and beyond 2034 are show on Table 6.

Table 6 GHG Emission Limit for Residential Buildings

Occupancy Group	Emissions Intensity Limit (tCO2e/sf/yr)	Multiplied by	Gross Floor Area (sf)	Year
R-1	0.00987	x	Unit size	2024-2029
R-2	0.00675	x	Unit size	2024-2029
R-1	0.00526	x	Unit size	2030-2034
R-2	0.00407	x	Unit size	2030-2034
R-1	0.0014	x	Unit size	beyond 2034
R-2	0.0014	x	Unit size	beyond 2034

Building GHG emission limits after 2034 will be reviewed later on by the energy department, however the limit revised cannot be over 0.0014 tCO2e/sf/yr. In case the building exceeds the limit shown on Table 6, a civil penalty of $268 per tCO2e/sf/yr will be given starting in 2025. The carbon taxes ensures that the built environment is properly penalized for emitting high levels of GHG to the atmosphere. Hence, encouraging compliance from the built environment to invest on more energy efficient measures.

2.4.3 Inspections

To ensure that the building owners are filling accurate energy usage reports and GHG emission reports, random inspections by governmental agents are required, so called energy audits and retro-commissioning. Energy audits is a tactic that the NYC government employs, which purposefully identifies opportunities to reduce energy usage without negatively affecting operations. While retro-commissioning inspects that the energy systems installed follow design intentions, functionality test and O&M capabilities. The Energy Audit report and Retro-commissioning report have to be filled once every ten years, according to the building block, and can be submitted through online tools provided by the city.

Buildings that are greater than 50,000 square feet are required to comply to inspections, which costs $375 per inspection. However, if they fail to have an Energy Efficient Report, a $3000 fine will be given for the first year, and a $5000 fine for each year after that.

These regulations and codes have been put in place to ensure that NYC's built environment develops sustainably throughout the next decades and are meant to assist with NYC achieving their 2030 and 2050 energy targets.

Chapter 3

Methodology

This research aims to identify to what extent will the NYC government achieve its high energy efficiency retrofitting targets by implementing the Green New Deal. To answer the main question, it is necessary to identify the optimal ERM configuration for typical buildings in NYC and understand how the built environment will be affected by the optimal ERM configuration. The first step was to determine the location and architectural building style for each New York borough, which is described in section 3.1. The second step was the collection of geographical and structural data from literature review, industry, and municipality, detailed in section 3.2. The next step was to create an energy model based for each building analyzed with the respective materials and operation times, which is discussed in more detail in section 3.3. In section 3.4, an optimization method was used to find the optimal ERM configuration (see section 2.3). Section 3.5 examines how much CO_2 emissions each building emitted. Finally, an economic analysis for the typical buildings with the optimal ERM configuration was performed, detailed in section 3.6.

3.1 Location and architectural style selection

The first step was to select the locations that this research will use to model the typical buildings. NYC is divided in five different boroughs (Manhattan, The Bronx, Queens, Brooklyn and Staten Island), which all have different architectural styles and area limitations. Manhattan is the most densely populated borough, which has caused buildings to be vertically high, and horizontally narrow. The Bronx, Queens and Brooklyn have a similar architecture style, which is a medium-rise multi-family complex building. Finally, Staten Island is known for its suburban look and more prevalent open areas. Therefore, this research picked three architectural styles to represent typical NYC buildings, a high-rise building located in Manhattan, a medium-rise multi-family apartment building located in Brooklyn, and a one-family sized house located in Staten Island. Further discussion on each building's architectural designs will be presented in section 4.1.

3.2 Data Collection

When modeling the energy use of a building in NYC, multiple data are gathered beforehand and used as inputs. These data consist of both geographical and structural data used for the 3D building modeling phase, which allows the program to properly calculate the energy use of the analyzed building. The geographical data is used to link the simulated building to a real location and the correct local weather. The structural data is vital to gather, as it will allow for a realistic modeled building to be designed. Structural data include construction materials, designs and electrical equipment which are commonly used in NYC buildings. Additionally, information on internal mass for each room, and schedules for the operation time and frequency of electronic equipment and human behavior are gathered. Data on internal mass are used to properly simulate the effect furniture and humans have in a room. While data on schedules for electronic equipment and human activity, is vital to model the daily, weekly, and annual energy use. Finally, data on the HVAC systems, hot water systems and electrical load was found and used to properly calculate the energy use. Since HVAC systems vary on fuel type, emissions and power output (see section 2.2.3), utilizing accurate data is necessary to achieve realistic results.

3.2.1 Location parameters

The initial data collected were geographical information for each building . The latitude, longitude, elevation, orientation and time zones were acquired from ASHRAE, the American Society of Heating, Refrigerating and Air-Conditioning Engineers. The weather data are derived from meteorological conditions from 1990-2005 and is used as parameters for the winter- and summer-design days, which were also provided by ASHRAE. Ground temperature and water mains temperature were also provided by ASHRAE, which vary throughout the year based on the season. Each typical building was designed structurally different, to match with their borough's location, therefore data was collected from Facilities Strategies Group (FSG), a NYC based company that work directly with building retrofit projects, for average number of rooms and average room sizes, for all three buildings.

3.2.2 Construction materials and equipment

The three buildings that were modeled are built using different materials and construction styles. ASHRAE provides typical construction materials used for high-rise buildings, small multi-family buildings and houses. The materials gathered were used to model the envelope for all three buildings. The data gathered to model envelope includes materials for the exterior walls, interior walls, ground floor, ceiling, roof, windows, window shading, and doors. A detailed table with the materials used for the envelope is found on Appendix A.

Additionally, electrical equipment was gathered and was included in the modeled buildings. The electrical equipment includes lights for the apartments, corridors and exterior settings. Additionally, electrical outlets, elevator, and elevator lights were also included. Data for the lights include the lighting level of the lightbulb, while power output was found for electrical outlets and elevator.

3.2.3 Internal Mass and Scheduling

Data was found for the internal mass for all three buildings, which was included to the building modeling. The internal mass used include furniture and amount of people per room. Since these amounts vary between every building, an assumption for the average input for both cases was used. The furniture was assumed to be mostly constructed from wood, while the amount of people was assumed to be 2.5 people per room.

Besides internal mass, the weekly and annual schedule for all devices and people were found. Every electrical device, hot water usage and human occupancy vary throughout the week at different times and at different frequencies; therefore, creating different schedules is necessary to include in the modeling. Typical schedules for electrical devices and human behavior were provided by ASHRAE. Lighting schedule for the living spaces vary throughout the day, as lighting usage is increased during evening hours compared to afternoon hours. Similarly, apartment occupancy varies throughout the day as people leave their homes during the day and stay home during the night. Table 7 demonstrates the schedules gathered and used in the building modeling.

Table 7 Schedules gathered from ASHRAE and their corresponding frequency

Schedule Name	**Frequency**
Apartment Lights	Hourly
Exterior Lights	Daily
Corridor lights	Daily
Elevator light	Daily
Elevator Usage	Hourly
Winter Design Day Heating Temperature	Hourly
Summer Design Day Cooling Temperature	Hourly

3.2.4 HVAC Systems, hot water systems and electric load

HVAC system data was provided by ASHRAE and include information for the air-conditioning, furnaces, boilers and heat pump systems. The data included aspects for the COP for each system based on their cooling and heating capacities. Similarly, the central boiler data was provided by ASHRAE which includes the nominal capacity and fuel type. Finally, electric load was also provided by ASHRAE. This includes the transformer used in each building which considers the rated capacity of the transformer to transmit the power from the grid to the building.

3.3 Typical building modeling

The EnergyPlus (version 9.2.0), energy simulation program, was used to model the energy use for all three buildings. The EnergyPlus program utilizes the data gathered from section 3.2 and calculates the energy profile of the modeled building. The EnergyPlus model is described in Figure 1.

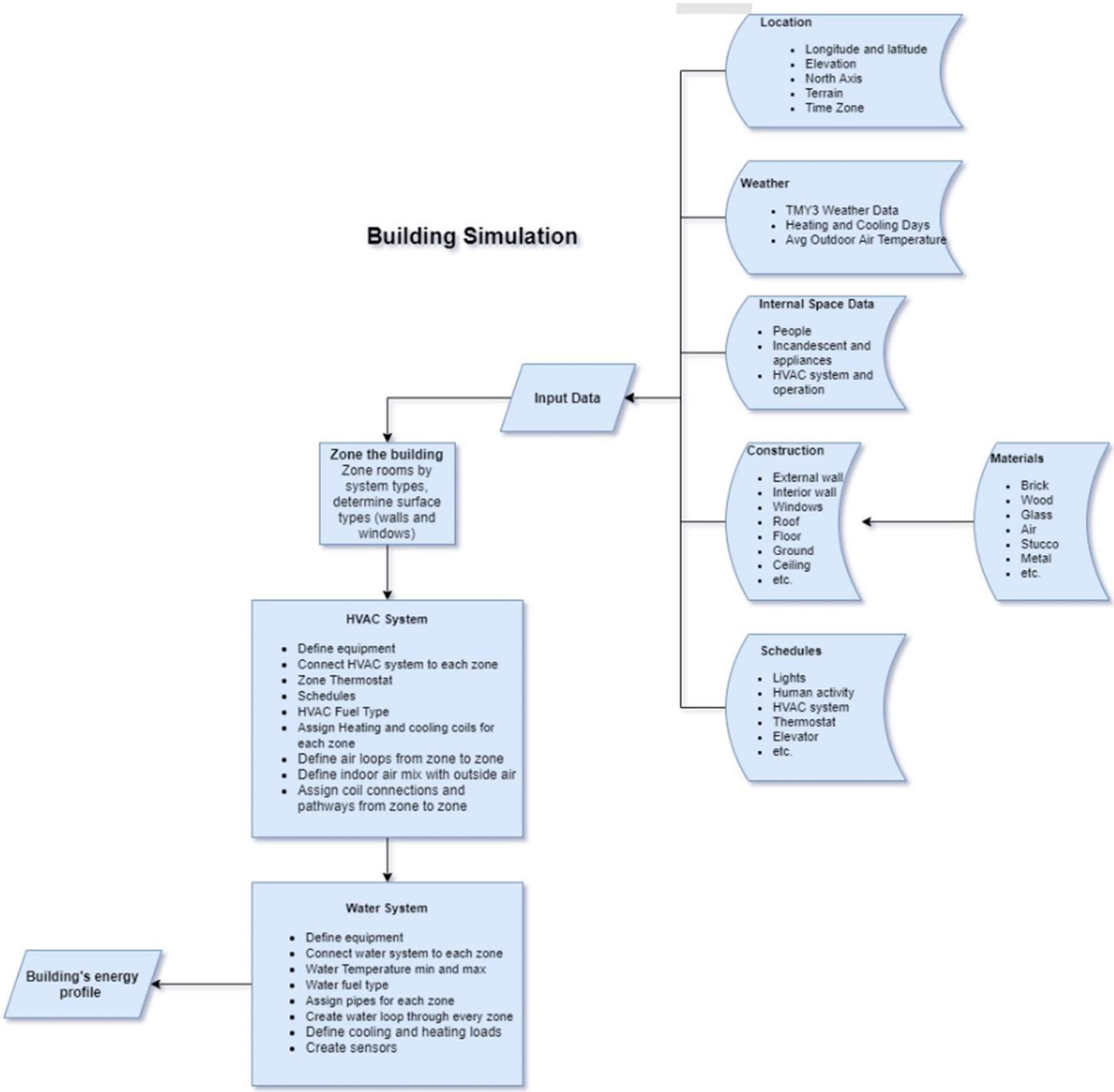

Figure 1 Flow diagram of the EnergyPlus model

As Figure 1 shows, the first step was to add the building's geographic location, and terrain type. The weather data gathered in Section 3.2, for each location, is added to the model, as well as inputs to develop the winter and summer design days. For the site weather input, building surface average temperatures and water mains temperatures were added. Since radiation, solar irradiance and cloud coverage varies throughout the day, multiple weather modeling algorithms are used to simulate these conditions: Convex Weiler Atherton, Simple sky diffuse modeling, TARP, DOE:2 and Conduction transfer function. Convex Weiler Atherton is an algorithm model developed in 1977 to calculate shadows that a polygon would create based on the solar position. Simple sky diffuse modeling calculates the diffuse solar radiation on an exterior surface by taking anisotropic radiance distribution into account. The anisotropic radiance distribution is determined by the surface orientation, sky radiance distribution, and shading. The sky radiance distribution is based on a real skies empirical model developed by Perez et al., 1990, which considers the isotropic distribution of the earth's circumference, solar position and horizon brightening. TARP is a shadow algorithm used to calculate the areas that receive direct sun and which areas would be shaded, depending on the building's shape and solar position. DOE:2 is a heat transfer convection algorithm used to calculate the radiation and convection coefficients for outside surfaces. Conduction transfer function is a module designed to calculate the heat transfer that occurs between outside and inside surfaces.

To model the envelope elements used in the buildings, the construction materials gathered in section 3.2 were used. The materials are added to the EnergyPlus model individually, starting from the outside layer and moving to the inside layer of each element, simulating how the real envelope would be constructed. This is done for all envelope objects: window, window shading, doors, walls, roof and ceilings.

The next step consists in adding the envelope elements to the specific zones (rooms and corridors) that these elements are related to. Each envelope element is then attributed to the specific location for each zone, and their X, Y and Z coordinates are specified. The internal mass, amount of people, lights and electrical equipment is added to the model during this phase. Schedules for both human behavior and electricity usage are included to their specific elements.

Information over air exchange throughout the building is then added to the model. Flow rate from infiltration that can occur from cracks in the envelope is simulated based on typical air flow rate, infiltration schedule and average wind speed given by ASHRAE. Air loops between each zone and the outside air is defined and supply air pathways from heating and cooling systems are specified for each zone. These pathways are created using connectors and nodes that illustrates how each zone is connected with air and water supplies, and define which zones the air and hot water will go through between the inlet and outlet connections of each system. The HVAC systems and hot water systems are specified based on their capacity, fuel type, cooling and heating loads, and efficiency. The temperature and water usage schedules are attributed to their respective systems during this step.

3.4 Optimal ERM configuration

To determine the optimal ERM configuration, a python code was written to connect the EnergyPlus software to Excel Solver tool. The first step was to isolate the materials and systems that are being optimized on the python code. This was done by using the eppy package, which allows python to run, identify and modify EnergyPlus files instantaneously.

The data above is put on different dictionaries on python, depending on their zones. A loop is then created to run the EnergyPlus model, which exchanges each material during every interaction, allowing every combination to be calculated. Afterwards, the EnergyPlus results on python are sent to an excel file, where the Excel Solver tool finds which combination resulted in the lowest energy use for each building, and the optimal configuration for each building is found.[1]

The combinations generated are used as the first step on understanding the effects that each ERM have on buildings in NYC. However, these combinations do not have any economical parameters attributed to them yet, which is covered in the next section.

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[1] The entire pyhton code for each building can be requested by email

3.5 CO₂ Emissions

Calculation of the total CO_2 emissions each building emits throughout the year is calculated using a general emission equation provided by the United States Environmental Protection Agency (EPA). The general equation calculates the CO_2 emissions from fossil fuel combustion and is demonstrated in Equation 1.

Equation 1 CO2 Emission Equation

$$\begin{aligned} Emissions\ (tCO_{2\,eq}) &= Consumption\ (GJ) \times Emission\ Factor\ \left(\frac{tCO_2}{GJ}\right) \\ &\times Combustion\ Efficiency\ (\%) \qquad Eq.1 \end{aligned}$$

(EPA, Energy Resources for State and Local Governments, 2020)

Based on the results of section 3.4, six configurations will be chosen that reflect the most with the decision of the NYC built environment. Using excel, the energy consumption for the electricity and natural gas fuel sources are added to equation 1. The emission factor in New York was provided by the EPA and is also added to the excel. The combustion efficiency accounts for the end-use emission distribution, which accounts for the losses attributed to the residential and transportation energy sectors. The emissions for these six configurations are calculated and used in section 3.6.

3.6 Economic Analysis

An economic analysis was conducted to validate the results and understand the impact of the costs these ERM configurations will have on the NYC built environment. The optimal ERM configuration from section 3.4 were used, since this configuration were the best possible solution for the NYC built environment to lower their energy use. The economic analysis relies on the NPV calculation for the optimal configuration of each building up to the year 2030 and 2050. It includes initial investment costs, maintenance and operation costs, electricity costs and CO_2 emission costs. The NPV calculation takes into consideration the initial investment cost (*I*), annual costs (*C*), capital recovery factor (*a*), discount rate (*r*), and life time (*n*) (Blok, 2017). There were no benefits added to the NPV equation since this research is focused on the impact the ERMs have on the total costs and not on how the built environment might be profitable. The NPV and capital recovery factor equations used are stated below:

Equation 2 NPV equation

$$NPV = -I - \frac{C}{a} \qquad \textit{Eq. 2}\ \text{(Blok, 2017)}$$

Equation 3 Capital recovery factor equation

$$a = \frac{r}{1-(1+r)^{-n}} \qquad \textit{Eq. 3}\ \text{(Blok, 2017)}$$

Where initial investment costs are compromised of the initial material and installation costs. Annual costs consist of operation and maintenance costs, electricity costs and CO_2 emission taxes. The CO_2

emission taxes are included based on the different GHG emission constraints imposed by the LL97 for their corresponding years.

The carbon taxes were calculated based on the excess emissions that the buildings produced from the emission cap given by the LL97. Using excel, the emission caps for each building were calculated by multiplying the emission intensity limit imposed by the LL97 to the total building's area. The emissions calculated in Section 3.5, were then compared to the emission cap found, and if the building emitted more than the emission cap allowed, \$268 per tCO_2 equivalent was multiplied to the excess emissions.

Chapter 4

Results

This chapter describes the results from the EnergyPlus for the three NYC buildings and the economic analysis for multiple ERM configurations. Section 4.1 describes the results of the building design for all three boroughs. Section 4.2 describes the results of the energy use for each ERM for the Staten Island house, Brooklyn mid-rise building and Manhattan's high-rise building. Section 4.2.1 describes the energy use for the Staten Island house and results for the ERM configurations. Section 4.2.2 focuses on the energy use of the mid-rise apartment building located in Brooklyn and how each ERM influenced it. Section 4.2.3 looks at the energy use and ERM configurations for the high-rise apartment building situated in Manhattan. For each building a description is given, followed by the annual energy use for each ERM configuration. Next, an analysis is presented on the total CO_2 emissions each building emitted based on which ERM configuration was used. Finally, an economic analysis for the optimal ERM for each building is presented.

4.1 Building Design

4.1.1 Staten Island

The house modeled in Staten Island was designed to have 5 living spaces (1 living room, 1 kitchen, and 3 bedrooms). The house is located in the center of Staten Island and it is modeled to be in a suburban environment. The house is designed to contain an overall surface area of 160 m^2. The living room and kitchen are located in the first floor, while the three bedrooms are located in the second floor, and connected by a corridor. The living room is the most spacious and it has three windows, 2 facing south-west and one facing north-east. The living room's south-west wall also includes a front door. The kitchen has a small window facing north east. On the upper floor, the south-west and north-west bedrooms have the same size and same size windows. While the master bedroom has two windows opposites of each other (south and north walls). Each room is assumed to have furniture which occupies between 55%-70% of the surface area for certain rooms. An HVAC system consisting of a Water to Air Heat Pump and ventilation in each room is included. The heat pump is powered by electricity, while the hot water system utilizes a central boiler that is powered by natural gas. A drawing of the Staten Island house can be seen in Figure 2.

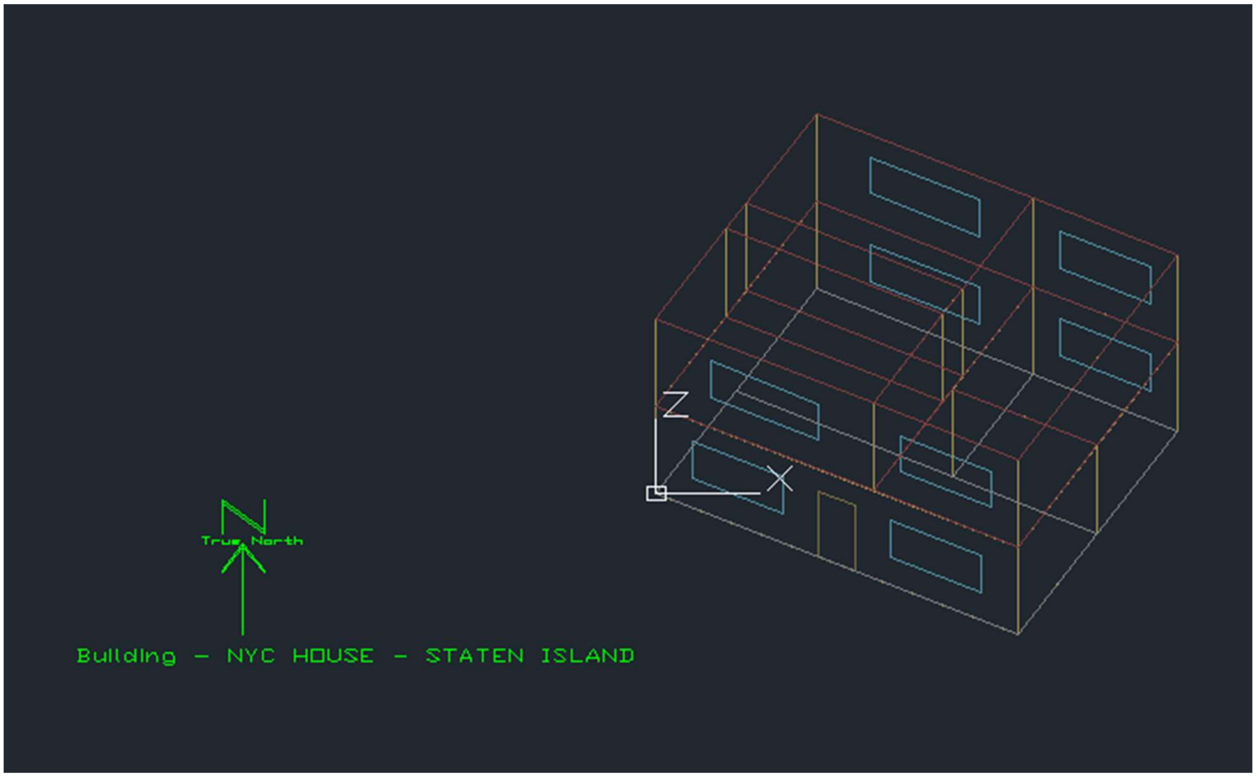
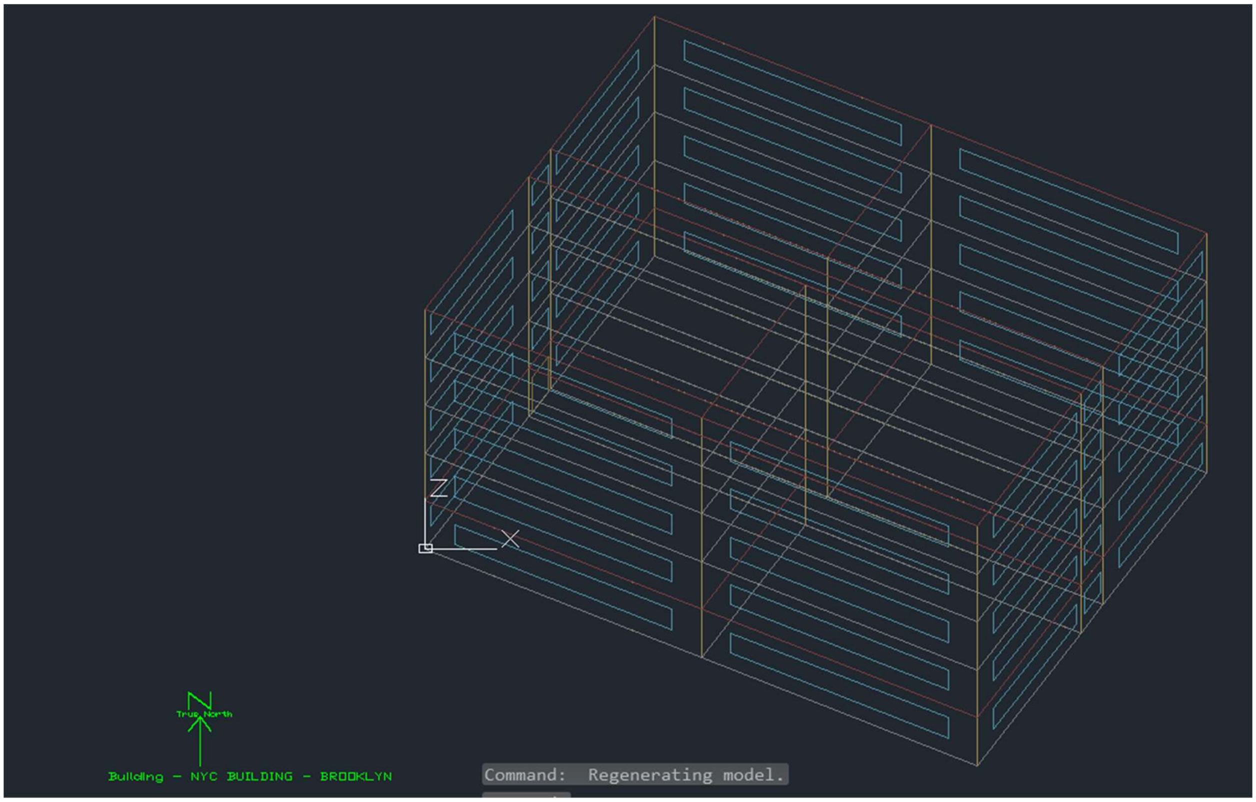


Figure 2 Staten Island House

4.1.2 Brooklyn, The Bronx and Queens

The building designed to represent the neighborhoods of Brooklyn, The Bronx and Queens, has five stories which include four apartments. The building is located in the heart of Brooklyn and it is modeled to be in a city environment. The building is situated in an elevation of 50m and has a total area of 2940 m^2. A large corridor connects all four apartments in every floor, and an elevator is included in the corridor. The elevator is scheduled to follow daily human activities and will turn on and off based on its frequency. The corridor includes a glass entrance door on the first floor, and 2 windows on opposite sides for all the other floors, which do not have any shading on it. A lighting system is also included in every corridor which remains on throughout the day. All four apartments are designed equally, with two large windows installed on the exterior walls. The apartment windows include a controlled shading system, which follows the schedule of the sun's direction and time of day, therefore it will open or close, depending if the apartment's temperature increases more than 22°C. To simulate furniture in each room, every apartment is designed to have 65% of its surface area be designated to be furniture, and an average of 2.5 people in each apartment is considered. The number of people is 2.5 as the decimal allows the model to simulate children or a guest. The number of people also changes throughout the day based on daily activity. Every apartment includes lights and electrical sockets, which are also scheduled to turn on and off based on time of day and human activity. Additionally, every apartment has an HVAC system and fans installed that are programmed to keep the apartment at 22°C throughout the day. The building also has a hot water system that goes through every apartment, which is heated by natural gas as its fuel intake and is also scheduled to turn on and off based on human activity and time of day. Figure 3 shows the Brooklyn building design in more detail.



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Command:  Regenerating model.
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Figure 3 Brooklyn Building Design

4.1.3 Manhattan

The building modeled in Manhattan was designed to be 10 stories high, and contains four apartments per floor, with each apartment being 130m^2. The building modeled is located near Central Park, and an orientation of 29 degrees from true north and a 40 m elevation is given. The Manhattan building is designed similarly to the Brooklyn building and utilizes similar equipment and human activity. A large corridor connects the four apartments, and an elevator is included in the corridor. Each apartment contains an average furniture surface area of 85m^2 and an average of 2.5 people reside in each apartment. An HVAC system is installed during this simulation, resulting on electricity usage for both cooling and heating hours. The hot water system utilizes a central boiler that is powered by natural gas. A drawing of the first floor of the building can be seen in Figure 4.

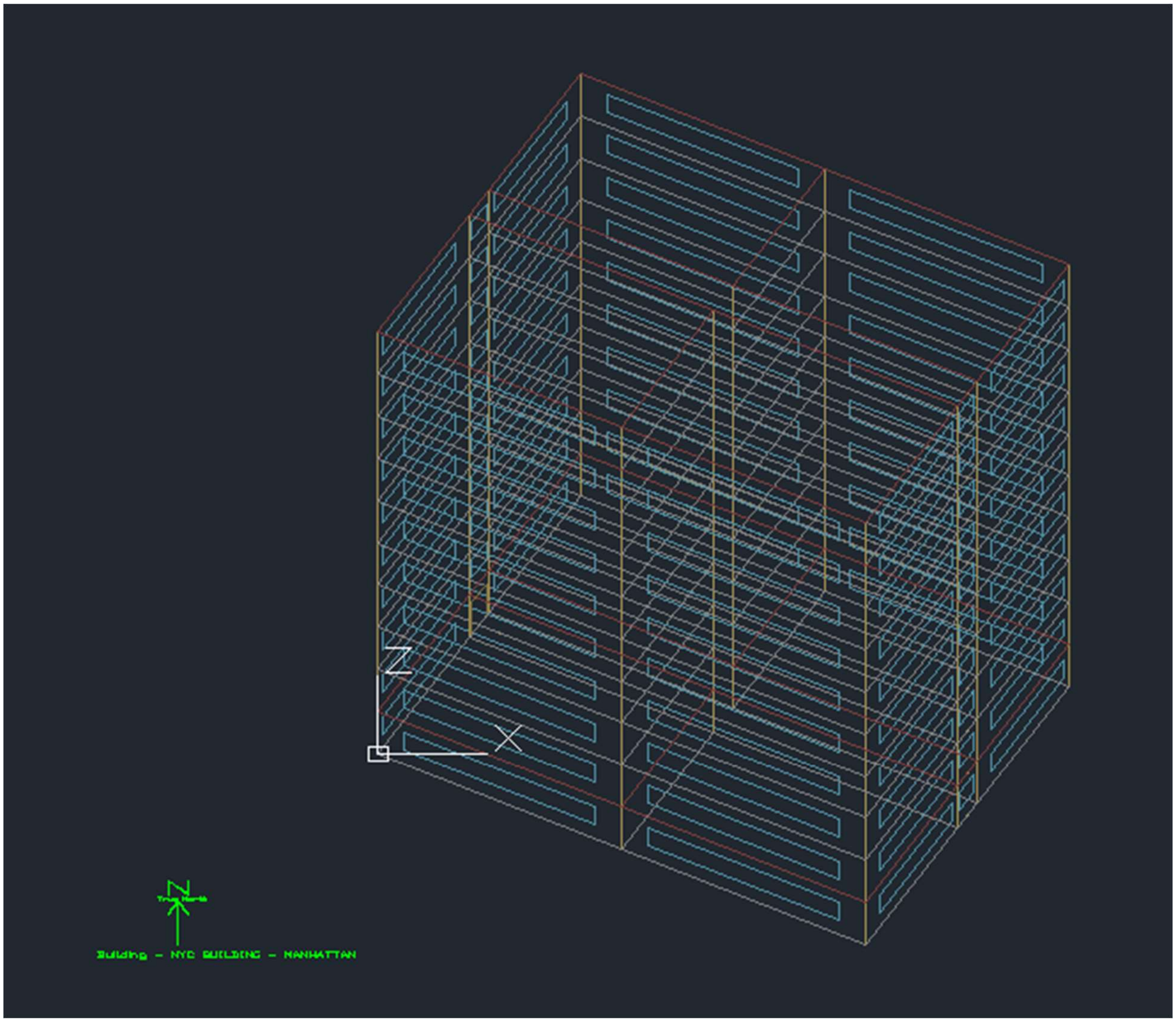

Figure 4 Manhattan Building Design

4.2 Energy Savings

The annual energy usage for the Staten Island house, Brooklyn's building and Manhattan's building was calculated using EnergyPlus. A reference configuration was used for the first simulation, and a code written on python would change an ERM for each iteration. The reference configuration is based on NYC's average 1970's buildings. The most common materials used during this period, is used as the reference materials in the reference configuration. Each ERM had multiple options that were analyzed: envelope modification, window upgrade, lighting improvements, shading optimization and HVAC system change. To lower heat transfer in the exterior walls, three insulation materials were included to the model: Batt-insulation, Rigid Foam Board Insulation and Spray-In insulation. Windows also have a big influence on heat loss in the house, therefore three window types were analyzed: uncoated window (single-glazed), window with low emissivity (double-glazed), and two suspended films (triple-glazed). Additionally, adding blinds or shading to the windows can reduce solar radiation in each room, therefore a high reflective blind and shade were included on the inside of the windows. Lighting can also influence the annual energy use; therefore, four different light bulbs were included: Standard light bulb (60W), New Halogen light bulb

(43W), CFL light bulb (13 W), LED light bulb (10W). Finally, switching from gas powered heating and cooling to electrical heat pump technology, was also analyzed. The reference configuration is shown on Table 8.

Table 8 Reference Configuration ERMs

Reference Configuration					
	Envelope Insulation	**Window**	**Shading**	**Lighting**	**HVAC**
Batt-insulation	**X**				
Rigid Foam Board Insulation					
Spray-In insulation					
Uncoated window (single-glazed)		**X**			
Window with low emissivity (double-glazed)					
Two suspended films (triple-glazed)					
Shade			**X**		
Blinds					
Standard light bulb (60W)				**X**	
New Halogen light bulb (43W)					
CFL light bulb (13 W)					
LED light bulb (10W)					
Gas Powered HVAC					**X**
Electrical Heat Pump					

4.2.1 Staten Island

The house in Staten Island had 72 different configurations which were analyzed. The reference configuration was used as the starting simulation, and for each iteration after that, one ERM was changed. The energy use for each configuration is shown in Figure 5.

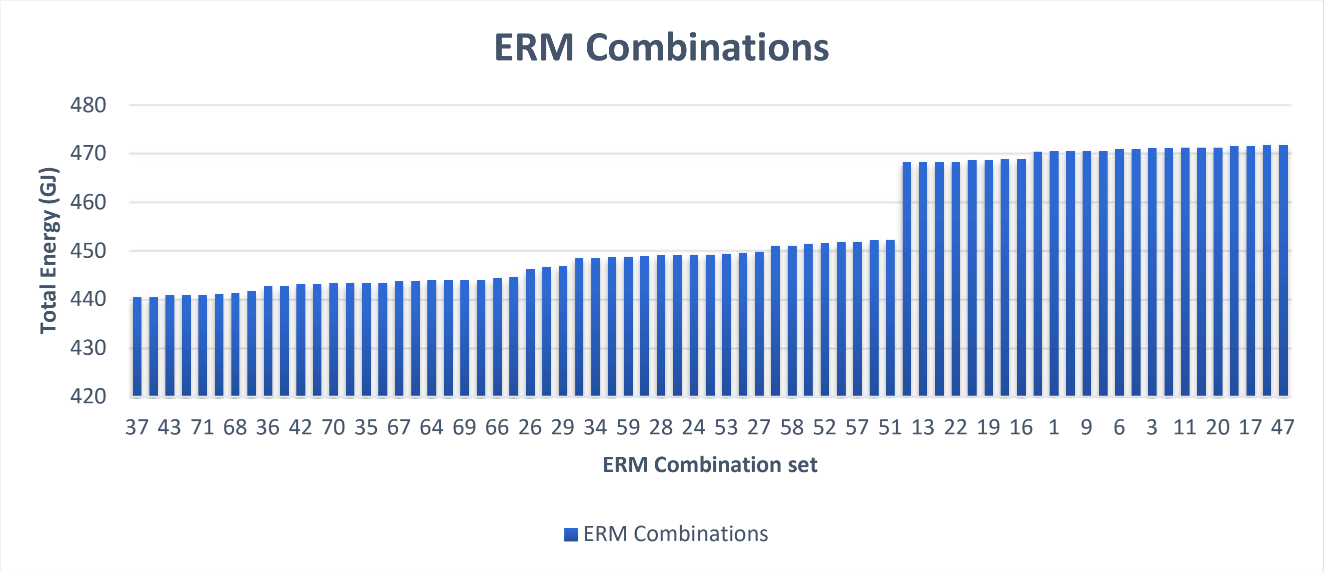

Figure 5 Total Energy for each ERM combination for Staten Island's house with heat pump installed

Figure 5 show the impact of the different ERMs have to the energy use of a house in Staten Island. The description of all ERMs is found on Appendix B. Configurations between 37 and 36, are configurations with the lowest annual energy usage, they include spray-In insulation, low emissivity windows, blinds or shades, and LED or CFL light bulbs. These configurations have the lowest energy use since the materials used are the best suited to lower heat transfer and keep electricity usage low. On the other side, the configurations with the highest energy usage, utilize the batt-insulation, Uncoated Window, shades and standard light bulbs. A large drop can be seen between configurations 13 and 51, which is linked to the change of window types. Configuration 13 and all of the other to the right of it, utilize the uncoated, single-glazed window, while configuration 51 until 29, utilize the triple-glazed window. While the difference in energy usage by upgrading the window type can be easily seen on Figure 5, other ERMs blend in more and vary depending on the configuration. For example, configurations 37 until 68, all have the same insulation (Spray-in insulation), window (double-glazed) and HVAC (electrical heat pump), however they vary on the lighting and shading options. Configuration 37, utilizes LED (10W) lightbulbs and blinds, while configuration 43 has CFL (13W) lightbulbs and blinds. Similarly, configurations 71 and 68, differ on the lightbulbs, LED and CFL, but have shades installed instead of blinds. These configurations all used very similar total energy, however, the combination of all the ERMs together influenced the total energy use. Overall, the 37 configurations, with its most energy savings potential, reduced total annual energy usage by 6.7%, compared to the reference configuration. A deeper analysis on each ERM and its energy savings capabilities for Staten Island is found below.

Envelope

There were three different insulations used on the model: Batt-insulation, Rigid Foam Board Insulation and Spray-In insulation. Each of these insulations are the most commonly used insulations in NYC and have corresponding R-values, recommended by the NYCECC. Batt-insulation, fiberglass based, is the cheapest of the three, and it is also the one with the lowest R-value, therefore it was used as the reference insulation in the model. Rigid foam board insulation is the middle option on both price and R-value. Table 9 portrays how the better R-value contributed to the energy savings in Staten Island.

Table 9 R-values and energy saving potential for the insulations in Staten Island per year

Insulation	R-value (m^2*K/W)	Energy Savings (%)
Batt-insulation	0.00802105	0.00%
Rigid Foam Board	0.01524	0.15%
Spray-In	0.04010526	0.62%

The energy savings shown on Table 9 represents the change in energy usage when only changing the insulations on the exterior walls. The energy savings are the percentage of total energy use change from the reference configuration, therefore Batt-insulation has 0% energy savings, since it is used as the reference insulation. Table 9 shows that the spray-in insulation had the highest energy savings, with 0.62% reduction in energy, equivalent to 2.94 GJ reduction per year from the reference configuration. The energy savings that each insulation has, are also influenced by the total surface area that these insulations are applied to, and the initial exterior wall design. The total surface area is impacted by the windows on each room, the windows in the building design occupy a large space of the southern exterior walls, which receives the most direct sunlight, therefore, the insulation by itself does not assist in the energy savings as much. Similarly, the exterior wall considered in the simulation uses outside bricks, structural sheathing and gypsum wall board, for all three insulation types, thus already containing an overall large R-value of the exterior wall, diminishing the overall effect that the insulations produce.

Window

Three different windows were analyzed: uncoated window, window with low emissivity, and two suspended films. These windows styles correspond to the NYCECC guidelines and range from single glazed, double glazed and triple glazed windows. All three windows are constructed using different glass materials and inner gases. The uncoated window is a single glazed window made of 6mm clear glass and has a conductivity of 0.9 W/m*K. The low emissivity window is a double-glazed window made up of two clear 6mm glass with a 12.7 mm air gap in between; each 6mm glass has a 0.9 W/m*K conductivity rate. Lastly, the two suspended films are a triple-glazed window that is constructed with two 3mm clear glasses with a 77% visible transmittance coated polyester in the middle, and two 6mm air gaps in between all three materials. The coated polyester has a conductivity of 0.14 W/m*K, while the 3mm clear glass has a conductivity of 0.9 W/m*K.

Table 10 Energy difference and energy savings potential for windows in Staten Island per year

Window	Energy difference (GJ)	Energy savings (%)
Uncoated window	0	0.00%
Low emissivity	-27.02	5.74%
Two suspended films	-21.3	4.53%

The uncoated window was used as the reference window in the reference configuration, as it has the highest conductivity rate, and it is included in the configuration with the highest energy usage. The energy usage differs drastically between the uncoated window, and the other two windows. The window with the highest energy saving was the low emissivity window, with 5.47 % energy reduction. The energy difference is the difference between the three windows to the reference configuration and the low emissivity window saved 27.02 GJ of energy in one year, compared to the uncoated window. The two suspended films window came close to the performance of the low emissivity window, however it lacked

1.2% behind in total savings. This change in performance from double-glazed to triple-glazed can be attributed to the window materials and gases. The low emissivity window utilized a thicker 6mm LOE clear glass and a 12.7mm air gap, while the two suspended films window used two 3mm clear glass, a 0.51mm polyester film and two 6mm air gaps. The difference in low emissivity clear glass and clear glass, and the varying thickness impacted the performance for both windows. Which the simulation showed that the Low emissivity (double-glazed) window performed better. The high energy savings seen are also related to the window positioning and surface area. Since the southern facing façade of the house contains a lot of windows, by improving the conductivity rate in those areas lead to energy efficiency improvements overall. Additionally, the southern facing windows increase direct sunlight in the rooms, which leads to higher temperatures in the room, lowering the heating load during winter times.

Shading

Two different shading strategies were utilized, blinds and shades. These two materials were added to the inside of every window. The shades were also added to the single, double and triple-glazed windows. The blind used was a high reflective slat, which has a slat conductivity of 0.9 W/m*K and a slat beam solar reflectance of 0.8. The shade used was a high reflective, low transmittance shade, with a conductivity of 0.1 W/m*K and a solar reflectance of 0.8. The energy savings, for the shade and blind, with each window type is shown on Table 11.

Table 11 Energy savings for shading strategies for Staten Island per year

Shading Configuration	Energy Savings (%)
Shade w/ uncoated window	0.00%
Shade w/ Low emissivity	0.00%
Shade w/ two suspended films	0.00%
Blind w/ uncoated window	0.14%
Blind w/ Low emissivity	0.12%
Blind w/ two suspended films	0.56%

The shades were used as the refence in the reference configuration, which is why it has 0% energy savings. Table 11 shows that the blinds can improve the energy use of the Staten Island house if installed, however, unlike the windows, the blinds assisted the energy reduction for each window type differently. Installing the blind to the two suspended films window, resulted on the largest energy reduction, 0.56%. While the low emissivity window, that yielded the most energy reduction in the previous section, had the least assist from the installation of blinds, only 0.12%. The difference in energy savings per window can be linked to the added resistance that the blinds give the overall window surface. Since the two-suspended films window utilizes a thinner clear glass, the addition of blinds in the windows increases the overall R-value and lower the energy loss in the room. This extra layer and decrease in direct sunlight entering the room, lead to a decrease of 0.56% in total energy usage in a year for the house. On the other hand, the additional resistance from the blinds, did not assist with the Low emissivity windows as much as the two-suspended films window. This can be attributed to the already high resistance that the window already had, and the addition resistance the blind was giving, did not influence the overall energy loss as much.

Lighting

There are four different light types analyzed: Standard light bulb (60W), New Halogen light bulb (43W), CFL light bulb (13 W), LED light bulb (10W). Each light bulb is in accordance with the NYCECC and vary in lighting level. All lights are distributed evenly in every room according to the room's surface area. The lights are scheduled to follow human activity and day/night cycles; therefore, they will mostly be turned on during the evening, while people are awake and home. Table 12 shows the energy savings that each light bulb has for a house in Staten Island.

Table 12 Energy reduction for each light bulb type in Staten Island per year

Lighting Types	Energy Savings (%)
Standard light bulb (60W)	0.00%
New Halogen light bulb (43W)	0.04%
CFL light bulb (13W)	0.12%
LED light bulb (10W)	0.13%

The standard light bulb is used as the reference lighting in the reference configuration. Table 12 shows that the LED light bulb achieves the biggest energy savings, 0.13%, while the new halogen light bulbs achieve the lowest energy savings, 0.04%, compared to the standard light bulb. When analyzing the total energy saved when installing LED lights, instead of standard light bulbs, a 0.61 GJ annual energy reduction can be seen. The energy savings is proportional to the decrease in lighting level the new halogen, CFL and LED lights have. The low energy savings is also linked to the hours of operation, as the lights are mostly used for a couple of hours during the evening, therefore the benefits of having a more efficient light bulb is limited.

HVAC

Two HVAC systems were studied in Staten Island, a natural gas-powered heat pump and an electrically powered water to air heat pump system. Both systems use fans that are installed in each room to blow hot and cold air into the living environment. Both systems have thermostats in each room that based on the room's temperature schedule, will turn on and off, maintaining the desired 22°C temperature. The fans used on both systems have a total efficiency of 55.6% and a motor efficiency of 85.5%, matching with ASHRAE's requirements. For the gas HVAC system, a heating burner efficiency of 65% was used (ASHRAE, 2018). The gas HVAC system is designed to have a cooling COP of 1.3, and a heating COP of 1.4 (ASHRAE, 2018). On the other hand, the electrically powered heat pump is designed to have an 100% heating coil efficiency, since it is electric (ASHRAE, 2018). The electric Heat Pump is also designed to have a much greater COP, 4.2 COP for cooling and 4.3 COP for heating, which is between the required NYCECC guidelines.

Table 13 Energy Difference and Energy Savings for HVAC systems in Staten Island per year

HVAC Systems	Energy Difference (GJ)	Energy Savings (%)
Gas HVAC - Heating	0	0.00%
Heat Pump - Electrical - Heating	7.13	-5.31%[2]
Gas HVAC - Cooling	0	0.00%
Heat Pump - Electrical - Cooling	-25.94	69.08%
Gas HVAC - Overall	0	0.00%
Heat Pump - Electrical - Overall	-18.95	11.01%

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[2] The energy savings is negative due to the fact that the heating energy use increased and did not save energy, compared to the reference heating period.

Table 13 shows the energy difference and energy savings that an electrically powered heat pump can provide to a house in Staten Island compared to the reference gas powered HVAC system. There is a great advantage on energy savings when cooling (69.08%); however, the electrical heat pump increases annual energy usage compared to the gas HVAC when heating the house, leading to a 5.31% increase in energy use. Although, throughout the year, the electrical heat pump can provide around 11.01% energy savings, since the cooling system strongly benefits from it. The difference in energy usage during heating and cooling periods is linked to the heat pumps performance under extreme cold temperatures. As the house in Staten Island can experience temperatures below -10°C for an extended number of days, the heat pump's efficiency drops drastically, which causes it to be less efficient than the gas-powered HVAC system. On the other hand, during summer, the heat pump performance during perfect weather conditions, and its efficiency is maximized. Which leads to an energy savings potential of 69.08%.

Table 14 Electricity Usage Difference During Heating Periods for Staten Island's House per year

HVAC	Electrical Use (GJ)	Energy increase (%)
Gas HVAC - Heating	190.99	0.00%
Heat Pump - Electrical - Heating	214.18	10.83%

Additionally, as shown on Table 14, by installing an electrical heat pump, the overall electrical usage of the house increases from 190.99 GJ to 214.18 GJ (10.83%), compared to the reference configuration. However, even though the total electrical usage increases, there are no natural gas usage from the HVAC system, which can contribute up to 42.15 GJ per year, compared to the reference configuration. The electricity usage increase is contributed to the shift in power supply that the natural gas-powered system was providing to the fully electrical heat pump.

4.2.2 Brooklyn, The Bronx and Queens

The mid-rise Brooklyn building had 81 ERM iterations analyzed. The reference configuration on Table 8 was used as the base configuration during the simulations. The same procedure as the Staten Island for running multiple iterations was used. Figure 6 shows the total energy usage per ERM configuration for the mid-rise Brooklyn building, and detailed information on each ERM combination can be found on Appendix B.

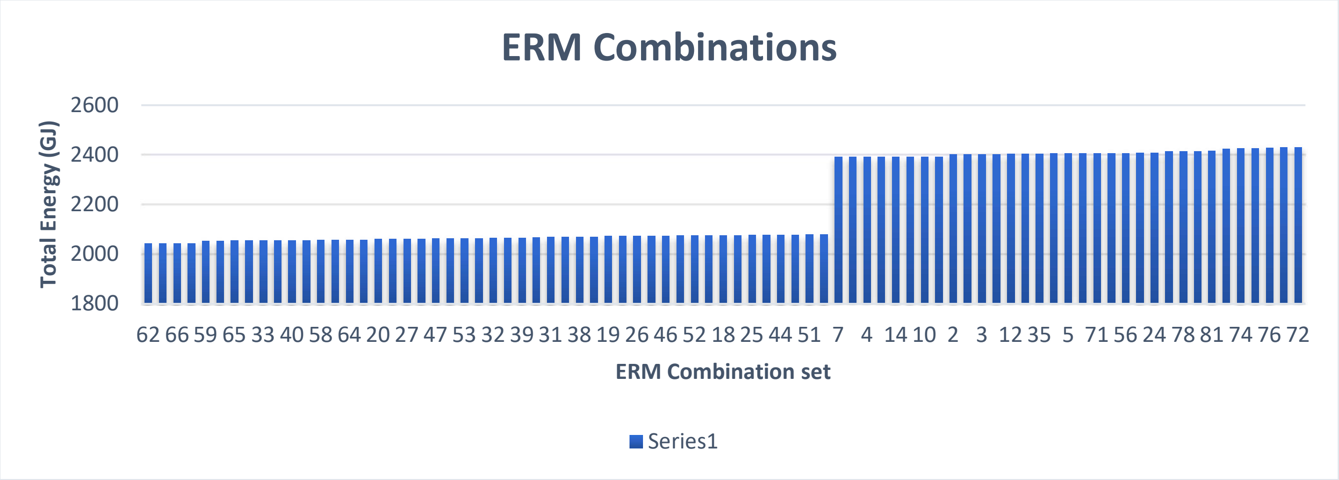

Figure 6 Total Energy for each ERM combination for Brooklyn's building with heat pump installed

Figure 6 shows the large difference that the double- and triple-glazed windows have in the energy use in the dip from configurations to the left of combination 7. Configuration 72, with single-glazed window, batt-insulation, standard lightbulbs and interior blinds, resulted on the largest energy use. Furthermore, the configuration 62 achieved the lowest energy use, which includes spray-in insulation, double-glazed windows, and LED lights. However, unlike the Staten Island house, the best shading type was high reflective shade instead on high reflective blinds. The largest energy use difference was experienced when installing double- or triple-glazed windows, instead of single-glazed windows. The combinations with single- and double-glazed windows that had blinds installed, yielded greater energy use overall than their single- and double-glazed windows with shades counterparts. Overall, the best performing configuration (62), reduced total annual energy usage by 16%, compared to the reference configuration.

Envelope

The insulations analyzed in the Brooklyn building were batt-insulation, rigid foam board insulation and spray-in insulation. The batt-insulation was used as the reference insulation as in accordance to the reference configuration. The R-values and energy savings for each insulation are given on Table 15.

Table 15 R-values and energy saving potential for the insulations in Brooklyn per year

Insulation	R-value (m^2*K/W)	Energy Savings (%)
Batt-insulation	0.00802105	0.00%
Rigid Foam Board	0.01524	0.14%
Spray-In	0.04010526	0.61%

Comparably with Staten Island's house, Table 15 shows that installing insulation with higher R-values, decreases the overall energy use. The spray-in insulation had the largest energy savings from the reference, batt-insulation, 0.61% decrease in energy use. The energy savings potential for Brooklyn's building similar to the Staten Island's house, which is interesting as the building design and total surface area are distinct. The Brooklyn building is five story high and has a greater surface area than Staten Island's house, however, the amount of surface area that the windows on the exterior walls take are relatively close. Therefore, the total surface area that the insulation materials can be installed is limited, which leads to a limited energy performance improvement.

Window

The three windows analyzed in the Brooklyn simulation were uncoated window, low emissivity window, and two-suspended films window. The uncoated (single-glazed) window was used as the reference window in accordance to the reference configuration. All three windows are constructed using the same glass and gas layout and conductivity rate than the Staten Island building. Table 16 shows the energy use difference and energy savings that the different windows have from the reference window.

Table 16 Energy difference and energy savings potential for windows in Brooklyn per year

Window	Energy difference (GJ)	Energy savings (%)
Uncoated window	0	0.00%
Low emissivity	-349.4	14.52%
Two suspended films	-328.3	13.64%

Table 16 shows that upgrading from single-glazed to double- or triple-glazed windows have a huge improvement in the total energy usage of the Brooklyn building. The low-emissivity window yielded the largest energy savings from the reference, single-glazed window, with a 14.52% decrease in energy usage. Similar to the Staten Island house, the difference between all three windows is linked to the construction of the windows. The low emissivity window is configured with a 6mm low emissivity clear glass, while the uncoated and two suspended films utilize a 6mm clear glass and 3mm clear glass respectively. Therefore, the difference in the glass and the air gap influences heat loss and the final performance. The large surface area that the windows take on the exterior walls, have a big influence on the total direct sunlight intake. Therefore, the double- and triple-glazed windows save up to 15% of annual energy use as it reduces the heat loss through the windows.

Shading

The two shading strategies used in the Brooklyn building are shades and blinds. The shades are used as the reference shade strategy in accordance with the reference configuration. The shades and blinds are added to the interior of the three types of windows and have the same construction as the Staten Island House. The energy savings that the shades and blinds have from the reference shading strategy is shown on Table 17

Table 17 Energy savings for shading strategies for Brooklyn per year

Shading Configuration	Energy Savings (%)
Shade w/ uncoated window	0.00%
Shade w/ Low emissivity	0.00%
Shade w/ two suspended films	0.00%
Blind w/ uncoated window	-0.92%
Blind w/ Low emissivity	-0.59%
Blind w/ two suspended films	0.06%

Unlike the Staten Island house, installing blinds to the single- and double-glazed windows resulted in an increase in energy use, with the blind with the single-glazed window adding almost 1% energy use increase. The increase in energy usage when blinds are installed is due to the difference in conductivity rate that the two materials have. The shades have a conductivity rate of 0.1 W/m*K, while the blinds have a 0.9 W/m*K. The higher conductivity rate influences the uncoated and low emissivity windows the most, increasing the heat loss through the windows, compared to the shades. This is seen when looking at the difference in the heating and cooling periods throughout the year. The switch from shade to blind raised the energy use during cooling periods, but lowered the energy used during heating periods. Since the blinds have a higher conductivity, heat from outside transfers easily during the summer times, therefore the HVAC system needs to be running more often to keep the room's temperature at 22°C. Similarly, since the conductivity rate is higher and the blinds have spaces in between the slats, more direct sunlight radiation enters the room, which during winter times, allows the HVAC system to work less frequently. Therefore, lowering the total energy use for heating. However, when the electricity used to power the fans in the room is added to the heating and cooling calculations, the higher electricity fan usage that the blinds cause, makes the overall building's energy use be higher than the shades. The difference in the HVAC system that the shades and blinds have on the single-glazed window can be seen on Table 18.

Table 18 Impact that the single-glazed windows with blinds and shades have on the HVAC system in Brooklyn per year

	Heating (GJ)	Cooling (GJ)	Fans (GJ)	Total HVAC Energy Use (GJ)[3]
Shade	946.61	142.19	285.43	1404.27
Blinds	918.08	157.21	318.52	1426.51

On the other hand, installing blinds to the triple-glazed window decreased the overall energy use, but very marginally, a 0.06% improvement. The higher conductivity rate that the blinds have, lowered the energy used during heating periods and raised the energy use during the cooling periods, similar to the single- and double-glazed windows. The fan usage also increased throughout the year, accordingly to the single- and double-glazed windows. However, when the adding all the components included in the HVAC system, the improvements that the blinds have during the heating periods, does overpass the disadvantages the blinds have during cooling periods and fan usage. Table 19 shows the impact that the triple-glazed window with blinds and shades have on the HVAC system in Brooklyn.

Table 19 Impact that the triple-glazed window with blinds and shades have on the HVAC system in Brooklyn per year

	Heating (GJ)	Cooling (GJ)	Fans (GJ)	Total HVAC Energy Use (GJ)[3]
Shade	687.39	134.79	228.06	1075.72
Blinds	631.27	154.41	260.12	1074.11

Lighting

The lighting options used in the Brooklyn building are: Standard light bulb (60W), New Halogen light bulb (43W), CFL light bulb (13 W), LED light bulb (10W). The standard light bulb was used as the reference light bulb in accordance to the reference configuration. Table 20 shows the energy savings that each light bulb provides for a building in Brooklyn.

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[3] The total HVAC system energy use also includes the electricity for the pumps and heat rejection

Table 20 Energy reduction for each light bulb type in Brooklyn per year

Lighting Types	Energy Savings (%)
Standard light bulb (60W)	0.00%
New Halogen light bulb (43W)	0.02%
CFL light bulb (13 W)	0.04%
LED light bulb (10W)	0.05%

Similarly, to the Staten Island house, the LED light bulb yielded the best energy savings with 0.05% improvement. However, the total energy savings in percentage, was lower than the Staten Island house, with the Staten Island house reaching more than double energy savings from installing LED lights than the Brooklyn building. The new halogen light bulbs installed in the Brooklyn building, marginally matched in energy savings with the Staten Island house. This difference is due to the fact that the Brooklyn building's corridor lights are programmed to stay on during the whole day, as the corridor is required to be lit at all times for safety reasons. Therefore, the advantages gained from having a more efficient lightbulb throughout the building is limited.

HVAC

Two HVAC systems were studied in Brooklyn, a natural gas-powered heat pump and an electrically powered water to air heat pump system. Both systems are designed similarly to the Staten Island house and have matching COPs and efficiencies. Both systems are scheduled to maintain all apartments in a steady 22°C temperature. The natural gas-powered HVAC system was used as the reference HVAC system in accordance to the reference configuration.

Table 21 Energy Difference and Energy Savings for HVAC systems in Brooklyn per year

HVAC Systems	Energy Difference (GJ)	Energy Savings (%)
Gas HVAC - Heating	0	0.00%
Heat Pump - Electrical - Heating	42.62	-4.72%
Gas HVAC - Cooling	0	0.00%
Heat Pump - Electrical - Cooling	-317.98	69.09%
Gas HVAC - Overall	0	0.00%
Heat Pump - Electrical - Overall	-277.08	20.25%

Table 21 shows the energy difference and energy savings that installing an electrical heat pump instead of a gas-powered HVAC system in Brooklyn can have. As shown on Table 21, the electrical heat pump was less efficient than the gas-powered HVAC system during heating periods, with a 4.72% increase in energy use. Similar to the Staten Island house, this is due to the extreme cold temperatures that the Brooklyn building may experience during winter times. The cold weather lowers the electrical heat pumps overall efficiency, leading to higher energy use. However, during cooling periods, the electrical heat pump drastically improved the energy use, with 69.09% decrease in energy usage, matching with Staten Island's house cooling results. Which is also linked to the heat pump being able to perform at its peak efficiency during the summer, when the outside temperatures are in perfect condition. Overall, the electrical heat pump achieved a 20.25% improvement on energy use throughout the year, doubling the energy savings in Staten Island. The improvement in energy usage can be contributed to the larger HVAC system that the

Brooklyn building has, compared to the Staten Island's house. The building design also influence the energy savings potential for Brooklyn's mid-rise building, compared to the house in Staten Island. Having more window coverage in the exterior windows increased the overall direct sunlight the building received. In addition, having all apartments being connected to a single corridor allows the flow of air to transfer throughout every floor more frequently, impacting the heating and cooling loads.

Table 22 Electricity Usage Difference During Heating Periods for Brooklyn per year

HVAC	Electrical Use (GJ)	Energy increase (%)
Gas HVAC - Heating	2081.85	0.00%
Heat Pump - Electrical - Heating	2099.91	0.86%

Additionally, as shown on Table 22, by analyzing on the year-round energy usage for the HVAC system alone, the gas-powered system used 0.86% less energy than the electrical heat pump. However, the gas-powered HVAC used close to 300 GJ of natural gas during heating periods, while the electrical heat pump increased its electrical usage by almost 350 GJ during heating periods. The increase in electricity usage is linked to the absence of the natural gas power switching to all electric power.

4.2.3 Manhattan

The high-rise Manhattan building had 72 ERM iterations analyzed and the reference configuration on Table 8 was used as the base configuration during the simulations. The same procedure as the Staten Island and Brooklyn's mid-rise building for running multiple iterations was used. Figure 7 shows the total energy usage per ERM configuration for the high-rise Manhattan building, and detailed information on each ERM combination can be found on Appendix B.

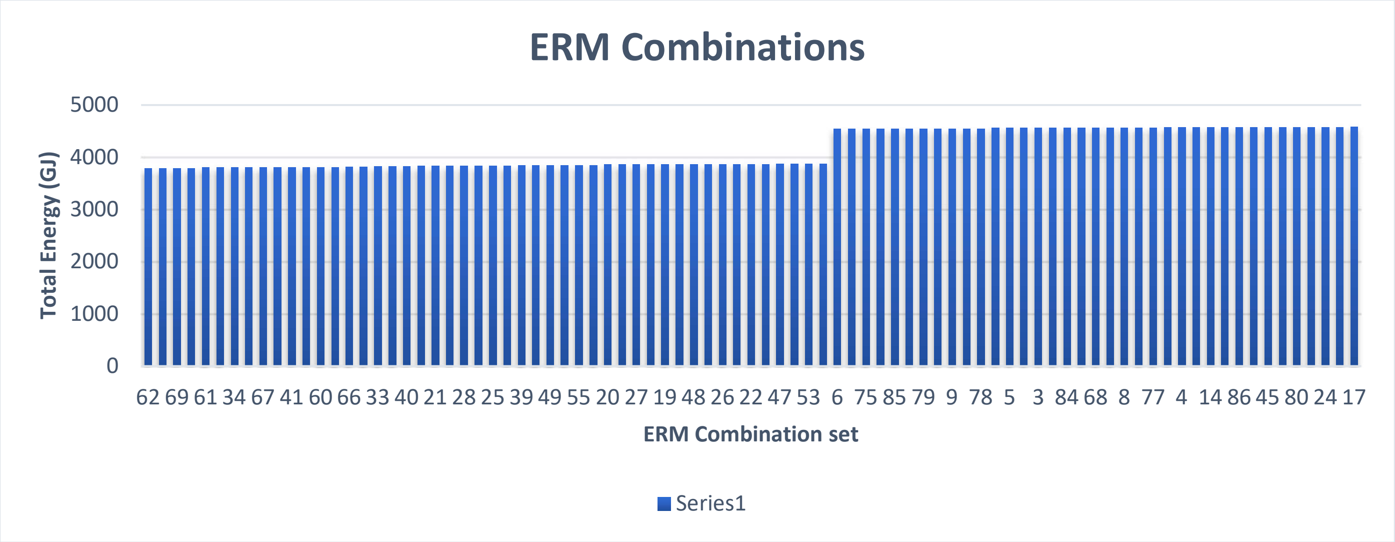

Figure 7 Total Energy for each ERM combination for Manhattan's building with heat pump installed

Similarly, to the Brooklyn building, the combination with the lowest energy use was the configuration with spray-in insulation, double-glazed windows, LED lights and utilizing shades instead of blinds. As the other two building's, the largest difference experienced was when upgrading the windows from single-glazed to double- or triple-glazed. Both, Brooklyn and Manhattan buildings, experienced similar energy use changes when utilizing the same ERM combinations. Overall, configuration 62, with its least energy consumption, reduced total energy usage by 17.45% compared to the reference configuration.

Envelope

There were three different insulations used on the model: Batt-insulation, Rigid Foam Board Insulation and Spray-In insulation. The same exterior wall construction and materials were used as the Brooklyn's mid-rise building. Batt-insulation was used as the reference insulation in the model in accordance to the reference configuration. Table 23 demonstrates how the R-value contributed to the energy savings in Manhattan.

Table 23 R-values and energy saving potential for the insulations in Manhattan per year

Insulation	R-value (m^2*K/W)	Energy Savings (%)
Batt-insulation	0.00802105	0.00%
Rigid Foam Board	0.01524	0.16%
Spray-In	0.04010526	0.69%

The Manhattan building experienced the biggest improvement between all three buildings, when utilizing insulations with greater R-values. Spray-in insulation achieved the best result, with 0.69% less energy use than batt-insulation, the highest between all three infrastructures. Rigid foam board insulation saved marginally the same amount of energy, in percentage, on all three buildings. The high performance that the spray-in insulation yielded compared to the other two infrastructures is due to the increase in exterior wall surface area that the Manhattan building has over the Brooklyn and Staten Island infrastructures. With more surface area for the insulation to be installed, a larger impact that the insulation has on decreasing heat loss through the walls.

Window

Three different windows were analyzed: uncoated window, window with low emissivity, and two suspended films. All three windows are constructed using different glass materials and inner gases. All three windows used the same construction style and materials as the Brooklyn building. The uncoated (single-glazed) windows were used as the reference window, in accordance to the reference configuration. Table 24 shows the energy difference and energy savings the different windows can provide in comparison with the reference configuration.

Table 24 Energy difference and energy savings potential for windows in Manhattan per year

Window	Energy difference (GJ)	Energy savings (%)
Uncoated window	0	0.00%
Low emissivity	-756.94	16.55%
Two suspended films	-697.36	15.24%

Window upgrades had a large influence on annual energy use for the Manhattan building. Similar to the house in Staten Island and Brooklyn's building, the low emissivity, double-glazed window, yielded the most energy savings, 16.55%. Both double- and triple-glazed windows saved more than double of energy use in Manhattan compared to Brooklyn's building, with the double-glazed window saving 756.94 GJ of energy throughout the year, compared to the reference configuration. The increase in energy savings experienced in the Manhattan building is linked to the increase in window surface the high-rise building has compared to the mid-rise Brooklyn building. With more surface area being modified to have better insulated windows throughout the exterior walls, the more impactful the annual energy savings can be. As discussed in section 4.2.2, the difference in glass material, thickness and air-gaps in the low emissivity and two suspended films are the cause for the difference in energy savings potential seen on Table 24.

Shading

Blinds and shades were the two different shading strategies utilized in the Manhattan building. These two materials were added to the inside of every window of all three buildings. The shades and blinds were also added to the single, double and triple-glazed windows, to see the impact it had with the different window types. The shade was used as the reference shading strategy, in accordance to the reference configuration. The energy savings, for the shade and blind, with each window type is shown on Table 25.

Table 25 Energy savings for shading strategies for Manhattan per year

Shading Configuration	Energy Savings (%)
Shade w/ uncoated window	0.00%
Shade w/ Low emissivity	0.00%
Shade w/ two suspended films	0.00%
Blind w/ uncoated window	-0.93%
Blind w/ Low emissivity	-0.62%
Blind w/ two suspended films	0.20%

Similar to the blinds installed in the Brooklyn building, Table 25 shows that the Manhattan building experienced an increase in energy usage when blinds were installed on single- and double-glazed windows. Installing blinds on the single- and double-glazed windows compared to the shades yielded in an energy increase of 0.93% and 0.62% respectively. The increase in energy use is linked to the conductivity rate and direct solar intake. The shades have a lower conductivity rate than the blinds 0.1 W/m*K compared to 0.9 W/m*K, therefore more energy is transferred through the blinds. Additionally, the blinds have slats which have small openings in between them, which allows for an increase in direct solar intake in the room. The combination of these two variables impacts the overall performance of the HVAC system throughout the building. Similar to the Brooklyn building, single- and double-glazed windows with blinds increased the cooling load, and decreased the heating load. This is linked to the increase in radiation from direct sunlight and more heat being transferred through the blinds, which causes the HVAC system to work harder during summer to keep the building cool, but alleviates the HVAC system during winter, as the apartments are slightly warmer and less work has to be done to keep the temperature warmer. However, this balance isn't equal, and when analyzing the fan usage throughout the year, the increase usage of the fans, causes an increase on annual energy use of the building. The impact that the single-glazed window with blinds have on the HVAC system is shown on Table 26.

Table 26 Impact that the single-glazed windows with blinds and shades have on the HVAC system in Manhattan per year

	Heating (GJ)	Cooling (GJ)	Fans (GJ)	Total HVAC Energy Use (GJ)[4]
Shade	1961.99	281.04	563.92	2867.66
Blinds	1905.02	311.19	628	2910.32

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[4] The total HVAC system energy use also includes the electricity for the pumps and heat rejection

On the other hand, when installing blinds to triple-glazed windows, a 0.20% energy savings throughout the year is seen. Similar to the single- and double-glazed windows, the higher conductivity rate and direct sunlight that the blinds have, are the leading cause of the change in energy use. The heating and cooling loads are impacted with the installation of blinds, leading to higher cooling energy usage and lower heating energy usage. However, benefits from lowering the heating load during winter, outweighs the disadvantage of increasing the cooling load during summer days, contributing to an annual energy use reduction of 0.20%. The impact that the triple-glazed window with blinds have on the HVAC system is shown on Table 27.

Table 27 Impact that the triple-glazed windows with blinds and shades have on the HVAC system in Manhattan per year

	Heating (GJ)	Cooling (GJ)	Fans (GJ)	Total HVAC Energy Use (GJ)[4]
Shade	1393.53	271.13	453.53	2170.29
Blinds	1276.25	311.49	517.23	2162.72

Lighting

There are four different light types analyzed: Standard light bulb (60W), New Halogen light bulb (43W), CFL light bulb (13 W), LED light bulb (10W). All lights are distributed evenly in every room according to the room's surface area. The lights are scheduled to follow human activity and day/night cycles. The lighting distribution and schedules are the same as Brooklyn's building. The standard light bulb is used as the reference lighting, in accordance to the reference configuration. Table 28 shows the energy reduction that each light bulb has for the Manhattan building.

Table 28 Energy reduction for each light bulb type in Manhattan per year

Lighting Types	Energy Savings (%)
Standard light bulb (60W)	0.00%
New Halogen light bulb (43W)	0.02%
CFL light bulb (13 W)	0.04%
LED light bulb (10W)	0.05%

Both Brooklyn and Manhattan buildings achieved the same energy savings, in percentages, by upgrading standard light bulbs to more efficient light bulbs. The LED light bulbs was the best light bulb option, achieving 0.05% energy savings throughout the year. However, the new halogen and CFL light bulbs were not that far away, with 0.02% and 0.04% improvement. These improvements and similar results to the Brooklyn building can be attributed to the fact that both buildings were using the same activity schedules and similar lighting distribution. Therefore, even though the Manhattan building had five more floors with lighting than the Brooklyn building, the overall energy savings, in percentages, was practically equal. Since upgrading the light bulbs only influence the electrical usage of the lighting system and does not have an impact on the other ERMs, the energy savings potential for the Brooklyn and Manhattan building match.

HVAC

Two HVAC systems were studied in Staten Island, a natural gas-powered heat pump and an electrically powered water to air heat pump system. Fans are installed in each room to blow hot and cold air. The same activity schedule and system performances were used as the Brooklyn building. The natural gas-powered HVAC system was used as the reference configuration, in accordance to the reference configuration. Table 29 shows the energy usage difference and energy savings that switching HVAC systems can have in Manhattan.

Table 29 Energy Difference and Energy Savings for HVAC systems in Manhattan per year

HVAC Systems	Energy Difference (GJ)	Energy Savings (%)
Gas HVAC - Heating	0	0.00%
Heat Pump - Electrical - Heating	90.3	-4.82%
Gas HVAC - Cooling	0	0.00%
Heat Pump - Electrical - Cooling	-628.24	69.09%
Gas HVAC - Overall	0	0.00%
Heat Pump - Electrical - Overall	-541.36	19.40%

Table 29 demonstrates the benefits that an electrical heat pump can have to a building in Manhattan. Similar to Brooklyn's building, the electrical heat pump yielded 69.09% energy use improvement during cooling periods. Additionally, it experienced a 4.82% increase in energy use during heating hours, 0.14% increase compared to Brooklyn's building. Overall, converting the HVAC system from gas powered to electrically powered heat pump, lead to a 19.40% decrease in energy use throughout the year. Since both the Brooklyn and Manhattan building are similarly designed and used the same activity schedule and system performances, it resulted on similar heating and cooling energy usages. The small increase in heating electrical use for the Manhattan building compared to the Brooklyn building is linked to the difference in overall surface area the two buildings have. With the Manhattan building containing more exterior walls and windows, the increased heat transfer through the exterior walls and windows, slightly impacted the HVAC during heating periods.

Table 30 Electricity Usage Difference During Heating Periods for Manhattan per year

HVAC	Electricity Use (GJ)	Energy increase (%)
Gas HVAC - Heating	2081.85	0.00%
Heat Pump - Electrical - Heating	2099.91	0.86%

Table 30 shows the difference in electricity usage during heating periods for the building in Manhattan. Similar to the other boroughs, the electrical heat pump increases the total annual electrical use of the building by 1.78%, more than Brooklyn's electrical increase, but less than Staten Island's house. Overall, the switch from gas powered HVAC to electrical lead to a 541.36 GJ reduction in the annual energy use. The rise in electricity usage is attributed to the change from power coming from natural gas in the gas-powered HVAC system, to the fully electrically powered heat pump.

4.2.4 Optimal Configurations

Based on the results stated on sections 4.2.1, 4.2.2 and 4.2.3, every building experienced different performance according to each ERM configuration. However, every building had a single configuration in which the best energy performance was experienced, and Table 31 demonstrates the optimal configurations for each building in more detail.

Table 31 Optimal ERM Configuration for NYC Boroughs

Optimal ERM Configuration for NYC Boroughs					
	Staten Island	**Brooklyn**	**The Bronx**	**Queens**	**Manhattan**
Batt-insulation					
Rigid Foam Board Insulation					
Spray-In insulation	**X**	**X**	**X**	**X**	**X**
Uncoated window (single-glazed)					
Window with low emissivity (double-glazed)	**X**	**X**	**X**	**X**	**X**
Two suspended films (triple-glazed)					
Shade		**X**	**X**	**X**	**X**
Blinds	**X**				
Standard light bulb (60W)					
New Halogen light bulb (43W)					
CFL light bulb (13 W)					
LED light bulb (10W)	**X**	**X**	**X**	**X**	**X**
Gas Powered HVAC					
Electrical Heat Pump	**X**	**X**	**X**	**X**	**X**

As demonstrated on Table 31 all boroughs have similar optimal ERM configurations. The Spray-in insulation was the best performing insulation for all boroughs, as with the better R-value between the insulation options, it yielded the lowest annual energy use. All boroughs performed better when the low emissivity (double-glazed) window was installed, which with its less conductive glass and thicker air-gap, achieved the most energy savings for all boroughs. However, when all ERMs are were simulated simultaneously, the shading ERM differed between the boroughs. Staten Island, with its different design layout and smaller total surface area, achieved the best energy performance when blinds and low emissivity windows were combined. On the other hand, Brooklyn, The Bronx, Queens and Manhattan buildings found a lower annual energy use when shades and the low emissivity windows were combined. The best performing light bulbs, 10W LED lights, were the best performing lighting option for all boroughs. Finally, with its huge energy usage reduction during cooling periods, the electrical heat pump was the HVAC system of choice for all five boroughs.

4.3 CO_2 Emissions

Reducing carbon dioxide emissions is one of the main strategies the NYC government plans on doing to achieve their 2030 and 2050 targets. Therefore, understanding where the CO_2 emission reduction is from when ERMs are employed is important. There were two main fuel sources used for the three infrastructures analyzed, electricity and natural gas. On the reference configuration, the final electricity usage was divided between the HVAC system, lighting and electrical equipment. The HVAC system included the electricity used during heating, cooling, fan usage, heat rejection and pump. While the lighting and electrical equipment included interior and exterior lights, and interior and exterior equipment. For the reference configuration, the final natural gas usage included the gas-powered boiler used for the HVAC system and the water system used in the building. While for the optimal configuration, only the water system was included in the final natural gas use.

The total CO_2 emission calculation for the electricity and natural gas fuel types were calculated using Equation 1, (which is found on) section 3.5. The CO_2 emissions were calculated for the reference configuration and the optimal configuration for each building. The emission factor and combustion efficiency for both fuel source was provided by the United States Environmental Protection Agency (EPA). While the total energy consumption was found during the EnergyPlus simulations. The electricity emission factor used was $1.969e^{-4}$ tCO_2/GJ and 0.05193 tCO_2/GJ (EPA, Greenhouse Gases Equivalencies Calculator - Calculations and References, 2020). The emission factors represent the average marginal CO_2 emission rate to convert reductions of KWh into CO_2 emission units. The electricity emission factor also included losses due to the power lines. Table 32 though Table 34 demonstrate the total annual CO_2 emissions that the buildings had during the reference configuration and the optimal configuration.

Table 32 Total CO2 Emissions for the Reference Configuration and Optimal Configuration for Staten Island per year

Staten Island			
Reference Configuration	Electricity	Natural Gas	
Consumption (GJ)	190.99	299.73	**Total**
Emissions (tCO2 eq)	0.037614419	13.0590173	**13.09**
Optimal Configuration	Electricity	Natural Gas	
Consumption (GJ)	182.83	257.58	**Total**
Emissions (tCO2 eq)	0.036007353	11.22257257	**11.26**

Table 33 Total CO2 Emissions for the Reference Configuration and Optimal Configuration for Brooklyn per year

Brooklyn			
Reference Configuration	Electricity	Natural Gas	
Consumption (GJ)	2081.85	602.29	**Total**
Emissions (tCO2 eq)	0.410008792	26.24133563	**26.65**
Optimal Configuration	Electricity	Natural Gas	
Consumption (GJ)	1735.17	307.17	**Total**
Emissions (tCO2 eq)	0.341732092	13.38317267	**13.73**

Table 34 Total CO2 Emissions for the Reference Configuration and Optimal Configuration for Manhattan

Manhattan			
Reference Configuration	Electricity	Natural Gas	
Consumption (GJ)	3911.06	1204.9	**Total**
Emissions (tCO2 eq)	0.770261539	52.49661342	**53.27**
Optimal Configuration	Electricity	Natural Gas	
Consumption (GJ)	3192.56	592.62	**Total**
Emissions (tCO2 eq)	0.628756956	25.82002079	**26.45**

As presented on the tables above, the ERMs heavily impacted the CO_2 emissions, from the reference configuration to the optimal configurations, for all buildings. The Staten Island house had the smallest CO_2 emissions change from the three buildings, dropping from 13.09 tCO_2 to 11.26 tCO_2. While both the Brooklyn and Manhattan buildings saw a decrease in the optimal configuration of almost half of the reference configuration. These drops in emissions are related to the change in fuel source that the HVAC systems utilized. By using electricity as the fuel source, the equivalent CO_2 emissions are dramatically low, compared to when natural gas is used. However, all buildings still include CO_2 emissions during the optimal configurations, which is due to the water system in the buildings still being powered by a natural gas-powered system. This thesis does not focus on optimizing the water system; therefore, the system was left equal to the reference configuration, which was in accordance to the NYCECC guidelines. However, if the water system for all buildings were electrically powered, the tCO_2 equivalent for all buildings would be less than 1 tCO_2/year, with Staten Island's house not even reaching 0.1 tCO_2/year, as seen on Table 35.

Table 35 Total CO2 Emissions for the Optimal Configuration with electric water system for all three buildings

Staten Island			
OC w/ Electrical Water System	Electricity	Natural Gas	
Consumption (GJ)	182.83	257.58	**Total**
Emissions (tCO2 eq)	0.036007353	0.05072895	**0.087**
Brooklyn			
OC w/ Electrical Water System	Electricity	Natural Gas	
Consumption (GJ)	1735.17	307.17	**Total**
Emissions (tCO2 eq)	0.341732092	0.060495425	**0.402**
Manhattan			
OC w/ Electrical Water System	Electricity	Electric Water system	
Consumption (GJ)	3192.56	592.62	**Total**
Emissions (tCO2 eq)	0.628756956	0.116713217	**0.745**

4.4 Economic Analysis

A net present value (NPV) calculation was performed to understand the impact the optimal ERM configuration have in future costs, compared to the reference configuration. Additionally, a NPV calculation was also performed for the optimal ERM configuration with an electrified water system. Equation 2 NPV equation, (found on) Section 3.6, was used for all three configurations for all three buildings. In the calculation, the benefits were neglected, as this research is interested on the impact the ERMs have on the future costs, instead of how the buildings will be profitable. The initial investment for the reference configuration for all three buildings was a new gas-powered HVAC system. While for the optimal configuration with and without the electric water system, the initial investment consisted the costs for: spray-in insulation, low emissivity windows, blinds or shades, LED lights, and new electrical heat pump. However, the optimal configuration with the electric water system, included an electric boiler in its initial investment. HVAC system replacement costs was added to the specific years according to the system's life expectancy for each configuration. The lighting replacement, refrigerator replacement, and electric sub-metering maintenance were included in the annual O&M costs, which accounted for the life expectancy of each system as well. Electricity and natural gas costs were also included to the annual costs, while annual carbon taxes were included to the configurations in which CO_2 emissions surpassed the emission cap imposed by LL97. Finally, the capital recovery factor utilized a 3.8% annual discount rate. Table 36 shows the costs breakdown utilized for all buildings.

Table 36 Cost Breakdown for each Retrofit Measure for all Buildings

Measures	Costs	Units
Envelope Retrofitting	4.5	$/ft^2
Window Retrofitting	315.27	$/m^2
Shading Retrofitting - Shades	90	$/window
Shading Retrofitting - Blinds	50	$/window
Replace Gas HVAC System	18	$/ft^2
Electric HVAC System	50	$/ft^2
Electricity price	0.04	$/MWh
Natural Gas price	0.0089	$/MWh
Lighting replacement (Common area)	0.21	$/ft^2
Lighting replacement (Apartment area)	0.39	$/ft^2
Refrigerator replacement	700	$/refrigerator
Electric sub-metering	1000	$/unit

To calculate the carbon taxes that each building would pay depending on how much excess CO_2 the building was emitting, the emission cap for each building was first found. The emission cap is defined by the LL97 and states the emission cap is based on the building's occupancy group (explained in Section 2.4.2). The occupancy group for all three buildings is R-2, which represents an emission intensity limit of 0.072656427 $tCO_2/m^2/yr$ for years between 2024-2029, 0.043809134 $tCO_2/m^2/yr$ for years between 2030-2034, and 0.015069481 $tCO_2/m^2/yr$ for years beyond 2035. The emission limits were then multiplied by the floor are of each building, and the emission cap was found. However, since the Staten Island House has an area less than 25,000 ft^2, according to LL97 it is excluded from the emission cap; therefore, the carbon tax was excluded for its NPV calculations. The Brooklyn and Manhattan building were large enough to be included in the emission cap, however the singular building did not emit enough tCO$_2$ equivalent annually, to pay the carbon tax. Therefore, a 9-building multi-family residential complex was simulated for Brooklyn and Manhattan. All 9-buildings had the same design, systems and energy profiles as the singular Brooklyn and Manhattan buildings, and in this case emitted over the annual emission cap. The carbon tax was found for each 9-building complex and each ERM configuration, and is shown on Table 37 and Table 38.

Table 37 Emission Cap, Total Annual Emission and Carbon Tax for Brooklyn's 9-Building Complex

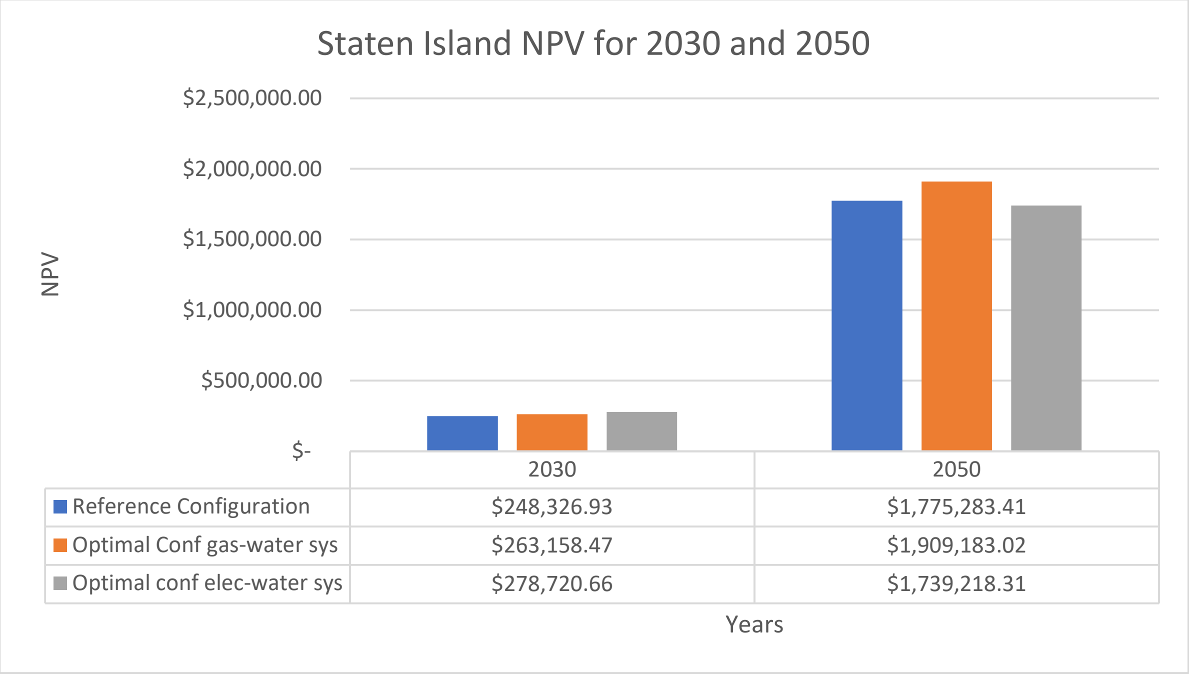
Brooklyn 9-building Complex	Emission Cap (tC02e/yr)	Annual Emission (tC02e/yr)	Carbon Tax ($/yr)
Reference Configuration			
2024-2029	213.6098942	239.8620998	$ 7,035.59
2030-2034	128.7988547	239.8620998	$ 29,764.95
beyond 2034	44.30427435	239.8620998	$ 52,409.50
Optimal Configuration			
2024-2029	213.6098942	123.5241428	$ -
2030-2034	128.7988547	123.5241428	$ -
beyond 2034	44.30427435	123.5241428	$ 21,230.92
OC w/ Electrical Water System			
2024-2029	213.6098942	3.62004765	$ -
2030-2034	128.7988547	3.62004765	$ -
beyond 2034	44.30427435	3.62004765	$ -

Table 38 Emission Cap, Total Annual Emission and Carbon Tax for Manhattan's 9-Building Complex

Manhattan 9-building Complex	Emission Cap (tC02e/yr)	Annual Emission (tC02e/yr)	Carbon Tax ($/yr)
Reference Configuration			
2024-2029	427.2197884	**479.4018747**	$ 13,984.80
2030-2034	257.5977094	**479.4018747**	$ 59,443.52
beyond 2034	88.6085487	**479.4018747**	$ 104,732.61
Optimal Configuration			
2024-2029	427.2197884	**238.0389997**	$ -
2030-2034	257.5977094	**238.0389997**	$ -
beyond 2034	88.6085487	**238.0389997**	$ 40,047.36
OC w/ Electrical Water System			
2024-2029	427.2197884	**6.70923155**	$ -
2030-2034	257.5977094	**6.70923155**	$ -
beyond 2034	88.6085487	**6.70923155**	$ -

4.4.1 Staten Island

Three configurations were used to compare the NPV's, the reference configuration, the optimal configuration with a gas-powered water system, and an optimal configuration with an electrical water system. The house in Staten Island is the smallest building and therefore has the lowest amount of initial costs and annual costs. The Staten Island house does not emit enough CO_2 annually to exceed the LL97 emission cap, therefore it does not pay any carbon taxes for all three configurations. The NPV to the year 2030 and 2050, for all three configurations is shown on Figure 8.



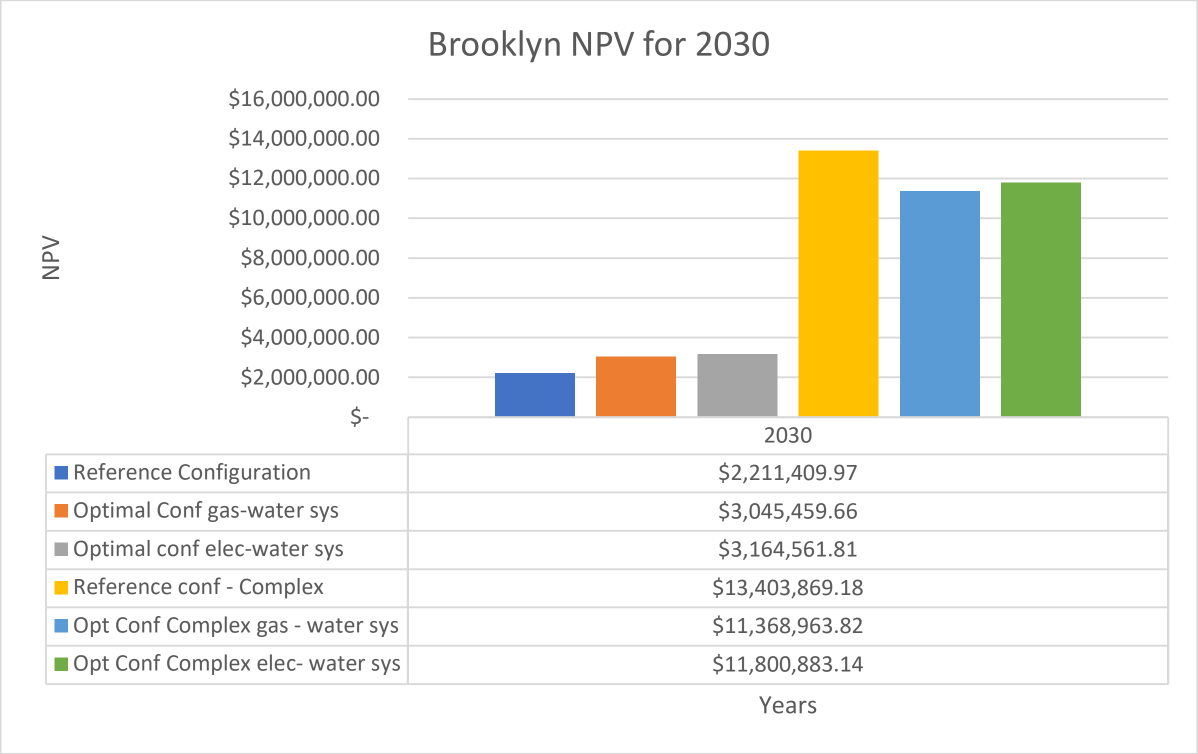
	2030	2050
■ Reference Configuration	$248,326.93	$1,775,283.41
■ Optimal Conf gas-water sys	$263,158.47	$1,909,183.02
■ Optimal conf elec-water sys	$278,720.66	$1,739,218.31

Figure 8 Staten Island NPV for the years 2030 and 2050

Figure 8 shows that for the house in Staten Island, the ERM configurations ends up being the least interesting. By the year 2030, the reference configuration yields the lowest costs, while in 2050 it is the second-best option. This is due to the fact that the Staten Island house does not enter the carbon tax bracket, as it does not emit passed its emission cap. therefore the annual costs are solitarily based on energy use and maintenance. The optimal configuration with the electrical water system ends up being the best option up to the year 2050, however it is the costliest option up to the year 2030. This is linked to the difference is energy savings and electricity costs that this configuration provides. However, the benefits that the optimal configuration with the electrical water system provides, is only relevant closer to the year 2050, almost 30 years after the initial investment. A detailed version of the NPV calculation throughout the years, up to 2050, is found of Appendix C.

4.4.2 Brooklyn, The Bronx and Queens

For the Brooklyn building, three configurations were used to compare the NPV's for the years 2030 and 2050. These configurations were: the reference configuration, the optimal configuration with a gas-powered water system, and an optimal configuration with an electrical water system. Additionally, the same configurations and building designs were added to a 9-building multi-family residential complex. The 9-building complex is used to understand the impact that the carbon taxes have on the three configurations. During the CO_2 emissions calculations, it was found that the Brooklyn building never surpasses the LL97 emission caps during the three configurations analyzed, since the EnergyPlus simulation had some simplifications and building's size was too small to overcome the emission cap. However, many multi-family residential complexes in NYC are assembled of multiple buildings that account for a single property, which this study simulated. When looking at the 9-buildings, the reference configuration and the optimal configuration with a gas-powered water system, both end up emitting more than the emission cap at a certain point, therefore the \$268/tCO_2 carbon tax is applied to the total costs of those corresponding years. Figure 9 and Figure 10 shows the NPV for the three configurations for Brooklyn's building for the years 2030 and 2050.

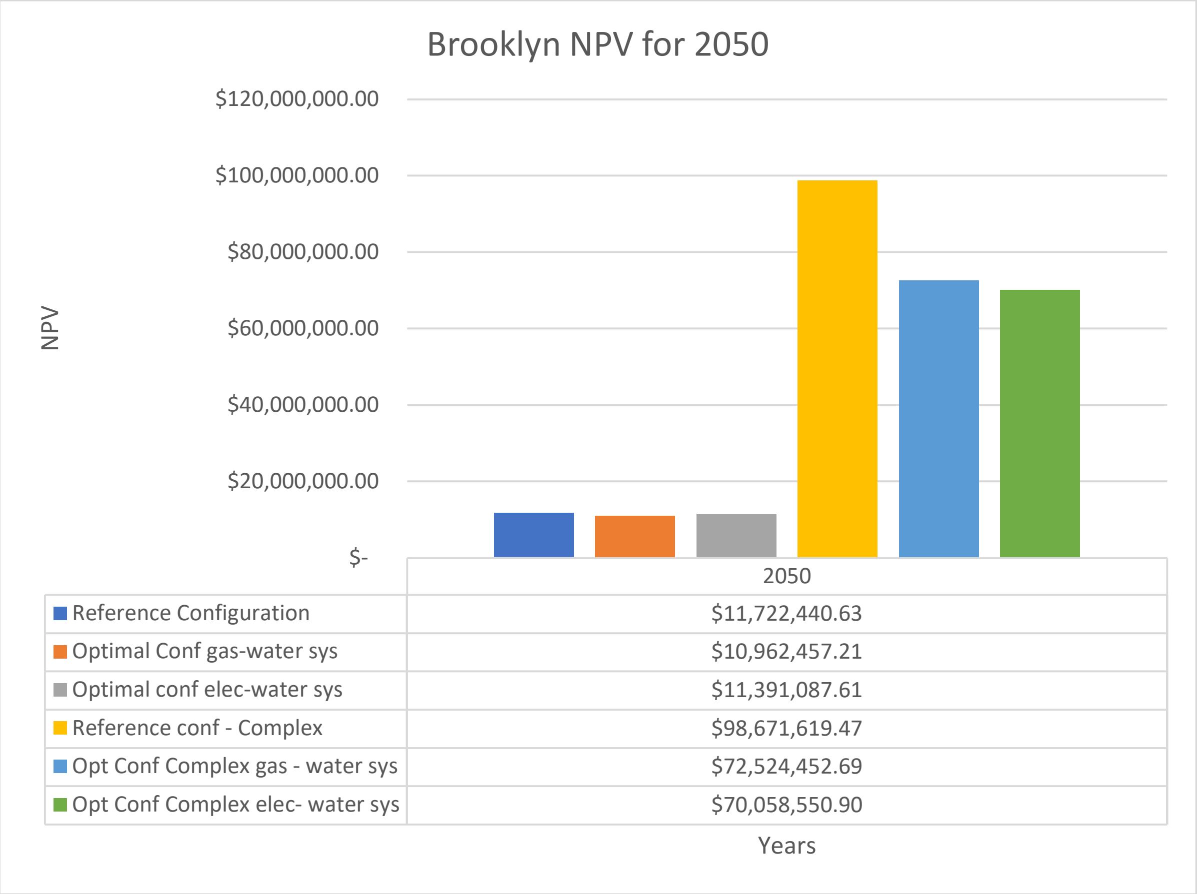


	2030
Reference Configuration	$2,211,409.97
Optimal Conf gas-water sys	$3,045,459.66
Optimal conf elec-water sys	$3,164,561.81
Reference conf - Complex	$13,403,869.18
Opt Conf Complex gas - water sys	$11,368,963.82
Opt Conf Complex elec- water sys	$11,800,883.14

Figure 9 Brooklyn's NPV for the year 2030

Figure 9 demonstrates how impactful the carbon tax throughout the years, by comparing the NPV of the Brooklyn building with the three configurations by its own and the 9-building complex with the three configurations. In the singular Brooklyn building, the configuration with the lowest cost by 2030 is the reference configuration. This is due to the high initial investment that retrofitting the building would cost and the fact that natural gas prices in NYC are cheaper than electricity prices; therefore, the energy savings potential that retrofitting provides, does not overcome the initial investment and operation and maintenance costs. This effect is also present when comparing the single-Brooklyn building with and without the electric water system. By the year 2030 the reference configuration will cost over \$2,2 million, while the optimal configuration with electric water system will cost over \$3,1 million.

On the other hand, when analyzing the 9-building complex, the carbon tax greatly influences the future costs of the three configurations. According to LL97, the carbon cap does not start until 2025, therefore the carbon tax is not included until after the year 2024, however, the huge carbon tax rate for the last five years, overcomes the energy costs and O&M costs rapidly. The reference configuration for the 9-building complex becomes the costliest, reaching $13.4 million in costs in less than 10 years. Hence, lowering the carbon emissions, decreases the excess CO_2 emissions, lowering the carbon tax per year. This is seen on both optimal configuration, gas and electrical water systems, that by the year 2030, these configurations saved over $2 million in future costs. Interestingly, the initial investment for the electrical water system, does not outweigh the carbon taxes that the gas-powered water system would pay based on additional natural gas emissions. Therefore, the best option for a multi-family apartment complex in Brooklyn by the year 2030 is to utilize the optimal configuration with a gas-powered water system.



	2050
🟦 Reference Configuration	$11,722,440.63
🟧 Optimal Conf gas-water sys	$10,962,457.21
⬜ Optimal conf elec-water sys	$11,391,087.61
🟨 Reference conf - Complex	$98,671,619.47
🟦 Opt Conf Complex gas - water sys	$72,524,452.69
🟩 Opt Conf Complex elec- water sys	$70,058,550.90

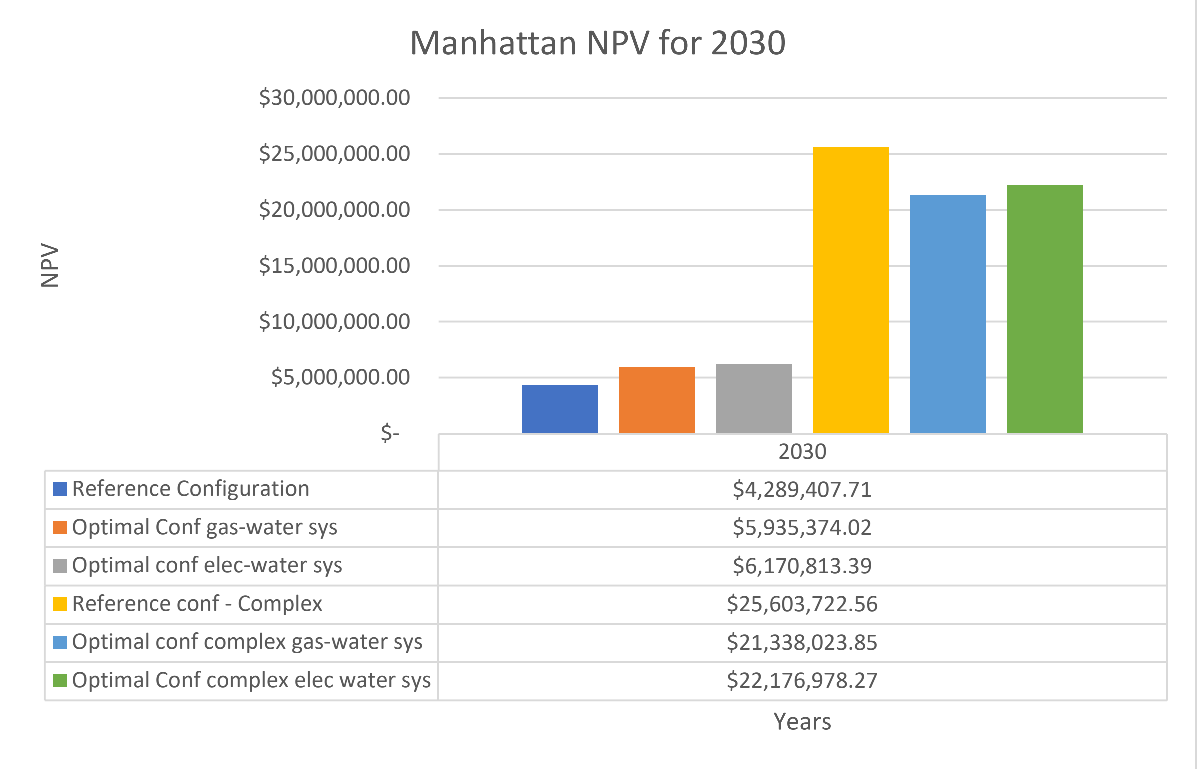
Figure 10 Brooklyn NPV for the year 2050

Figure 10 shows the NPV for the singular-building and 9-building complex in Brooklyn by the year 2050. The reference configuration becomes the costliest for both cases, exceeding $11.7 million for the singular building and $98.6 million for the 9-building complex. Similarly, to the year 2030, when looking at the singular building in Brooklyn, the electrical water system does not benefit the costs by 2050. As, comparable to the year 2030, the increase in energy costs due to the price of electricity being higher compared to natural gas, leads to this configuration costing more overall. Therefore, the best configuration for a singular building in Brooklyn is the optimal configuration with a gas-powered water system, saving almost $800,000 compared to the reference configuration by the year 2050.

In contrast, the 9-building complex, with a much higher carbon emissions, has the impact of the carbon tax in its future costs. The reference configuration emitted past the emission cap all the way through 2050; however, the optimal configuration with a gas-powered water system does not emit past the cap until after 2035, which then carbon taxes are added to its yearly costs until 2050. On the other hand, the optimal configuration with an electric water system never passes the emission threshold, therefore carbon taxes are never included. The reference configuration is the most-costly, since the high carbon taxes since the year 2025 until 2050, increases the annual costs dramatically. However, the addition of the electric water system becomes cost-effectively only after the year 2035, where the gas-powered water system emits past the lower emission cap, costing this configuration almost $340 million in carbon taxes between 2035 and 2050. The carbon tax accounts for 15% of the total costs for the reference configuration up to the year 2050, and 7% for the optimal configuration with gas water system. Hence, it is important to retrofit and electrify the building's systems to decrease the total carbon taxes in future costs. A complete NPV calculation throughout the years for the Brooklyn building is found on Appendix C.

4.4.3 Manhattan

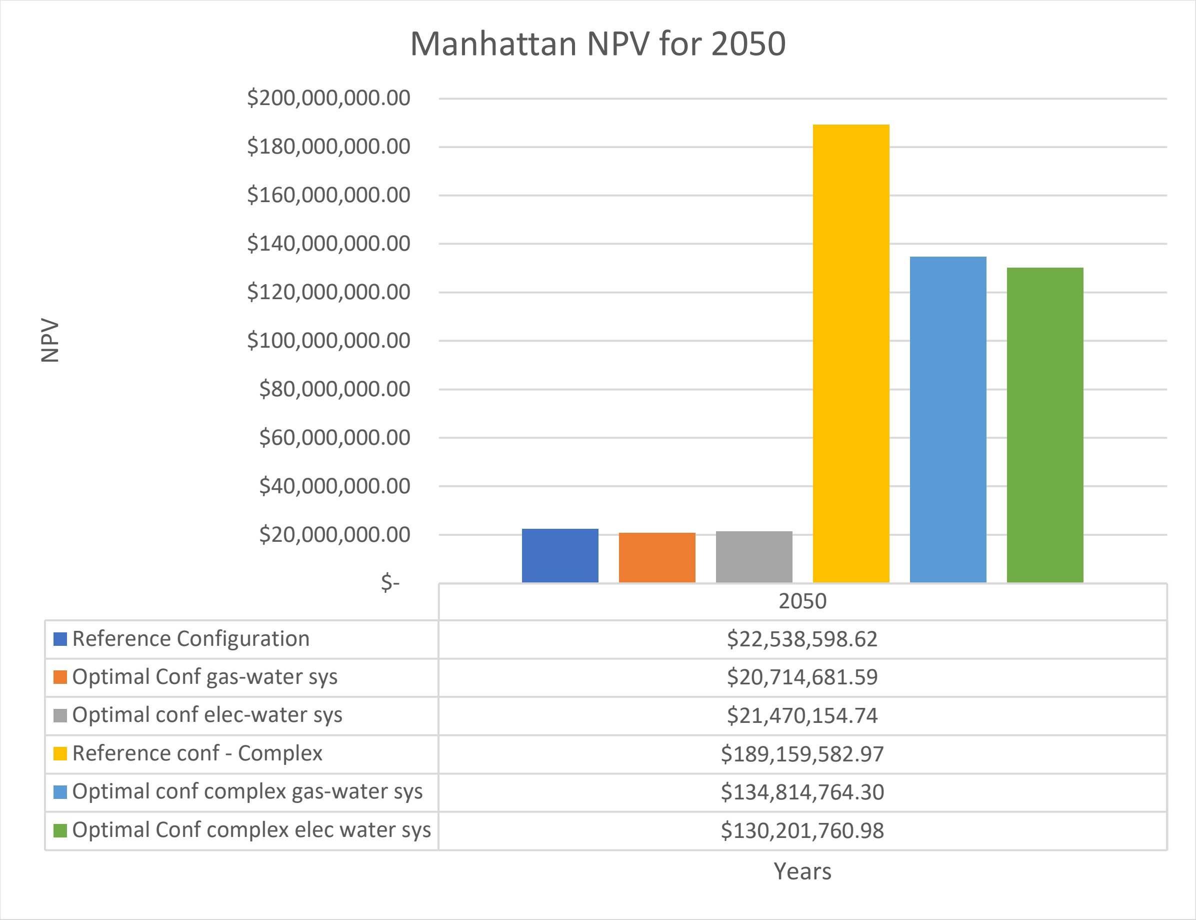
Similar to the Brooklyn building, the Manhattan building economic analysis utilizes the same three configurations and a singular and a 9-building multi-family residential complex. The NPV's for the year 2030 and 2050 were calculated for all three configurations and shown on Figure 11 and Figure 12. The Manhattan building is the largest and most energy consuming building on all five boroughs, therefore the CO_2 emissions that it produces, have a big impact of the carbon tax. For the singular-Manhattan building, all three configurations emitted less CO_2 than the emission cap, therefore no carbon taxes were added to the NPV calculations. For the 9-building complex, the reference configuration and the optimal configuration with a gas-powered water system, surpassed the emission cap for certain periods after 2025, therefore the carbon tax was added to the annual costs, accordingly. Figure 11 and Figure 12 shows the NPV for the Manhattan building for all three configurations for the years 2030 and 2050.



	2030
🟦 Reference Configuration	$4,289,407.71
🟧 Optimal Conf gas-water sys	$5,935,374.02
⬜ Optimal conf elec-water sys	$6,170,813.39
🟨 Reference conf - Complex	$25,603,722.56
🟦 Optimal conf complex gas-water sys	$21,338,023.85
🟩 Optimal Conf complex elec water sys	$22,176,978.27

Figure 11 NPV for the Manhattan building for all three configurations for the year 2030

Similar to the Brooklyn building, the singular building yielded similar future results for the three configurations by 2030, as shown on Figure 11. The reference configuration was the best option, as it had the lowest costs by 2030. While the optimal solution with the electrical water system achieved the highest costs between the three configurations. The difference in costs is a result of the additional energy costs that an electrically powered system contributes, while also being influenced by the large initial investment to retrofit the building. Similar to the Brooklyn building, the gas water system was less costly than the electric water system up to 2030. This is linked to the high electricity and O&M costs, since natural gas prices are cheaper than electricity prices in the NYC, but also due to the lack of incentives that transitioning to fully electric has on buildings that do not emit passed the emission cap. However, the incentives are widely seen when analyzing the 9-building complex in Manhattan. The addition of carbon taxes after the year 2025, greatly influence the future costs for the complex. The reference configuration, with its large energy consumption, yielded the costliest NPV in 2030, with over $25.6 million on costs, while the optimal configuration with a gas water system a total cost of $21.3 million. The carbon taxes contributed to 7% of the total costs for the reference configuration by the year 2030, while the biggest cost for the optimal configuration with the gas water system came from the initial investment of $3.5 million, which accounts for 17% of the total costs by 2030. Similar to the Brooklyn 9-building complex, the carbon taxes savings that the electrical water system provides between the years 2025 and 2030 compared to the gas water system, did not benefit the buildings total costs. The fewer carbon equivalent emissions that the electric water system emits.



	2050
🟦 Reference Configuration	$22,538,598.62
🟧 Optimal Conf gas-water sys	$20,714,681.59
⬜ Optimal conf elec-water sys	$21,470,154.74
🟨 Reference conf - Complex	$189,159,582.97
🟦 Optimal conf complex gas-water sys	$134,814,764.30
🟩 Optimal Conf complex elec water sys	$130,201,760.98

Figure 12 NPV for the Manhattan building for all three configurations for the year 2050

Figure 12 shows the NPV results for the singular-Manhattan building and the 9-building complex for all three configurations until the year 2050. Comparable to the singular-Brooklyn building, the singular-Manhattan building had the lowest total costs from the optimal configuration with the gas water system. The switch from utilizing natural gas to electricity, did not benefit the total energy costs due to the higher energy cost. However, when carbon taxes are added to the NPV the same results seen on the 9-building Brooklyn complex can be seen. The 9-building Manhattan complex had the least costly configuration come from the electric water system optimal configuration. As mentioned in the Brooklyn 9-building complex, it is due to the lack of annual carbon taxes added to the costs, since this configuration does not emit over the emission cap until 2050. On the other hand, the reference and gas water system configuration both crossed the emission cap at a certain point, year 2025 and 2035 respectively. The reference configuration had the highest cost since it had 25 years of carbon taxes added to its annual costs, resulting in 17% of it coming directly from the carbon tax. The optimal configuration with a gas water system, only surpassed the emission cap after 2035; however, this increase in annual costs was harmful enough to render being costlier than the electric water system configuration. Overall, the optimal configuration with an electric water system reduced costs by $59 million by 2050. The benefit of not having to pay the carbon taxes, immensely impact the configuration's total costs. A complete NPV calculation throughout the years for the Manhattan building is found on Appendix C.

Chapter 5

Discussion

This chapter describes the implications of this study. Firstly, the implementation of the laws and regulations that the city of New York has done and plans on doing is discussed in section 5.1. Next, the results of the optimal ERM configurations and its economic impact on the NYC built environment is discussed in section 5.2. Section 5.3 discusses how the optimal configuration and the regulations might impact the built environments and NYC's 2030 targets. Section 5.4 describes the limitations and suggestions for further research. Finally, recommendations for the NYC government to focus on in the future is presented in Section 5.5.

5.1 Regulations

The NYC government has implemented many regulations and financial mechanisms to encourage the built environment to invest in more energy efficient measures. By creating an energy conservation code (NYCECC) which mandates all buildings to follow, the NYC government ensures that its built environment is constructed and maintained properly. An annual energy and water consumption report for every building needs to be submitted to the government, allowing the NYC government to collect data and create a transparent understanding of the built environment's energy and water usage. Financial penalties are also enforced to ensure that the built environment follows the energy and water usage submissions and display of the energy performance label. Additionally, buildings are given a CO_2 emission cap based on its occupancies and surface area, and a financial penalty is imposed if the building surpasses the emission cap. Finally, random inspections are performed to ensure that the built environment is following the regulations and fines are given if they fail to comply.

However, most of these financial penalties are not severe enough or strict to encourage compliance. It has been found that the fines the government can give for non-compliance, and the lack of additional punishments for continuous non-compliance, may result on many buildings to pay the $3,000 fine and not comply with the new building codes (Blumberg, 2018). The study also reported that the lack of expertise in the energy auditing and retro-commissioning fields may hinder the government's target of continuous inspections and compliance (Blumberg, 2018). Similarly, (Kontokosta, 2020) examined the impact that mandatory energy audits had on NYC buildings' energy use by seeing the effect that the LL87 imposed from the year 2011 until 2016. The study found that the energy use in the buildings rose between 2.5% to 4.9%, even though the mandatory auditing was meant to increase the city's building's energy efficiency. The lack of enforcement, insufficient financial mechanisms and the absence of punishment for continuous non-compliance are a few challenges that the NYC government needs to be aware so it can achieve its energy targets.

5.2 Findings

The results of the EnergyPlus simulations for the three buildings, seen in the Chapter Results, demonstrated that the biggest energy reduction can be achieved when retrofitting the windows and the HVAC system. This corresponds with the expectations stated in Section 2.2, which mentioned that the one-third of the heat loss in a typical apartment building in the US, is derived from windows, and that installing electrical heat pumps could provide 40-60% reduction in cooling energy use. Additionally, retrofitting lighting and shading, could provide a cheaper and less time-consuming energy saving solution.

What stands out the most from the optimal ERM configurations is the influence that the windows and the shading type have on the overall building's energy use. The difference between the single-glazed and the double- and triple-glazed windows were staggering for all three buildings, with the Manhattan building experiencing around 15% energy improvement for retrofitting the windows. The biggest influence in this is the big difference in R-values that the different types of windows have, which leads to the single-glazed window, with its low R-value, to lose more heat throughout the year. The shading type, also influenced the energy use differently, depending on what window type was being used. Even though all buildings had the biggest energy savings with the double-glazed window, the shading type varied as shades or blinds impacted the building's performance differently. For the Staten Island house, the blinds were the best performing shading option, and when installed, it improved the house's energy efficiency with all window types. However, for the Brooklyn and Manhattan building, the blinds were less efficient than the shades for the single- and double-glazed windows, increasing the building's annual energy use. This change in performance between the three buildings is linked to the different building designs and the impact of direct sunlight has on the building. Since the Staten Island house is smaller, only two stories high, in a suburban area and has limited window space, the influence that the direct sunlight has on its HVAC system is crucial. As with the increase in direct sunlight, the house's inner temperature increases, allowing the HVAC system's cooling loads to decrease. In which the blinds, with a higher conductivity rate and openings between the slabs, was the better solution to increase direct sunlight exposure. On the other hand, the Brooklyn and Manhattan buildings are high structures, with an abundant amount windows and in an urban environment. Therefore, shading from trees or other objects, besides neighboring buildings is limited, and its direct sunlight intake is plentiful from its abundant window exposure. In that case, the shades, with low conductivity rate and low sunlight exposure possibilities, was the best solution to keep heat entering the apartments through the windows. Since the Brooklyn and Manhattan buildings were already experiencing high direct sunlight, by minimizing it, the heating load of the HVAC system in the buildings decreased.

This research focused on the building's energy use retrofitting, however when analyzing the CO_2 emission results, a relevant issue was found. The water system, which was powered by natural gas in all three buildings, was a continuous carbon emitter and contributed to almost a fourth of the total energy use of the building. Therefore, when analyzing the CO_2 emissions, the inclusion of an electric water system was included, as it was vital to understand how impactful the water system was in the building's energy efficiency. We found that the optimal ERMs for all three buildings majorly decreased the overall CO_2 emissions, when retrofitting the water system was excluded. With Brooklyn's and Manhattan's buildings experiencing almost half in emission reduction. However, since the water system was still one-fourth of the building's energy use, a big share of the building was still utilizing natural gas, and emitting a large amount of CO_2. The addition of electrifying the water system to the optimal ERM configuration, immensely decreased CO_2 reductions, going from over 26.45 tCO_2 equivalent to 0.745 tCO_2 equivalent, for the Manhattan building. This difference is due to the fact that burning natural gas is largely more impactful to the environment than utilizing electricity, which uses various amounts of energy sources in its scheme. This big influence that the water system has on the emission of the buildings compares with the findings of a 2016 study which showed that replacing existing natural-gas powered water heaters with high-efficient electrical heat pumps is an effective and economically viable way to reduce CO_2 emissions (Howarth, 2016).

Similarly, the same approach was used when calculating the NPVs for all three buildings. Three ERM configurations were used: reference configuration, optimal configuration with gas-powered water system and optimal configuration with electrical water system. The NPVs were used to see how the ERMs impacted the overall costs of the buildings, and were used to visualize if the retrofit investments would be beneficial or not. However, the buildings simulated in EnergyPlus used simplified systems and were limited in total surface area; therefore, a 9-building complex was used for both the Brooklyn and Manhattan building. The 9-building complex consisted of 9 identical Brooklyn or Manhattan buildings, where the total annual emission surpassed the emission caps, which allowed to proper calculate the impact that the carbon taxes have on the NPV. The biggest impact on the NPV was the inclusion of the carbon tax imposed by the LL97, which states that for every excess tCO_2 equivalent passed the given cap, $268 would be taxed to the building. The impact that the carbon tax has on the NPV is seen when comparing the singular Brooklyn and Manhattan building with the 9-building complex. Since the singular buildings hadn't emitted over its carbon cap, the carbon tax was not included in the NPV calculation, which resulted on the reference ERM being the most profitable for the first 10 years, and the optimal ERM with the electric water system never surpassing its gas counterpart, even 30 years after the initial investment. This is due to inexpensive natural gas prices, high initial investment for building retrofit and the lack of incentives for buildings that do not emit over its emission cap. Therefore, the reduction in energy usage that the ERMs provide, do not overcome the costs until a few decades later. However, adding a financial burden to utilizing natural gas, seriously impacts the future costs. When analyzing the Brooklyn and Manhattan 9-building complex, the carbon tax was 5% of the total costs after 10 years and 17% after 30 years. The initial investment of retrofitting was extremely beneficial to both buildings, as in the configuration with the natural gas water system, costs decreased by 29%; and when retrofitting the water system, a 31% cost reduction occurred. The optimal configuration with an electric water system provided the lowest NPV for the year 2050 for the Brooklyn and Manhattan 9-building complex because the buildings never surpassed their carbon emission cap, therefore never having to pay for the carbon tax. These results are compatible with a 2020 study that examined the effect that large carbon taxes have in the residential sector. The study looked at the Swedish carbon policies and found that when the penalty for emitting CO_2 increases, the annual CO_2 emissions widely decreases (Runst, 2020). The financial penalty that the carbon tax has, is a great incentive for the built environment to improve its energy efficiency and lower its energy emissions, as the built environment is wary of the increased costs.

5.3 Reaching NYC's Targets

The results of this study demonstrate that properly retrofitting the built environment leads to a decrease in energy use and carbon emissions. Additionally, when adding local laws and carbon taxes in the equation, retrofitting becomes the most powerful tool to lower future costs. The goal of the NYC government is to achieve 40 percent reduction in GHG emissions from covered buildings by the end of 2030. In 2020, the city of New York emitted a total of 56 million tCO_2 equivalent, where 79% of it came from buildings, equaling to 44.24 million tCO_2 equivalent. To reach the 40 percent reduction in GHG from the covered buildings, then NYC built environment should be emitting 26.54 million tCO_2 equivalent by 2030. From the results in this study, the optimal ERM configuration with an electric water system was the best-case scenario that the built environment could take. Since it was the most cost-effective configuration by 2050 and it yielded the greatest CO_2 emission reduction. When utilizing this configuration, NYC has the potential to decrease its emissions by 94%, between all five boroughs. According to the 2020 census, NYC has over 3.5 million housing units in its city limits. Therefore, by using the 94% emission reduction potential to the current built environment, 1,516,002 apartment units have to be retrofitted, for NYC to reach their 2030 emission target. This accounts to 43% of NYC's total apartment units in 2020.

5.4 Limitations and Further Research

There were multiple limitations in this research, as many assumptions and exclusions were conducted. Firstly, many ERMs were excluded from the research, such the use of renewable technology, waste recycling and others. The ERMs chosen were in accordance with the NYCECC retrofitting guidelines and the NYC Green New Deal's recommendations. The ERMs chosen were also the most widely used measures in NYC, this information was provided by FSG, a New York City based company which works directly with the City of New York on retrofitting low- and medium-income apartment complexes. For future research, implementing other forms of ERMs might influence the optimal ERM configurations and their cost estimates, allowing an even better understanding on the impact they have to the NYC built environment.

Additionally, the water system was excluded during the optimization process, as this research was focusing on the influence that the ERMs had on the building's energy efficiency related to the heat loss, during the optimal ERM optimizations. However, a gas and electric water system option was used during the CO_2 emission calculations and economic analysis. Similarly, many materials were excluded from the research, and only a range of different energy performing materials were utilized for simplicity.

The EnergyPlus simulation was also simplified, as many systems and equipment could not be included. For example, buildings may have centralized or unit-based HVAC systems, which influence the overall building energy performance differently. Also, the use of electronic devices in every apartment may vary, which might influence the total energy use, but an assumption in outlet energy usage was used for all apartments. The apartments were also designed as a single unit, instead of consisting of multiple rooms and walls. This simplification might have influenced the direct sunlight and air-loop systems that EnergyPlus calculated, also influencing the building's energy use. Additionally, this research assumed that all buildings in all five boroughs fit a specific design and architecture, which it is not realistic. However, this research was interested in looking at the potential in energy savings and costs that these ERMs could have for an average building in set borough. Which is why, the three buildings were designed based on the borough's architecture and size. Therefore, this research understood that the buildings energy profile would include some simplifications. Hence, this research looked at the energy savings potential the different materials had, and utilized this to make assumptions to the NYC's built environment. Future research should include more materials, systems and building designs, which could enhance the understanding of its influence in NYC's built environment.

A discount rate was used when in the economic analysis, however each measure and costs might raise and fall differently in the upcoming years. Since the price of natural gas and electricity might vary throughout the years, based on drops or increase in consumption. Additionally, the electricity emission factor utilized in the carbon emission calculations, are the NYC's current electricity emission factor. However, the city plans on having the entire grid be powered from 100% renewable technology by 2050, which means that the electricity emission factor will decrease throughout the year. Future research should take these considerations more in depth and added to the economic analysis, as they could influence the future costs.

Lastly, when accounting for the number of units the city of New York needs to retrofit to achieve its 2030 emission target, emissions from newer developments were excluded. This research was interested in understanding how the combination of the new regulations and ERMs can have on NYC 2030 emissions based on current units. Therefore, future research should include the emission increase that new development will cause, as this will increase the number of current units needed to be retrofitted.

5.5 Recommendations

The NYC Green New Deal imposed sustainable and strict regulations which encourage energy efficiency in its built environment. The law standardized energy codes, mandated the gathering of annual energy and water usage data for all buildings, mandated that the building's energy performance rating be displayed to the public, and enforced GHG emission caps and taxes for certain buildings. However, the implementation and impact of these regulations on the built environment have yet to be well documented. At the time of writing this research, only two studies on the NYC Green New Deal have been published, (Blumberg, 2018) and (Kontokosta, 2020), which focus on the enforcement and compliance to the law. This research went one step further, and analyzed how the regulations and the carbon taxes, will impact the NYC's built environment. Since the NYC Green New Deal has a deadline for revision up to the year 2023, the combination of this study and the findings of (Blumberg, 2018) and (Kontokosta, 2020), should assist the NYC government with revising the law. (Blumberg, 2018) and (Kontokosta, 2020), found that the lack of stricter financial penalties for non-compliance and no penalty for continuous non-compliance, encourages the built environment to not comply to the annual energy reporting and pay the fines. Similarly, this research found that the buildings that emit more than their emission cap, are strongly affected by the carbon tax; hence they are more likely to invest on retrofit measures, as it is the most cost-effective solution in the short and long term. However, the results of this study found that for buildings that are not affected by the carbon tax, such as mid-rise buildings or houses, lack the financial encouragement to invest on retrofitting measures. This is caused by the higher electricity prices in NYC compared to natural gas prices, and the lack of financial benefits such as grants, subsidies or tax reductions that the government could provide for buildings who want to invest in reducing their GHG emissions. This study found that retrofitting measures can reduce annual energy consumption by over 17%, which this accounts for a 94% of CO_2 equivalent emission reduction. Nevertheless, there are no financial benefits for lowering GHG emissions, unless you fall into the carbon tax. This situation can already be seen in the current NYC built environment, as according to FSG, many building owners are worried about having to pay the carbon taxes, but have less incentive to invest on retrofitting if they don't emit over their emission cap (McIntyre, 2021). Additionally, the built environment is worried about the increase in electricity prices from the increase in electricity demand that could occur in the upcoming years, since more buildings are choosing to electrify their systems, and the NYC grid is not yet ready to handle the spike (McIntyre, 2021).

Therefore, this research states a few recommendations that the NYC government should consider:

- Create stricter penalties for non-compliance, including higher financial penalties and temporary closure for continuous non-compliance.
- Create financial benefits for buildings and facilities which are not included in the carbon taxes, but have the desire to invest in retrofits.
- And/or create grants or tax reductions for buildings that have a high energy performance rating.
- Subsidize electricity prices or increase taxation on fossil fuels, to ensure electricity prices are more competitive than fossil fuels.

Conclusion

The aim of this research was to understand how the optimal ERM configurations for each borough in NYC, in combination with the NYC's Green New Deal regulations, impacted their progress in reducing carbon emissions by 2030. To understand to what extent the policies and ERMs had on the NYC's emission targets, the following sub questions were answered.

1. "How does the NYC government currently implement the Green New Deal policies towards achieving the higher energy efficient retrofitting targets?"

The NYC government has created energy conservation codes, auditing, inspections and financial penalties to encourage compliance. However, some worry about the lack of expertise in the field and the low financial penalties that non-complying has. Nevertheless, this research utilized the guidelines and regulations presented in the Green New Deal and attributes them into the ERM optimization and economic analysis.

2. "What is the optimal configuration of ERMs that can be applied in NYC based on the guidelines dictated by the Green New Deal?"

Since NYC varies in building structure and environment from borough to borough, three buildings with different designs were used to represent all five boroughs. The optimal ERMs for the boroughs differed based on their locations, since size and location influence the energy use. The optimal configuration for Staten Island differed from the other four boroughs, on one ERM. However, all of the boroughs achieved the lowest energy usage when better performing materials and electrically powered system were used. The optimal configurations for all boroughs are presented on Table 31, and were used in the economic analysis.

3. "What will be the effect of the optimal configuration of ERMs on NYC's built environment in the following decades and will they be sufficient to achieve the Green New Deal's retrofitting targets?"

An economic analysis was performed to understand the impact that the regulations and the optimal ERMs have on the NYC's built environment. It was found that the best-case scenario for the built environment is to fully electrify its HVAC and water systems and in addition retrofit its envelope, windows, and lighting, as this will be the only way for the built environment to not fall into the carbon taxation. Therefore, with the implementation of these measures, the NYC government needs 43% of its current apartment units to implement these measures for them to achieve their 2030 emissions target.

With these sub-questions the main research question was answered:

To what extent will the policies of NYC's Green New Deal allow for the achievement of the deal's high energy efficient retrofitting targets from the perspective of optimal ERMs?

The policies of the NYC's Green New Deal will allow the NYC government to reach their high energy efficient retrofitting targets by the year 2030, as long as more than 43% of the built environment invests in their respective optimal ERM configuration.

With this research, an initial understanding of how the NYC's Green New Deal policies impact the built environment is presented. To understand how the NYC Green New Deal will impact the city's-built environment, this research analyzed the government plans on encourage compliance, studied how much energy savings can be achieved on all five boroughs, and examined the economic impact that these savings could contribute to the built environment. This research has shown how these policies will affect the NYC's built environment and has provided recommendations, based on its results, that the NYC government should consider if they hope to reach their emission targets. This research hopes to that its findings can assist the NYC government and the NYC built environment to allow them to better prepare for the more sustainable future the city aims on developing.

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Appendix A

Manhattan and Brooklyn Building

Table 39 Manhattan and Brooklyn Building's Optimized Materials and Systems

Name	Zone	Construction (layers from exterior to interior)
Steel Framed Wall with Batt Insulation	Exterior Wall	8’’ Brick Wall, 1’’ Air Space, Structural Sheathing, Steel Studs, Batt Insulation, and Gypsum Wall Board
Steel Framed Wall with Rigid Foam Boards	Exterior Wall	8’’ Brick Wall, 1’’ Air Space, Structural Sheathing, Steel Studs, Rigid Foam Boards, and Gypsum Wall Board
Steel Framed Wall with Spray-In Place	Exterior Wall	8’’ Brick Wall, 1’’ Air Space, Structural Sheathing, Steel Studs, Spray-In Place Insulation, and Gypsum Wall Board
Insulation Above Deck	Roof	Roof Membrane, Rigid Insulation, Metal Deck with Concrete, and Structural Framing
Metal Building Roof	Roof	Exterior Roof Skin, Uncompressed Batt Insulation, Compressed Barr Insulation, and Metal Framing Members
Opaque Door	Main Entrance Door	Opaque door
Glass Door	Main Entrance Door	Glass
Uncoated Window	Window	Uncoated Double Pane
Soft Coat Lo-e Window	Window	Soft Coat Lo-e and Argon
Two Suspended films	Window	Two Suspended films and Argon
Window Interior Shade	Window Shade	Low, medium and high reflective shade
Window Interior Blind	Window blind	Low, medium and high reflective blind
Standard light bulb	Lighting	800 lumens - 60 W
New Halogen light bulb	Lighting	800 lumens - 43 W
CFL light bulb	Lighting	800 lumens – 13 W
LED light bulb	Lighting	800 lumens – 10 W
Forced Air Units	HVAC	Heating and Cooling systems
Heat Pump	HVAC	Heating and Cooling systems

Staten Island

Table 40 Staten Island Building's Optimized Materials and Systems

Name	Zone	Construction (layers from exterior to interior)
Wood Framed Wall with Batt Insulation	Exterior Wall	8’’ Brick Wall, 1’’ Air Space, Structural Sheathing, wood Studs, Batt Insulation, and Gypsum Wall Board
Wood Framed Wall with Rigid Foam Boards	Exterior Wall	8’’ Brick Wall, 1’’ Air Space, Structural Sheathing, wood Studs, Rigid Foam Boards, and Gypsum Wall Board

Wood Framed Wall with Spray-In Place	Exterior Wall	8’’ Brick Wall, 1’’ Air Space, Structural Sheathing, wood Studs, Spray-In Place Insulation, and Gypsum Wall Board
Attic Roof	Roof	Roof Deck and Rafters, Insulation Layer, Purlins, and Air Tight Ceiling
Metal Building Roof	Roof	Exterior Roof Skin, Uncompressed Batt Insulation, Compressed Barr Insulation, and Metal Framing Members
Opaque Door	Main Entrance Door	Opaque door
Glass Door	Main Entrance Door	Glass
Uncoated Window	Window	Uncoated Double Pane
Soft Coat Lo-e Window	Window	Soft Coat Lo-e and Argon
Two Suspended films	Window	Two Suspended films and Argon
Window Interior Shade	Window Shade	Low, medium and high reflective shade
Window Interior Blind	Window blind	Low, medium and high reflective blind
Standard light bulb	Lighting	800 lumens - 60 W
New Halogen light bulb	Lighting	800 lumens - 43 W
CFL light bulb	Lighting	800 lumens – 13 W
LED light bulb	Lighting	800 lumens – 10 W
Forced Air Units	HVAC	Heating and Cooling systems
Heat Pump	HVAC	Heating and Cooling systems

Appendix B

Possible ERM Combinations for Staten Island

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Batt-insulation	X					X			X			X			X			X		
Rigid Foam Board Insulation		X		X			X			X			X			X			X	
Spray-In insulation			X		X			X			X			X			X			X
Uncoated window (single-glazed)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Window with low emissivity (double-glazed)																				
Two suspended films (triple-glazed)																				
Shade	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Blinds																				
Standard light bulb (60W)	X	X	X	X	X										X	X	X			
New Halogen light bulb (43W)						X	X	X										X	X	X
CFL light bulb (13 W)									X	X	X									
LED light bulb (10W)												X	X	X						
Gas Powered HVAC																				
Electrical Heat Pump	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Batt-insulation	X				X			X			X			X		X			X	
Rigid Foam Board Insulation		X		X		X			X			X			X		X			X

Spray-In insulation			X				X			X			X					X		
Uncoated window (single-glazed)	X	X	X	X																
Window with low emissivity (double-glazed)																X	X	X	X	X
Two suspended films (triple-glazed)					X	X	X	X	X	X	X	X	X	X	X					
Shade	X	X	X																	
Blinds				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Standard light bulb (60W)				X				X	X	X									X	X
New Halogen light bulb (43W)											X	X	X							
CFL light bulb (13 W)	X	X	X											X	X					
LED light bulb (10W)					X	X	X									X	X	X		
Gas Powered HVAC																				
Electrical Heat Pump	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	40	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**

Batt-insulation		X			X			X	X			X			X			X		
Rigid Foam Board Insulation			X			X				X			X			X			X	
Spray-In insulation	X			X			X				X			X			X			X
Uncoated window (single-glazed)								X												
Window with low emissivity (double-glazed)	X	X	X	X	X	X	X													
Two suspended films (triple-glazed)									X	X	X	X	X	X	X	X	X	X	X	X
Shade								X	X	X	X	X	X	X	X	X	X	X	X	X
Blinds	X	X	X	X	X	X	X													
Standard light bulb (60W)	X							X				X	X	X						
New Halogen light bulb (43W)		X	X	X											X	X	X			
CFL light bulb (13 W)					X	X	X											X	X	X
LED light bulb (10W)									X	X	X									

Gas Powered HVAC																				
Electrical Heat Pump	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

	60	61	62	63	64	65	66	67	68	69	70	71
Batt-insulation	X			X			X			X		
Rigid Foam Board Insulation		X			X			X			X	
Spray-In insulation			X			X			X			X
Uncoated window (single-glazed)												
Window with low emissivity (double-glazed)	X	X	X	X	X	X	X	X	X	X	X	X
Two suspended films (triple-glazed)												
Shade	X	X	X	X	X	X	X	X	X	X	X	X
Blinds												
Standard light bulb (60W)				X	X	X						
New Halogen light bulb (43W)							X	X	X			

CFL light bulb (13 W)										X	X	X
LED light bulb (10W)	X	X	X									
Gas Powered HVAC												
Electrical Heat Pump	X	X	X	X	X	X	X	X	X	X	X	X

Possible ERM Combinations for Brooklyn

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Batt-insulation	X					X			X			X			X			X		
Rigid Foam Board Insulation		X		X			X			X			X			X			X	
Spray-In insulation			X		X			X			X			X			X			X
Uncoated window (single-glazed)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Window with low emissivity (double-glazed)																				
Two suspended films (triple-glazed)																				
Shade	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Blinds																				

Standard light bulb (60W)	X	X	X	X	X										X	X	X			
New Halogen light bulb (43W)						X	X	X										X	X	X
CFL light bulb (13 W)									X	X	X									
LED light bulb (10W)												X	X	X						
Gas Powered HVAC																				
Electrical Heat Pump	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Batt-insulation	X				X			X			X			X		X			X	
Rigid Foam Board Insulation		X		X		X			X			X			X		X			X
Spray-In insulation			X				X			X			X					X		
Uncoated window (single-glazed)	X	X	X	X																
Window with low emissivity (double-glazed)																X	X	X	X	X

Two suspended films (triple-glazed)					**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**					
Shade	**X**	**X**	**X**																	
Blinds				**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
Standard light bulb (60W)				**X**				**X**	**X**	**X**									**X**	**X**
New Halogen light bulb (43W)											**X**	**X**	**X**							
CFL light bulb (13 W)	**X**	**X**	**X**											**X**	**X**					
LED light bulb (10W)					**X**	**X**	**X**									**X**	**X**	**X**		
Gas Powered HVAC																				
Electrical Heat Pump	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**

	40	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**
Batt-insulation		**X**			**X**			**X**	**X**			**X**			**X**			**X**		
Rigid Foam Board Insulation			**X**			**X**				**X**			**X**			**X**			**X**	
Spray-In insulation	**X**			**X**			**X**				**X**			**X**			**X**			**X**

Uncoated window (single-glazed)								X												
Window with low emissivity (double-glazed)	X	X	X	X	X	X	X													
Two suspended films (triple-glazed)									X	X	X	X	X	X	X	X	X	X	X	X
Shade								X	X	X	X	X	X	X	X	X	X	X	X	X
Blinds	X	X	X	X	X	X	X													
Standard light bulb (60W)	X							X				X	X	X						
New Halogen light bulb (43W)		X	X	X											X	X	X			
CFL light bulb (13 W)					X	X	X											X	X	X
LED light bulb (10W)									X	X	X									
Gas Powered HVAC																				
Electrical Heat Pump	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81
Batt-insulation	X			X			X			X			X			X			X		X	

Rigid Foam Board Insulation		X			X			X			X			X			X			X		X
Spray-In insulation			X			X			X			X			X			X				
Uncoated window (single-glazed)													X	X	X	X	X	X	X	X	X	X
Window with low emissivity (double-glazed)	X	X	X	X	X	X	X	X	X	X	X	X										
Two suspended films (triple-glazed)																						
Shade	X	X	X	X	X	X	X	X	X	X	X	X										
Blinds													X	X	X	X	X	X	X	X	X	X
Standard light bulb (60W)				X	X	X							X	X	X							
New Halogen light bulb (43W)							X	X	X							X	X	X				
CFL light bulb (13 W)										X	X	X							X	X		
LED light bulb (10W)	X	X	X																			X	X

Gas Powered HVAC																						
Electrical Heat Pump	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Possible ERM Combinations for Manhattan

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Batt-insulation	X					X			X			X			X			X		
Rigid Foam Board Insulation		X		X			X			X			X			X			X	
Spray-In insulation			X		X			X			X			X			X			X
Uncoated window (single-glazed)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Window with low emissivity (double-glazed)																				
Two suspended films (triple-glazed)																				
Shade	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Blinds																				
Standard light bulb (60W)	X	X	X	X	X										X	X	X			
New Halogen light bulb (43W)						X	X	X										X	X	X

CFL light bulb (13 W)									X	X	X									
LED light bulb (10W)												X	X	X						
Gas Powered HVAC																				
Electrical Heat Pump	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Batt-insulation	X				X			X			X			X		X			X	
Rigid Foam Board Insulation		X		X		X			X			X			X		X			X
Spray-In insulation			X				X			X			X					X		
Uncoated window (single-glazed)	X	X	X	X																
Window with low emissivity (double-glazed)																X	X	X	X	X
Two suspended films (triple-glazed)					X	X	X	X	X	X	X	X	X	X	X					
Shade	X	X	X																	
Blinds				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Standard light bulb (60W)				**X**				**X**	**X**	**X**									**X**	**X**
New Halogen light bulb (43W)											**X**	**X**	**X**							
CFL light bulb (13 W)	**X**	**X**	**X**											**X**	**X**					
LED light bulb (10W)					**X**	**X**	**X**									**X**	**X**	**X**		
Gas Powered HVAC																				
Electrical Heat Pump	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**

	40	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**
Batt-insulation		**X**			**X**			**X**	**X**			**X**			**X**			**X**		
Rigid Foam Board Insulation			**X**			**X**				**X**			**X**			**X**			**X**	
Spray-In insulation	**X**			**X**			**X**				**X**			**X**			**X**			**X**
Uncoated window (single-glazed)								**X**												
Window with low emissivity (double-glazed)	**X**	**X**	**X**	**X**	**X**	**X**	**X**													

Two suspended films (triple-glazed)									X	X	X	X	X	X	X	X	X	X	X	X
Shade								X	X	X	X	X	X	X	X	X	X	X	X	X
Blinds	X	X	X	X	X	X	X													
Standard light bulb (60W)	X							X				X	X	X						
New Halogen light bulb (43W)		X	X	X											X	X	X			
CFL light bulb (13 W)					X	X	X											X	X	X
LED light bulb (10W)									X	X	X									
Gas Powered HVAC																				
Electrical Heat Pump	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82
Batt-insulation	X			X			X			X			X			X			X		X		
Rigid Foam Board Insulation		X			X			X			X			X			X			X		X	
Spray-In insulation			X			X			X			X			X			X					X

Uncoated window (single-glazed)													X	X	X	X	X	X	X	X	X	X	X
Window with low emissivity (double-glazed)	X	X	X	X	X	X	X	X	X	X	X	X											
Two suspended films (triple-glazed)																							
Shade	X	X	X	X	X	X	X	X	X	X	X	X											
Blinds													X	X	X	X	X	X	X	X	X	X	X
Standard light bulb (60W)				X	X	X							X	X	X								
New Halogen light bulb (43W)							X	X	X							X	X	X					
CFL light bulb (13 W)										X	X	X							X	X			
LED light bulb (10W)	X	X	X																		X	X	X
Gas Powered HVAC																							
Electrical Heat Pump	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Appendix C

Staten Island NPV

NPV

Electricity Cost ($/kWh)	Natural Gas ($/kBtu)		Lighting replacement (Common area) ($/ft2)	Lighting replacement (Apartment area) ($/ft2)	Refrigerator replacement
0.04	0.0089		0.21	0.39	700
		Life expextancy (years)	3.5	3.5	14
	Staten Island	Cost/year ($/yr)	3.875009418	184.7087823	50
	Brooklyn	Cost/year ($/yr)	180.8337729	3118.459961	1000
	Manhattan	Cost/year ($/yr)	361.6675457	6236.919921	2000

Staten Island - Reference Conf	2020	2021	2022	2023	2024	2025	2026
HVAC replacement costs	10,990	0	0	0	0	0	0
Annual Costs - O&M	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917
Ann Costs - Electricity costs	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111
Ann Costs - Natural Gas costs	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314
Carbon taxes	0	0	0	0	0	0	0
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		4806.342213	9436.729701	13897.60397	18195.1707	22335.40839	26324.0767

Staten Island - Optimal Conf	2020	2021	2022	2023	2024	2025	2026

Investment	25821.54516						
HVAC replacement costs	0	0	0	0	0	0	0
Annual Costs - O&M	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917
Ann Costs - Electricity costs	2031.444444	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111
Ann Costs - Natural Gas costs	2172.743816	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314
Carbon taxes	0	0	0	0	0	0	0
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		4806.342213	9436.729701	13897.60397	18195.1707	22335.40839	26324.0767

Staten Island - Opt Conf Water sys	2020	2021	2022	2023	2024	2025	2026
Investment	29821.54516						
HVAC replacement costs	0	0	0	0	0	0	0
Annual Costs - O&M	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917
Ann Costs - Electricity costs	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444
Ann Costs - Natural Gas costs	0	0	0	0	0	0	0
Carbon taxes	0	0	0	0	0	0	0
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		5040.48963	9896.452665	14574.64441	19081.57288	23423.50782	27606.48946

Electric sub-metering

1000

10
100
2000
4000

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
0	0	0	0	0	0	0	0	0	0
338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917
2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111
2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314
0	0	0	0	0	0	0	0	0	0
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651
30166.72439	33868.69711	37435.14483	40871.02894	44181.12925	47370.05054	50442.22906	53401.93861	56253.29655	59000.26953

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
0	0	0	0	0	0	0	0	9350	0
338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917
2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111
2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314
0	0	0	0	0	0	0	0	0	0
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651
30166.72439	33868.69711	37435.14483	40871.02894	44181.12925	47370.05054	50442.22906	53401.93861	161679.2521	59000.26953

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
0	0	0	0	0	0	0	0	0	0
338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917
4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651

31636.33689	35518.65619	39258.8482	42862.11602	46333.47231	49677.74619	52899.59001	56003.48578	58993.75146	61874.54692

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
0	0	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667
5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299
$ (43,484.44)	$ (43,484.44)	$ (43,484.44)	$ (23,383.64)	$ (23,383.64)	$ (23,383.64)	$ (23,383.64)	$ (23,383.64)	$ (3,357.85)	$ (3,357.85)
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651
208679.0252	234287.5086	258958.4945	282726.3036	305624.0003	327683.4384	348935.3055	369409.1659	389133.5015	408135.7516

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036
0	0	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667
2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346
$ (53,569.18)	$ (53,569.18)	$ (53,569.18)	$ (30,839.82)	$ (30,839.82)	$ (30,839.82)	$ (30,839.82)	$ (30,839.82)	$ (8,195.27)	$ (8,195.27)
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651
170334.6739	191237.65	211375.3918	230775.9139	249466.2048	267472.2655	284819.1447	301530.9744	317631.0031	333141.628

2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
0	0	0	10990	0	0	0	0	0	0	0
338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917
2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111

2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314
0	0	0	0	0	0	0	0	0	0	0
0.080928662	0.077714611	0.074850768	0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534
61646.67895	64196.20632	66652.3984	221056.7073	71298.31917	73494.51097	75610.30268	77648.63767	79612.35153	81504.17605	83326.74303

2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
0	0	0	0	0	0	0	0	0	0	0
338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917
2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111	2122.111111
2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314	2528.288314
0	0	0	0	0	0	0	0	0	0	0
0.080928662	0.077714611	0.074850768	0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534
61646.67895	64196.20632	66652.3984	69018.67208	71298.31917	73494.51097	75610.30268	77648.63767	79612.35153	81504.17605	83326.74303

2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
0	0	0	3500	0	0	0	0	0	0	0
338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917	338.5837917
4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444	4893.444444
0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0
0.080928662	0.077714611	0.074850768	0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534
64649.87972	67323.61075	69899.45953	120800.7659	74771.71256	77074.8948	79293.76015	81431.39536	83490.77418	85474.76148	87386.11726

2048	2049	2050	
0	0	0	
338.5837917	338.5837917	338.5837917	2030
2122.111111	2122.111111	2122.111111	**total**

2528.288314	2528.288314	2528.288314	**$ 237,336.93**		
0	0	0	2050	2030	2050
0.058636947	0.057493885	0.056434041	**total**	**NPV**	**NPV**
85082.58791	86774.1533	88403.79241	**$ 1,764,293.41**	**$ 248,326.93**	**$ 1,775,283.41**

2048	2049	2050			
0	0	9350			
338.5837917	338.5837917	338.5837917	2030		
2122.111111	2122.111111	2122.111111	**total**		
2528.288314	2528.288314	2528.288314	**$ 237,336.93**		
0	0	0	2050	2030	2050
0.058636947	0.057493885	0.056434041	**total**	**NPV**	**NPV**
85082.58791	86774.1533	254083.9367	**$ 1,883,361.47**	**$ 263,158.47**	**$ 1,909,183.02**

2048	2049	2050			
0	0	0			
338.5837917	338.5837917	338.5837917	2030		
4893.444444	4893.444444	4893.444444	**total**		
0	0	0	**$ 248,899.11**		
0	0	0	2050	2030	2050
0.058636947	0.057493885	0.056434041	**total**	**NPV**	**NPV**
89227.50048	91001.47275	92710.50191	**$ 1,739,218.31**	**$ 278,720.66**	**$ 1,739,218.31**

Brooklyn NPV

Brooklyn - Reference Conf	2020	2021	2022	2023	2024	2025	2026

HVAC replacement costs	569,626	0	0	0	0	0	0
Annual Costs - O&M	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
Ann Costs - Electricity costs	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667
Ann Costs - Natural Gas costs	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ (43,484.44)	$ (43,484.44)
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		33247.98526	65278.79957	96137.00219	125865.5211	154505.7127	182097.4195

Brooklyn - Optimal Conf	2020	2021	2022	2023	2024	2025	2026
Investment	1705350.357						
HVAC replacement costs	0	0	0	0	0	0	0
Annual Costs - O&M	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
Ann Costs - Electricity costs	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667
Ann Costs - Natural Gas costs	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ (53,569.18)	$ (53,569.18)
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		27138.73482	53283.95142	78472.02135	102737.9847	126115.5987	148637.3848

Brooklyn - Opt Conf Water sys	2020	2021	2022	2023	2024	2025	2026
Investment	1785350.357						
HVAC replacement costs	0	0	0	0	0	0	0
Annual Costs - O&M	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
Ann Costs - Electricity costs	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667
Ann Costs - Natural Gas costs	0	0	0	0	0	0	0
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		27930.59769	54838.68795	80761.70361	105735.7071	129795.4408	152974.3749

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
0	0	0	0	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667
5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299
$ (43,484.44)	$ (43,484.44)	$ (43,484.44)	$ (23,383.64)	$ (23,383.64)	$ (23,383.64)	$ (23,383.64)	$ (23,383.64)	$ (3,357.85)	$ (3,357.85)	$ (3,357.85)	$ (3,357.85)
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611

208679.0252	234287.5086	258958.4945	282726.3036	305624.0003	327683.4384	348935.3055	369409.1659	389133.5015	408135.7516	426442.351	444078.7666

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
0	0	0	0	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667
2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346
$ (53,569.18)	$ (53,569.18)	$ (53,569.18)	$ (30,839.82)	$ (30,839.82)	$ (30,839.82)	$ (30,839.82)	$ (30,839.82)	$ (8,195.27)	$ (8,195.27)	$ (8,195.27)	$ (8,195.27)
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611
170334.6739	191237.65	211375.3918	230775.9139	249466.2048	267472.2655	284819.1447	301530.9744	317631.0031	333141.628	348084.4265	362480.1862

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
0	0	0	0	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667
0	0	0	0	0	0	0	0	0	0	0	0
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611

175304.7547	196817.6446	217542.972	237509.5688	256745.2112	275276.6586	293129.6907	310329.1437	326898.9442	342862.1431	358240.9475	373056.7514

2039	2040	2041	2042	2043	2044	2045	2046	2047
0	10990	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667	23131.66667
5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299	5080.448299
$ (3,357.85)	$ (3,357.85)	$ (3,357.85)	$ (3,357.85)	$ (3,357.85)	$ (3,357.85)	$ (3,357.85)	$ (3,357.85)	$ (3,357.85)
0.074850768	0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534
461069.533	477438.2868	493207.7991	508400.0076	523036.0465	537136.2767	550720.3135	563807.0541	576414.704

2039	2040	2041	2042	2043	2044	2045	2046	2047
0	11102.88	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667	19279.66667
2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346	2591.046346
$ (8,195.27)	$ (8,195.27)	$ (8,195.27)	$ (8,195.27)	$ (8,195.27)	$ (8,195.27)	$ (8,195.27)	$ (8,195.27)	$ (8,195.27)
0.074850768	0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534
376348.9334	543309.6032	402581.8578	414982.5285	426929.2247	438438.5659	449526.5633	460208.6416	470499.6612

2039	2040	2041	2042	2043	2044	2045	2046	2047
0	17102.88	0	0	0	0	0	0	0

6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667	22692.66667
0	0	0	0	0	0	0	0	0
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
0.074850768	0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534
387330.1655	637685.9845	414328.5227	427091.0242	439386.305	451231.4695	462642.9961	473636.7596	484228.054

2048	2049	2050			
0	0	0			
6299.293733	6299.293733	6299.293733	2030		
23131.66667	23131.66667	23131.66667	**total**		
5080.448299	5080.448299	5080.448299	**$ 1,641,783.77**		
$ (3,357.85)	$ (3,357.85)	$ (3,357.85)	2050	2030	2050
0.058636947	0.057493885	0.056434041	**total**	**NPV**	**NPV**
588560.8023	600262.2456	611535.3125	**$ 11,152,814.43**	**$ 2,211,409.97**	**$ 11,722,440.63**

2048	2049	2050			
0	0	0			
6299.293733	6299.293733	6299.293733	2030		
19279.66667	19279.66667	19279.66667	**total**		
2591.046346	2591.046346	2591.046346	**$ 1,340,109.31**		
$ (8,195.27)	$ (8,195.27)	$ (8,195.27)	2050	2030	2050
0.058636947	0.057493885	0.056434041	**total**	**NPV**	**NPV**
480413.9383	489965.265	499166.9285	**$ 9,257,106.85**	**$ 3,045,459.66**	**$ 10,962,457.21**

2048	2049	2050			
0	0	0			
6299.293733	6299.293733	6299.293733	2030		
22692.66667	22692.66667	22692.66667	**total**		
0	0	0	**$ 1,379,211.45**		
$ -	$ -	$ -	2050	2030	2050
0.058636947	0.057493885	0.056434041	**total**	**NPV**	**NPV**
494431.6131	504261.6315	513731.7841	**$ 9,605,737.25**	**$ 3,164,561.81**	**$ 11,391,087.61**

Brooklyn Multi-Complex facility - Reference Conf	2020	2021	2022	2023	2024	2025	2026
HVAC replacement costs	569,626	0	0	0	0	0	0
Annual Costs - O&M	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	$ 6,299.29	6299.293733
Ann Costs - Electricity costs	23131.66667	208185	208185	208185	208185	$ 208,185.00	208185
Ann Costs - Natural Gas costs	5080.448299	45724.03469	45724.03469	45724.03469	45724.03469	$ 45,724.03	45724.03469
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ 7,035.59	$ 7,035.59
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		250682.3973	492187.5971	724851.566	948997.9715	1196436.593	1410096.833
						$ 31,497.96	$ 37,122.88

Brooklyn Multi-Complex facility - Optimal Conf	2020	2021	2022	2023	2024	2025	2026

Investment	1705350.357						
HVAC replacement costs	0	0	0	0	0	0	0
Annual Costs - O&M	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
Ann Costs - Electricity costs	19279.66667	173517	173517	173517	173517	173517	173517
Ann Costs - Natural Gas costs	2591.046346	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		195699.1434	384233.9636	565866.7384	740850.1438	909427.6056	1071833.638

$ - $ -

Brooklyn Multi-Complex facility - Opt Conf Water sys	2020	2021	2022	2023	2024	2025	2026
Investment	1785350.357						
HVAC replacement costs	0	0	0	0	0	0	0
Annual Costs - O&M	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
Ann Costs - Electricity costs	204234	204234	204234	204234	204234	204234	204234
Ann Costs - Natural Gas costs	0	0	0	0	0	0	0
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		202825.9092	398226.5924	586473.8787	767829.6459	942546.1847	1110866.55

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
0	0	0	0	0	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
208185	208185	208185	208185	208185	208185	208185	208185	208185	208185	208185	208185	208185
45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469
$ 7,035.59	$ 7,035.59	$ 7,035.59	$ 29,764.95	$ 29,764.95	$ 29,764.95	$ 29,764.95	$ 29,764.95	$ 52,409.50	$ 52,409.50	$ 52,409.50	$ 52,409.50	$ 52,409.50
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611	0.074850768
1615935.214	1814238.087	2005281.316	2375535.4	2567927.436	2753276.218	2931839.591	3103865.963	3524923.314	3697053.121	3862881.452	4022638.995	4176547.997
$ 42,541.88	$ 47,762.50	$ 52,791.99	$ 243,842.10	$ 263,590.60	$ 282,616.14	$ 300,945.17	$ 318,603.20	$ 590,943.46	$ 619,800.53	$ 647,601.19	$ 674,384.09	$ 700,186.50

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
0	0	0	0	0	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
173517	173517	173517	173517	173517	173517	173517	173517	173517	173517	173517	173517	173517
23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 21,230.92	$ 21,230.92	$ 21,230.92	$ 21,230.92	$ 21,230.92

0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611	0.074850768
1228294.171	1379026.861	1524241.398	1664139.797	1798916.674	1928759.523	2053848.973	2174359.04	2529846.733	2653384.748	2772400.177	2887058.586	2997519.481
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 239,389.36	$ 251,079.27	$ 262,341.23	$ 273,190.90	$ 283,643.38

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
0	0	0	0	0	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
204234	204234	204234	204234	204234	204234	204234	204234	204234	204234	204234	204234	204234
0	0	0	0	0	0	0	0	0	0	0	0	0
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611	0.074850768
1273024.897	1429246.812	1579749.62	1724742.692	1864427.732	1998999.061	2128643.887	2253542.563	2373868.841	2489790.111	2601467.634	2709056.771	2812707.191

2040	2041	2042	2043	2044	2045	2046	2047	2048
10990	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
208185	208185	208185	208185	208185	208185	208185	208185	208185
45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469	45724.03469
$ 52,409.50	$ 52,409.50	$ 52,409.50	$ 52,409.50	$ 52,409.50	$ 52,409.50	$ 52,409.50	$ 52,409.50	$ 52,409.50
0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534	0.058636947

4324822.565	4467668.97	4605285.93	4737864.89	4865590.285	4988639.798	5107184.609	5221389.628	5331413.732
$ 725,044.31	$ 748,992.11	$ 772,063.20	$ 794,289.69	$ 815,702.50	$ 836,331.40	$ 856,205.10	$ 875,351.25	$ 893,796.48

2040	2041	2042	2043	2044	2045	2046	2047	2048
11102.88	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
173517	173517	173517	173517	173517	173517	173517	173517	173517
23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712	23319.41712
$ 21,230.92	$ 21,230.92	$ 21,230.92	$ 21,230.92	$ 21,230.92	$ 21,230.92	$ 21,230.92	$ 21,230.92	$ 21,230.92
0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534	0.058636947
3257536.17	3206457.769	3305225.823	3400378.092	3492046.943	3580359.903	3665439.825	3747405.068	3826369.657
$ 293,713.20	$ 303,414.38	$ 312,760.41	$ 321,764.29	$ 330,438.55	$ 338,795.26	$ 346,846.03	$ 354,602.08	$ 362,074.18

2040	2041	2042	2043	2044	2045	2046	2047	2048
17102.88	0	0	0	0	0	0	0	0
6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733	6299.293733
204234	204234	204234	204234	204234	204234	204234	204234	204234
0	0	0	0	0	0	0	0	0
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534	0.058636947
3149168.026	3008763.373	3101441.876	3190727.523	3276744.525	3359612.542	3439446.856	3516358.525	3590454.546

2049	2050	
0	0	
6299.293733	6299.293733	2030
208185	208185	**total**

Carbon taxes/tot costs
14%

45724.03469	45724.03469	**$ 12,834,242.98**		
$ 52,409.50	$ 52,409.50	2050	2030	2050
0.057493885	0.056434041	**total**	**NPV**	**NPV**
5437409.979	5539525.823	**$ 98,101,993.27**	**$ 13,403,869.18**	**$ 98,671,619.47**
$ 911,566.46	$ 928,685.89			

2049	2050			
0	0			
6299.293733	6299.293733	2030		Carbon taxes/tot costs
173517	173517	**total**		7%
23319.41712	23319.41712	**$ 9,663,613.46**		
$ 21,230.92	$ 21,230.92	2050	2030	2050
0.057493885	0.056434041	**total**	**NPV**	**NPV**
3902443.441	3975732.251	**$ 70,819,102.34**	**$ 11,368,963.82**	**$ 72,524,452.69**
$ 369,272.74	$ 376,207.77			

2049	2050			
0	0			
6299.293733	6299.293733	2030		
204234	204234	**total**		
0	0	**$ 10,015,532.78**		
$ -	$ -	2050	2030	2050
0.057493885	0.056434041	**total**	**NPV**	**NPV**
3661837.996	3730608.179	**$ 68,273,200.54**	**$ 11,800,883.14**	**$ 70,058,550.90**

Manhattan NPV

Manhattan - Reference Conf	2020	2021	2022	2023	2024	2025	2026

HVAC replacement costs	1,139,252	0	0	0	0	0	0
Annual Costs - O&M	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
Ann Costs - Electricity costs	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222
Ann Costs - Natural Gas costs	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ (100,219.38)	$ (100,219.38)
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		63794.22501	125253.016	184461.8704	241503.1561	296456.2251	349397.5247

Manhattan - Optimal Conf	2020	2021	2022	2023	2024	2025	2026
Investment	3410700.213						
HVAC replacement costs	0	0	0	0	0	0	0
Annual Costs - O&M	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
Ann Costs - Electricity costs	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889
Ann Costs - Natural Gas costs	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ (107,406.63)	$ (107,406.63)
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		51127.51068	100383.3013	147835.8934	193551.3001	237593.1177	280022.6145

Manhattan - Opt Conf Water sys	2020	2021	2022	2023	2024	2025	2026
Investment	3570700.213						
HVAC replacement costs	0	0	0	0	0	0	0
Annual Costs - O&M	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
Ann Costs - Electricity costs	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556
Ann Costs - Natural Gas costs	0	0	0	0	0	0	0
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		52655.24376	103382.8389	152253.3545	199334.776	244692.6002	288389.926

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
0	0	0	0	0	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222
10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587
$(100,21	$ (100,219.38)	$(100,21	$ (54,760.66)	$ (54,760.66)	$ (54,760.66)	$ (54,760.66)	$ (54,760.66)	$ (9,471.57)	$ (9,471.57)	$ (9,471.57)	$ (9,471.57)	$ (9,471.57)

9.38)		9.38)										
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611	0.074850768
400400.7035	449536.7139	496873.9109	542478.1469	586412.8636	628739.1803	669515.9787	708799.9848	746645.8481	783106.2174	818231.814	852071.5025	884672.3584

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
0	0	0	0	0	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889
4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727
$(107,406.63)	$ (107,406.63)	$(107,406.63)	$ (61,947.91)	$ (61,947.91)	$ (61,947.91)	$ (61,947.91)	$ (61,947.91)	$ (16,658.82)	$ (16,658.82)	$ (16,658.82)	$ (16,658.82)	$ (16,658.82)
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611	0.074850768
320898.8156	360278.5854	398216.7066	434765.9564	469977.1796	503899.36	536579.688	568063.6262	598394.9733	627615.9243	655767.1295	682887.751	709015.5174

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
0	0	0	0	0	0	0	0	0	0	0	0	0

12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556
0	0	0	0	0	0	0	0	0	0	0	0	0
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611	0.074850768
330487.5424	371044.013	410115.7572	447757.1293	484020.4936	518956.2973	552613.141	585037.8459	616275.5192	646369.6167	675362.0036	703293.0122	730201.4983

2040	2041	2042	2043	2044	2045	2046	2047	2048
10990	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222	43456.22222
10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587	10163.59587
$ (9,471.57)	$ (9,471.57)	$ (9,471.57)	$ (9,471.57)	$ (9,471.57)	$ (9,471.57)	$ (9,471.57)	$ (9,471.57)	$ (9,471.57)
0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534	0.058636947
916079.7341	946337.3214	975487.2129	1003569.96	1030624.63	1056688.859	1081798.906	1105989.703	1129294.902

2040	2041	2042	2043	2044	2045	2046	2047	2048
11102.88	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889	35472.88889

4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727	4998.879727
$ (16,658.82)	$ (16,658.82)	$ (16,658.82)	$ (16,658.82)	$ (16,658.82)	$ (16,658.82)	$ (16,658.82)	$ (16,658.82)	$ (16,658.82)
0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534	0.058636947
887786.4176	758436.5435	781798.5545	804305.3088	825988.1165	846877.1412	867001.4425	886389.0159	905066.8324

2040	2041	2042	2043	2044	2045	2046	2047	2048
17102.88	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556	42057.55556
0	0	0	0	0	0	0	0	0
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534	0.058636947
992729.8336	781099.2662	805159.3538	828338.6289	850669.3371	872182.5435	892908.1758	912875.0663	932110.9917

2049	2050	
0	0	
12598.58747	12598.58747	2030
43456.22222	43456.22222	**total**
10163.59587	10163.59587	**$ 3,150,155.49**
$ (9,471.57)	$ (9,471.57)	2050
0.057493885	0.056434041	**total**
1151746.924	1173377.004	**$ 21,399,346.40**

Carbon taxes/tot costs
0%

2030	2050
NPV	**NPV**
$ 4,289,407.71	**$ 22,538,598.62**

2049	2050	
0	0	
12598.58747	12598.58747	2030
35472.88889	35472.88889	**total**

4998.879727	4998.879727	**$ 2,524,673.80**		
$ (16,658.82)	$ (16,658.82)	2050	2030	2050
0.057493885	0.056434041	**total**	**NPV**	**NPV**
923060.8752	940396.1766	**$ 17,303,981.38**	**$ 5,935,374.02**	**$ 20,714,681.59**

2049	2050			
0	0			
12598.58747	12598.58747	2030		
42057.55556	42057.55556	**total**		
0	0	**$ 2,600,113.18**		
$ -	$ -	2050	2030	2050
0.057493885	0.056434041	**total**	**NPV**	**NPV**
950642.7116	968496.0064	**$ 17,899,454.52**	**$ 6,170,813.39**	**$ 21,470,154.74**

Manhattan complex - Reference Conf	2020	2021	2022	2023	2024	2025	2026
HVAC replacement costs	1,139,252	0	0	0	0	0	0
Annual Costs - O&M	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
Ann Costs - Electricity costs	391106	391106	391106	391106	391106	391106	391106
Ann Costs - Natural Gas costs	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ 13,984.80	$ 13,984.80
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		477049.085	936633.9454	1379393.926	1805944.968	2279489.651	2686562.043

$ 62,609.19 $ 73,789.97

Manhattan complex - Optimal Conf	2020	2021	2022	2023	2024	2025	2026
Investment	3410700.213						
HVAC replacement costs	0	0	0	0	0	0	0
Annual Costs - O&M	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
Ann Costs - Electricity costs	319256	319256	319256	319256	319256	319256	319256
Ann Costs - Natural Gas costs	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		363048.6561	712806.5136	1049760.134	1374378.264	1687112.495	1988397.88

$ - $ -

Manhattan complex - Opt Conf Water sys	2020	2021	2022	2023	2024	2025	2026
Investment	3570700.213						
HVAC replacement costs	0	0	0	0	0	0	0
Annual Costs - O&M	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
Ann Costs - Electricity costs	378518	378518	378518	378518	378518	378518	378518
Ann Costs - Natural Gas costs	0	0	0	0	0	0	0
Carbon taxes	$ -	$ -	$ -	$ -	$ -	$ -	$ -

Capital recovery factor	#DIV/0!	1.038	0.528677134	0.358981536	0.274192713	0.223366555	0.189521679
NP Costs		376798.2538	739802.3519	1089517.283	1426429.547	1751007.837	2063703.684

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
0	0	0	0	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
391106	391106	391106	391106	391106	391106	391106	391106	391106	391106	391106	391106
91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281
$ 13,984.80	$ 13,984.80	$ 13,984.80	$ 59,443.52	$ 59,443.52	$ 59,443.52	$ 59,443.52	$ 59,443.52	$ 104,732.61	$ 104,732.61	$ 104,732.61	$ 104,732.61
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611
3078731.977	3456545.016	3820526.749	4543592.984	4911573.652	5266082.966	5607614.097	5936642.161	6764282.222	7094597.094	7412819.514	7719392.173
$ 84,561.44	$ 94,938.57	$ 104,935.81	$ 486,976.52	$ 526,416.22	$ 564,412.08	$ 601,016.95	$ 636,281.76	$ 1,180,912.90	$ 1,238,579.49	$ 1,294,134.97	$ 1,347,656.63

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
0	0	0	0	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
319256	319256	319256	319256	319256	319256	319256	319256	319256	319256	319256	319256
44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 40,047.36	$ 40,047.36	$ 40,047.36	$ 40,047.36

0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611
2278653.55	2558283.29	2827676.103	3087206.752	3337236.278	3578112.508	3810170.533	4033733.177	4700665.595	4930209.5	5151350.064	5364394.922
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ 451,554.15	$ 473,604.54	$ 494,847.69	$ 515,313.15

2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038
0	0	0	0	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
378518	378518	378518	378518	378518	378518	378518	378518	378518	378518	378518	378518
0	0	0	0	0	0	0	0	0	0	0	0
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
0.165380343	0.147303665	0.133270039	0.122066494	0.112921134	0.105319356	0.098904892	0.09342326	0.088687837	0.084558651	0.080928662	0.077714611
2364952.092	2655172.139	2934767.559	3204127.309	3463626.104	3713624.944	3954471.61	4186501.154	4410036.359	4625388.195	4832856.246	5032729.126

2039	2040	2041	2042	2043	2044	2045	2046	2047	2048
0	10990	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
391106	391106	391106	391106	391106	391106	391106	391106	391106	391106
91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281	91472.36281
$ 104,732.61	$ 104,732.61	$ 104,732.61	$ 104,732.61	$ 104,732.61	$ 104,732.61	$ 104,732.61	$ 104,732.61	$ 104,732.61	$ 104,732.61
0.074850768	0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534	0.058636947
8014741.555	8299278.533	8573398.935	8837484.101	9091901.409	9337004.788	9573135.212	9800621.169	10019779.12	10230913.96
$ 1,399,218.93	$ 1,448,893.58	$ 1,496,749.70	$ 1,542,853.87	$ 1,587,270.21	$ 1,630,060.52	$ 1,671,284.33	$ 1,710,998.98	$ 1,749,259.72	$ 1,786,119.78

2039	2040	2041	2042	2043	2044	2045	2046	2047	2048
0	11102.88	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
319256	319256	319256	319256	319256	319256	319256	319256	319256	319256
44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754	44989.91754
$ 40,047.36	$ 40,047.36	$ 40,047.36	$ 40,047.36	$ 40,047.36	$ 40,047.36	$ 40,047.36	$ 40,047.36	$ 40,047.36	$ 40,047.36
0.074850768	0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534	0.058636947
5569640.451	5920971.816	5957865.164	6141384.422	6318185.248	6488513.597	6652606.419	6810691.99	6962990.227	7109712.999
$ 535,029.39	$ 554,023.85	$ 572,322.93	$ 589,952.12	$ 606,935.91	$ 623,297.95	$ 639,060.99	$ 654,246.97	$ 668,877.00	$ 682,971.45

2039	2040	2041	2042	2043	2044	2045	2046	2047	2048
0	17102.88	0	0	0	0	0	0	0	0
12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747	12598.58747
378518	378518	378518	378518	378518	378518	378518	378518	378518	378518
0	0	0	0	0	0	0	0	0	0
$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
0.074850768	0.072284544	0.069973364	0.067882392	0.065982849	0.06425075	0.062665945	0.061211382	0.059872534	0.058636947
5225284.888	5647396.34	5589506.734	5761679.5	5927549.217	6087346.633	6241294.047	6389605.62	6532487.676	6670138.982

2049	2050			
0	0			
12598.58747	12598.58747	2030	Carbon taxes/tot costs 2030	Carbon taxes/tot costs 2050
391106	391106	**total**	5%	15%
91472.36281	91472.36281	**$ 24,464,470.34**		
$ 104,732.61	$ 104,732.61	2050	2030	2050
0.057493885	0.056434041	**total**	**NPV**	**NPV**

10434319.38	10630278.36	**$ 188,020,330.75**	**$ 25,603,722.56**	**$ 189,159,582.97**
$ 1,821,630.44	$ 1,855,841.09			

2049	2050			
0	0			
12598.58747	12598.58747	2030	Carbon taxes/tot costs 2030	Carbon taxes/tot costs
319256	319256	**total**	0%	7%
44989.91754	44989.91754	**$ 17,927,323.64**		
$ 40,047.36	$ 40,047.36	2050	2030	2050
0.057493885	0.056434041	**total**	**NPV**	**NPV**
7251064.417	7387241.12	**$ 131,404,064.09**	**$ 21,338,023.85**	**$ 134,814,764.30**
$ 696,549.91	$ 709,631.29			

2049	2050			
0	0			
12598.58747	12598.58747	2030		
378518	378518	**total**		
0	0	**$ 18,606,278.06**		
$ -	$ -	2050	2030	2050
0.057493885	0.056434041	**total**	**NPV**	**NPV**
6802751.031	6930508.303	**$ 126,631,060.76**	**$ 22,176,978.27**	**$ 130,201,760.98**