Exploring the Use of Grid-Scale Compressed Air Energy Storage in the Urban Landscape

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A THESIS PRESENTED BY

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DEDICATION

To my brother Alex, my parents Todd and Kimberly, and my girlfriend Janie:
Thanks so much for everything.

ABSTRACT

EXPLORING THE USE OF GRID-SCALE COMPRESSED AIR ENERGY STORAGE IN THE URBAN LANDSCAPE

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Energy storage is becoming a crucial element to the renewable energy grid, and new facilities will have to go somewhere. This thesis will propose to co-locate compressed air energy storage on a site with residential units, and a community park.

This thesis will make the argument that co-locating a compressed air energy storage system with residential units could create a new start for the communities most harmed by fossil fuel infrastructure. This thesis will propose a design for a site in East Boston; a community badly scarred by heating oil and natural gas storage; with the goal of creating a model for healing both the physical site, and the social injustices created by the fossil fuel grid, arguing for using compressed air energy storage as both a spatial and an economic resource.

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CHAPTER 1.1.1. INTRODUCTION

The Earth's climate is being changed by human activity, most profoundly by our combustion of fossil fuels. The carbon dioxide released by this combustion has built up in the atmosphere, allowing less of the energy dispensed by the sun to radiate off into space. This has resulted in a chain of outcomes unfavorable to the health of our ecosystems. To prevent further damage, we should both quickly and broadly reimagine the sources of our energy, while changing how that energy is used and embodied.

There are many challenges to this new paradigm: the current organization of our energy grid is one. The grid is built and organized with combustion in mind; when we burn fossil fuels to spin turbines to create power, it is very easy to ramp power production up and down to match demand. Engineers call this *load matching*, and it is a foundational aspect of electricity production today. The typical highest daily load occurs in the evening, when people return home from work and turn on their air conditioners, ovens, and other appliances.[1] Knowing this, electrical engineers ramp up the rate of fossil fuel combustion to increase the power flowing through the grid.

Consider what happens when this power is generated from renewable sources, such as windmills or photovoltaic panels. Engineers can no longer control the rate of power production. Instead, the amount of power generated is proportional to the wind speed, or to the angle of sunlight. There will always be times at which we, accustomed to using electricity on a human timeframe, will want power when no supply exists.

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[1] Jacqueline DeRosa, Joanne Morin, and Michael Alteiri, "Massachusetts Energy Storage Initiative Study" (Massachusetts Department of Energy Resources, 2016).

There are many technologies and methods for storing power, and they will each be examined in this paper. My goal is to examine the architectural implications of the adoption of one particular technology: compressed air energy storage, or CAES. This thesis will show that careful design of energy storage could be an opportunity for municipalities to accomplish other goals in parallel: remediating polluted land, creating economic opportunities for people who are disadvantaged, and building ecologically vibrant neighborhoods.

CHAPTER 2.1.1. LITERATURE REVIEW

This section will summarize the findings of a few key resources of this paper. The State of Charge Report will illustrate how crucial energy storage is, and will continue to be, to the health of our renewable energy grid. Solar City: Linz Pichling will describe an eco-community in Linz, Germany, which can model a successful urban planning project built around the needs of green infrastructure. Lastly, the Greater Boston Housing Report Card 2019 will offer the context for designing a site, in East Boston, Massachusetts, which integrates energy storage into its program.

2.2.1 State of Charge: Massachusetts Energy Storage Initiative Study

2.2.2 Subchapter Intro

In May of 2015, the Commonwealth of Massachusetts commissioned the "State of Charge: Massachusetts Energy Storage Initiative Study" to examine the potential impact of grid-scale energy storage. Completed in 2016, its conclusions are these:

> *There is great potential in Massachusetts for new advanced energy storage to enhance the efficiency, affordability, resiliency, and cleanliness of the entire electric grid by modernizing the way we generate and deliver electricity. In order to increase energy storage deployment, this Study presents a comprehensive suite of policy recommendations to generate* ***600 MW of advanced energy storage*** *in the Commonwealth by 2025, thereby* ***capturing $800 million in systems benefits*** *to Massachusetts ratepayers.*[2]

[2] DeRosa, Morin, and Alteiri.ii

Massachusetts is in a good position to capitalize on an abundant natural resource: access to consistent, powerful offshore winds.[3] With its current low capacity to store this energy, however, much of this energy could be left untapped. Upgrading the state's energy storage capacity would both allow current renewable plants to work more consistently by guaranteeing them a buyer and incentivizing the construction of new renewable energy plants. If proposed offshore wind projects like Vineyard Wind[4] are to go forward, developing energy storage in parallel will be key to their success.[5]

2.2.3 How Energy Storage Works

Currently, the electrical grid works by matching the amount of electricity required by all of the grid's users, or *load*, with the amount of electricity generated as closely as it can. This is measured in *power*, which is a rate: one watt is equivalent to one joule/second. This is different from *energy*, which is an amount, measured in watt-hours, meaning: the amount accumulated by a consistent one joule/second rate, over an hour. Load-matching is easy to do when we get our power from fossil fuels like natural gas or coal. Engineers increase the rate at which we burn the fuel to match the rate of power generation needed. It is much harder to implement load matching when the sun or wind is the power source, because they produce energy on natural and sometimes unpredictable

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[3] "SuccarWilliams_PEI_CAES_2008April8.Pdf," accessed July 23, 2020, https://wayback.archive-it.org/all/20120119134651/http://www.princeton.edu/pei/energy/publications/texts/SuccarWilliams_PEI_CAES_2008April8.pdf.

[4] Megan Geuss, "Massachusetts Offshore Wind Project Gets Green Light at Roughly 8.9 Cents/KWh," Ars Technica, April 24, 2019, https://arstechnica.com/tech-policy/2019/04/massachusetts-offshore-wind-project-gets-green-light-at-roughly-8-9-centskwh/.

[5] DeRosa, Morin, and Alteiri, "Massachusetts Energy Storage Initiative Study."

timetables. In different ways, we have been utilizing energy reservoirs for hundreds of years: one example is in water towers, seen on building roofs and freestanding in communities across the country. The tanks are considered a genuine architectural vernacular of New York. These tanks enable consistent water pressure by acting as a reservoir for potential mechanical energy. Rather than paying for powerful pumps which could always meet the required water pressure, a smaller pump continually fills a tower, converting the energy the pump uses into potential energy, ready to discharge when it is needed. The concept of energy storage applies this principle to power: smaller, intermittent generation stations continually feed into large reserves. Power is drawn down from these reserves when it is needed.[6]

2.2.4 Types of Energy Storage

There are five primary types of energy storage: mechanical, electrochemical, thermal, electrical, and chemical.[7] These modes work best across a wide range of scales and applications. From this diverse portfolio, this thesis will select one emerging technology to investigate: Compressed Air Energy Storage, or CAES. This section will examine the different types of storage, and then explain why CAES is a compelling technology to investigate moving forward in the project.

Mechanical energy storage uses kinetic and potential energy as reservoirs. Consider an example near the University of Massachusetts Amherst campus: the Northfield Mountain Hydroelectric Facility Reservoir in Erving, Massachusetts. It is an

[6] DeRosa, Morin, and Alteiri, i.
[7] DeRosa, Morin, and Alteiri, 6.

example of what is called a pumped-hydro storage facility, and it works this way: two reservoirs of water are either constructed, found, or created with dams. One must be at a significantly higher elevation than the other. Water is pumped into the upper reservoir when electricity is cheap, converting electrical energy (used to power the pump) into gravitational potential energy, using the mass of the water held at the elevation of the upper reservoir. When electrical demand is peaking, and energy can be sold at a higher price, the water is released through a turbine, converting the water's potential energy back into electrical energy[8]

Pumped Hydro facilities like this exist throughout the world, serving a variety of functions. The Northfield Mountain facility was built in conjunction with the Vermont Yankee Plant to supply power while the nuclear plant was down for planned maintenance.[9] Pumped Hydro energy storage stations are the oldest and most proven technology in the sector.[10] They have an extremely low operating cost and are very long-lived. Their drawback is the amount of space required, the partial or complete flooding of natural landscapes and habitats, and the embodied carbon in their concrete pours. The construction of a new facility could displace residents, tapping into the ugly history of the U.S. infrastructure projects- including right here in Massachusetts, where the Quabbin Reservoir displaced entire towns to supply Boston with potable water. Limitations like these "make it unlikely that new pumped storage will be built".[11]

The next smallest scale of mechanical energy storage facility uses compressed air rather than elevated water as a reservoir for energy. In Compressed Air Energy Storage,

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[8] DeRosa, Morin, and Alteiri, 4.
[9] DeRosa, Morin, and Alteiri, 2.
[10] DeRosa, Morin, and Alteiri, 7.
[11] DeRosa, Morin, and Alteiri, 2.

or CAES, a pump compresses air into a tank when power is inexpensive, and releases it back through a turbine to convert the mechanical energy back into electricity. Recent developments in the technology improve efficiency by storing the heat energy released by the compression cycle. CAES has a number of traits which make it suitable to function of this thesis: the facilities don't combust anything, or rely on exotic or toxic chemicals. Most critically, CAES facilities exist on a volumetric scale similar to buildings.[12] This paper will continue to examine CAES in Chapter 3, and some existing and proposed CAES facilities will be described in Chapter 3.3.1-3.3.4.

The smallest-scale mechanical energy storage method summarized by the report are flywheels. Flywheels consist of spinning masses, supported on a stator. The mass is accelerated when power is available, and as it decelerates is feeds power back.[13] Flywheels generally deal with relatively fast timeframes-the flywheel in a car's engine, for instance, uses inertia to keep the motor cycling.

Electrochemical storage methods use chemicals with appropriate properties to store electricity. There are two subgroups: solid rechargeable batteries and flow batteries. Solid rechargeables include lead-acid and lithium-ion batteries; which should sound familiar to readers familiar with consumer electronics. Both technologies are mature and commercially viable, with good round-trip efficiency.[14] We largely owe the improvement of electric cars, appliances, and electronics to advances in lithium-ion batteries. That said, there are drawbacks to using lithium-ion on the grid, due to its relatively short duration of discharge. Smaller applications "typically require systems with a high C-rate and short

[12] DeRosa, Morin, and Alteiri, 2.
[13] DeRosa, Morin, and Alteiri, 5.
[14] DeRosa, Morin, and Alteiri, 7.

discharge duration. These applications are particularly suitable for lithium ion. "…Sodium based flow batteries, as well as CAES and PHS, are more suitable for high energy and longer duration application" according to the report.[15] While flow batteries, which store electricity in a liquid electrolyte[16] have an exciting future in the energy storage space- California's first experimental grid-scale flow battery came online in 2019[17]- the proven technological success of CAES remains more appealing for the purposes of this research.

Thermal energy storage encompasses both active and passive strategies where energy in the form of heat is stored for later use. Active strategies convert electricity into heat stored with molten salt or rock, converting it back into electricity as needed. These strategies closely resemble other methods of energy storage. Passive strategies like large-thermal-mass walls, and night flushing, bank heat during the warm daytime hours and release that heat when it is needed at night. This adds to the efficiency of buildings by doing much of the work of the heating and cooling equipment.[18] These strategies are an excellent way to make buildings more efficient and connected to their contexts, but applying them at a gid-scale would be outside of the scope of this thesis, and possible unfeasible.

Electrical storage stores energy inside an electromagnetic field. While "a few small SMES systems have become commercially available…These technologies are ideal

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[15] DeRosa, Morin, and Alteiri, 6.
[16] DeRosa, Morin, and Alteiri, 5.
[17] "California ISO Adds Flow Battery to the Grid," T&D World, May 2, 2019, https://www.tdworld.com/distributed-energy-resources/energy-storage/article/20972544/california-iso-adds-flow-battery-to-the-grid.
[18] DeRosa, Morin, and Alteiri, "Massachusetts Energy Storage Initiative Study," 5.

for storing and releasing high levels of energy over short bursts".[19] Additionally, this technology is not mature enough yet for reliable operation on a larger scale. The same is true of *chemical storage*, which powers technologies like hydrogen fuel cells. While this technology is developing rapidly on a smaller scale, it is currently unsuitable for large applications.

Of these choices, this paper will move forward with researching and applying Compressed Air Energy Storage, because of its scale, which is similar to the scale of typical architectural design, because of its proven technology, and because of its relatively small ecological impact.

2.2.5 Use Models

The "State of Charge: Massachusetts Energy Storage Initiative" report describes a number of options for how an energy storage facility fits within the greater energy grid, both as a grid asset and an economic asset. This section will summarize these use cases and select one for the purposes of designing a facility in Chapter 5. These descriptions will begin at the smallest scale, and progress upwards in energy capacity, cost, and size of utility.

A *microgrid,* or *"behind-the-meter" system* describes a system which owns and operates energy storage to better serve an enclosed community, such as a medical center or a university campus. In this context, energy storage can help to reduce electricity costs at peak demand times, as well as provide backup power in the case of an outage. These systems can be mated with photovoltaic panels to generate power and store it for later use. This can benefit the owner, in terms of a reduced electricity cost, or, in a *Residential*

[19] DeRosa, Morin, and Alteiri, 6.

Storage Dispatched by Utility system, this system could have the ability to feed power back into the grid as required, creating revenue for the owner.[20]

A *merchant* system involves a privately-owned system selling power back to the grid for profit. Systems like these require coordination between many stakeholders. Several scenarios include a *Merchant Solar + Storage* system, where a developer co-locates photovoltaic (PV) panels and an energy-storage system, to integrate PV energy more profitably into the market by selling it back to the grid at off-peak times for solar generation. This type of system is typically smaller than an *Alternative Technology Regulation Resource*, which operates on a grid-wide scale to provide frequency regulation.

The largest systems for energy storage are designed as grid-level energy assets. Of these three, the smallest are Load Serving Entities, or LSEs. Next largest are Municipal Light Plants, which could acts as hubs where energy storage improves the functionality of their power delivery. At the largest scale, an Investor Owned Utility, like Eversource or National Grid, could own and operate energy storage at distribution substations to improve the grid's performance.[21]

Because of the limited scope of this project, and the extreme complexity of imagining energy storage at the scale of an Investor Owned Utility (IOU), which serves tens of thousands of properties, the energy storage proposed by this paper will be on the behind the meter, or at largest, the merchant scale. The project will propose selling power back to the IOU as a revenue stream. Further investigation into the local grid's

[20] DeRosa, Morin, and Alteiri, "Massachusetts Energy Storage Initiative Study." 19.
[21] DeRosa, Morin, and Alteiri, "Massachusetts Energy Storage Initiative Study." *xv.*

requirements would be needed to confirm the effect of such a system, and how it relates to the site- this is described in Chapter 5.3.

2.3.1 The Greater Boston Housing Report Card 2019: Supply, Demand and the Challenge of Local Control

2.3.2 Introduction to the Research

This section will examine the findings of The Boston Foundation's "Greater Boston Housing Report Card 2019: Supply, Demand and the Challenge of Local Control"[22], so that the design of a site in Chapter 5 is more responsive to the region's opportunities and challenges.

The Boston Foundation was founded in 1915 and claims to be "one of the largest community foundations in the nation—with net assets of more than $1.3 billion".[23] The foundation's mission statement aligns the group as a civic center, a philanthropic group, and a lender to nonprofit organizations, especially those which "broaden participation, foster collaboration and heal racial, ethnic and community divisions".[24] In this context, the report examines the social, economic, and racial landscape of Greater Boston and makes suggestions for future development. The key insights, as they pertain to this research, are broken into two subchapters: the low supply of housing in the Greater Boston area, and the lack of affordable housing options.

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[22] Modestino, et. al., "The Greater Boston Housing Report Card 2019: Supply, Demand and the Challenge of Local Control" (The Boston Foundation, 2019).
[23] Modestino, et. al., 1.
[24] "Mission and Values Statements," accessed December 23, 2020, https://www.tbf.org/who-we-are/mission.

2.3.3 Low Supply of Housing

The Greater Boston Metro area is experiencing population growth. Since 2017, the population of Suffolk County has grown by approximately 6% from births, grown approximately 12% from international migration, and decreased by approximately 5% from domestic migration.[25] The region has not permitted construction of residential new units at an appropriate rate: in 2017, Greater Boston permitted only 13,000 new units- 0.3% [26] of the population. Additionally, Boston's housing stock is considerably older than that of other U.S. cities: nearly 25% of its housing stock was built before 1920, which is a much higher percent than even comparably old cities like Philadelphia or Washington, D.C.[27]

Several legislative goalposts have been set to alleviate the shortfall in housing production compared to the increase in population. The Housing Choice Initiative establishes a goal of 135,000 new units statewide between 2018 and 2025. According to the Boston Foundation, the commonwealth was on pace to meet this goal, as of 2017.[28] It remains to be seen whether or not the effects Covid-19 will detrimentally affect the rate of housing production. The Metropolitan Mayors Coalition has set a more aggressive goal, of 185,000 units before 2030, but is underproducing.[29] In Boston, the Housing

[25] Modestino, et. al., "The Greater Boston Housing Report Card 2019: Supply, Demand and the Challenge of Local Control," 12.
[26] Modestino, et. al., 27.
[27] Modestino, et. al., 26.
[28] Modestino, et. al., 34.
[29] Modestino, et. al., 34.

Boston 2030 plan aims to permit 53,000 new units by 2030, with a consideration of a mix of market-rate and income-restricted units.[30]

2.3.4 Low Access to Affordable Housing

The fast growth in population and concurrent slow growth in housing stock described above leads to a low regional vacancy rate and high price for housing. Vacancy rates, according to the report, "are a useful proxy to determine the tightness of the region's housing market".[31] A "stable" vacancy rate for rental units is approximately 6%, and Boston's has trended downward since the 2008 financial crisis, and was approximately 3% in 2018. For ownership units, a stable vacancy rate is 2%; Boston's hovers below 1%.[32]

Home prices "have established Boston as one of the most expensive metro areas in the country… home prices now exceed even the New York City metropolitan area.[33] Rents have increased substantially in every county analyzed by the report.[34]

One of the major barriers for affordable housing, and for development of badly-needed new housing units in Massachusetts has been the "home rule" of local municipalities, using zoning to exclude new construction. Chapter 40B, the Comprehensive Permit Law, was enacted in 1969, in part to desegregate housing is Massachusetts by allowing the state to supersede local zoning boards to permit multifamily projects in primarily single-family neighborhoods.[35] The condition under

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[30] Modestino, et. al., 34.
[31] Modestino, et. al., 24.
[32] Modestino, et. al., 25.
[33] Modestino, et. al., 41.
[34] Modestino, et. al., 43.
[35] Modestino, et. al., 32.

which the chapter can be applied is this: at least 20% of the units in the proposed project must have long-term affordability restrictions in place. Once subsidized low- or moderate-income housing represent 10% of a city's overall housing stock, however, the state appeals board loses the authority to override the locality. This threshold has already been reached in Boston and East Boston, potentially removing an incentive for developers to integrate affordable units into their proposals. According to the Greater Boston Housing Report Card, Chapter 40B has led to the creation of over 60,000 units of diverse housing stock in the state, but its remaining capacity is diminishing quickly as more municipalities reach the 10% threshold.[36] Clearly, new and more powerful incentives are needed to encourage the construction and management of affordable units in Massachusetts.

2.4.1 SolarCity: Linz Pichling

2.4.2 Introduction to SolarCity

This section will examine Linz Pichling, an ecologically sustainable village in Germany, as a case study, to understand specific, feasible steps towards sustainable and human-centered development on an undeveloped site. These lessons will be referenced and applied to the site in Chapter 5.

The history of the Linz Pichling "Solar City" development beings in the 1974, when Germany and much of the world was impacted by an oil embargo organized by the Organization of Arab Petroleum-Exporting Countries. This sudden awareness of the tenuous supply chain for oil, according to architect Thomas Herzog, of Herzog +

[36] Modestino, et. al., 43.

Partners, made "clear to us that the use of renewable sources of energy- above all solar energy- and the integration of this theme would, in the future, be of central important for architecture and town planning".[37] Beginning in the late 1990s, the city of Linz began issuing competitions for various parts of the Solar City development, and "15 years after the idea for the project was born, some 3,000 people now reside in the new urban district called SolarCity. During the years 2001 to 2005, twelve housing developers in Linz built a total of 1,300 dwellings on a 35-hectare site in Pichling," according to Mayor of Linz Franz Dobusch.[38]

2.4.3 Urban Planning

While the focus of the examination of SolarCity Linz Pichling will be on its architectural methods, this thesis will begin by exploring how sustainability drives the design of the city on the scale of its urban planning. Here, the goals of the project "were to achieve maximum permissible density, variety, possibilities of mixed use, and subsidized social housing at a low overall cost".[39]

A key factor in the design of SolarCity is its residents' proximity to public transportation, pedestrian thoroughfares, and bicycle routes. This is a crucial aspect in designing a city for a small impact on the larger ecosystem: "even in a case of moderate annual use […] the amount of energy used by modern vehicles is more than the potential energy saving per apartment."[40] Therefore, the urban plans of the SolarCity are radial,

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[37] Martin Treberspurg, *Solar City, Linz Pichling, Nachhaltige Stadtentwicklung = Sustainable Urban Development* (New York, 2008), 27.
[38] Treberspurg, 11.
[39] Treberspurg, 32.
[40] Treberspurg, 32.

with the municipal light rail system of the City of Linz passing through the center point. Important service facilities are located in the center, and housing extends outwards. In this way, citizens have pedestrian access to services, and using the light rail, to other city centers.

Orientation of streets and buildings is another crucial factor. Typically, buildings optimizing for exposure to sunlight are oriented with a long east-west axis. This gives their south façades (so long as you're in the Northern Hemisphere) long exposure to solar radiation and heat because, relative to a point on the ground, the sun travels east-west, on a semicircle tilted towards the equator. A crucial aspect of SolarCity's planning had to be reconciling this ideal orientation with pleasant outdoor spaces, which require diversity of building and street orientation. The planning team worked to develop "a spectrum of possibilities that could provide for an impulse for future developments, and to bring the diversity of possible building forms into a structural and functionally sensible harmony…".[41] This meant that some buildings would have to be oriented on a north-south axis. This is unfavorable because the building's envelope is mostly composed of east facades, which get direct sunlight only early in the morning, and west facades, which are typically known to experience harsh, direct light in the already-hot late afternoon and evening. These buildings act as excellent models for accommodating poor solar orientation.

[41] Treberspurg, 35.

2.4.4 Architecture

The architecture of SolarCity Linz is largely driven by building performance and efficiency, and the balance of solar passive strategies with human factors. Different buildings were planned by different firms and built with different contractors, which helped the area to have a pleasing variety of architectural styles.

Herzog + Partner's GWG Housing Development, in SolarCity, Linz Pichling, demonstrates methods for designing housing with excellent performance, in the worst possible solar orientation. Each building is a rectangle, 15 meters wide and between 50 and 110 meters long. Individual apartments are 15 meters wide, spanning the east and west walls of the building. These shorter apartment walls are transparent, glazed curtain walls. Opaque, structural masonry walls run east-west, separating the apartments. Each apartment, therefore, has short, transparent walls on its east and west walls, and long, opaque walls on its north and south. These long, interior walls reduce heat loss through the exterior envelope, while the short exterior walls admit light, and allow for favorable cross-ventilation during cooling degree-days.[42]

Apartments are accessed by stair cores, running east-weStreet These cores span with building parallel to apartments, and use shed roofs to accommodate south-facing solar water reheaters. In addition to providing vertical circulation, these areas allow for light to penetrate the inner area of the deep apartments, by using a semi-opaque glazing which allows for light, but not intrusions, to pass between the public stair cores and private apartments.[43]

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[42] Treberspurg, 99.
[43] Treberspurg, 99.

To accommodate parking requirements, the buildings contain parking garages in their basement levels. Enclosed, subterranean parking garages have extremely high requirements for energy use, due to the ventilation and lighting they require. Instead, the Hezog + Partners buildings open these basements levels to the outside by excavating earth away from the buildings, allowing for natural lighting and ventilation. This additionally makes the building more pleasant and less alarming for users who might be uncomfortable in dark, hidden public spaces.[44] This becomes an important design principle in the architecture described by Chapter 5.

Another group of multifamily residential buildings, designed by Iassy | architektur + raumplanung (Architecture and Spatial Planning), leverages more favorable solar orientation to create pleasant and highly efficient living spaces. Design choices vary between the six buildings.

Two buildings are structurally supported with mass timber construction. This allows for a high level of prefabrication, which generally helps reduce waste and speed up construction timetables. The structural frame is spanned with modular timber panels, also built off-site. Using structural wood, if it is logged, laminated, and shipped correctly, can have great benefits for both the embodied and operation carbon released over the lifetime of the project. Two of the buildings, called "Haus 1" and "Haus 5" in Iassy's nomenclature, meet Passivehaus building criteria. Building 1 uses only 7 kWh/m2 (2.21899 kBTU/ft2) annually. This metric will come up again in this paper. A building's energy usage is measured in the energy used, per unit of floor space, per year. This paper

[44] Treberspurg, 101.

will use the metric unit, kilowatt-hours per square meter, and then the imperial unit kBTU per square foot. Haus 5 uses 13.5 kWh/m2 (4.3 kBTU/ft2). To achieve this high level of efficiency, Hauses 1 and 5 use an extremely well-insulated wall assembly, designed with a cardboard lattice structure to trap and retain warm air.[45] Both buildings are oriented loosely east-west, with larger windows on the south face for solar gains of heat energy during winter.

In addition to these passive strategies, active technology helps the housing to heat and ventilate itself with a minimum use of power. Solar collectors on the south-facing shed roofs heat 60% of the hot water used in kitchens and bathrooms annually.[46] In order not to lose heat energy from escaping warm air, modern buildings are designed to trap air inside the building envelope. This technology has, for several decades, worked well enough to create a new problem: air trapped in the building must be mechanically circulated to prevent the buildup of stale air. Circulating air mechanically gives building designers an opportunity to pass the outgoing air through a heat exchanger, which critically allows a building to intake fresh outside air without paying the energy penalty of heating the incoming air.

Moreover, the SolarCity project aims to achieve more than just energy efficiency goals. It also address a number of social inequities, ranging from the century-old western focus on car-centric urban planning, to the separation between the human and natural spheres. It is important to keep in mind that architecture which meets rigorous

[45] Treberspurg, 142.
[46] Treberspurg, 143.

environmental standards, but fails to equitably meet the needs of the people who live in a neighborhood, is bad architecture.

2.4.5 Conclusion

SolarCity represents a well-documented, city-scale experiment is the design of low-cost, maximally efficient urban housing. Many of the lessons realized in SolarCity Linz Pichling will be emulated in the design of a site in Chapter 5.

CHAPTER 3.1.1. COMPRESSED AIR ENERGY STORAGE

As discussed in Chapter 2.3.1, energy storage represents a crucial aspect for the development of the Commonwealth of Massachusetts' renewable energy grid. This chapter will expand on the opportunities of Compressed Air Energy Storage (CAES), describe existing CAES facilities, and describe other case studies where energy storage infrastructure coexists with the urban landscape. This section will attempt to roughly size a system and discuss its place in the region's energy portfolio. Necessarily this analysis will be coarse: sizing and designing energy storage systems is work for a team of engineers, geologists, and economists. This section will conclude with an interview with an engineer about energy storage.

3.2.1 Properties of CAES

This section will examine what role CAES has to play in the renewable energy grid. The 2016 paper "Compression and Air Storage Systems for Small Size CAES Plants: Design and Off-design Analysis", presented at the 2016 International Conference on Energy and Environment Research, by Coriolano Salvini, et. al, concludes that "small CAES can play an important role for offgrid and self-consumption applications as well as in providing ancillary services on the lower grid level".[47] The "State of Charge: Massachusetts Energy Storage Initiative" report includes CAES in its analysis of energy

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[47] Salvini, Coriolano, Pietro Mariotti, and Giovannelli, Ambra, "Compression and Air Storage Systems for Small Size CAES Plants: Design and Off-Design Analysis | Elsevier Enhanced Reader," 375, accessed June 29, 2020, https://doi.org/10.1016/j.egypro.2016.12.178.

storage types[48], calling the technology "moderately" mature, and proven by the operation of two CAES plants.[49]

Long-term storage is a necessity for completing the renewable energy grid, but there are relatively few candidates for this function. The important metric here, described by the "State of Charge" report, is called "C-Rate": the inverse of the duration of time over which an energy storage facility can discharge. Only a few storage technologies can store and release power over weeks, or months-long periods of time without unacceptable loss: sodium-based batteries, flow batteries, pumped-hydro and CAES.[50] CAES could provide power and grid disruption resiliency over long periods of low generation, such as overcast winters. Investing exclusively in short-term storage would create situations where the grid would have to rely on low-efficiency fossil-fuel "peaker plants" to pick up the load disparity in these situations.

Flywheels are ineffective for long-term storage because of power losses through friction. Even when levitated on magnetic bearings and placed in a vacuum, flywheels spin down too quickly to be used for long term storage[51]: the mass would have to be too big.

Chemical batteries, like lithium-ion, batteries, are a powerful contender in the market for many instances of storage. These types of batteries do have drawbacks: they slowly discharge over time, and rely on harmful mining practices[52] to replace them when

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[48] DeRosa, Morin, and Alteiri, "Massachusetts Energy Storage Initiative Study," 7.
[49] "SuccarWilliams_PEI_CAES_2008April8.Pdf," 22.
[50] DeRosa, Morin, and Alteiri, "Massachusetts Energy Storage Initiative Study," 6.
[51] DeRosa, Morin, and Alteiri, 4.
[52] Amit Katwala, "The Spiralling Environmental Cost of Our Lithium Battery Addiction," *Wired UK*, accessed April 27, 2021, https://www.wired.co.uk/article/lithium-batteries-environment-impact.

they go. Their extremely high energy density comes with too high of an environmental cost.

New pumped-hydro facilities aren't being considered for the Commonwealth. "While Massachusetts has benefitted from pumped storage operating in the region," says the report, "geographic and environmental limitations make it unlikely that new pumped storage will be built".[53] Reservoirs flood too much valuable land to be feasible: their energy density is too low, creating a different environmental cost.

This thesis contends that CAES may have a role to play in the middle area between these two options.

Another important metric to consider is the *amplitude*, or the amount of energy which can be stored. While this is variable for each type of storage, some systems are better suited to larger storage capacities than others. A pumped-water reservoir is an example of a very high-amplitude storage facility. Millions of gallons of water are stored and discharged at a time, producing large amounts of power over sustained periods. The unit this thesis will use here generally, is megawatt-hours (MwH), meaning the amount of energy represented by 1000 joules/second, outputting for an hour. Another critical unit will be each system's *energy density*- the amount of energy stored as a function of each battery's volume. This will help us to determine how viable a given system is for a space. This unit will be measured in MwH/m^3: how many megawatt-hours of energy can be contained within one cubic meter of each storage type. A contention of this paper is that energy storage is a spatial problem, requiring the consideration of architects and urban planners, and this unit is important for evaluating energy storage from that perspective.

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[53] DeRosa, Morin, and Alteiri, "Massachusetts Energy Storage Initiative Study." v.

3.2.2. Benefits of CAES

When compared to batteries, CAES technology relies on relatively few extractive mining technologies, like lithium or cobalt mining. Furthermore, once the infrastructure is in place, it can store energy indefinitely so long as it is maintained, while batteries have a finite lifespan limited by battery degradation and corrosion.[54]

The "State of Charge: Massachusetts Energy Initiative" report, prepared by the city of Boston in 2016, lists CAES technology as "moderately" mature, more so than some types of batteries, and flywheels, but less so than pumped hydro, and three types of chemical batteries.[55] Chapter 3.3 will examine several existing CAES facilities to examine the results their performance: a facility in Huntorf, Germany; a facility in McIntosh, Alabama, and a proposed facility at the Kahe Power Plant in Hawaii.[56] Because compressed air storage relies on existing technologies to operate, common in the industrial sector, CAES may offer relatively low maintenance and operation costs.[57]

3.3.1 Existing CAES Facilities

Currently there are two CAES facilities operating currently in the world. The first was built in 1978, in Huntorf, Germany, and the second in 1991 in McIntosh, Alabama. Many more have been planned, with varying degrees of success. One planned facility is in Anderson Country, Texas, where Texas-based Apex CAES envisions a 324MW

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[54] DeRosa, Morin, and Alteiri, 7.
[55] DeRosa, Morin, and Alteiri, 7.
[56] Schainker and Kerschen, "Advanced CAES Analysis Using Above Ground Air Storage for Hawaiian Electric Company" (ELECTRIC POWER RESEARCH INSTITUTE, 2011), 1–2.
[57] "SuccarWilliams_PEI_CAES_2008April8.Pdf," 22.

facility, which they claim is “fully permitted and construction-ready”.[58] Berkeley-based LightSail Energy raised over $70 million from venture capital funding, promising cost-effective above-ground CAES facilities. Ultimately the company failed to build cost-effective storage tanks and went bankrupt.[59] A 2011 paper published by the EPRI, or Electric Power Research Institute, imagines a 54MW, 2-hour storage facility using a series of pipes as an aboveground storage vessel, chosen for their low cost and familiarity to the infrastructure grid.[60]

3.3.2 Huntorf Germany

The first grid-scale CAES plant was completed in 1978 in Huntorf, Germany. It uses two subterranean salt caverns as its primary pressure vessels, with a combined volume of 310,000 m^3.[61] The plant can supply the grid with 290MW of power over 3 hours; the amount of energy the plant is capable of storing is 870MwH. The relationship between the amount of energy the plant can store, and the volume of its primary pressure vessels is something this thesis will return to. This is the *energy density* of the pressure vessel. Here, the salt caverns have an energy density of 870MwH -the energy the plant can store- divided by 310,000 m^{3,} -the volume of the pressure vessel- or 0.00280MwH/m^3.

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[58] “Bethel Energy Center,” APEX CAES, August 17, 2016, http://www.apexcaes.com/bethel-energy-center.
[59] “LightSail Energy Storage and the Failure of the Founder Narrative | GTM Squared,” accessed January 4, 2021, https://www.greentechmedia.com/squared/letter-from-sand-hill-road/lightsail-energy-storage-and-the-failure-of-the-founder-narrative.
[60] Schainker and Kerschen, “Advanced CAES Analysis Using Above Ground Air Storage for Hawaiian Electric Company.”
[61] “SuccarWilliams_PEI_CAES_2008April8.Pdf.”

The plant is still operational today, helping to store energy from Germany's renewable energy portfolio. When it was built in 1978, it helped to store excess energy from a nearby nuclear plant, and to fill in quickly when load was high while coal-fired peaker plants came online.[62]

3.3.3. McIntosh Alabama

Operational since 1991, the Alabama Electric Cooperative's CAES plant in McIntosh, Alabama can release power at a rate of 110MW for 26 hours. This gives the plant a storage capacity of 2,860MwH.[63] The plant's primary pressure vessel makes use of an existing geological feature: a salt dome with an interior volume of 560,000m^3. This plant's energy density is 2,860MwH/560,000m^3, or 0.005107142857 MwH/m^3. Salt domes are geological features present in some parts of the United States and the world. Frequently, they are used as reservoirs for petroleum products, serving as a ready-made high-pressure vessel. The two existing CAES facilities use these features to store the compressed air. The next example will describe the plan of a facility-unbuilt- where salt domes aren't available.

3.3.4 EPRI Report: "Advanced CAES Analysis Using Above Ground Air Storage for Hawaiian Electric Company

As demonstrated by the facilities in Huntorf, Germany, and McIntosh, Alabama, using saline caves as a primary pressure vessel for a CAES facility is a cost-effective

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[62] "SuccarWilliams_PEI_CAES_2008April8.Pdf," 22.
[63] "SuccarWilliams_PEI_CAES_2008April8.Pdf," 22.

method for containing air at a high pressure for a low initial cost.[64] While helpful, this would constrain CAES facilities to areas where saline caves are present. A 2011 report by the EPRI (Electric Power Research Institute) designs a facility which leverages the low cost and high pressure capacity of 42" diameter, carbon-steel pipe. "The above ground advanced CAES plant integrates equipment and processes commonly used in both the power generation and oil and gas industries" the authors claim. "The size and design of the advanced CAES plant can be tailored to local generation and demand needs".[65] Chapter 5 will use the design of this site as a starting point for a facility in East Boston.

The EPRI report describes the aboveground pressure vessel as "a network of pipes, connected in series and mounted on pipe supports. The piping matrix…is arranged in a single 500 foot run, 20 rows wide by eight rows high… [it] comprises approximately 71,000 lineal feet of nominal 42 inch diameter steel pipe".[66] This system would able to generate 58MW for four hours, meaning it has an energy capacity of 232 MwH. In Chapter 5, this thesis utilizes the volume, and general design of this facility, and integrates it into the design for a site. Because the engineering of such a facility is outside of my field, using this existing proposal will serve as a baseline for assumptions in my thesis about the size and shape of a new installation.

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[64] "SuccarWilliams_PEI_CAES_2008April8.Pdf." 22.
[65] Schainker and Kerschen, "Advanced CAES Analysis Using Above Ground Air Storage for Hawaiian Electric Company," 2.
[66] Schainker and Kerschen, "Advanced CAES Analysis Using Above Ground Air Storage for Hawaiian Electric Company."

3.3.5. Phone Conversation with Eric Kashiwamura

I reached out to Hawaiian Electric, to learn more about this report, and how viable this plan might be. Mr. Eric Kashiwamura, the Manager of Research & Development was nice enough to call back, and help to contextualize the report. He spoke about Hawaii's unique position: being an isolated state, with independent islanded grids on each island and separated from the rest of world by more than 2,000 miles of ocean. Kashiwamura described Hawaii as a "postcard of the future, in terms of what to expect" for a sustainable model of renewable-generated electric power.[67] Hawaii has abundant resources for wind, solar, and even geothermal power. As these powerful but intermittent generators come online, "balancing supply and demand is important." says Kashiwamura. "Energy storage is actually a requirement for the Company's utility-scale RFPs for developers of PV or wind in Hawaii. It's to their advantage to integrate energy storage, to avoid an excess of power and avoid renewable curtailment".[68] Curtailment refers to reducing renewable power generation assets online, at times where there is already an abundance of power available to the grid. While these powerful natural forces can provide, they can also destroy: Kashiwamura spoke about the 2018 eruptions at Kīlauea, and regular hurricanes which can damage infrastructure catastrophically.

[67] Eric Kashiwamura, Phone Conversation Between Eric Kashiwamura and Connor Slover, Telephone, April 26, 2021.
[68] Kashiwamura.

According to Kashiwamura, "CAES is an alternative storage technology but a rather expensive option, since we don't have caverns here, so it would have to be above-ground tanks that are costly".[69]

I asked Kashiwamura about the cost of the facility described in this report, as it related to the amount of energy storage the project would provide. "Its extremely high." he replied instantly. "Extremely high, especially since the project is in Hawaii, and not cost effective when compared to other options. A CAES project is not a good fit".[70]

He adds, encouragingly, "In R&D at early stages, things are very expensive. Lithium-ion was expensive too." While Kashiwamura seems to regard CAES as one technology of many, which serve an equally complex grid, where small changes in location, geology, or weather make different systems viable, currently, without a pre-existing storage tank like the salt caverns in Germany or Alabama, "it would just not be cost effective".[71]

3.4.1. Existing Co-Located Program and Energy Infrastructure

The site designed in Chapter 5 will incorporate CAES and other program. This section will describe several precedents, where projects integrate energy storage, or other grid-scale energy infrastructure, into the urban landscape, and into their other uses.

3.4.2. Various Projects by Leers Weinzapfel

Founded in 1982 in Boston, Leers Weinzapfel Associates is a 30-person architecture design firm focused on a wide range of project types. In 2007, they were

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[69] Kashiwamura.
[70] Kashiwamura.
[71] Kashiwamura.

awarded the AIA's Firm Award, and were the first firm founded by women ever to do so.[72] A number of their projects center around infrastructure, and more specifically around the integration and beautification of power stations into campus or urban settings: The Ohio State University East Regional Chilled Water Plant, the Harvard University District Energy Facility, and the University of Pennsylvania Gateway Complex all fit this description.

Completed in 2014, the Ohio State University East Regional Chilled Water Plant is a facility which centralizes heat exchange for the campus. It accepts hydronic system water, exchanges its heat with the environment, and reintroduces cold water into the system. The project is composed of two stacked, overlapping rectangular volumes, offset by around one quarter of their length. The upper volume is clad with perforated copper panels, which are mostly transparent, and allow for the cooling towers inside to exchange heat with the outside air. The lower volume contains the water chillers, and is a white, semi-translucent but enclosed space, consisting of six bays bound together with tensioned cross-bracing, behind a glass skin. Because of this skin, the structure reads more like a building than an infrastructure project, which allows it to fit in visually with the campus. While the goal of the project is semiotic, there are secondary benefits: the visual appeal of a campus can be a large factor in student applications, for instance, and thus might produce a revenue benefit when compared with a similar plant, left unclad.

Harvard's 58,000 square foot District Energy Facility was completed in 2019, as part of the school's expansion into Allston. It houses an array of facilities relating to hot water generation and distribution. Most relevantly, the facility features "…a 1.3 million

[72] "Commitments," Leers Weinzapfel Associates, accessed September 16, 2020, https://www.lwa-architects.com/commitment/.

gallon tank for storing chilled water produced off-peak, when electricity is less expensive, and distributed during daytime hours to buildings as needed".[73] Much like other means of energy storage. The existence of this project makes a strong case for the financial feasibility of district-scale energy storage, in Boston, in 2020.

Architecturally the project is rectiform, with fillets easing the corners. The envelope is largely transparent, with a series of upright, white fins obscuring the view to the interior when viewed from a low angle. The equipment inside is largely visible, so that the project communicates its function outwardly, without clearly reading as infrastructure or revealing its specific function.

3.4.3 Copenhill by Bjarke Ingels Group

These projects all represent a strategy of visual integration into the landscape, and not necessarily a functional integration. Copenhagen's Amager Resource Center is the cleanest waste-to-energy (WTE) power station in the world. Essentially it burns trash and the heat generated boils water, while the steam rotates turbines. The smoke is passed through a series of filters to sequester harmful chemicals. The plant is an important part of Copenhagen's goal to become carbon-neutral by 2025.[74] The project takes an ambitious stance towards relating to the urban landscape of Copenhagen. Bjarke Ingels Group (BIG) won the design competition in 2011, with a proposal to clad the building in large panels, and to define a continuous slope on the top of the building which would be

[73] "District Energy Facility (DEF) | Harvard Capital Projects," accessed September 17, 2020, https://hcp.campusservices.harvard.edu/active-projects/DEF.
[74] Michael Birnbaum, "What It Takes to Be Carbon Neutral — for a Family, a City, a Country," Washington Post, 2018, https://www.washingtonpost.com/climate-solutions/2019/11/19/what-it-takes-be-carbon-neutral-family-city-country/.

used as a ski hill. “The ski slope idea came from realizing that Copenhagen has a cold climate with several months of snow, but absolutely no mountains,” Ingels told *Architectural Digest* for a 2018 article. “…The roof is not only going to function as a ski slope, but as a real mountain with a green forest area, a hiking trail, and climbing walls—all while allowing spectacular views of the city skyline”.[75]

This project, and the approach this thesis will take to the design of its site, is a expression of what William McDonough, author of “Cradle to Cradle”, laconically calls “good”, as compared to “less bad”: large, typically unsightly infrastructure projects can, when considered carefully, not only harm the landscape around them less, but beautify and enliven them.[76] In the BIG project, the WTE plant requires a large structure. Without secondary program, this structure would take up space, somewhere, and degrade some neighborhood. By giving the building’s massive volume another function, this design, and design interventions like this, could be an important way for green infrastructure to get built. If people really ski there, and if the WTE plant really does what it claims to do, this project could be a landmark example of co-locating green infrastructure with human spaces.

3.6.1. Lessons for Planning an Integrated CAES System

It’s possible that Compressed Air Energy Storage (CAES) will exist in the Commonwealth of Massachusetts, due to the necessity of energy storage in the firming of the renewable grid, and because of the unique position of CAES within the energy

[75] Brooke Porter Katz, “BIG’s Bjarke Ingels on His Singular Vision for CopenHill—the Power Plant–Ski Slope,” Architectural Digest, accessed September 16, 2020, https://www.architecturaldigest.com/story/big-bjarke-ingels-copenhill.
[76] William McDonough, “Why Being ‘Less Bad’ Is No Good,” *The Globalist* (blog), June 21, 2010, https://www.theglobalist.com/why-being-less-bad-is-no-good/.

storage portfolio. CAES could store energy on the scale of a Pumped-Hydro facility, while using a fraction of the space.[77] CAES tanks will exist at some size, in some shape, and to be successful, they will have to relate to the landscape around them in ways which will enrich their surroundings. In his book on underground buildings, “Gentle Architecture”, the architect Malcolm Wells writes that he “grew less and less willing to see someone buy a valuable site simply for the purpose of having it destroyed by another of my buildings… If you want an ideal building site, tell the realtor to show you his worStreet What a rich life you’ll have, if he gets it for you, undoing that little bit of civilization’s damage”.[78]

CAES facilities shouldn’t look like natural gas facilities, or traditional power plants, characterized by vast arrays of pipes and tanks, with mile-radius exclusion zones for housing and development. And in fact, they do not have to: an adiabatic CAES facility doesn’t combust anything. It will produce no smoke or gasses, and not discharge chemicals into the groundwater.[79] In part, this project will imagine a facility which is an integral part of its neighborhood, enriching the lives of those nearby.

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77 DeRosa, Morin, and Alteiri, “Massachusetts Energy Storage Initiative Study.” P.4
78 Malcolm Wells, *Gentle Architecture* (McGraw-Hill, Inc., 1981), 106.
79 DeRosa, Morin, and Alteiri, “Massachusetts Energy Storage Initiative Study,” 4.

CHAPTER 4.1.1. HOUSING

The purpose of this paper is to introduce a viable site plan integrating grid-scale energy storage. As we learned in chapter 2.4, more housing is badly needed in the Commonwealth of Massachusetts to accommodate the rate of population growth. This section will expand on the lessons learned from The Boston Foundation's Housing Report Card, examine precedents for projects where housing and grid infrastructure successfully meet, and lastly propose a set of rules by which the housing aspect of the site will be designed in Chapter 5.

4.2.1. Precedents

This subchapter will highlight several projects which revolve around sustainable, affordable housing. Lessons from the projects will influence the design of the site in Chapter 5. More analysis of sustainably designed housing and urban planning can be found in Chapter 2.4.1., which summarizes a textbook describing SolarCity: Linz Pichling.

4.2.2. Via Verde

Via Verde, "The Green Way", is a mixed-use and mixed-income residential development in the Bronx, New York designed by Grimshaw. Its 290,000 square feet of floor area contain 222 residential units, split between a 20-story tower, a midrise building, and townhouses.[80]

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[80] "Via Verde – The Green Way / GRIMSHAW," accessed September 22, 2020, https://grimshaw.global/projects/via-verde-the-green-way/.

The development is designed around a series of rooftop gardens, stitched together into a single “promenade”. This promenade drives much of the design of the building, which steps upwards incrementally to allow for continuity in the green path. This gesture makes the project relevant to this paper’s proposal: in both cases, a large, external programmatic requirement; here, outdoor green space; in my project, compressed air vessels; are wedded to affordable residential units, to the benefit of both functions. Spatially they compliment one another. Low-rise apartment buildings create a lot of square footage on their roofs, which, if left unconsidered, would be covered in conventional rubber roofing, and create both wasted space in a dense urban area and contribute to the urban heat island effect. Instead, the space is used for roof gardens and green space, which both ameliorate the heating effect and provide the opportunity for residents for agriculture and exposure to the outdoors. The spatial excess of one system is used to solve a spatial need in another system. In Via Verde, the roofs of buildings provide a park. In this proposal, the pressure vessels of a CAES facility will serve as the landforms in a park.

4.2.3. Various Projects by Utile

Utile is a Boston-based architecture firm founded in 2002. They built many successful projects in Boston’s residential real estate expansion in the early 2000s, especially in “vacant post-industrial sites at the edges of established working class residential districts”.[81] Utile’s projects fit within the economic, aesthetic, and political climate of the Boston Metropolitan area, and as such can represent an important yardstick

[81] Tim Love et al., *Urban Housing Atlas* (Pink Comma Books, 2008), 7.

for a successful housing project. This section will examine a few of their projects and extract specific, proven design choices applicable to residential architecture in Boston.

The "First + First" site is a development of 22 single-family rowhouses, on a triangular site abutted by streets on its three edges. Cost necessarily drives many of the design choices which shape the building. Given the high cost of steel, the rowhouses are built with primarily traditional wood framing, with the notable exception of a steel moment frame to allow the lower level of each rowhouse to contain an unobstructed span for a two-car garage. Parking requirements are described by city code. The main living space of each rowhouse is on the second story, comprised a largely unobstructed living area with a kitchen. The third floor contains two bedrooms and a full bath. The fourth floor contains a flexible room, capable of performing as a bedroom, studio, or office. A small bath, shower, and outdoor deck round out the space.[82] Further stories are prohibited by the wooden construction of the structure in fire code.[83] The rowhouses are sometimes bookmatched, and sometimes repeated, in order to create a interesting streetscape.

The multifamily "Trolley House" represents many of the same design considerations applied to the "First + First" project, in a multifamily residential building rather than in a series of townhouses. The building's torus design, with a courtyard at the center, allows for two window exposures in each unit.[84] The building's lower level is dedicated to parking, resulting in a favorable two parking spaces per unit ratio. On the street-facing façade, the parking garage is screened by the lobby entrances, making the building appear solid throughout. Some unit plans are designed with more open spaces,

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[82] Love et al., 15.
[83] Love et al., 8.
[84] Love et al., 59.

nodding to the contemporary loft apartment typology, while others are modeled after more familiar, discrete spaces.[85]

4.3.1 Lessons for successful housing design

Specific lessons from urban housing precedent will be applied to the design of the site in Chapter 5. Successful precedents consider the character of their neighborhoods, and carefully design the effect new construction will have on the streetscape, as well as the access to views and light of its abutters. Accessibility should be considered for elevator served apartments and apartments on the ground level. Specific lessons like daylighting the basement, tucking parking underneath the buildings, and keeping building height within the limits of wooden framing will be used in Chapter 5.

[85] Love et al., 59.

CHAPTER 5.1.1. PROJECT DESIGN

This chapter will propose to design a site which, 1., provides stability to the renewable energy grid by incorporating CAES, 2., adds to the housing supply of the Boston Metropolitan area, and 3., ameliorates a contaminated site, leaving it at a viable park space for use by the neighborhood. The purpose of this project is to demonstrate that when these problems are considered together, important cost and space savings can be achieved. It is hoped that this project can represent a case study for co-locating aspects of the next-generation renewable energy grid with other program, from an architectural perspective. This section will contend that it is possible to use the revenue generated by the CAES facility to help offset the cost of the affordable housing on the site.

5.1.1. Site Context

This paper examines a site located in East Boston because East Boston exemplifies many of the problems symptomatic of reliance on fossil fuel infrastructure. Frequently, lower-income neighborhoods are forced to coexist with undesirable urban conditions. Daniel Faber, director of the Northeastern University Environmental Justice Research Collaborative, puts it this way: “Communities that lack the political, economic power to defend themselves, where residents work longer hours, and they have less resources and are less educated- those are the communities that are often targeted for the siting of some of the most dangerous or ecologically hazardous facilities”.[86] Consider

[86] Shannon Dooling, “How One Massachusetts City Came To Bear Environmental Burdens For The Region,” New England Public Media, 2010, https://www.nepm.org/post/how-one-massachusetts-city-came-bear-environmental-burdens-region.

East Boston: Hispanic and Latino people make up 53% of the neighborhood. In Greater Boston, they make up only 18%. The median household income for East Boston is $43,511, compared to $52,433 for Greater Boston.[87] While examining the root causes and effects of environment racism is outside of the scope of this paper, this paper contends that East Boston is an example of this structural inequality, because according to neighborhood activist Roseann Bongiovanni, who the head of the East Boston and Chelsea environmental justice group Green Roots, the neighborhood is used as a depot for 100% of the jet fuel used at Logan airport, 70% of New England's heating fuel, and the road salt for 350 communities around Boston.[88]

Obviously, displacing people from this contaminated neighborhood is both ethically and logistically unfeasible, tapping into ugly chapters of the American past. Instead, as our infrastructure transitions away from using fossil fuels, we have an opportunity to use these sites as focal points for a designed enrichment of victimized areas so that they can succeed in the future.

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[87] "At a Glance | Boston Planning & Development Agency," accessed December 2, 2020, http://www.bostonplans.org/neighborhoods/east-boston/at-a-glance.
[88] Dooling, "How One Massachusetts City Came To Bear Environmental Burdens For The Region."

Figure 1. Aerial map of East Boston, locating the fossil fuel infrastructure locations

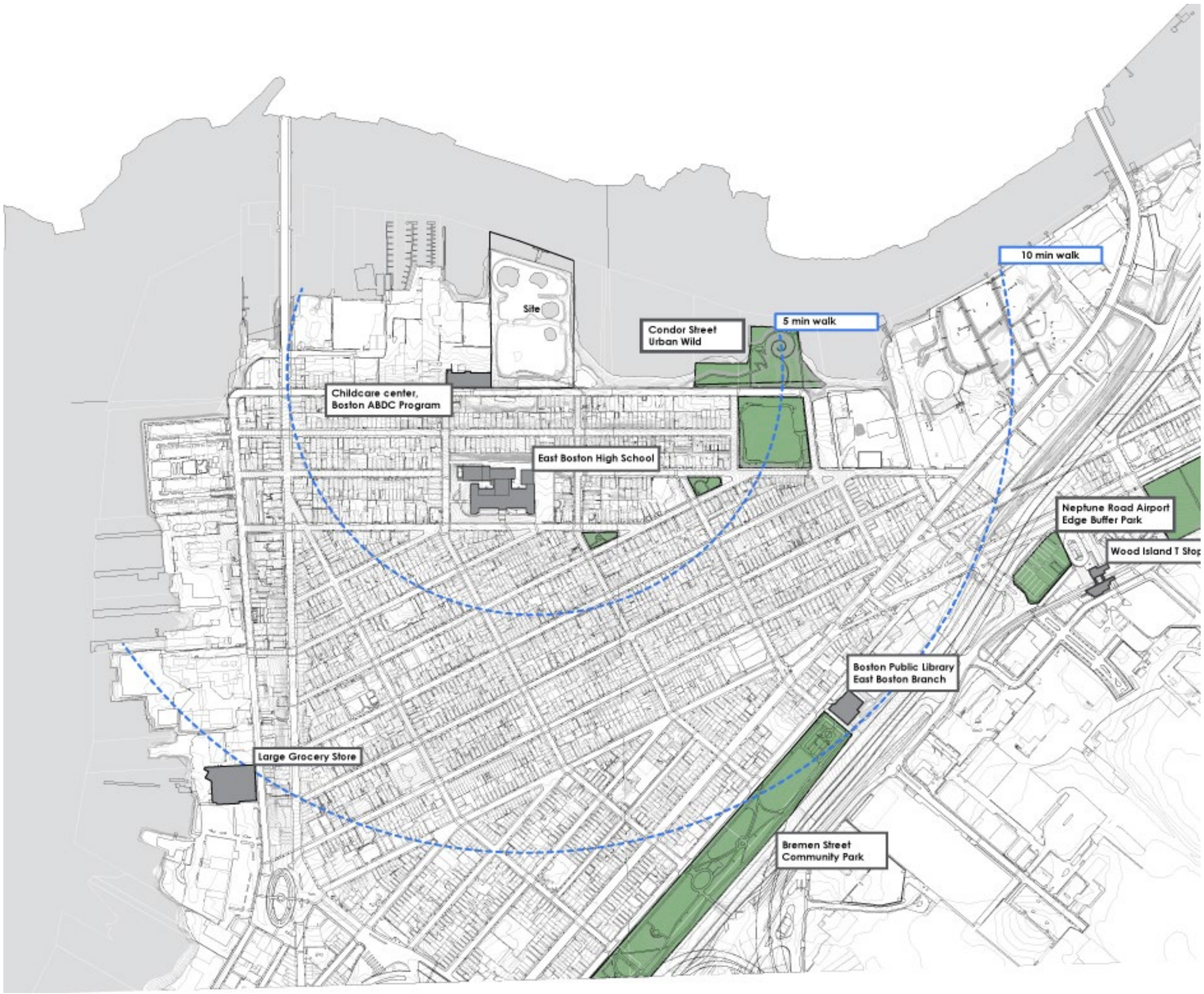

Figure 2. Map of East Boston. GIS data provided by the BPDA[1].

One ought to consider East Boston in terms of its available resources rather than its shortcomings. The site this thesis will choose to examine is 146-172 Condor Street, in East Boston. It juts out into the Chelsea river, a manmade pier with an area of six acres. From the site at 146-172 Condor Street, pedestrians could access several schools, libraries, and green spaces within a short walk. The Condor Street Urban Wild, a park designed by landscape architecture firm Hargreaves and Associates, is visible from the site, although several parcels separate the two. Designed to rehabilitate heavily contaminated land while creating a beautiful green space, the park features several rolling landforms, which functionally serve both to cap polluted soils and provide an interesting topological feature and a view down Chelsea Creek. The park features a path along its west edge which seems almost to reach out the 146-172 Condor Street site, potentially beckoning pedestrians to move be

tween the two.

Figure 3. The site's relationship to sea level rise

Figure 3. shows the site at the level of the annual highest tide. The second panel shows this plane, translated upwards in the model space by five feet. Boston’s “Climate Ready Boston” uses a 36” expected SLR (sea level rise) at the year

2070.[89] This image shows that it would be irresponsible to build on the interior of the site.

The third panel of Figure 3 shows this plane, translated upwards in the model space by 10'. Only the rim to the south of the site remains above the flood plane.

5.1.2. Site Photography

This section will include some photographs of the site, to give the viewer a sense for what the site looks and feels like. If good architecture is extremely sensitive to its context, an understanding of the site will be crucial to the design of this project.

[89] Carl Spector et al., "Coastal Resilience Solutions for East Boston and Charlestown" (City of Boston, October 2017), 15.

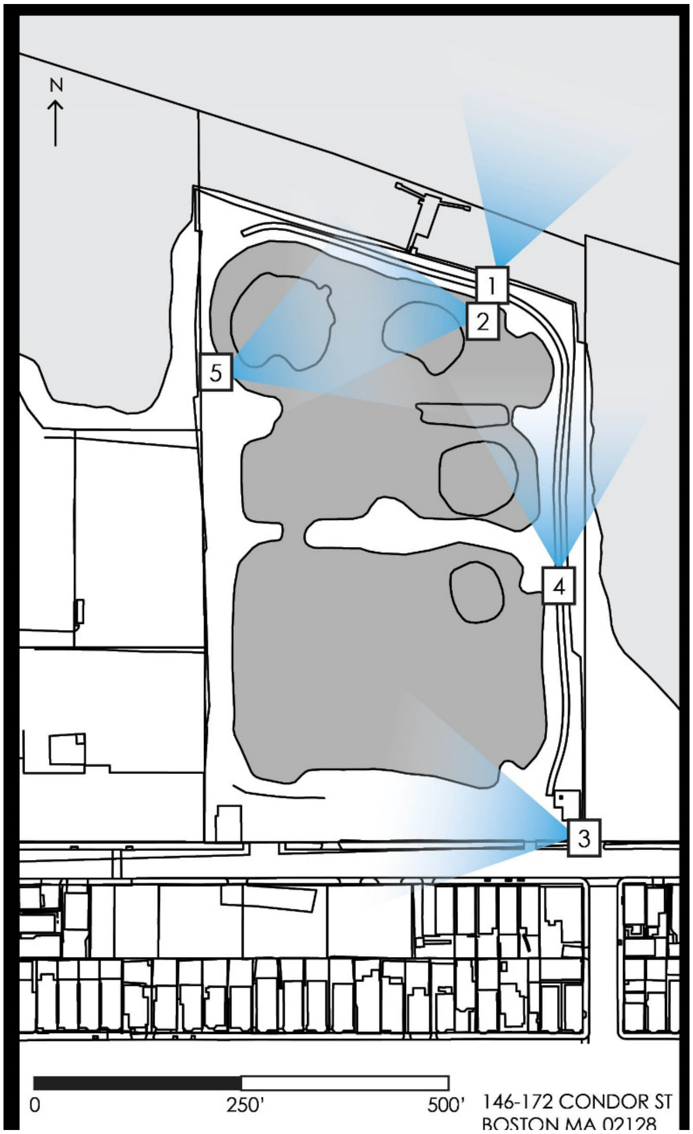

Figure 4: Site map showing view locations. This map, *right,* shows the site, and where each photograph is taken from, and what it depicts. Several of the photographs are panoramic images, in which my phone stitched together a series of stills into a nearly 180 degree view. None of these views are taken from the interior of the site, which as the reader can see in the map, is inundated with drainage water.

Figure 4 Site map with view locations

Figure 5 View 1

View 1, shows Chelsea Creek, from the North of the site looking North. The change in elevation from the top of the seawall and the water level is evident. Also visible is the dock at the north of the site formerly used to load and unload fuel from bulk transport ships. Across the river is one of several road salt piles, visible as a mountainous white form. A chain-link fence with barbed wire on its top discourages site visitors. Since the site is vacant, contaminated by fossil fuels, and owned by the city, fences reduce the city's liability if a visitor were to be injured.

Figure 6 View 2

View 2, is from the North, river-edge of the site, looking south across the site, and west along the seawall and berm (photo is a panorama). The swamp visible on the left of the photograph is the interior of the site. This water level is higher than the water level of Chelsea Creek. The McArdie Bridge is visible in the distance, and while it is small in this photograph, the bridge is very striking in real life. Maintaining the view to this bridge is important.

Figure 7 View 3

View 3, is taken from the southeast corner of the site, looking to the west along the sidewalk. In person, it is very apparent that this platform is a good candidate for building: it is level with the street, and roughly 30’ wide. The site drops off dramatically on the north edge of this platform, and that slope overgrown with bushes and small trees. There are two small structures on the southwest and southeast corners of the platform. The structure on the southwest is brick, with a rusty row of clerestory windows. The structure on the southeast is built with cinderblocks. Both are vacant and overgrown.

Figure 8 View 5

Figure 9 View 4

View 4 looks North, from the eastern edge of the site, along the berm and seawall. The view is included to show the characteristics of the berm, and what the view across the river would look like if the fence in View 1 were removed, while View 5, is taken from the western edge of the site, looking down and east, into the swampy interior of the site. Clearly, building on the interior of the site would take some extensive regrading. Two ducks are visible in the photograph, which speaks to the functionality of the site as an ecosystem.

5.2 Addition of Residential Buildings

5.2.1. Building Schematic Design

For the reasons discussed in Chapter 4, it is critically important to build more housing in Boston, affordable housing especially. Therefore, my proposal for the development of the site at 146-172 Condor Street will include residential buildings.

Several driving schematic ideas underlie the forms of these buildings. First and foremost, the design must respond to the needs of the neighborhood. As explained in Chapter 5.1.1., the majority of households in East Boston are Latino, most of whom are born outside of the US. Almost 60% of East Boston's households are families.[90] In order to allow these people to continue to live in the neighborhood, and to provide them with places to grow and thrive, the residential units in this development will be large, containing at least three bedrooms. Immigrant families are an important part of Boston's social, economic, and cultural spheres, and designing small units, disadvantageous to this demographic, in a context already so exploited, would be a gesture of bad faith on behalf of a developer.

Next, the buildings will span the rim of the site, so that one of their long facades will be at street level, and one will be at the site's interior level, a difference of approximately 12 feet. The basement level, open at the north of the site, will be used for parking. This strategy is used in several of Utile's projects in order to save money on

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[90] "At a Glance | Boston Planning & Development Agency."

HVAC for the parking level, and the operating cost of lighting the area during the day.[91] Here, this strategy is used because the rim around the site provides a perfect opportunity to both leverage this design idea, and make use of the topology of the site. Figures 2.1 and 2.2., *below*, show schematic building sections. Figure 2.2 explore how designing holes in the south face could allow for cross ventilation of the basement level.

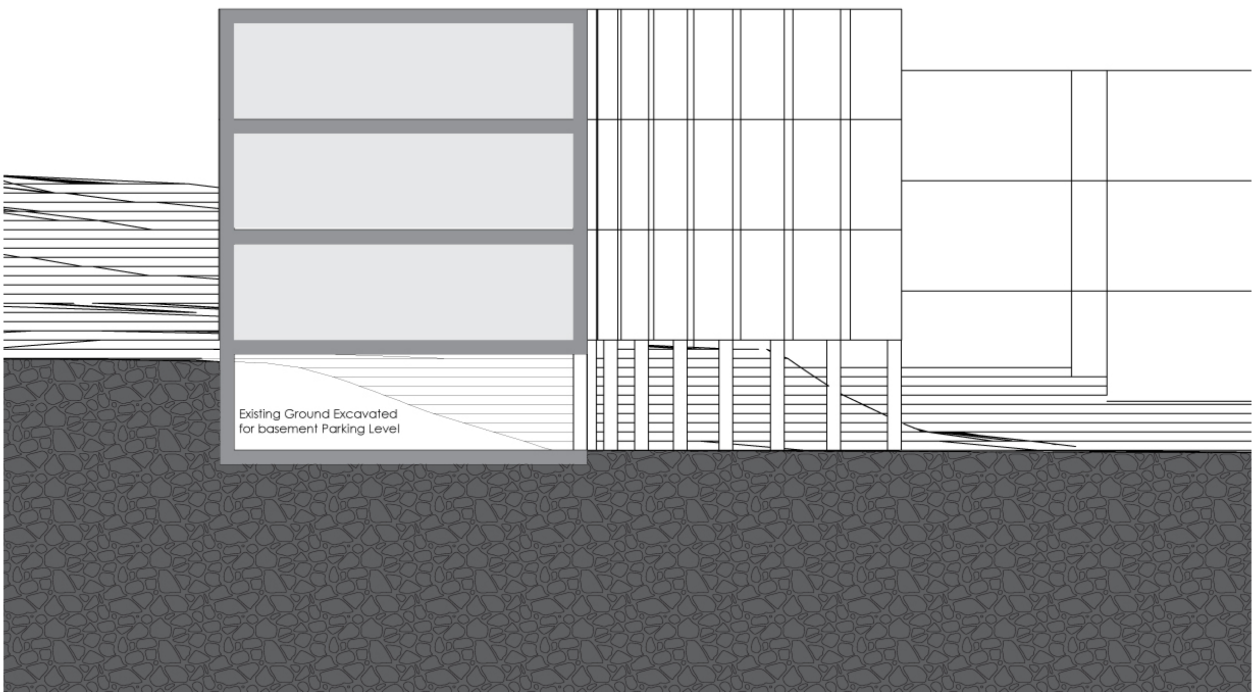


Figure 10 A schematic section through Building 2, showing the change in level between the North and South sides.

[91] Love et al., *Urban Housing Atlas*.

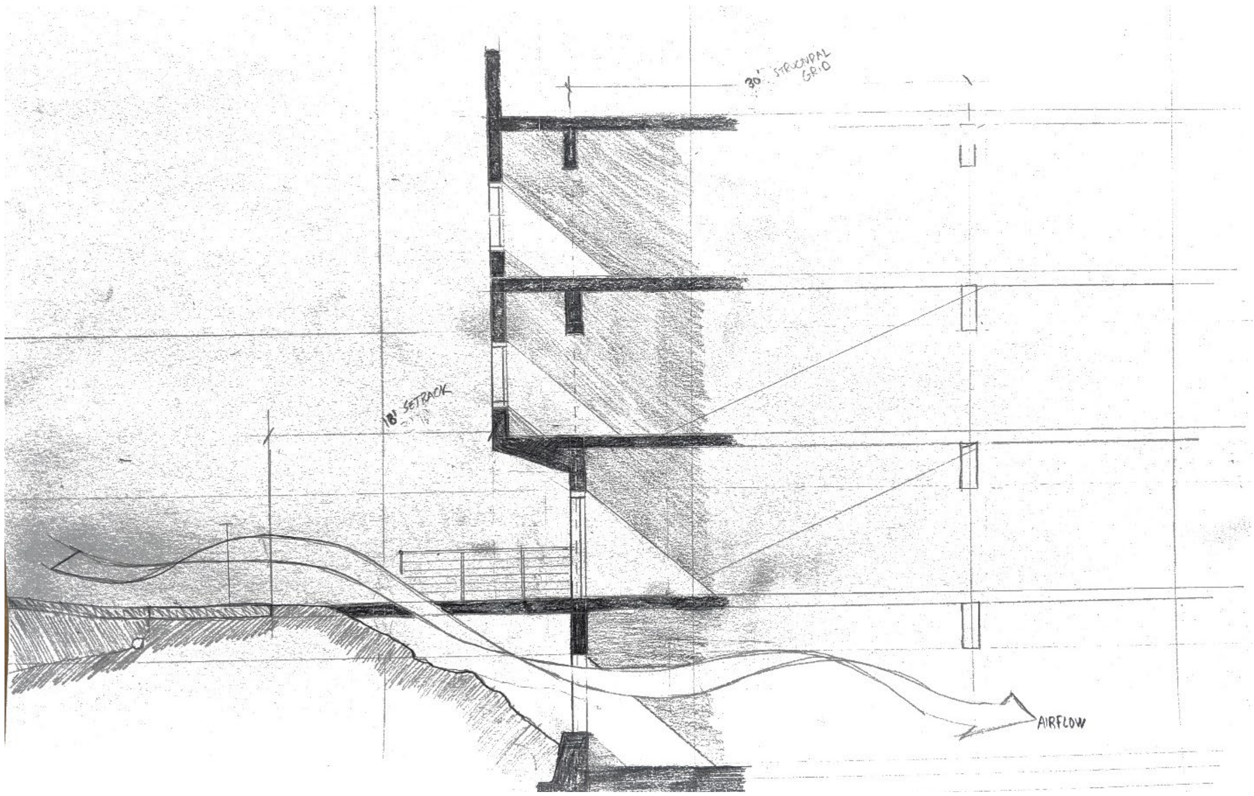


Figure 11 Leaving a punched opening in the street side of the basement level could introduce light and cross-breezes, saving power and money. This strategy is employed by Utile and at SolarCity, see Chapters 2.4.1 and 4.3.3.

Another principle this thesis uses as a baseline for designing these buildings was the idea that they ought to develop a formal transition from the traditional three-decker to more novel building forms. This transition takes place moving from west to east along Condor Street., because the southwestern urban corner of the site abuts a school, and relates to three-deckers across the street, while on the southeastern corner, a new building creates the opportunity to control its own design language. This transition could affect building height also, getting taller on the site's East side. This concept is represented by a hand sketch, Figure 2.3, *below.*

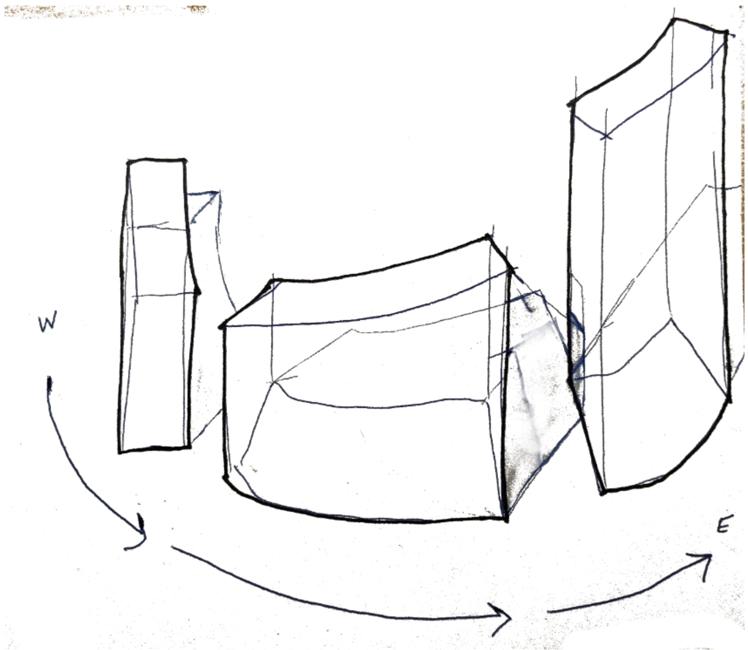


Figure 12 Sketch of the building massing changing along an east-west axis

These foundational concepts drive the general building massing. The width and depth of a three-decker is used as a building block, both because it will fit the character of the neighborhood, matching the facades of the buildings nearby, and because its structural proportions and size fit with the construction methods used and known in the area. The diagrams below, Figures 2.4.1., 2.4.2., 2.4.3., 2.4.4., and 2.4.5, show the iterative process of designing building massing for the site.

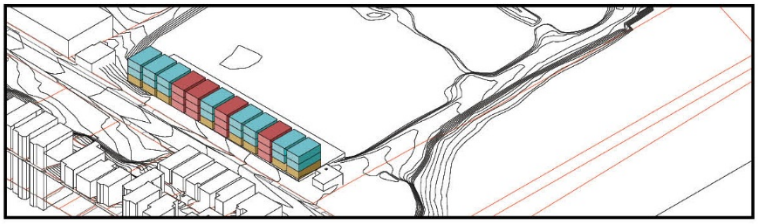


Figure 13.1.

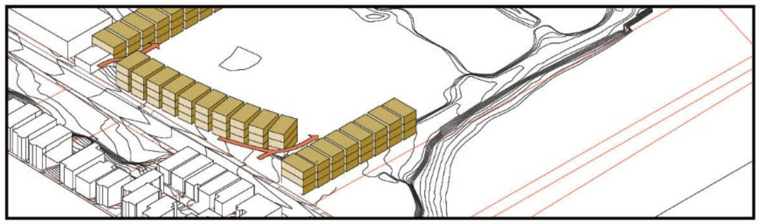


Fig 13.2.

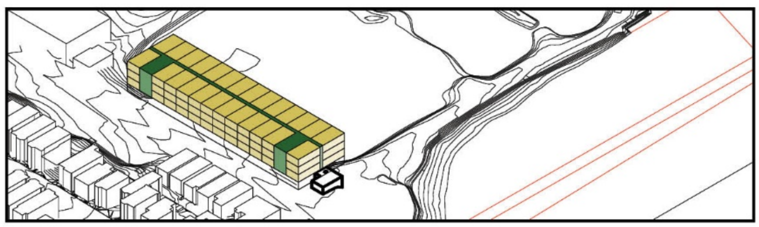


Fig 13.3.

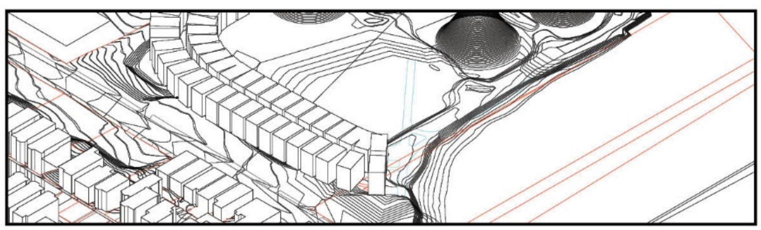


Fig 13.4.

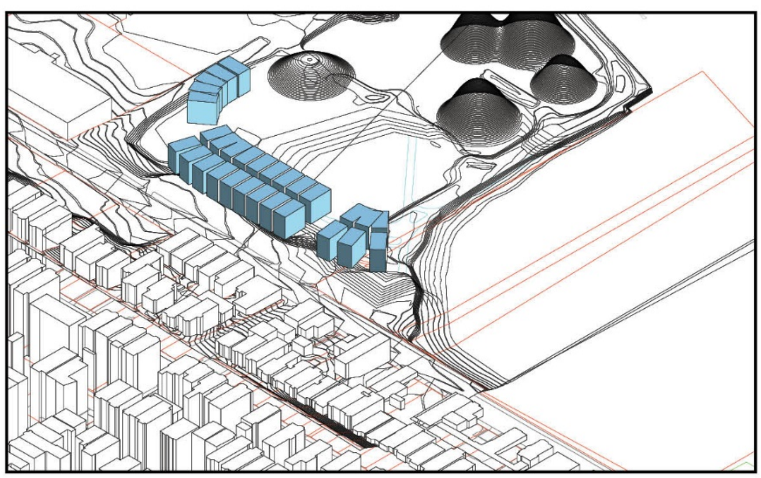


Fig 13.5.

Figure 13 Schematic design of building massing

The first experiment, Figure 13.1, was to place a row of three-deckers along the southern, urban edge of the site. This type of development would allow most if the site to remain as a park, or a CAES facility, and would relate visually very consistently with the neighborhood. This image uses colors to distinguish between shared buildings, with a studio or 1-br apartment on the bottom story; or a family-oriented unit taking up all three levels. As shown, however, this arrangement would only create 19 units on a 6-acre site, resulting in a very low density for a project aiming to address Boston's housing shortage.

Figure 13.2. takes this same model, and continues along the western and eastern edges of the site, resulting in a U-shape of three-story buildings, with exterior walls on both the north and south faces of each unit. This condition is very favorable: when designing the interiors of the buildings, these buildings would be very easy to daylight. However, the density of the site remains too low, and adding any more buildings would mean construction on the low-lying site interior.

In order to increase the density of the site's development. I tried moving to double-loaded corridor buildings, still positioned on the southern edge's landform- Figure 13.3. Moving to a double-loaded corridor helps to achieve a greater site density, but it comes with some major drawbacks. Imagine a unit on the second level; only one of its walls is exposed to air, sunlight, and views. The other 5 faces are floor, ceiling, the two abutting units, and the corridor. This makes designing 3- and more-bedroomed units is difficult, since code and quality of life demand that bedrooms have exterior windows. Additionally, the long, straight corridor between egress stairs is oppressive to look down, reminding residents constantly of the scale of the building. The site is still no densely-enough loaded with residential units.

Figure 13.4. shows a schematic design with a much-increased density, achieved by continuing the double-loaded corridor shape along the entire southern edge, as well as some of the western and eastern edges. The building uses a gentle radius to avoid a blocky appearance, and unlivable interior corners. Unfortunately, the southern edge of the building would feel extremely oppressive from the sidewalk of Condor Street, and the unbroken building mass would restrict access to the site for pedestrians and cars, precluding parking on the bottom level.

Figure 13.5. is the final schematic design of the buildings. The double-loaded corridor from the previous iteration endures, but it is now punctured in two places, breaking up the massive volume of the forms. This allows pedestrians and cars access to the interior of the site, while allowing views from the street to the site's interior and the river. This scheme includes 29 "three-decker" sized units, which could be split into a variety of one, two, and three-story options. The division into three buildings allows for each building to develop its own language, so that the development feels like an organic extension of the city, rather than a walled-off community. Working between this view and floor plans, I began to develop the floor plans for each unit, and for the buildings as a whole.

5.2.2. Building 1 Design Development

Building 1 is the westernmost building volume, shown in Figure 2.4.5. on the left of the image. The building is the depth of one three-decker block unit, or 38'. If this volume were the same double-loaded corridor as used in Buildings 2 and 3, and spanned over the change in level of the site's rim, it wouldn't fit within the western edge of the site line, as shown in Fig 13.4.. This single-depth allows for both the eastern and western facades to have access to the exterior, and so it seemed logical to plan these buildings within a typical three-story, townhouse model. Such a model will provide adequate space for families to live and grow, while providing a legible face for the entire project, relating to the neighborhood's existing character.

Figure 14 shows the difference between arraying a typical floor plan along the building line, or mirroring pairs across to form a bookmatched effect. Building 1, and this project generally, will favor mirroring when identical units are placed in a row: mirroring creates fewer, larger graphic elements on a façade, while arraying creates more, smaller patterns, which is important when trying to relate new construction to the existing streetscape. Additionally, mirroring is more favorable for reducing the number of plumbed walls by having bathrooms and kitchen mirrored across a shared wet wall.

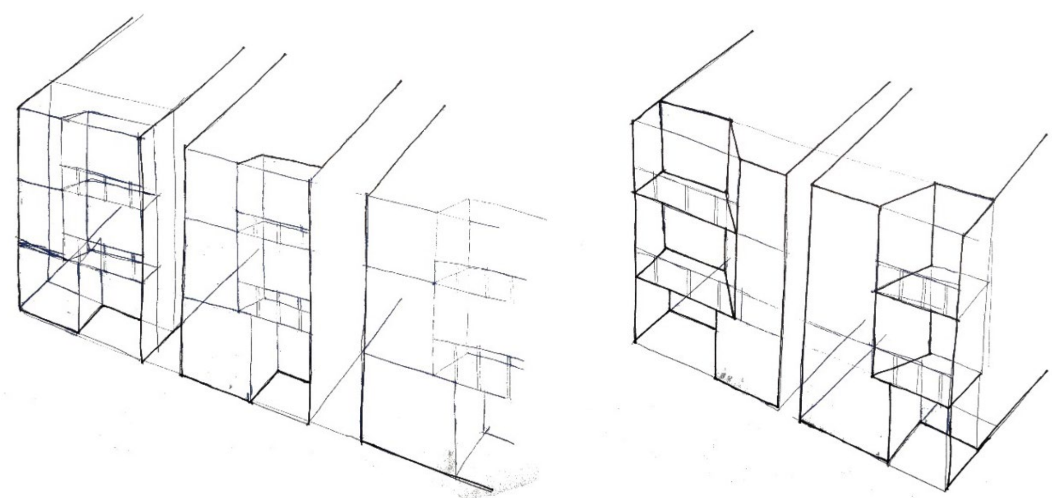


Figure 14 Arrayed and mirrored units

When creating the floor plans for these units, the first step was to consider the factors which drove their design. Placing vertical circulation along a continuous vertical line was the first consideration. Because cars have to park under the buildings, and because they access the space from the east face, the stairs are pushed to the weStreet This principle is illustrated in Figure 15. After experimenting with several stair paths, a standard, switchback U-shaped staircase isimplemented, because it takes up a small amount of floor space. Figure 3.2., *below,* shows U-shaped, L-shaped, and straight stair runs, positioned so that cars can enter easily on the basement level.

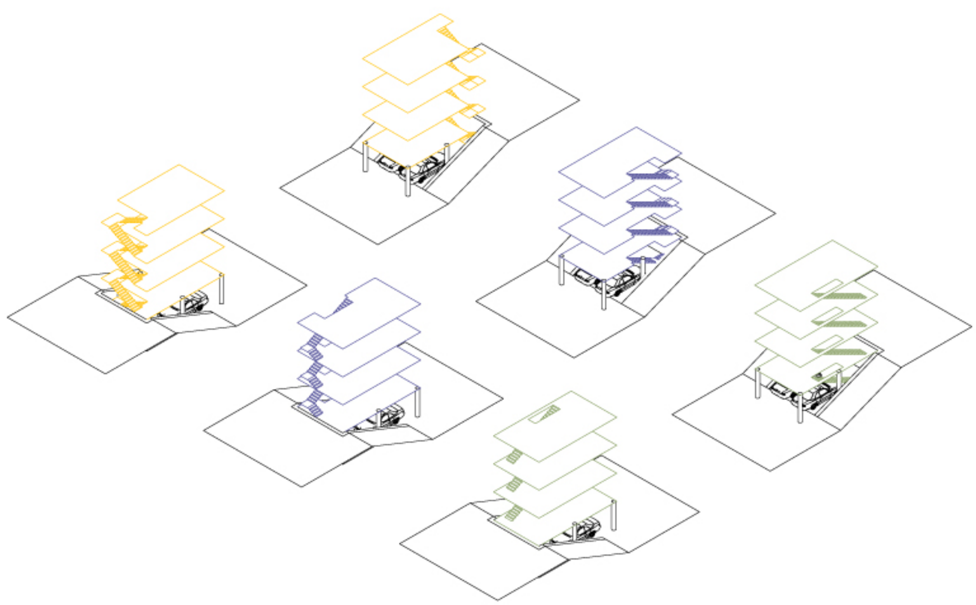


Figure 15 Iterations for the placement and shape of stair runs

Once these basic elements were in place, the process for designing floor plans was to work back and forth in BIM software, between floor plans, which had to be spatially appropriate, allow light into the interiors of buildings, and provide enough circulation and closet space; and renders/elevations, which had to give the complex a pleasing and appropriate outward appearance, while maintaining good outware views from the interior. The next several pages contain Figure 16*,* a final render of the western façade of Building 1; Figure 17*,* plans for a single townhouse, and; Figure 18, a key plan showing where these units exist within the building complex. Plans of Building 1, and the full building complex are all consolidated on Appendix A.

Figure 16 Western facade of Building 1

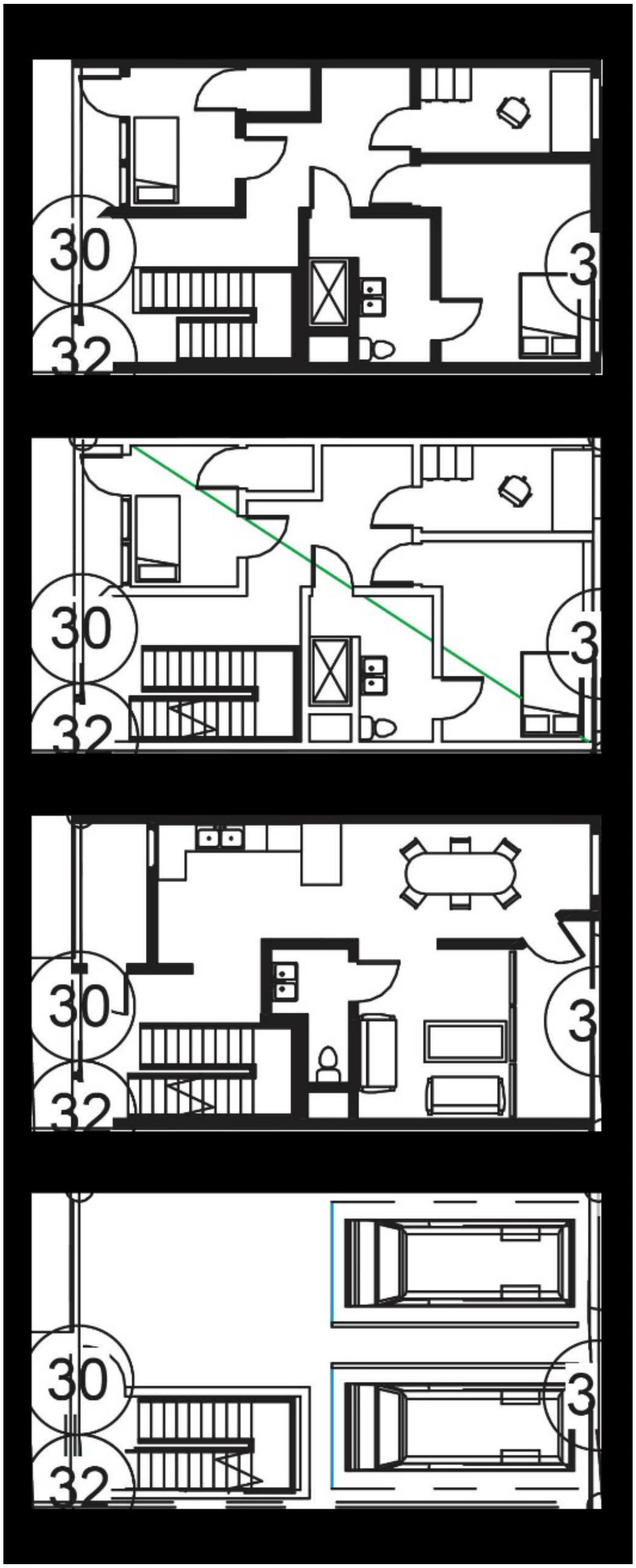


Figure 17 Townhouse unit plans

Figure 17, showing plans for a single townhouse- Level 3, *top*, features two bedrooms, on the eastern and western walls. A resident comes to the top of the stairs to see a door off the the western deck on their left, and a corridor to their right. From this corridor one can access both bedrooms, a small office apce, and the bathoom, containing a shower. Level 2 is identical to level 3. Level 1, the ground story on the west façade, contains a large, open living space, including a kitchen, dining room, and living room. Access to the bathroom is from the living room, adding a little bit of privacy. Bathrooms are ganged along one plumbed wall. Decks are included on both the eastern and western facades, allowing residents to have an outdoor, sunny or shaded spot, at any time of day. On the basement level, cars enter on the eastern side, and residents access the building upwards, using the stairs. Although these units aren't designed explicity to be accessible, the site offers an accessible, but much longer, path from the parking level to the ground floor. Buildings 2 and 3 contain many single-story, accessible units.

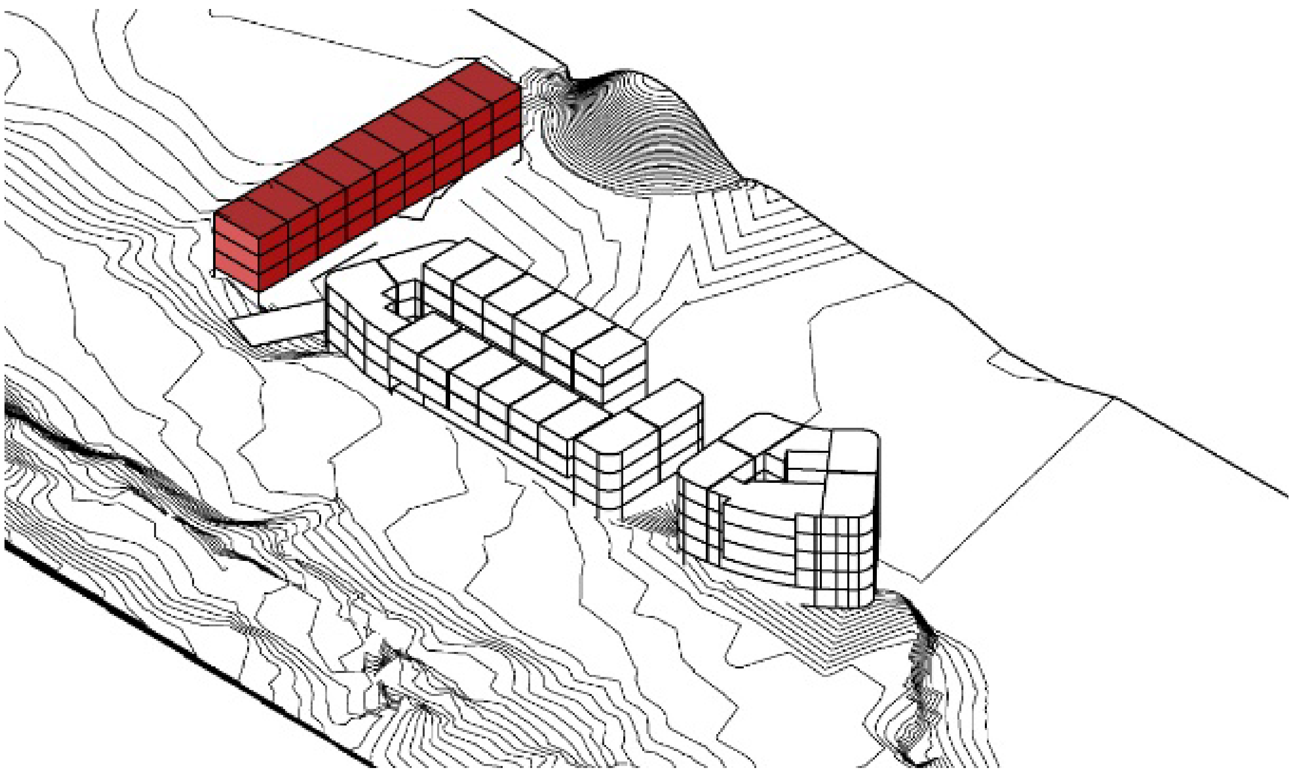


Figure 18 Schematic Design of Building 1. Helps to locate where Building 1 sits on the site, relative to Buildings 2 and 3.

5.2.3. Building 2 Design Development

Building 2 is the largest building proposed for the site. It is an east-west, double-loaded corridor building, with its long southern façade facing Condor Street, and its north facing into the site, and towards Chelsea Creek. Some of the driving principles for the building were to use large, multifloor units to create spaces for families mixed with large single-story accessible units. Parking is slipped under the building again, taking advantage of the grade change. The ground floor contains retail space, both for revenue and to encourage the idea that the ground floor of the building volumes is permeable, so that the site is open to the public. Corner units have more access to daylight than interior units, so these can be single story.

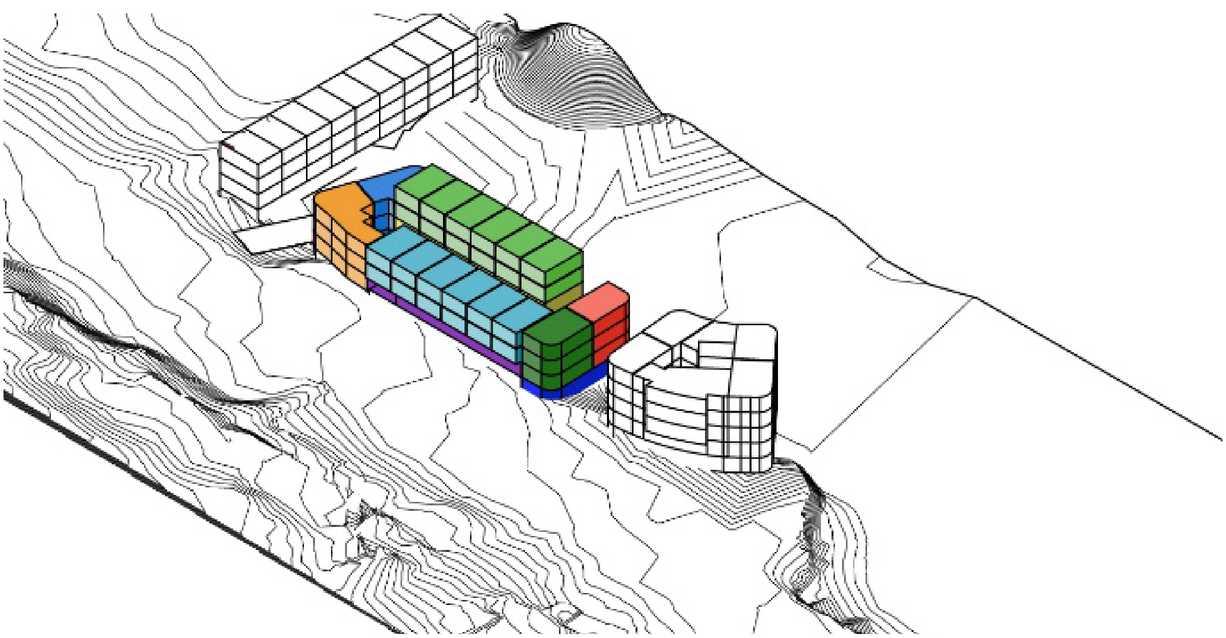


Figure 19 Schematic Design of Building 2.

Daylighting is the driving concern for this building's schematic design. Where the inside faces of the two-story units meet the center corridor, there can be huge, windowless areas which are unfavorable for bedrooms, living rooms, or kitchens. Figure 20 shows in a blocky diagram, how the building volumes shift to accommodate a light well down the center of the building, to daylight the upper story of the southern three-bedroom units (blue).

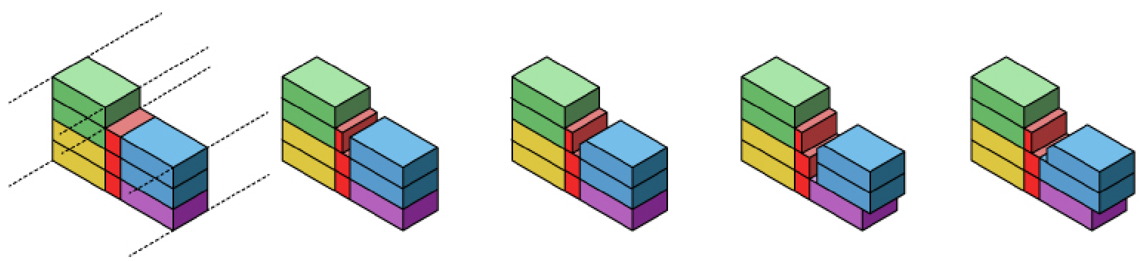


Figure 20 Design for the lightwell

Figure 20.1., Fig 20.2., Fig 20.3., Fig 20.4., Fig 20.5.,

Figure 20.1. shows one structural bay of Building 2. Purple represents retail space, on the ground floor (Condor Street level). Yellow, blue, and green represent 3-BR units, and red represents the center corridor. The center corridor is 10 feet wide, to accommodate an accessible path through the basement parking level. Therefore, in Figure 20.2., the first move was to cut the corridor in half along its length, leaving a 5-foot corridor and a 5-foot lightwell (wall thickness is ignored for now). In a rendered view from the upper floor of the blue unit, it was clear that this lightwell wasn't deep enough to provide meaningful access to the outdoors.

Figure 20.3. cuts a chamfer into the northern, upper edge of the blue unit to allow southern light to shine lower onto the northern face of the interior of the lightwell.. Figure 20.4. pushes the blue unit five feet south, creating an overhang for the retail space on the ground floor, and expanding the width of the lightwell on Level 3 to 10 feet. In Figure 20.5., the blue unit's lower story expands five feet back towards the center corridor, adding space to the lower level of the blue unit.

Figure 21 A perspectival, sectional, view, showing the lightwell described in Figure 20., as well as the retail space on the first floor, the center corridor, and the character of the interior of the south, 3BR apartments.

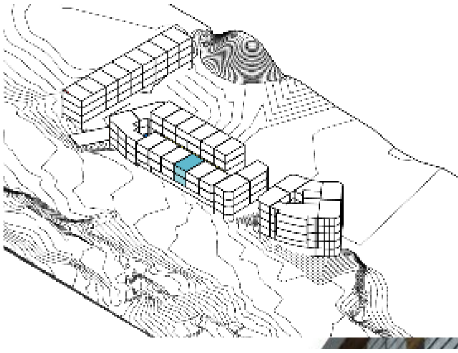


Figure 22 Key plan for typical South 3BR Apartment

Figure 23 An enlarged view of the previous view. The apartment in this view with its lights on is the design for the typical 3BR unit for the south side of the corridor in Building 2. Plans for apartment type are shown in Appendix A.

5.2.4. Building 3 Design Development

Building 3 is the easternmost of the line of buildings along the south face of the site. It is also where this thesis takes the most liberties with a novel design language, because the building is relatively isolated on the far east side of the site.

The building's footprint is driven by its relation to the rim of the site and the punctures in the building massing described by Figure 13, and its position can be located inside the new construction by Figure 24., *below.* The egress stairs, elevators, and shared spaces form a central service core, surrounded by apartments with favorable access to the exterior walls.

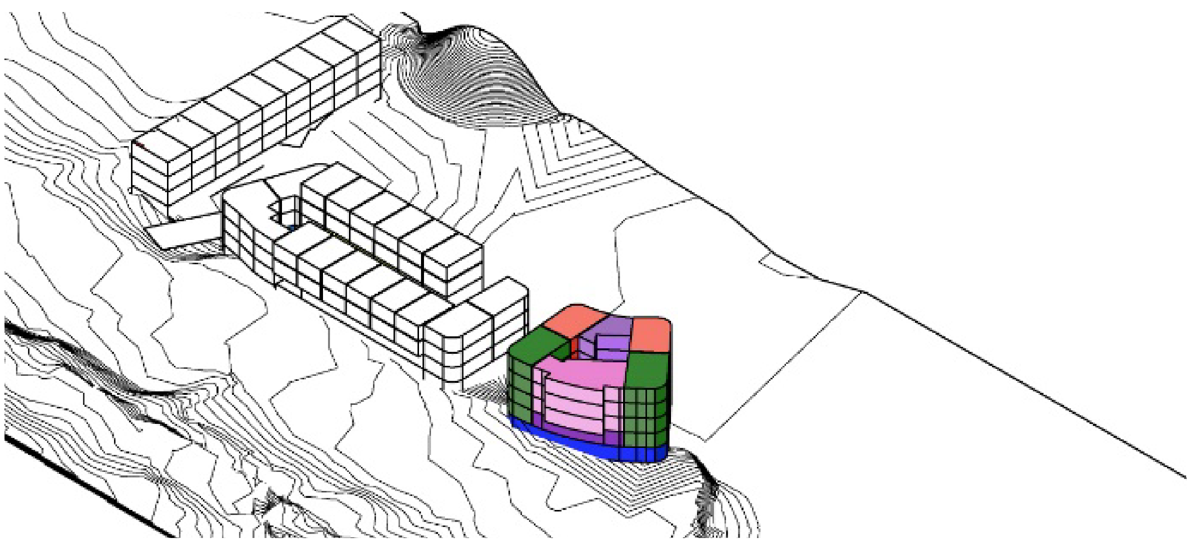


Figure 24 Schematic design of Building 3

Unlike Building 2, all of the units in Building 3 are kept to one floor because the ratio of exterior walls to interior space is better, meaning more of the units are corner units, which are easier to daylight and so can be kept to one floor. The development of the ground floor of Building 3 was generally driven by the development of the site's paths, which you can read more about in Chapter 5.4. The design of the corner apartments is shared with the northeast and southeast corner units in Building 2. The design of the larger, four-bed room apartments, stacked up the southern side of Building 3, is described in Appendix A.

5.3 Addition of Energy Storage

This section will design a system for Compressed Air Energy Storage (CAES) for the 146-172 Condor Street site, building off the research and learning described in Chapter 3. While proposing the design of the intricate financial structures of this arrangement is outside of the scope of this paper, what the design aims to say is this: here, at this site, co-locating this type of energy storage facility could create revenue which could help to offset the cost of income-restricted housing. This type of project could add a new perspective to three critical frameworks: the list of legal tools the Commonwealth of Massachusetts has to encourage the construction of affordable housing; the list in the "State of Charge: Massachusetts Energy Initiative" report detailing possible models for grid-scale energy storage; and the list describing how to remediate brownfield sites. This thesis argues that CAES facilities like this one could do all three, for a lesser cost than considering these three objectives as three distinct projects.

The engineering design of a CAES facility that does not rely on geological saline caverns for their primary pressure vessel is outside the scope of this project. As such, this paper takes such a facility, designed by the Electric Power Research Institute, or EPRI, designed for the Hawaiian Electric Company, or HECo, in 2011. This facility proposed using a series of commonly available steel pipes as an above-ground CAES primary pressure vessel.[92] My thesis project proposes to take this design and turn in on its side, modulating the length of each pipe section to create a series of rolling landforms. The cost of altering the design in this way, surely, is worth transforming this pressure vessel from an alienating and industrial piece of equipment, to an appealing ground-form. Figure 25, shows the volume proposed in the EPRI paper, superimposed on the Condor Street site. Figure 26, shows graphically the design-move used to make the tanks more sculpturally malleable.

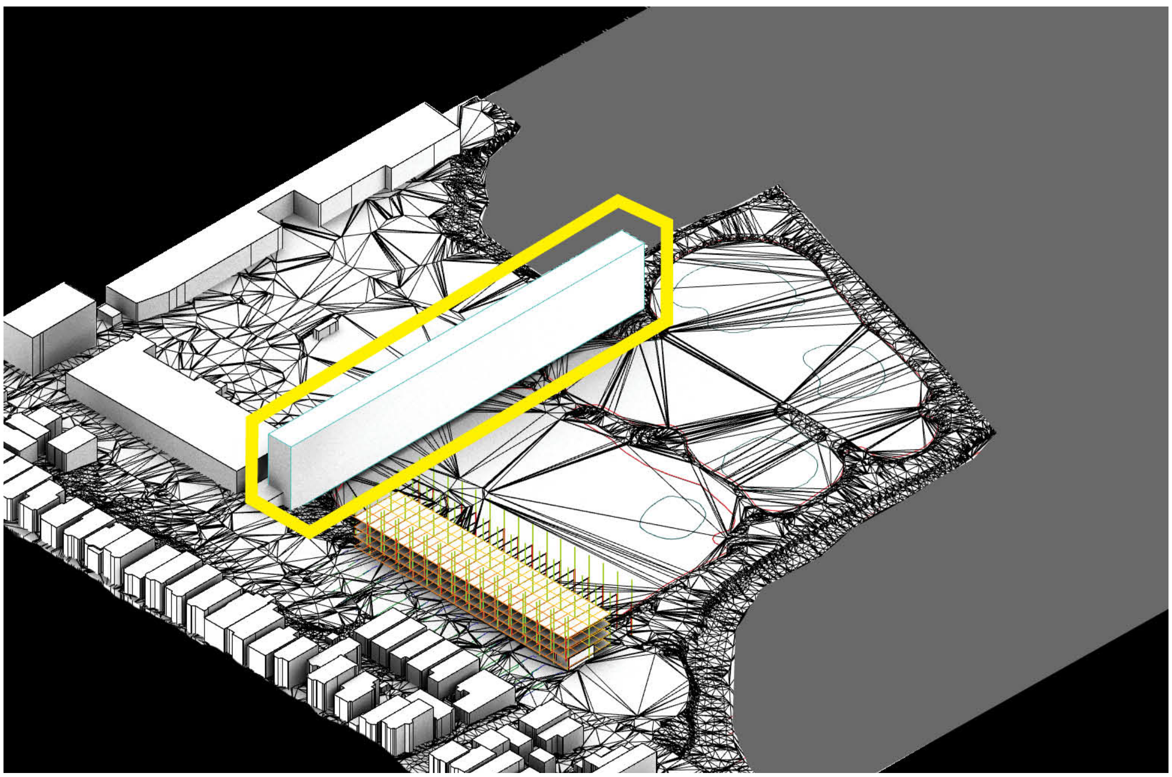


Figure 25 Volume of the pressure vessel for the EPRI report represented as a white block.

[92] Schainker and Kerschen, "Advanced CAES Analysis Using Above Ground Air Storage for Hawaiian Electric Company."

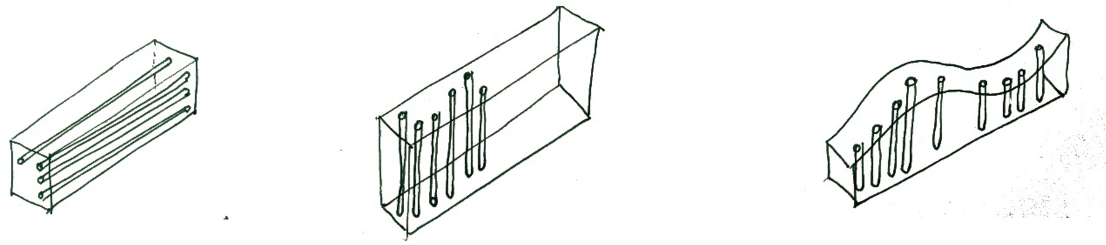


Figure 26 Modulating the length of the pipes to sculpt a landform.

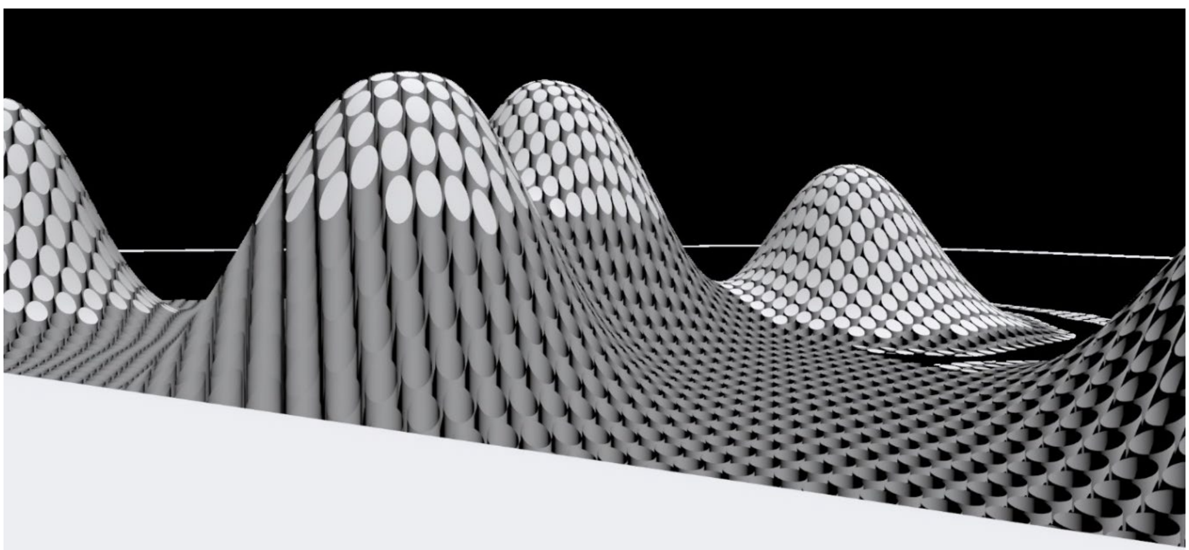


Figure 27Rendered View of the tanks proposed by this thesis.

Figure 28 Speculative rendered view, showing vegetation as the tanks as integrated into the groundform to create a park, like at the Condor Street Urban Wild.

Although it's a step in the right direction, without careful implementation, these grassy, rolling objects would themselves alienate or discourage pedestrians from using the site. Two critical design choices shape the location of the vessels, beyond their volume. First, a point in the southeastern corner of the site serves as a viewing platform. From this point, it is possible to see both the McArdie and Chelsea Street bridges. This is demonstrated in Figure 29, with arrows. The schematic design of the mounds, leaves these view corridors unobstructed. Additionally, it is important to remember the Condor Street Urban Wild, just nearby. This site is an important design precedent for using the creation of groundforms to create a novel urban park while remediating badly damaged land. Down the road, careful detailing in the design of the paths could work to blur the line between the two sites, sewing them together to create the beginnings or a green, biophilically pleasing shore for the East Boston neighborhood.

5.4 Addition of Walking Path

It's important to interrelate the energy storage system with the residential units in a clear, functional, and beautiful way. This section will describe the design of the site's walking path, and the design of the edges between street/building and building/site.

Figure 29 shows the site at 146-172 Condor Street, overlaid with green along the Condor Street site, the Condor Street Urban Wild, and the American Legion Ballfield. Each schematic-level design consideration is labelled: goals for the site design were to create a functional area along the edge of Condor Street, to provide a place for the neighborhood to walk along the water's edge, to connect to the Condor Street Urban Wild to the east, and not obstruct the views from the reference point in the southeastern corner to the McArdie and Chelsea Street bridges.

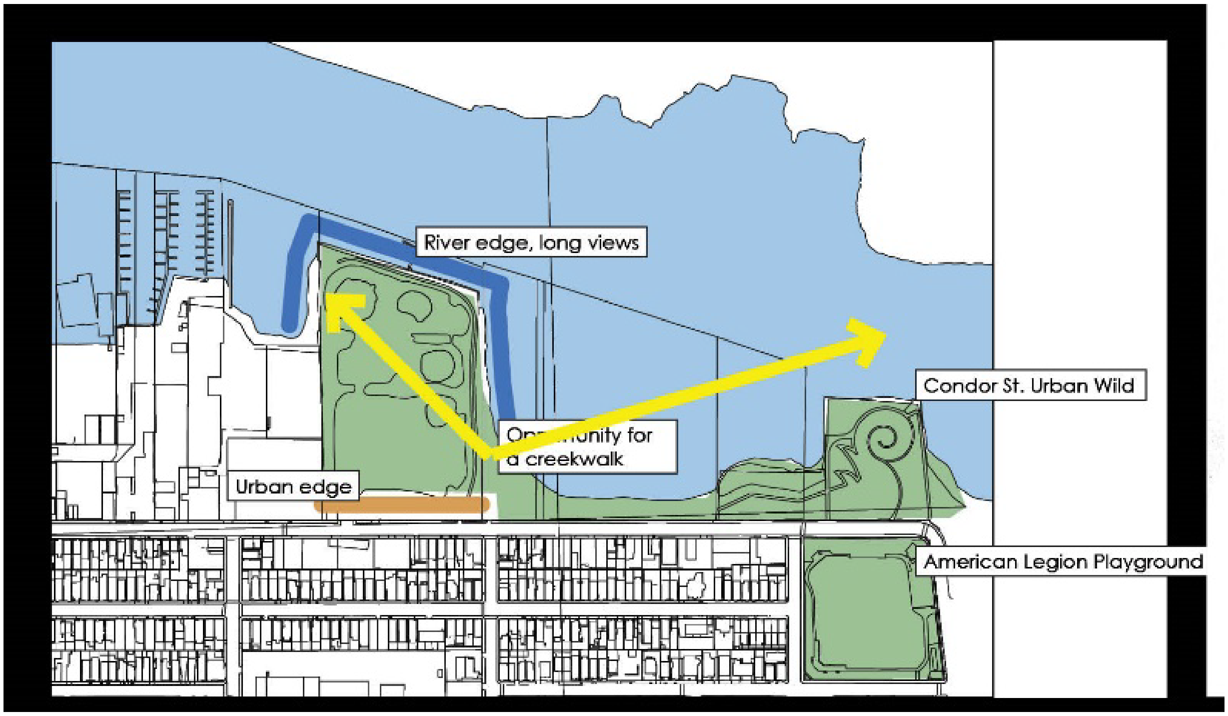
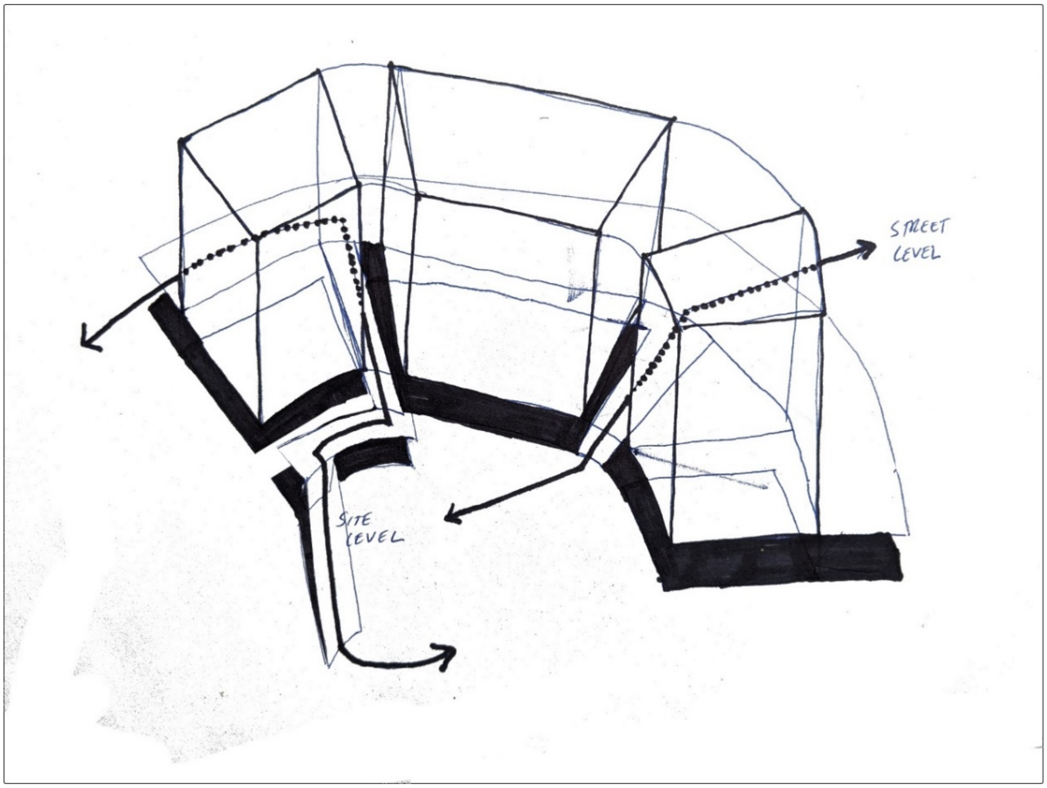


Figure 29 Driving considerations for the design of the site.

Change in grade between the street and site interior levels was also considered. Pedestrian ramps can't exceed a 1:12 slope., and have to be separated from an automotive entrance, for bringing cars down from the street, under the buildings.



. Figure 30. Sketch showing these two entrances: one steeper ramp for cars and one shallower ramp for pedestrians.

Figure 30 The ground and parking levels of the buildings, overlaid with the relationship between public and private spaces.

CHAPTER 6.1.1. CONCLUSIONS

The energy grid is a crucial piece of infrastructure, impacting our lives in profound ways. Currently, this infrastructure is designed around the combustion of fossil fuels, and grid operators' ability to ramp production of power up and down depending on demand. As our country transitions to a grid which gets its power from renewable, intermittent sources like wind and solar, energy storage will be needed on a massive scale to bank energy so that it can be available during times of low production.

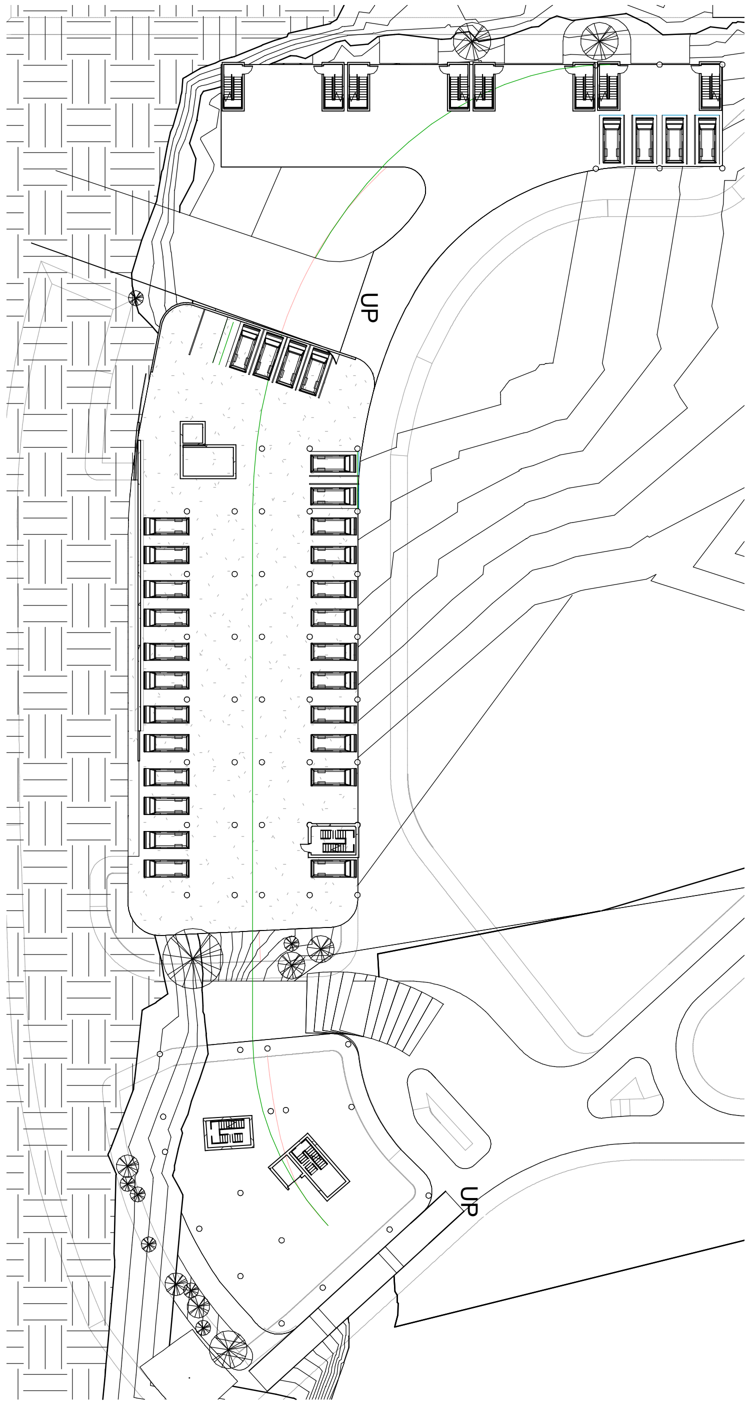
CAES is one technology which can address this need. Although other storage technologies like lithium-ion batteries may prove more reliable and cost-effective, CAES has several important characteristics which may make it an important player in the future of our country's energy storage portfolio. This thesis contends that energy storage is a spatial problem, worth considering through the lens of architecture.

In parallel, this thesis examines the housing market in East Boston, with a particular interest in equity, and around how badly the neighborhood has been impacted by the fossil fuel industry. The city is underproducing affordable units, and new tools are needed to incentivize developers to build them.

This paper proposes a project which entangles these two ideas, by developing a site in East Boston with a CAES facility and affordable units. Critics at the oral presentation of this thesis were excited about the potential for the project to examine renewable grid assets within the context of an architectural intervention. They also raised issues concerning relating, or offsetting, the residential buildings with the CAES facility, softening the edge between the site and the river, and defining the space between the south façade of building two and Condor Street. All of this, and more, would have to be addressed should a project like this ever advance. To properly determine the feasibility of a project like this would be work for a team of experts and estimators. Despite the challenges, there is money to be made by "firming" the renewable grid, and this thesis proposes to use that revenue to offset the cost of affordable housing on the site. There is great value in designing projects where energy infrastructure enriches its community, and a great opportunity to consider projects like these, while the grid undergoes a transition away from combustion-based power generation.

APPENDICES

A: BUILDING PLANS



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Connor Slover

146-172 Condor St.

Parking Lot Level

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Date	Issue Date
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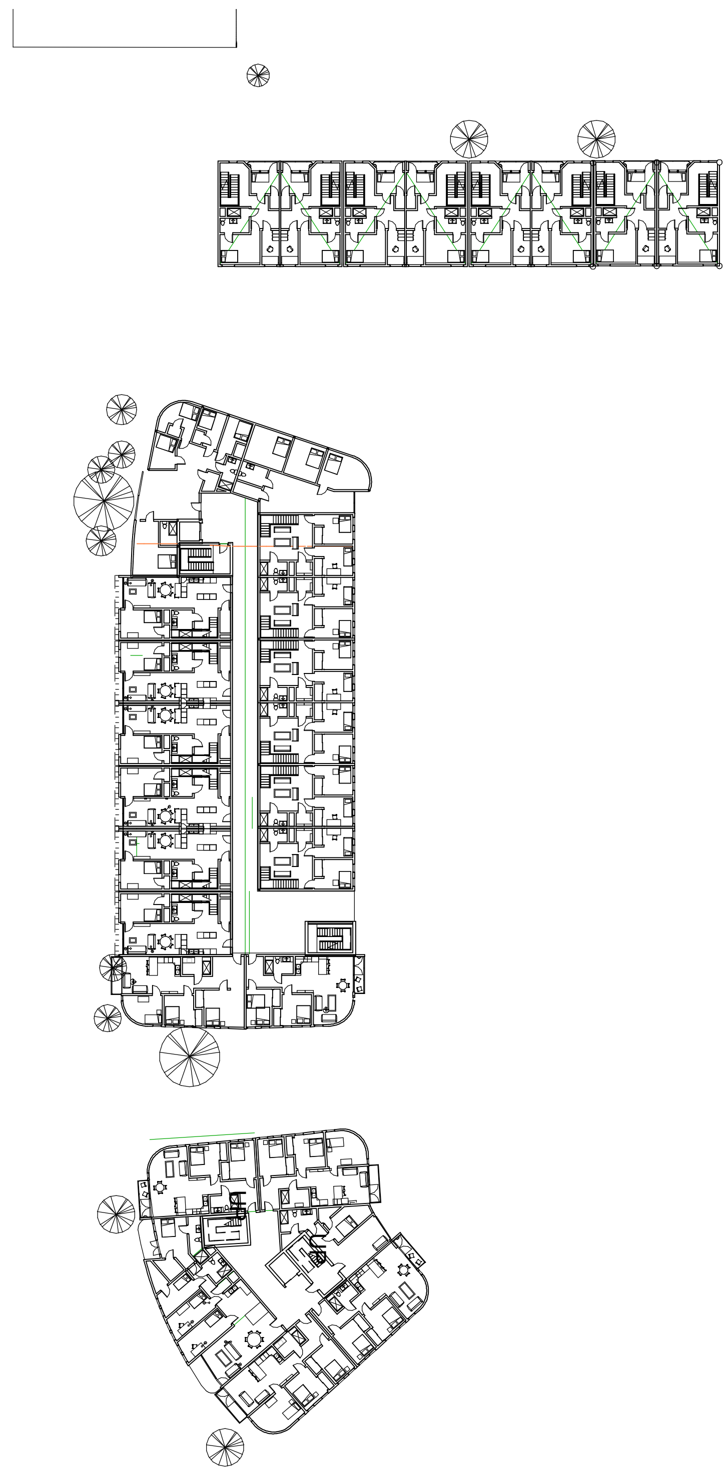

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Connor Slover

146-172 Condor St.

Level 2

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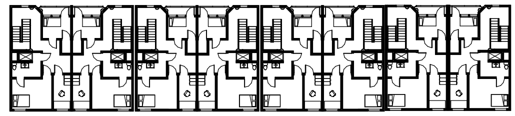

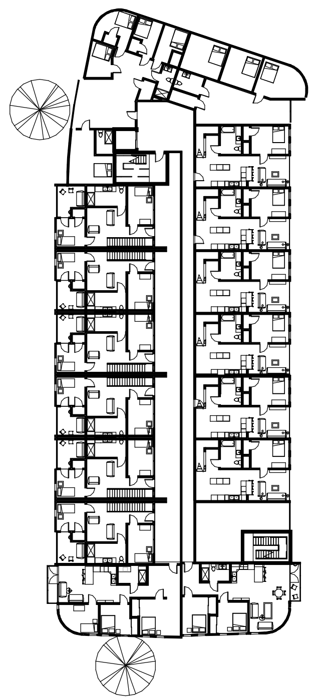

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Connor Slover

146-172 Condor St.

Level 3

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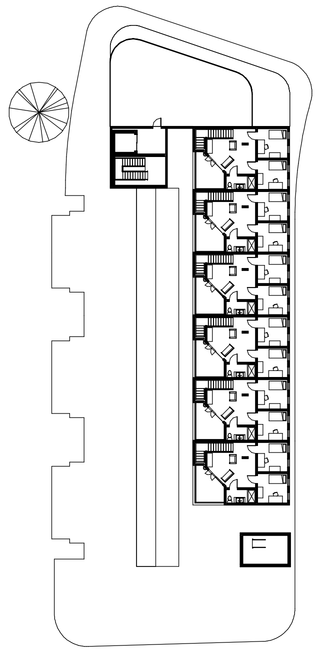

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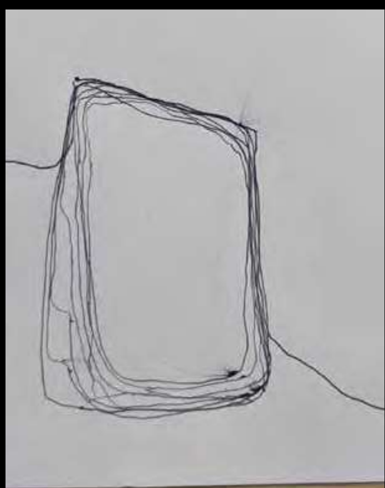
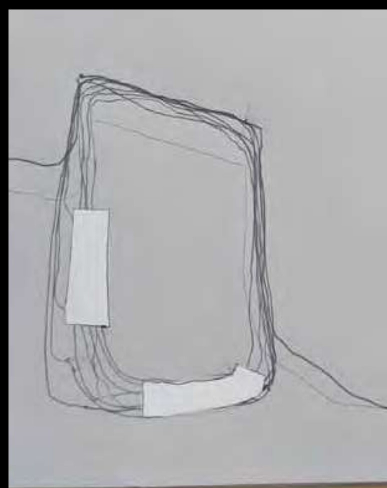
B: ORAL DEFENSE PRESENTATION BOARDS

Chapter 5: Design



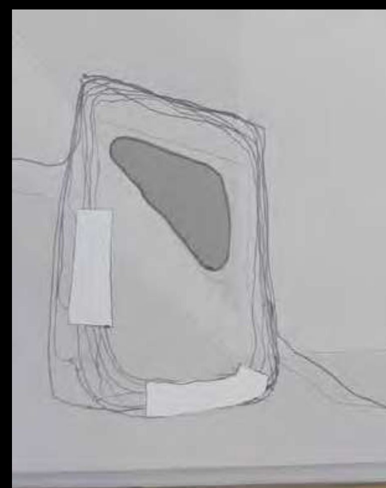
Part 5.1:
Existing Site

5.1.1.: Site Context
5.1.2. Site Photography



Part 5.2.:
Addition of
Residential Buildings

5.2.1.: Building Schematic Design
5.2.2.: Building 1 Design Development
5.2.3.: Building 2 Design Development
South 3BR Apartment
North Lower 3BR Apartment
North Upper 3BR Apartment
5.2.4.: Building 3 Design Development
Corner 3BR Apartment
South 4BR Apartment
5.2.5.: Building plans

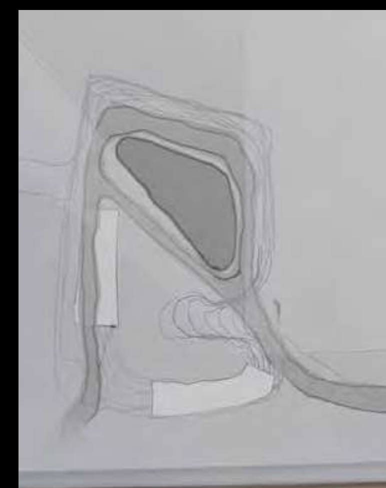


Part 5.3:
Addition of
Energy Storage

5.3.1.: What is Energy Storage?
5.3.2.: Why Co-Locate with
Affordable Housing?
5.3.3.: Energy Storage Schematic Design

Part 5.4:
Addition of
Walking Path

5.4.1.: Path Schematic Design

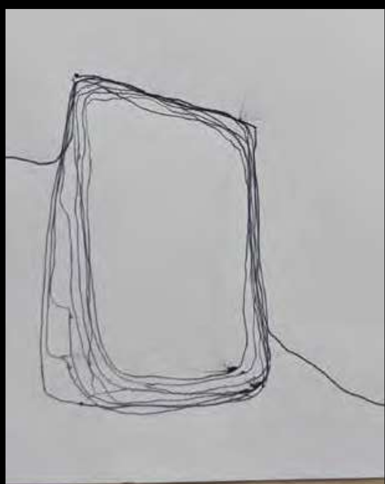


Part 5.5
Site Design and
Site Remediation

5.5.1.: Site Schematic Design
5.5.2.: Site Design Development

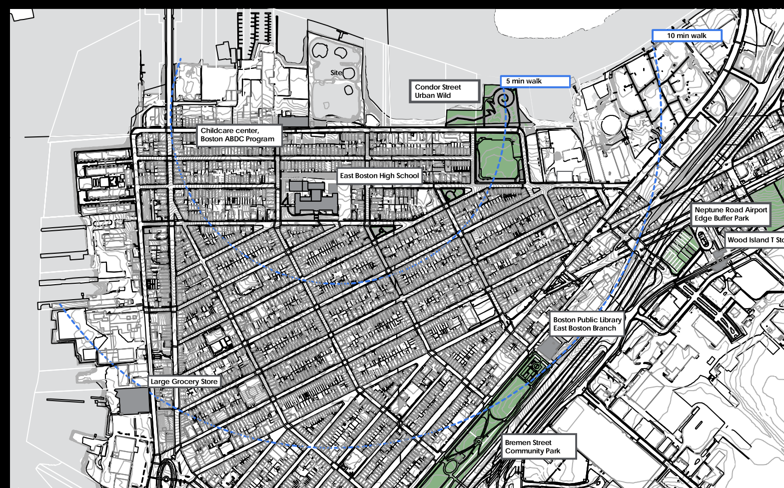
Part 5.1:
Existing Site

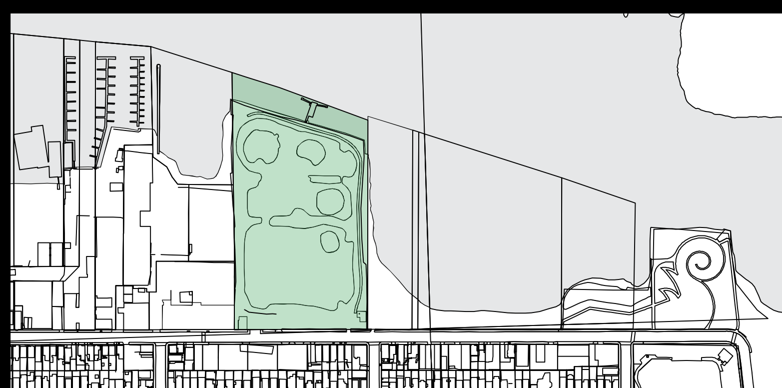
5.1.1.: Site Context
5.1.2. Site Photography

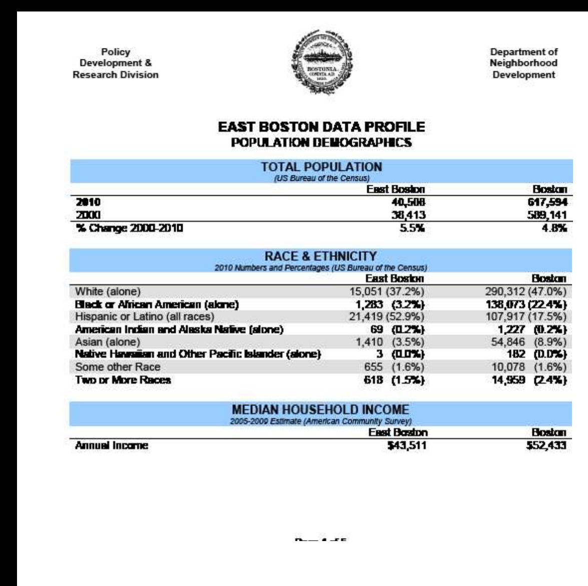


Part 5.1:
Existing Site

5.1.1.: Site Context
5.1.2.: Site Photography







Policy Development & Research Division

Department of Neighborhood Development

EAST BOSTON DATA PROFILE
POPULATION DEMOGRAPHICS

TOTAL POPULATION
(US Bureau of the Census)

	East Boston	Boston
2010	40,508	617,594
2000	38,413	589,141
% Change 2000-2010	5.5%	4.8%

RACE & ETHNICITY
2010 Numbers and Percentages (US Bureau of the Census)

	East Boston	Boston
White (alone)	15,051 (37.2%)	290,312 (47.0%)
Black or African American (alone)	1,283 (3.2%)	138,073 (22.4%)
Hispanic or Latino (all races)	21,419 (52.9%)	107,917 (17.5%)
American Indian and Alaska Native (alone)	69 (0.2%)	1,227 (0.2%)
Asian (alone)	1,410 (3.5%)	54,846 (8.9%)
Native Hawaiian and Other Pacific Islander (alone)	3 (0.0%)	182 (0.0%)
Some other Race	655 (1.6%)	10,078 (1.6%)
Two or More Races	618 (1.5%)	14,959 (2.4%)

MEDIAN HOUSEHOLD INCOME
2005-2009 Estimate (American Community Survey)

	East Boston	Boston
Annual Income	$43,511	$52,433

"Communities that lack the political, economic power to defend themselves, where residents work longer hours, and they have less resources and are less educated, **those are the communities that are often targeted for the siting of some of the most dangerous or ecologically hazardous facilities,**"

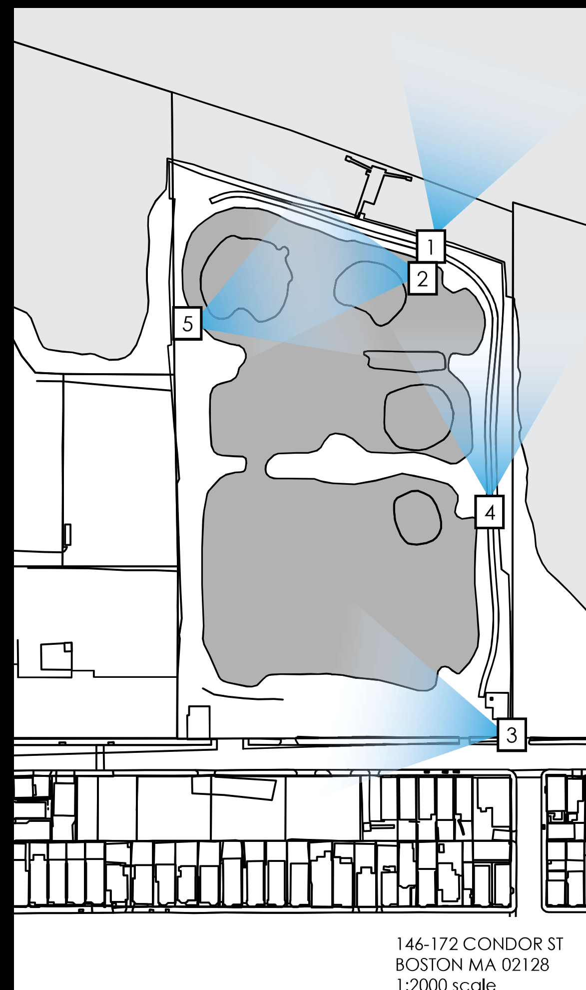
Daniel Faber, director of the Northeastern University Environmental Justice Research Collaborative

Dooling, Shannon. n.d. "How One Massachusetts City Came To Bear Environmental Burdens For The Region." Accessed December 2, 2020. https://www.nepm.org/post/how-one-Massachusetts-city-came-bear-environmental-burdens-region.

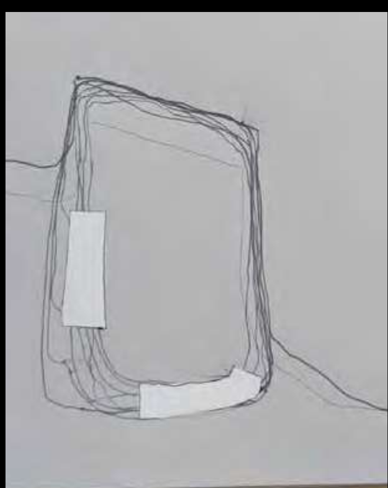
"East Boston Data Profile." 2010. City of Boston Department of Neighborhood Development. https://www.cityofboston.gov/images_documents/East_Boston_Planning_District_Profile_tcm3-12989.pdf.

Part 5.1:
Existing Site

SITE VISIT
JANUARY 17, 2021



Part 5.2.: Addition of Residential Buildings



Master's Thesis Proposal:
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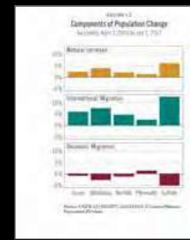
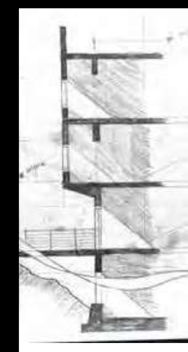
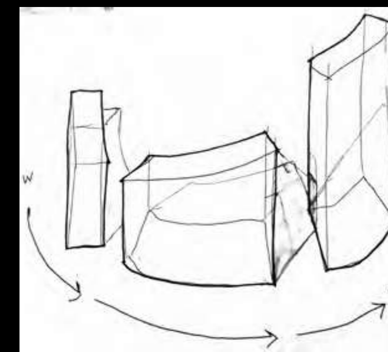
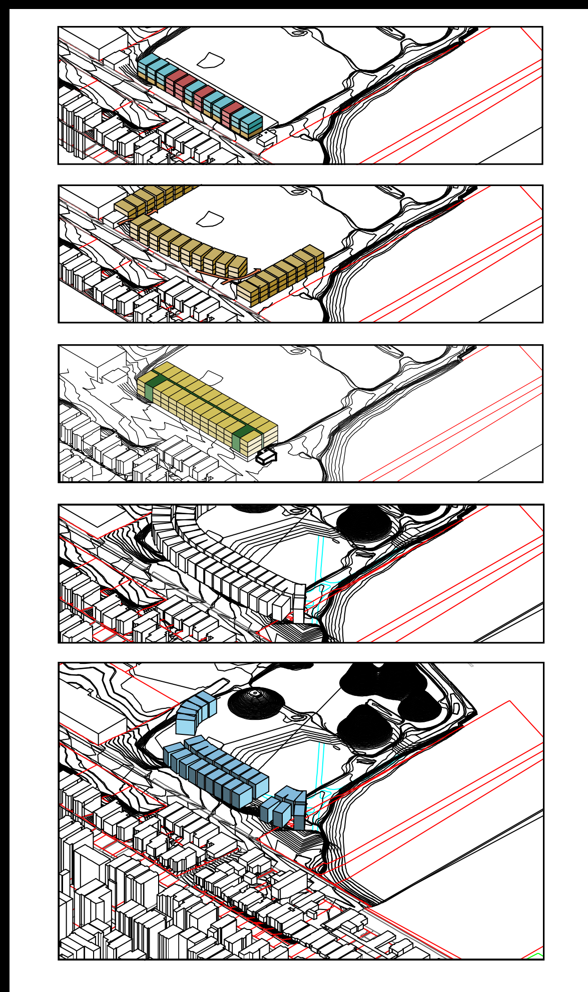
Connor Slover

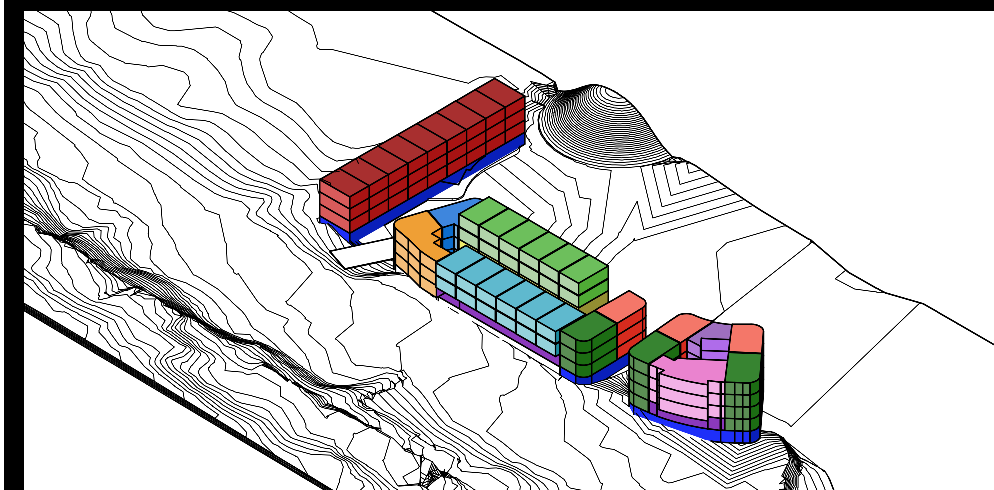


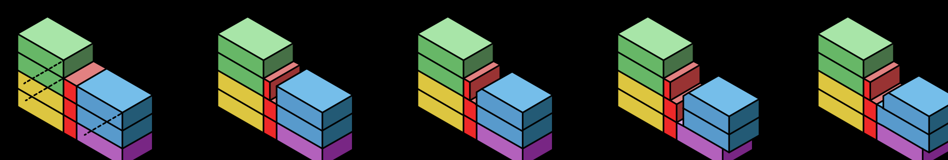


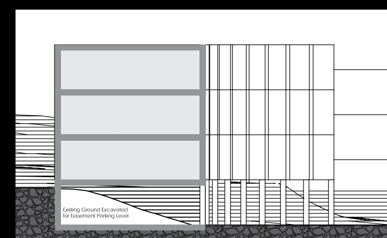


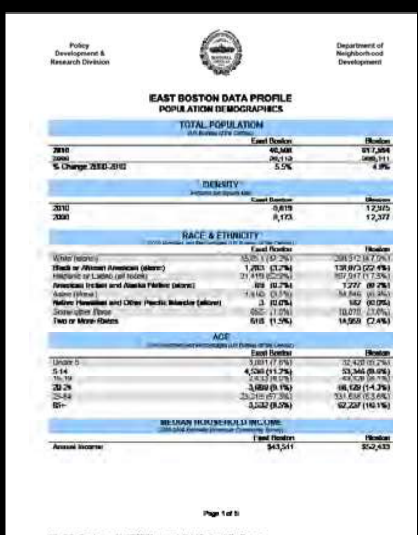


Part 5.2.: Addition of Residential Buildings









Policy Development & Research Division

Department of Neighborhood Development

EAST BOSTON DATA PROFILE
POPULATION DEMOGRAPHICS

TOTAL POPULATION	East Boston	Boston
2010	40,508	617,594
2000	38,413	589,141
% Change 2000-2010	5.5%	4.8%

DENSITY	East Boston	Boston
2010	8,819	12,975
2000	8,173	12,377

RACE & ETHNICITY	East Boston	Boston
White (alone)	[illegible]	[illegible]
Black or African American (alone)	1,283 (3.2%)	138,073 (22.4%)
Hispanic or Latino (all races)	21,419 ([illegible])	107,917 (17.5%)
American Indian and Alaska Native (alone)	[illegible] (0.2%)	1,277 (0.2%)
Asian (alone)	[illegible]	[illegible]
Native Hawaiian and Other Pacific Islander (alone)	3 (0.0%)	182 (0.0%)
Some other Race	[illegible]	10,078 [illegible]
Two or More Races	618 (1.5%)	14,959 (2.4%)

AGE	East Boston	Boston
Under 5	[illegible]	32,428 [illegible]
5-14	4,536 (11.2%)	53,344 (8.6%)
15-19	[illegible]	[illegible]
20-24	3,689 (9.1%)	88,129 (14.3%)
25-64	[illegible]	[illegible]
65+	3,432 (8.5%)	62,227 (10.1%)

MEDIAN HOUSEHOLD INCOME	East Boston	Boston
Annual Income	$43,511	$52,433

Page 1 of 5

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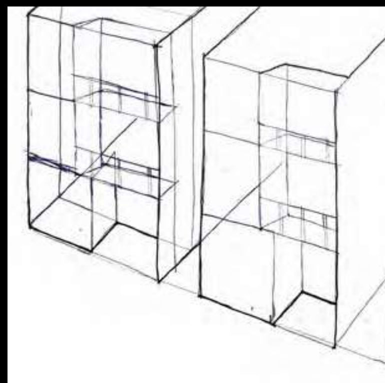
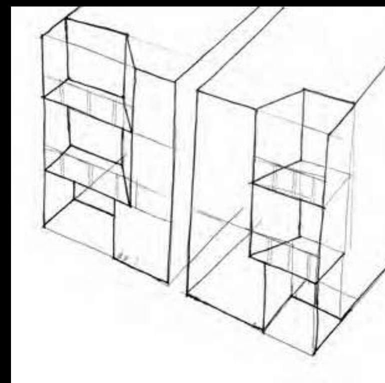
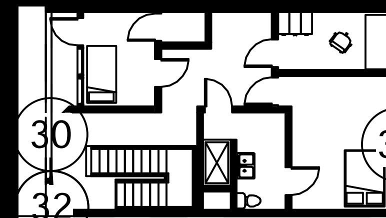
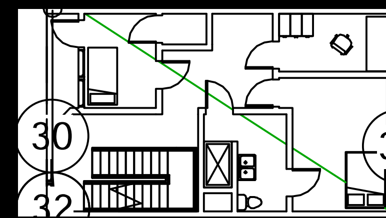
Connor Slover

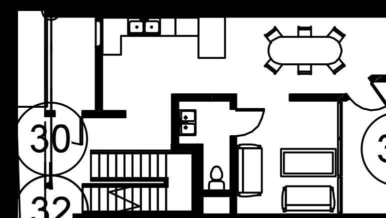


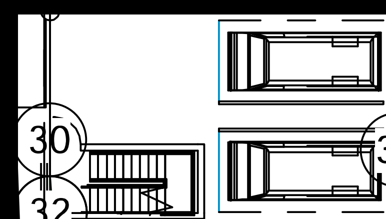


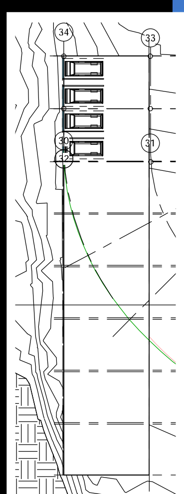


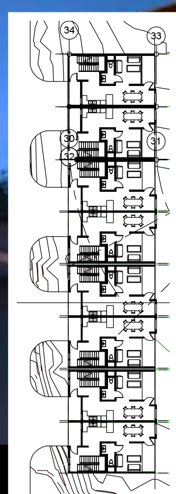
Part 5.2.: Addition of Residential Buildings

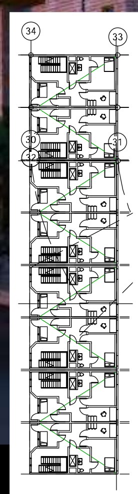


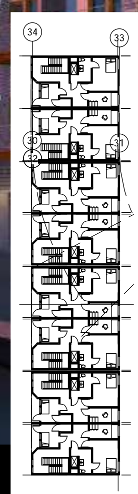


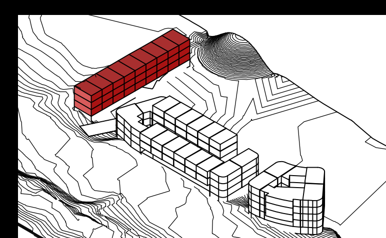


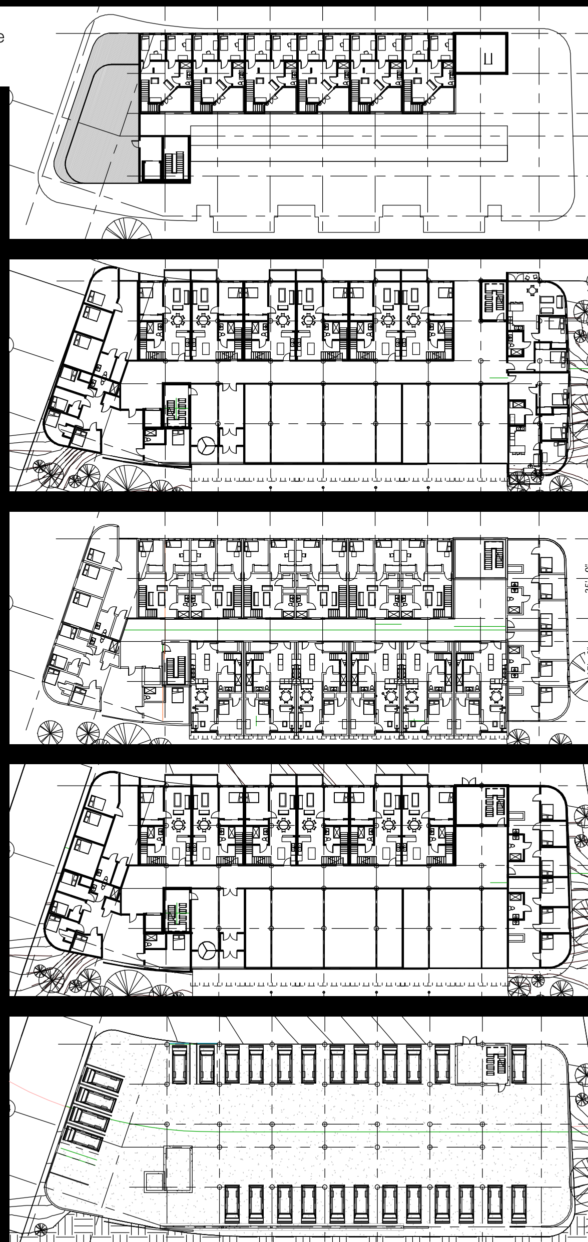


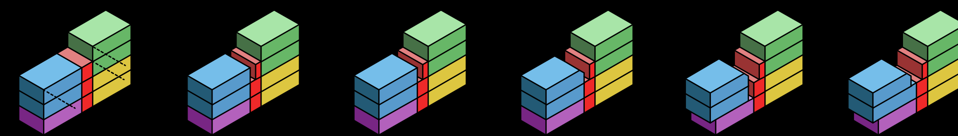




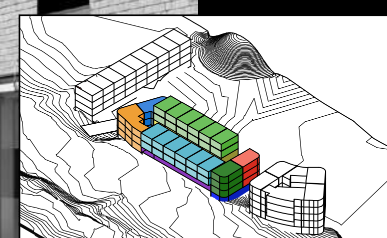




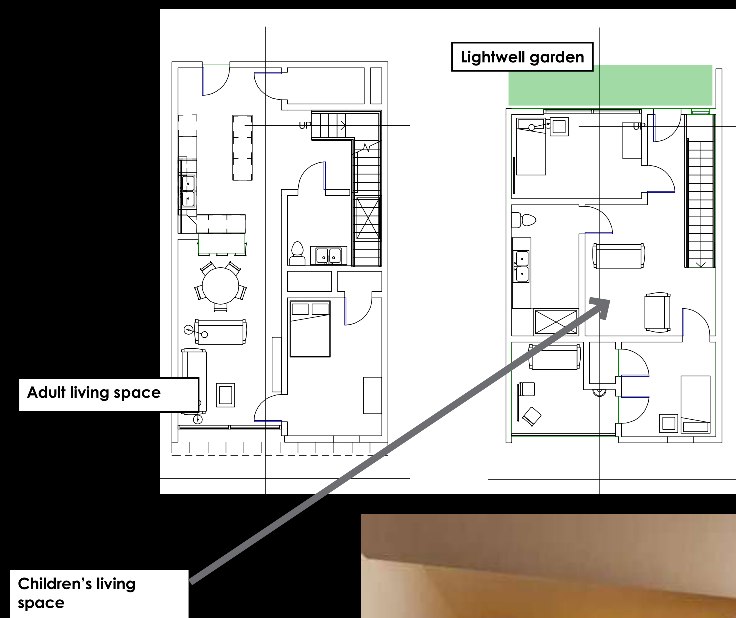


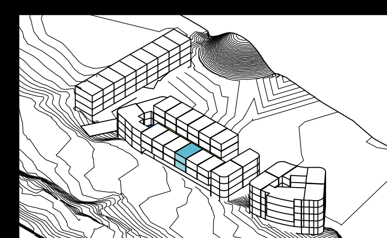


Part 5.2.:
Addition of
Residential Buildings

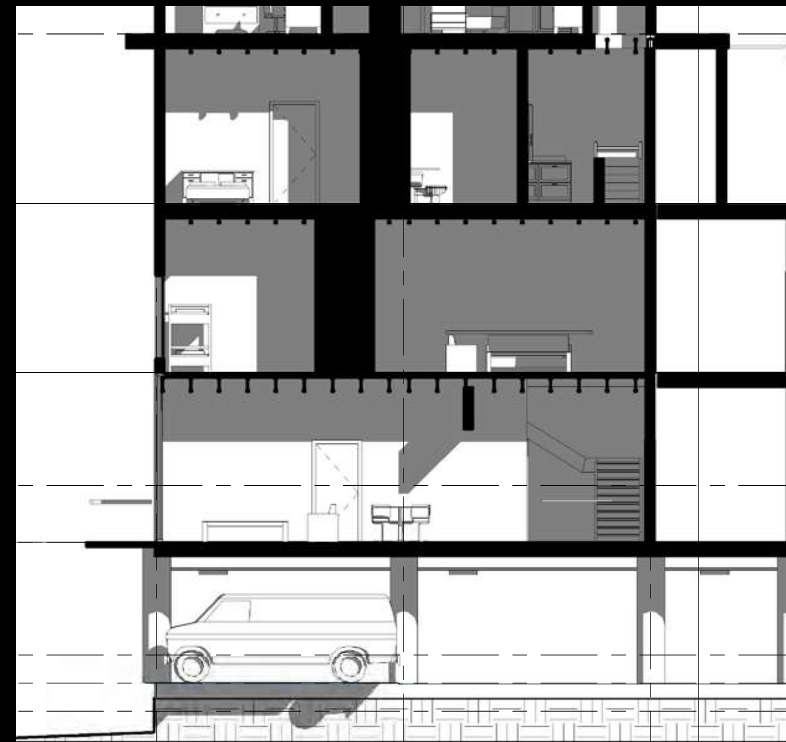


Part 5.2.: Addition of Residential Buildings



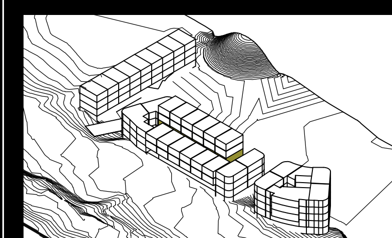


Part 5.2.: Addition of Residential Buildings

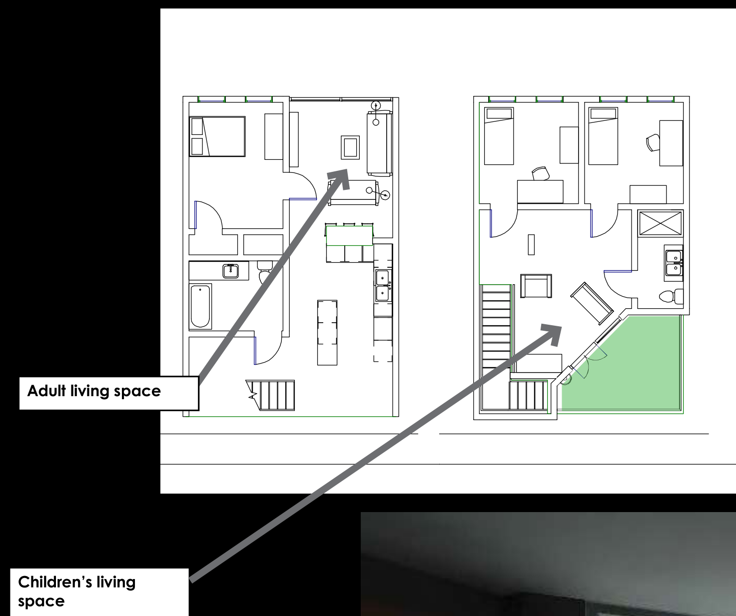


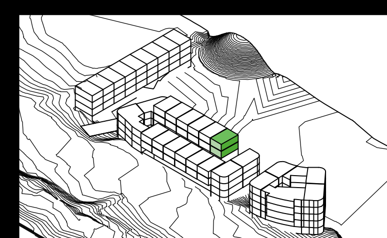
Adult living space

Children's living space



Part 5.2.: Addition of Residential Buildings

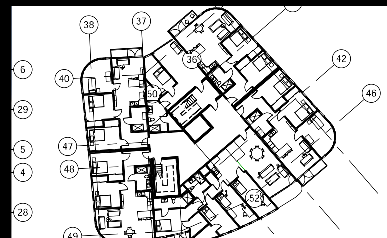


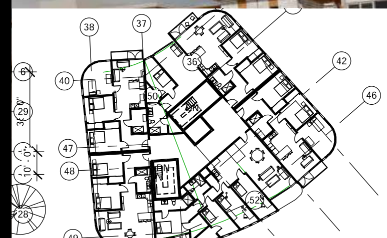


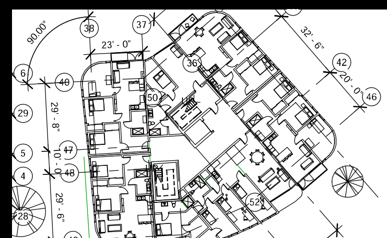
Master's Thesis Proposal:
Exploring the Use of Compressed Air Energy Storage in the Urban Landscape
Connor Slover

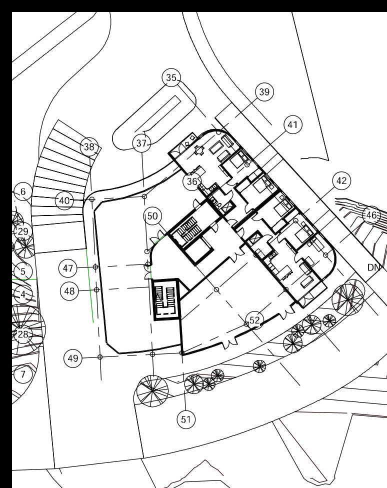
Part 5.2.: Addition of Residential Buildings

5.2.1.: Building Schematic Design
5.2.2.: Building 1 Design Development
5.2.3.: Building 2 Design Development
South 3BR Apartment
North Lower 3BR Apartment
North Upper 3BR Apartment
5.2.4.: Building 3 Design Development
Corner 3BR Apartment
South 4BR Apartment
5.2.5.: Building plans





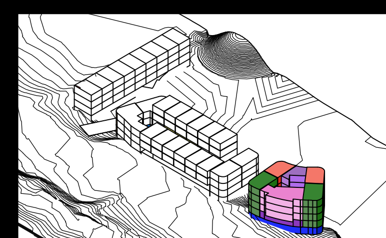


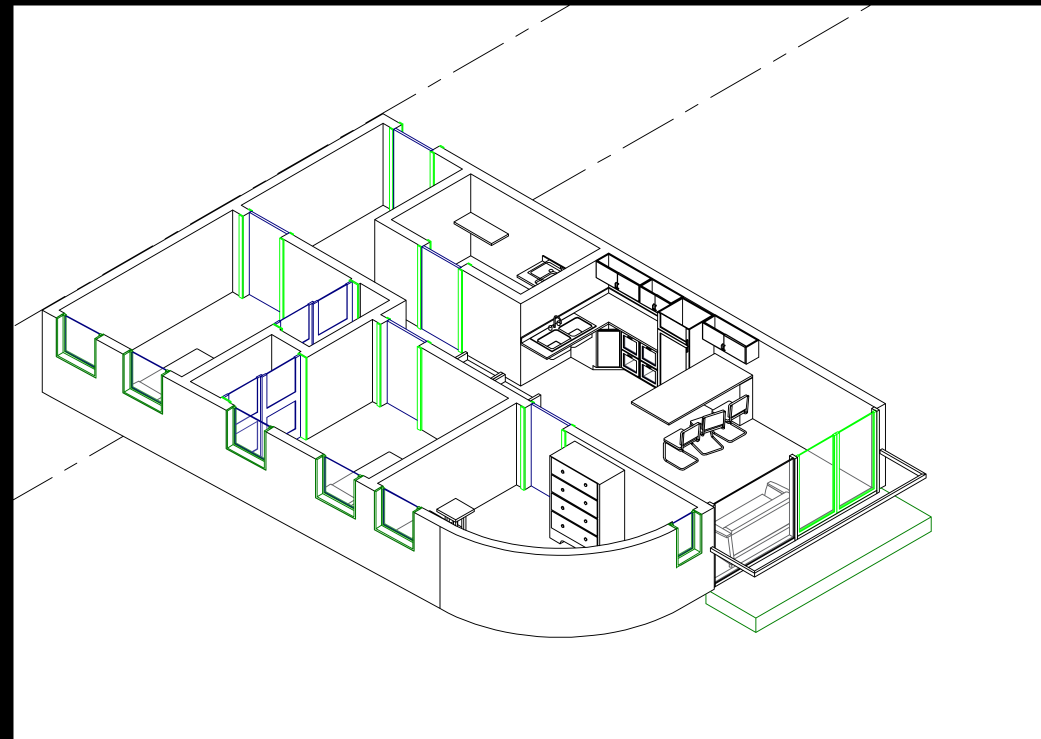


Floor Plans

0 25' 50' 75' 100'

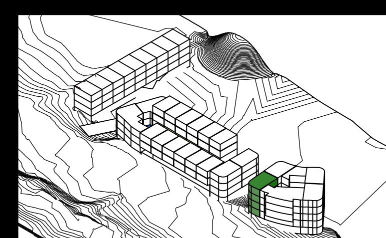
N



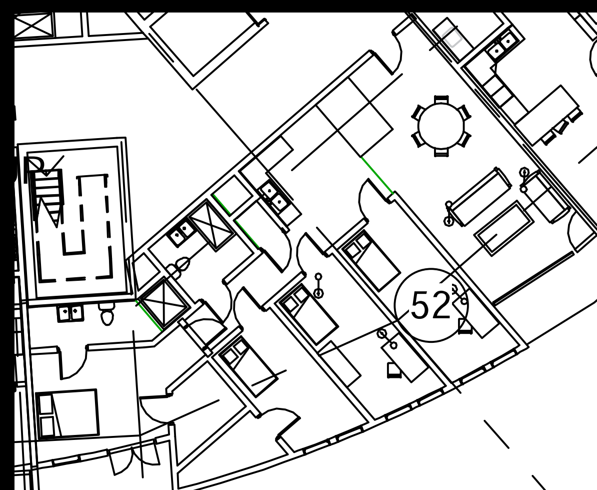


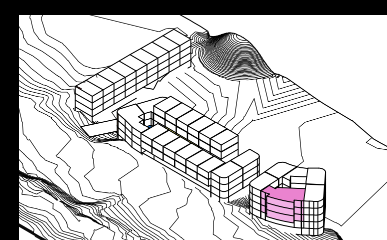
Part 5.2.: Addition of Residential Buildings

These units are good candidates for a removable wall, adding flexibility for different family sizes and patterns.

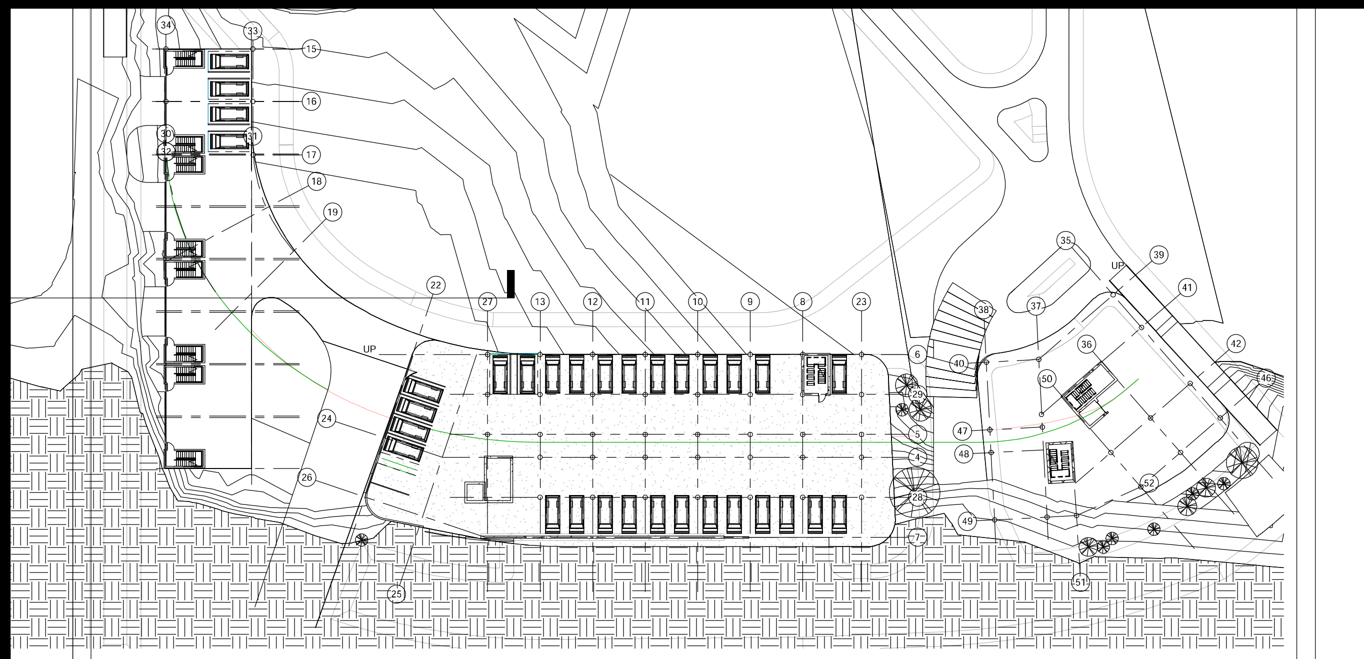


Part 5.2.: Addition of Residential Buildings





Part 5.2.: Addition of Residential Buildings

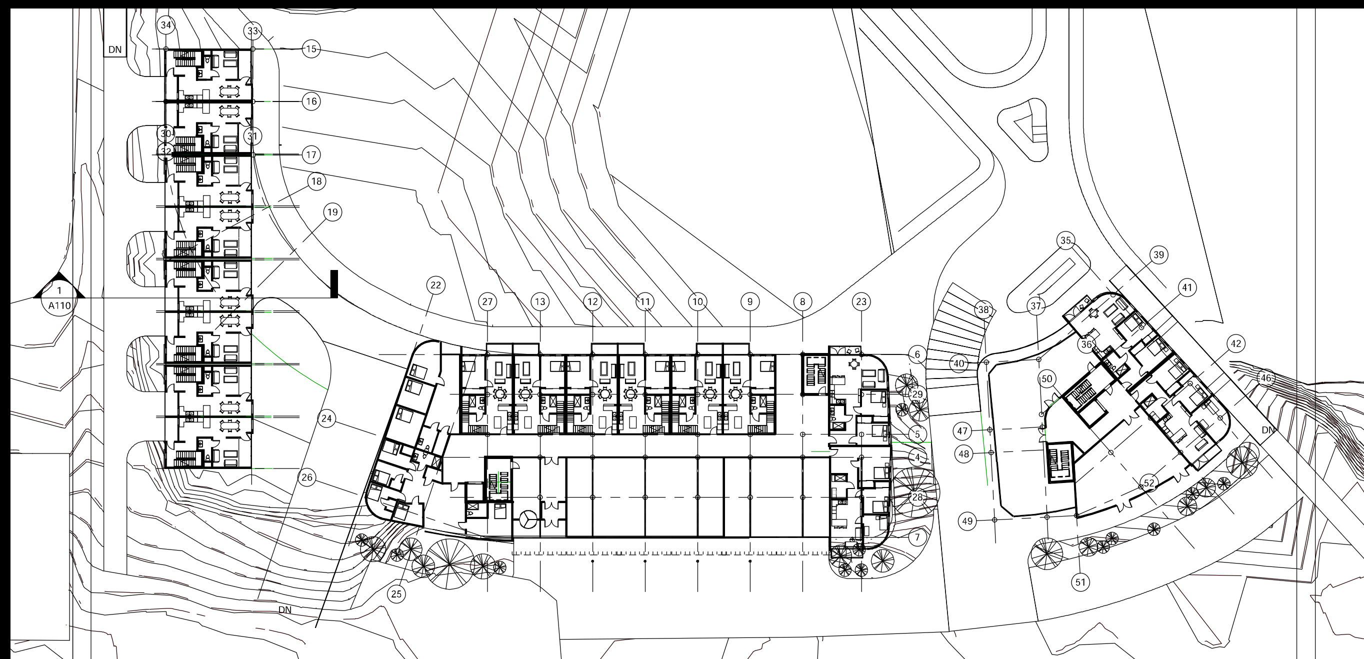


Basement/Site Level Plan

0 25' 50' 75' 100'

N

Part 5.2.: Addition of Residential Buildings

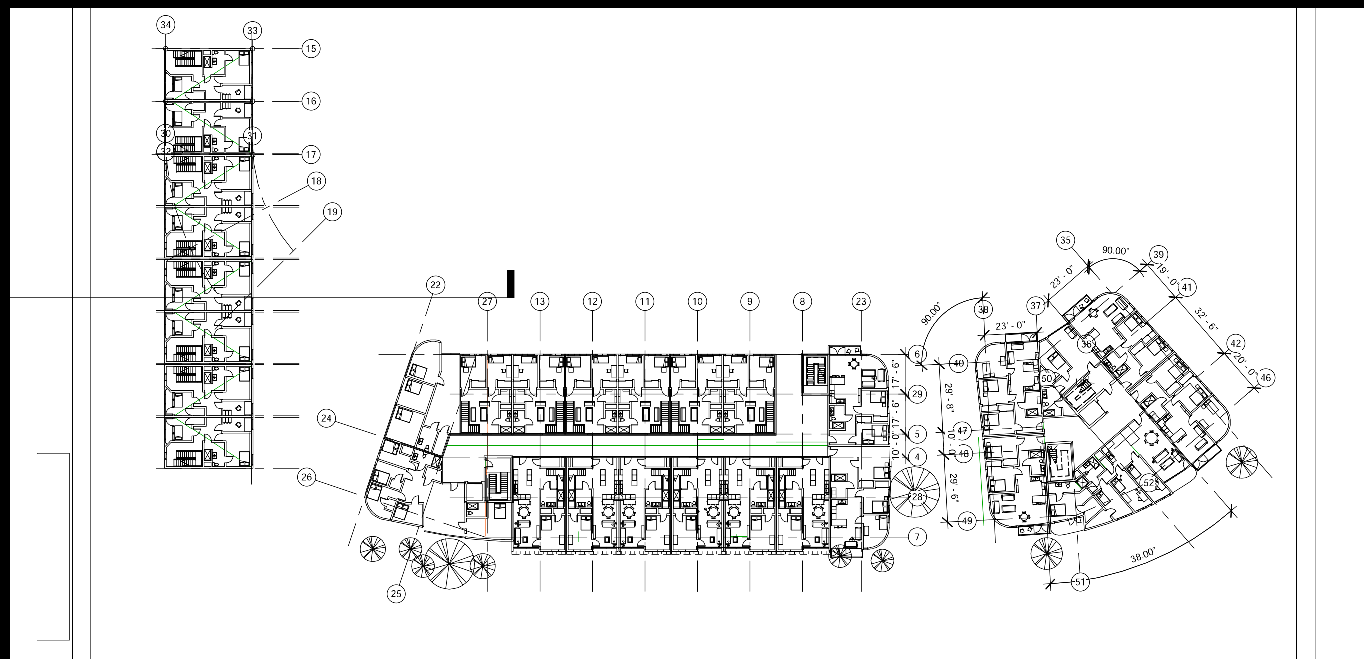


Ground/Street Level Plan

0 25' 50' 75' 100'

N

Part 5.2.:
Addition of
Residential Buildings

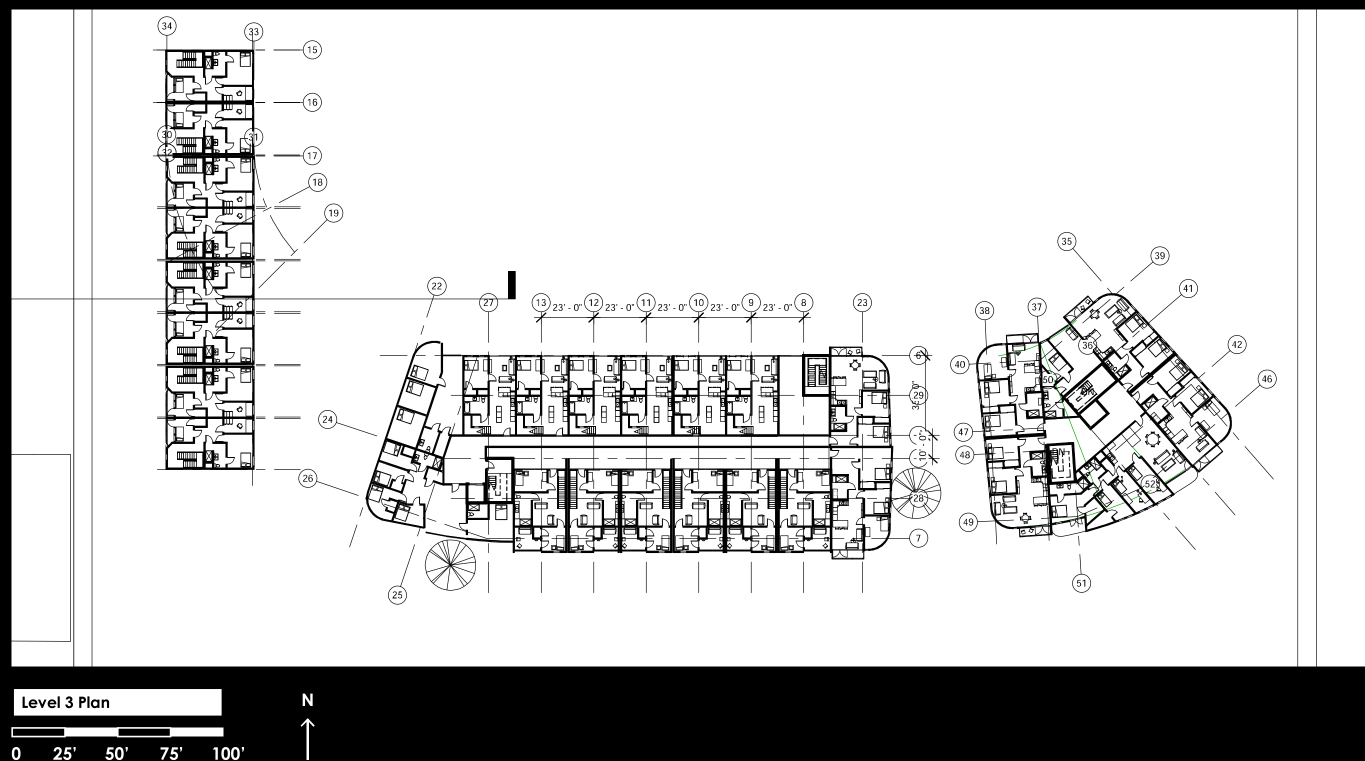


Level 2 Plan

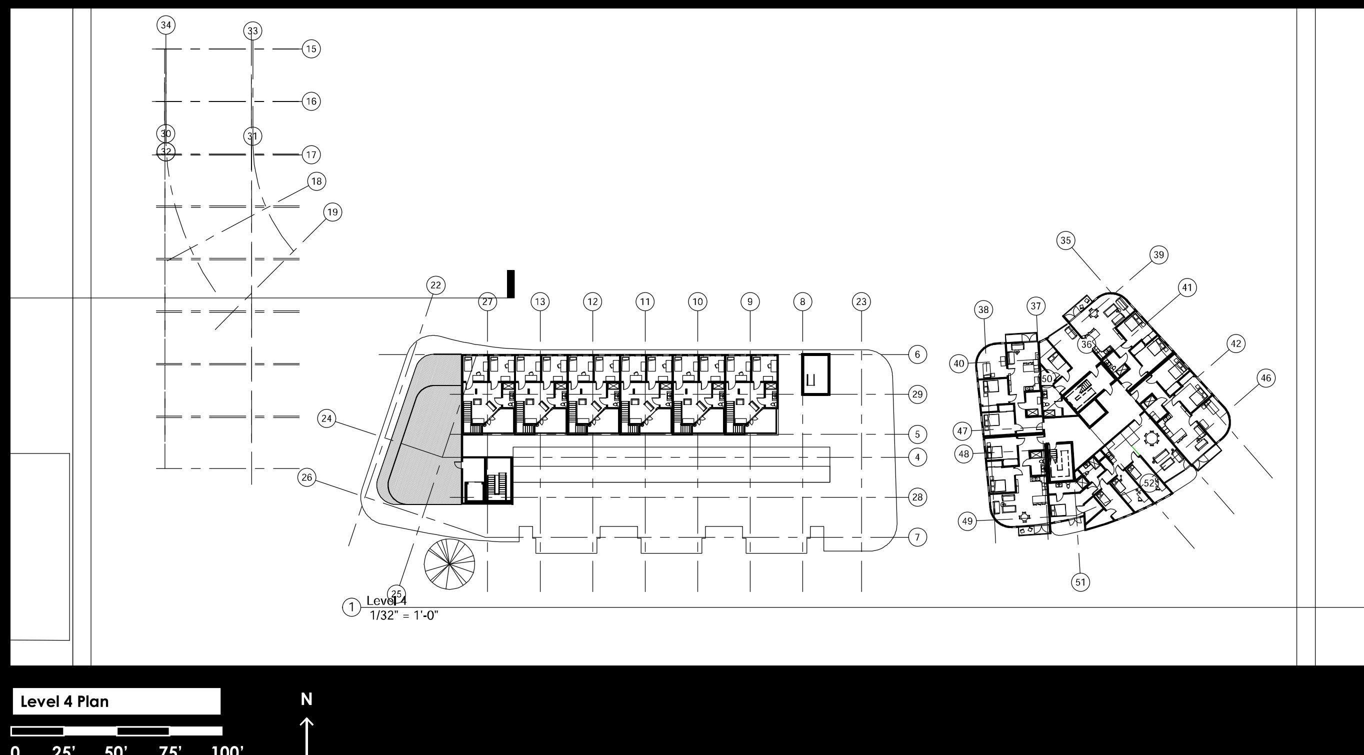
0 25' 50' 75' 100'

N

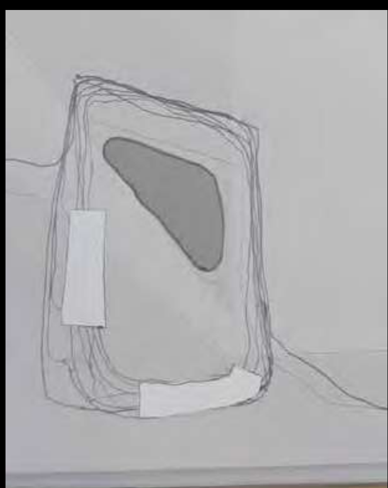
Part 5.2.: Addition of Residential Buildings



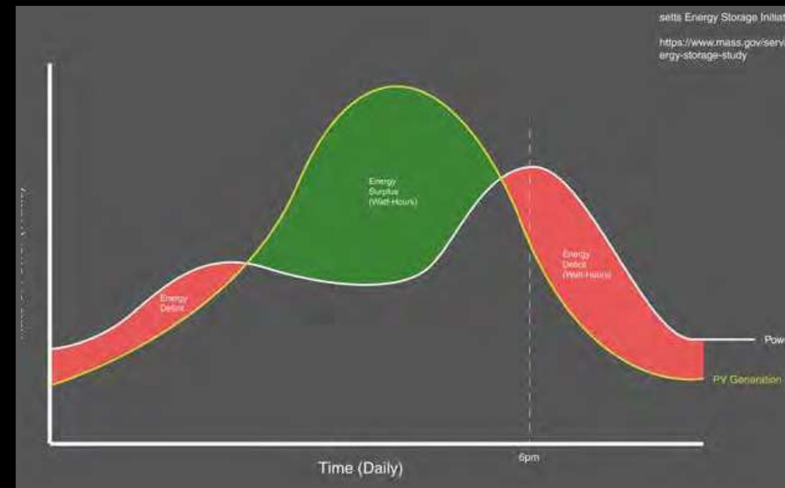
Part 5.2.: Addition of Residential Buildings



Part 5.3: Addition of Energy Storage



Part 5.3: Addition of Energy Storage

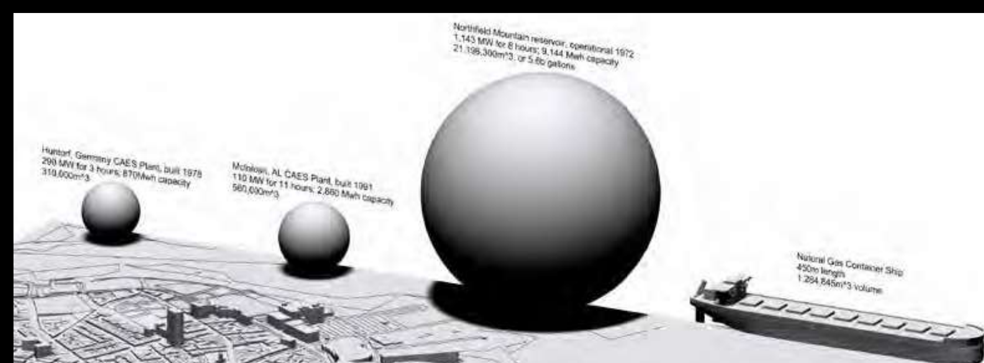


"The study provides a suite of recommendations to support 1) the growth of cost-effective storage deployment on the MA grid and 2? the growth of storage companies as part of Massachusetts' robust clean tech economy. These recommendations are

expected to yield 600MW of new energy storage technologies on the Massachusetts grid by 2025 providing over $800 million in cost savings to ratepayers..."

(DeRosa, et. al. 2016, pXV)

(DeRosa, et. al. 2016, pXV)



DeRosa, Jacqueline, Joanne Morin, and Michael Alteiri. "Massachusetts Energy Storage Initiative Study." Massachusetts Department of Energy Resources, 2016.

Part 5.3: Addition of Energy Storage

Energy Storage, Co-located with Income-Restricted Housing

Legal Tools for Encouraging Construction of Affordable Housing in Massachusetts
Chapter 40B
Chapter 40R

(Modestino, et. al. 2019, p56)

Models for Grid-Scale Energy Storage
Investor-Owned Utility Asset
Municipal Ligh Plant Asset
IOU-owned Load Serving Entity
Behind the Meter
Merchant Storage Developer
Resiliency/Microgrid

(DeRosa, et. al. 2016, pXV)

DeRosa, Jacqueline, Joanne Morin, and Michael Alteiri. "Massachusetts Energy Storage Initiative Study." Massachusetts Department of Energy Resources, 2016.
Modestino, et. al. 2019. "The Greater Boston Housing Report Card 2019: Supply, Demand and the Challenge of Local Control." The Boston Foundation.

Baseline vs. Peak energy price, for summer, and winter days.

DeRosa et. al, 2018, 30

Tank spills pollute site heavily

Profits from the exploitation of the site are nonlocal

Builds reliance on a grid based on combustion of fossil fuels

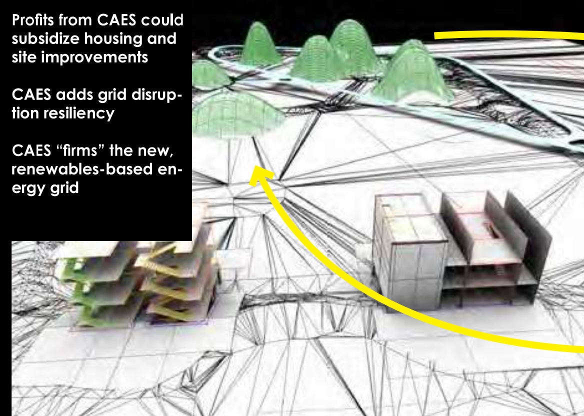
Visually unappealing

Site can be remediated while installing the tanks

Profits from CAES could subsidize housing and site improvements

CAES adds grid disruption resiliency

CAES "firms" the new, renewables-based energy grid



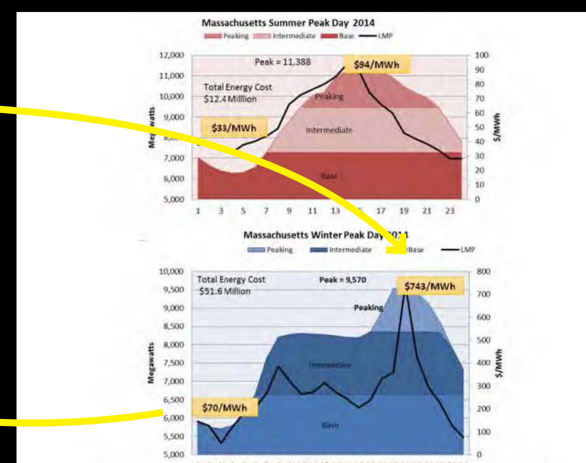
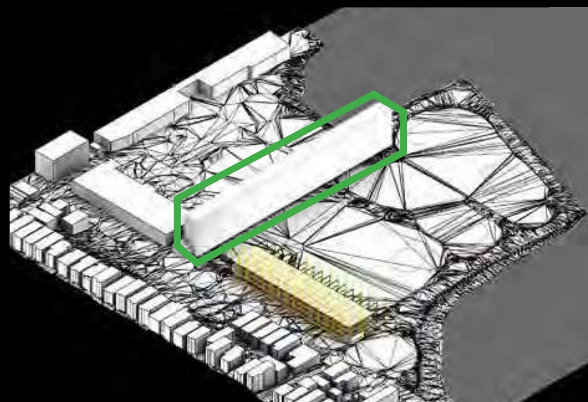
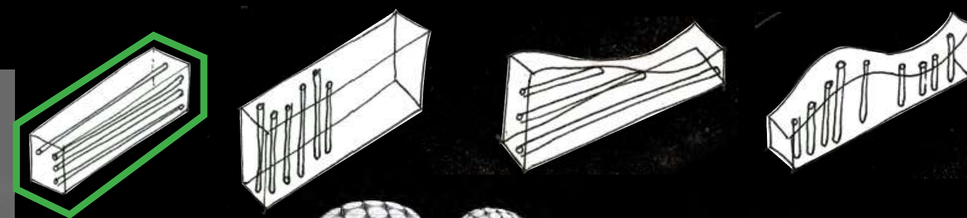
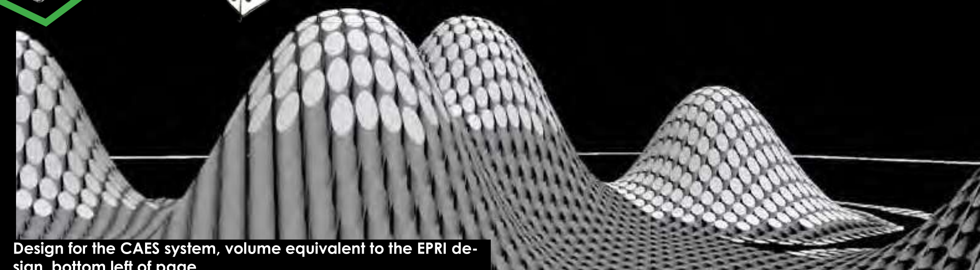


Figure 2-4: Average Demand and Price Peaks for a Peak Summer and Winter Day in Massachusetts 2014[40]

Part 5.3:
Addition of
Energy Storage

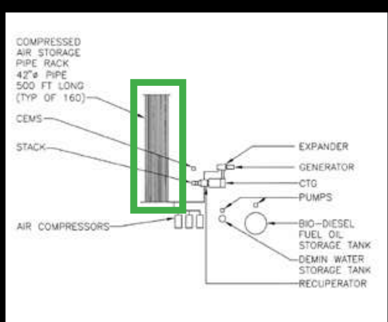






Design for the CAES system, volume equivalent to the EPRI design, bottom left of page.

Site Remediation incorporating the tanks



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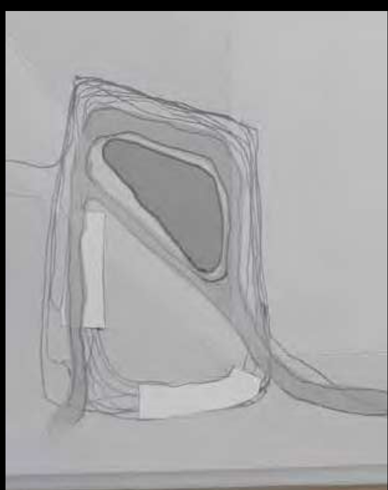
"Condor St. Urban Wild"
Hargreaves Associates, and East Boston Community Development Corp.

Neighboring site

Part 5.4: Addition of Walking Path

5.4.1.: Path Schematic Design



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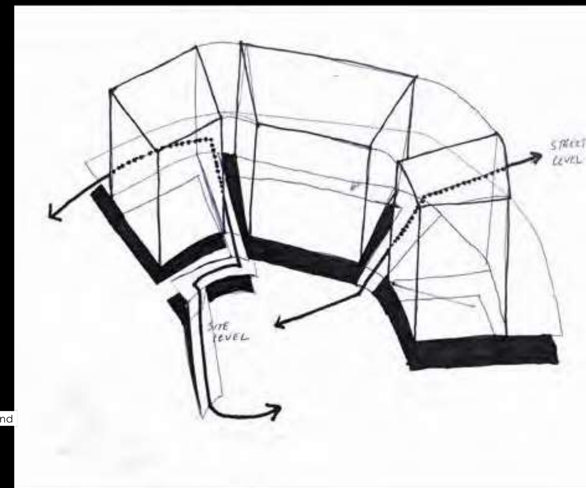
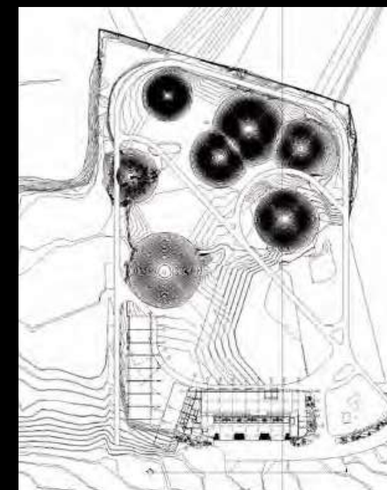
Connor Slover

Part 5.4: Addition of Walking Path

5.4.1.: Path Schematic Design

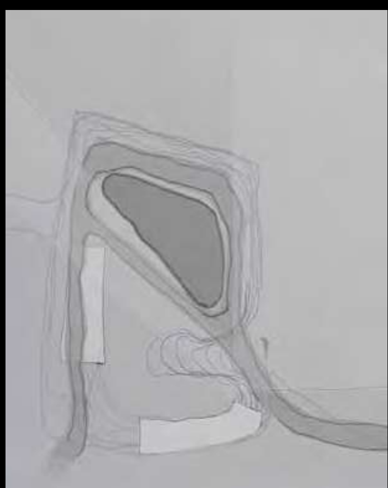




Public/Private diagram with outdoor paths

- Outdoor path (pedestrian)
- Outdoor path (auto)
- Indoor public space
- Indoor resident common ares
- Indoor private space

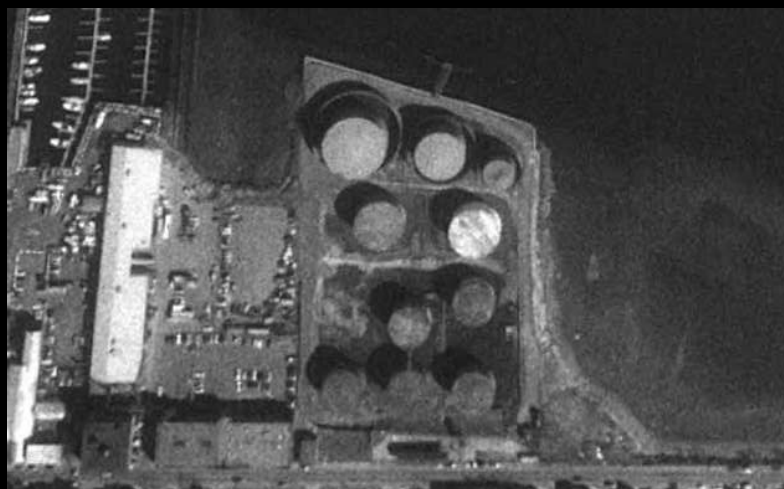
Part 5.5
Site Design and
Site Remediation

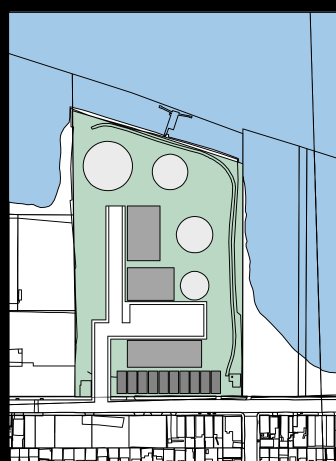


Master's Thesis Proposal:
Exploring the Use of Compressed Air Energy Storage in
the Urban Landscape
Connor Slover

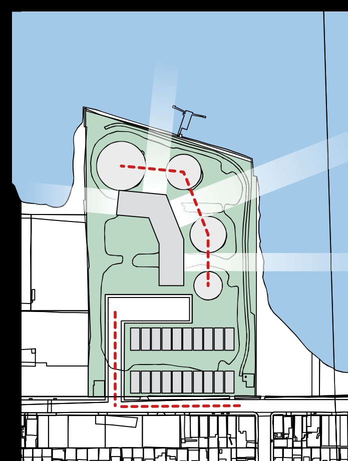
Part 5.5
Site Design and
Site Remediation

5.5.1.: Site Schematic Design
5.5.2.: Site Design Development

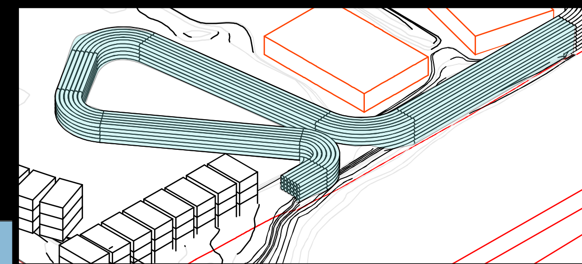




Draft site plan

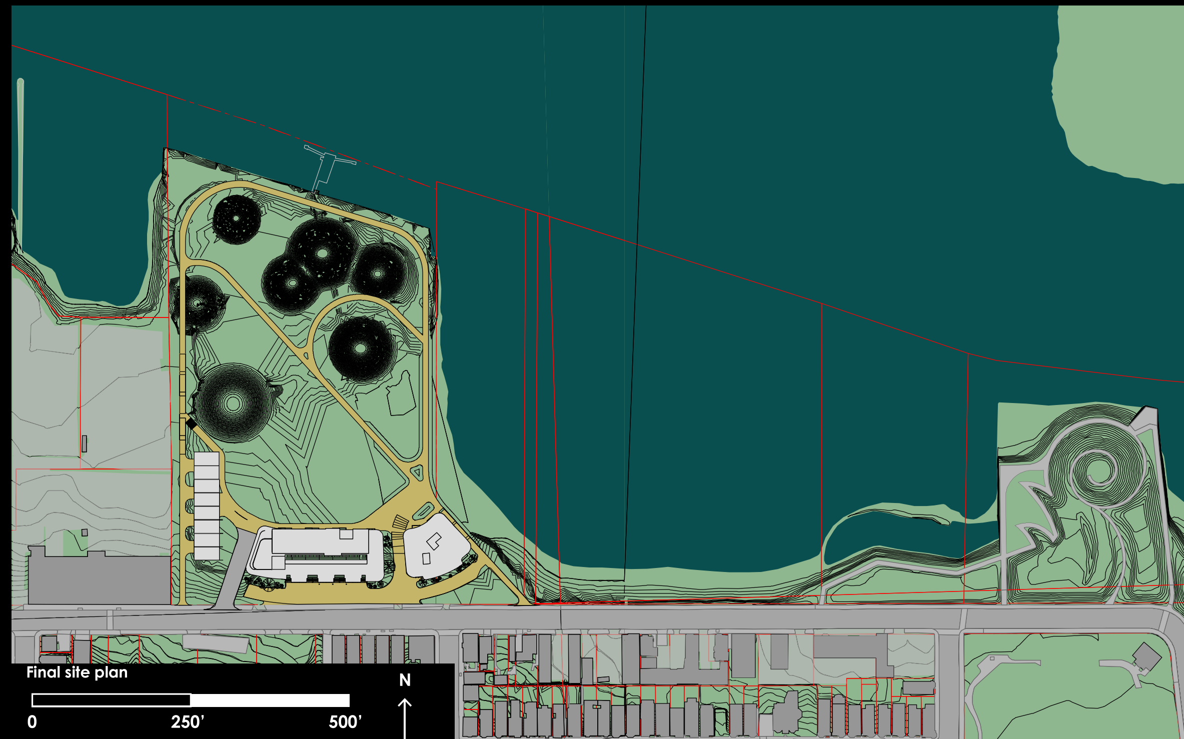


Draft site plan



Draft site plan

Part 5.5
Site Design and Site Remediation



Final site plan

View of the buildings, looking south

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