Cohousing in the Flower City: A Carbon Capture Design

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COHOUSING IN THE FLOWER CITY: A CARBON CAPTURE DESIGN

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M. Arch Thesis

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ABSTRACT

Our climate is changing rapidly due to an excess of greenhouse gases in the Earth’s atmosphere. A major force behind the release of these gases is the means by which we generate our energy — the combustion of fossil fuels. One of the biggest drivers of this energy demand within the United States is our built environment and more pointedly our cold-climate, urban based, residential building stock. All signs indicate that unless steps are taken, this demand will continue to grow. Ed Mazria’s Architecture 2030 Challenge proposes an ambitious plan for achieving carbon neutrality in buildings by 2030. What if there was an opportunity for buildings to not only be carbon neutral but carbon negative? This could be accomplished through a combination of carbon sequestration and designing for net-zero energy usage. Many avenues for inactive sequestration of carbon have been explored but of the active methods suitable for the built environment, only the application of an algae facade has been explored and brought to fruition to-date. Using an algae facade in concert with design for net-zero energy use, the goal of this project is to showcase a concept for a carbon negative building through the lens of a common house for the Flower City Cohousing Community, an intentional urban community in Rochester, NY.
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CONTEXT

The end result of this project will be a building design that demonstrates the practicality of a carbon negative building. However, to substantiate design decisions sufficient research will be conducted and presented. The following context section documents this exploratory process, detailing the premise behind the design and presenting the foundational and driving factors that ultimately inform the end result.

CLIMATE CHANGE

Since 1850, the approximate start of the industrial age, the mean global temperature has been rising steadily. It is estimated that over the last two decades, 1990-2010, we have witnessed the warmest temperatures on record for the last fourteen hundred years (Allen et al. 2014) with the period between 2000 and 2010 being certifiably the warmest that we have on record. Further, the last two years have been the warmest on record since 1880 (NASA 2015, 2016). This warming is not without cause. An excessive amount of energy has become trapped in the Earth’s climate systems in the form of heat, much of which can be found in the Earth’s oceans. Our oceans have not only warmed but have also become more acidic by an estimated 26% (Allen et al. 2014). We are living during a period which will surely be seen as a turning point, for better or worse. We are in the era of climate change.

What does this mean? Our climate is undergoing a dramatic, monumental adjustment and we are already starting to see the ramifications. New York State Attorney General Eric Schneiderman presents the monumental snowfall event in Buffalo, New York during the week of November 16,
2014 as a prime example stating: “You [cannot] connect one specific storm to climate change, but the pattern is irrefutable…. We’ve had more extreme weather incidents in the last five years or so then we’ve ever had before” (Dewitt 2014). We have already begun seeing changes to weather patterns as we know them. This is only one of many shifts that have been documented as of this date.

Between the years 1992-2011 both the Greenland and Antarctic ice sheets have lost a large amount of mass, with the rate of loss having increased between the years 2002-2011. Globally, glaciers have also decreased in size and the northern hemisphere has had smaller and smaller amounts of accumulated snow present at the start of the springtime thaw. From 1901 to 2010 the sea level has risen an average of 0.19m with the rate of rise being higher in the past hundred years than it has been over the entirety of the last two millennia (Allen et al. 2014). Every indication suggests that this is only the beginning.

**RAMIFICATIONS OF CLIMATE CHANGE**

There are a wide range of predicted outcomes as a result of climate change. Under all climate models, the average world-wide temperature is expected to continue rising. The degree to which it will rise is not certain though. It is predicted that we will see a minimum rise of 1.5 degrees Celsius on average with a continuation of warming and sea rise through at least the year 2100. The resulting world-wide mean sea level after this period of rise is unknown but it is predicted that 70% of the world’s coastlines will see water levels grow by as much as 20% above their current height.

Although the oceans have already noticeably increased in acidity, it is expected that this trend will continue. Rainfall in regions that are already dry and arid are expected to see a decrease in
precipitation, while heatwaves are expected to become longer and increase in frequency. Vice-versa it is anticipated that regions where rainfall is a common occurrence will see precipitation events occur in higher frequency and with more intensity. As a result, there is and will be a pronounced risk of mass extinctions for plants and animals. For ourselves we will most likely face issues of food scarcity and availability of fresh, potable water (Allen et al. 2014). In short, climate change is predicted to cause a multitude of problems.

Summed up these problems include changing rain patterns; changing behavioral patterns in land, sea, and air creatures; reductions in crop yield; a decrease in cold temperature extremes; an increase in warm weather extremes; an increase in high sea level events (i.e. flooding at high tide); and extreme weather events, which could mean an increase in heavy rains, floods, heat waves, drought, cyclones and wildfires. We are going to become much more vulnerable unless we find ways to address these changing conditions (Allen et al. 2014).

Climate change is the direct result of an excess of greenhouse gases in the atmosphere including carbon dioxide, methane, and nitrous oxide (Allen et al. 2014). Each of these substances drive climate change by trapping energy in the Earth’s atmospheric system (Stocker et al. 2013). Atmospheric concentrations of these compounds are at unprecedented levels, such that we have not measured such a large abundance in the entirety of 800,000 years (Allen et al 2014).

THE CAUSE OF CLIMATE CHANGE

Despite policies in place to mitigate or minimize climate change, there has been an increase in the amount of greenhouse gases emissions from 1970-2010, with the largest increases in the rate of release occurring between 2000 and 2010 (Allen et al. 2014). These emissions are primarily
anthropogenic, meaning as a result of human activity (NASA 2015). Human activity is also at an all-time high due to an explosion of our population. Between 2000-2010 the rate of population growth was equivalent to the growth of the past three decades combined (Allen et al. 2014).

The climate as we know it is becoming destabilized due to our activities. Bluntly, the continued growth of emissions is creating a bleak situation. Further release of greenhouse gases will continue the warming trend, will most likely lead to severe, irreversible changes for the climate, and will contribute to the creation of inhospitable living conditions (Allen et. al 2014). With a definite cause, a growing list of issues, and a shrinking window of time with which to address them, it is paramount that we work to limit our emissions to lessen the impacts of climate change.

Climate change is going to persist. If we want to alleviate the growing list of stressors on our society and environmental systems, adaptation is an adequate stop-gap measure but not a long-term solution. For the impacts to be lessened and perhaps reversed, climate change demands that we address the roots of the problem — the means by which we thrive — our energy.

**ENERGY DEMAND AND THE BUILT ENVIRONMENT**

Modern society relies on electricity. The anthropogenic emissions described in the section above are a direct result of this constant need, with much of our electricity coming from the combustion of fossil fuels. The U.S. is one of the world’s largest emitters of greenhouse gases, due to our energy consumption (UNFCCC 2014). In 2012 electricity generation accounted for 32% of the United State’s greenhouse gas emissions with 70% of that electricity coming from the combustion of fossil fuels. Of the fossil fuels that were used to produce electricity, 75% came from coal combustion (EPA 2014). Approximately 39% of the total energy consumed in the United States
comes from coal-powered facilities (EPA 2014).

According to the EPA, at 33%, approximately one-third of the electricity consumed in the U.S. is used by the commercial and residential sectors (EPA 2014). Between the two sectors, 53% of the total energy usage was attributable to the residential sector with 71% of the energy coming from generated electricity. Unfortunately when we generate electricity, we are only able to capture about 33% of the available energy (U.S. Energy Information 2015, 2.2). The other 67% is lost in the electricity generation process. Most of our power plants are steam-electric power plants, which rely on combustion to create the steam that drive our electric generators. Nearly all of the energy waste occurs in the combustion process. An additional amount of loss, approximately 7%, occurs when the generated electricity gets transmitted to from the power generation facility to its end destination (U.S. Energy Information Administration 2016). When you take into consideration the percentage of energy consumed that is sourced from electricity and the amount of emissions that come from the electric generation process and energy consumption by the United States’ residential sector stands as a substantial driver of U.S.-based greenhouse gas emissions.

The decision to design a common house for a co-housing community was rooted in the fact that the residential sector comprises such a large portion of the country’s total energy consumption. The next few paragraphs explore the composition of the residential sector to better understand where and how the electricity is being used.

To define simply, the residential sector encompasses all single family residences, multifamily residences and mobile homes in the United States (U.S. Department of Energy 1999). Single family residences, also known as single family housing units, are distinguished by having enough living space for one family or household. Further, the walls that run from the lowest point of the structure to the highest point must only house a single family. They may be attached or free
standing structures (i.e. a mobile home). If a unit is an attached single family residence then it must have a separate entrance and the residents may not have people living above for it to be counted as such. Homes that would fall under this criteria include townhouses, rowhouses, and duplexes (U.S. Energy Information Administration 2009). On average in the U.S. a detached single family home is 2,483 square feet and an attached single family home is 1,769 square feet (U.S. Energy Information Administration 2013, HC10.9).

Vice versa, a multifamily residence consists of multiple families living within the same structure — either below or above one another. Houses that were originally intended for one family unit but have been split up also fall into this category (U.S. Department of Energy Administration 2009). Typically apartments with two to four units have an average size of 1,100 square feet per unit. Units in apartment buildings with five or more units have an average area of 849 square feet (U.S. Energy Information Administration 2013, HC10.9).

Mobile homes are living units that have been moved to the site. Mobile homes can be transient but it is not a requirement for them to fall into this category — they can be affixed to permanent foundations. Further, mobile homes can come with one or more rooms but if rooms are added to the structure after it is on-site, the home would then be considered a single family residence. One item to note is that although prefabricated homes are also moved and delivered to the site where they are assembled, they do not fall under the category of mobile home housing (U.S. Energy Information Administration 2009). Mobile homes on average are 1,087 square feet (U.S. Energy Information Administration 2013, HC10.9).

Out of the 113.6 million housing units in the country more than three quarters, 88.1 million, are located in urban areas (U.S. Energy Information Administration 2012). As reported by the Building America program established by the U.S. Department of Energy's Office of Energy and
Efficiency and Renewable Energy, 34% of the residences that are located in urban areas, are located in Cold or Very cold regions. Following that, 31% are in Mixed-Humid regions, 12% are in Mixed-Dry/Hot-Dry climates, 17% in Hot-Humid Conditions, and 6% in a Marine environment. 69% of the housing units are single-family, using approximately 80% of the energy that is consumed by the residential sector. Multi-family units make up about 25% of the housing stock, comprising a much smaller 16% of the residential energy demand. Mobile homes make up the last type of residential unit, demanding about 4.5% of the country’s total residential energy consumption. (U.S. Energy Information Administration 2013, CE2.1). Of the single-family housing stock, 91% are detached, while the remaining 9% are attached. 85% are privately owned while the remainder are rented units (U.S. Energy Information Administration 2012).

The construction dates of the country’s total housing stock is spread fairly evenly between pre-1940 to 2009 (the terminal year for this study), except for the period of 1940-1949 during World War II. Despite advances in energy efficiency, there was a sharp jump in residential electricity usage between the 1960’s and 1970’s. From 1960-1969, total electrical energy consumption was 0.461 quadrillion BTU and from 1970-1979 that number ballooned to .702 quadrillion BTU. For the first decade of the twenty-first century that number grew again to .731 quadrillion BTU (U.S. Energy Information Administration 2013, CE 2.1). These increases are attributable to growth in home size and appliance use (C2ES 2009).

While the majority of energy used in homes comes from electricity, natural gas, propane, wood, fuel oil, kerosene, and solar power are also contributors to the residential pool of energy (U.S. Energy Information Administration 2013, HC1.1). From the Residential Energy Consumption Survey, we find that about 41% of residential energy use goes towards space heating, 35% to electronics, appliances and lighting, 18% to heating water, and 6% to air conditioning. In New
York State, the amount of energy used for heating is skewed due to the fact that it is a colder climate. Instead, the energy end use breakdown is as follows: 56% for space heating, 26% for appliances, electronics, and lighting, 17% for water heating, and 1% for air conditioning (U.S. Energy Information Administration 2013).

Ed Mazria’s Architecture 2030 cites energy consumption from the built environment as being even higher, with 47.6% of our total consumed energy being used by buildings, 75% of our produced electricity going toward buildings, and 44.6% of our 2010 emissions coming from the built environment (Architecture 2030 2011). Additionally, since 1990, there has been a 26% increase in indirect emissions due to larger demands from lighting, heating, conditioning interior spaces, and appliances (EPA 2014). Even in the last two decades there has been a 10% rise in the use of energy for lighting, water heating, appliances, and electronics with their consumption totaling around 66% of the approximate 11,320 kWh that an average household will use in a typical year. More so, while residents living in houses built in the 1980’s consumed around 77 million BTU on a yearly basis combined, those living in units built in the early 2000’s are consuming around 92 million BTU, which is a 19% spike in energy use (U.S. Energy Information Administration 2013, Heating and cooling). Effectively we (and by extension our buildings) are using a large amount of energy and that consumption seems to be expanding quickly.

Unless we take action, it has been forecasted that there will be dramatic growth in the amount of energy that our buildings consume. Over the next twenty years, it is expected that there will be a 34% increase in world-wide building energy consumption expanding at a rate of approximately 1.5% each year. More over, it has been predicted that in 2030, energy consumption attributed to dwellings and non-domestic buildings will be 67% and 33% respectively (Pérez-Lombard 2008). Given these statistics it would seem that if the continued release of greenhouse
gases is bad and buildings are such large contributors to greenhouse gas emissions, then we should attempt to minimize emissions that the built environment creates and therefore the amount of energy that buildings use.

**PROBLEM STATEMENT**

Instead of merely reducing emissions released, buildings could be a means to negate worldwide carbon emissions through carbon sequestration. This isn’t to suggest that buildings should be the sole means of reducing the amount of carbon in the atmosphere. Rather, this project intends to investigate and apply a solution that would demonstrate one way in which the built environment can be part of the solution to climate change instead of part of the causation.

Considering the contribution that the residential sector makes to United States carbon emissions, the aim of this project is to focus on exploring how a residential building in a cold-climate region can be made to act as a source of carbon sequestration rather than a source of carbon emissions.

A caveat — given the complex and unique nature of such an undertaking, the feasibility of creating a “silver-bullet” solution to emissions from the entirety of the built environment is unrealistic within this exercise and is not the intention of this project. Rather, a decision was made to focus on one typology. There is no reason why the methods explored and applied here could not be expanded to include other building types as replication and reapplication could be impactful. In lieu of this qualifying criteria, given the widespread nature of housing in cold-climate, urban regions in the United States, it made sense to use these factors to define a proof of concept. The following pages will explore how this could be achieved and then, lay out a system that could hypothetically
achieve a carbon negative multi-family residence.

Looking for inspiration, the decision was made to focus specifically on a residence in Rochester, New York because it fits a number of criteria. With a population estimated at 209,983 as of 2014, Rochester qualifies as a small city and therefore fits into the definition of an urban area (United States Census Bureau 2015). That’s the first qualifying criteria that makes it a viable location.

Second, Rochester is located in a “cold/very cold” region as identified by the United States EPA Building America program. The definition for a cold region is one having between, “5400… and 9,000 heating degree days (65°F basis),” and a very cold region is one that has 9,000 - 12,600 heating degree days with 65 degrees fahrenheit as a basis. Heating degree days are the difference between a base temperature and the average outdoor temperature over twenty-four hours. While Rochester technically falls into the “very cold” region according to the Building America map, by International Energy Conservation Code (IECC) standards, it is geographically located in Climate Zone 5. While near Climate Zone 6, it remains less harsh than Climate Zone 7, with which “very cold” regions are typically associated (Baechler et al. 2010).

Lastly, there is a question of housing stock itself. While nationally, a majority of the residential stock is found in single family homes, the ownership rate of homes for Rochester is only 39.9%, with 49.9% of the city’s housing units contained within multi-residential structures; this means that many Rochesterians rent their home (United States Census Bureau 2015). Looking at the data on multi-residential structures, the decision to design a single or multi-residence building in this thesis could go either way. However that’s only when looking at the ratio individually — when combining it with the fact that more than half of the city’s residents do not actually own their own home, the argument shifts toward the design of a multi-family residence. Also, using a multi-family residence as a test bed helps to defray the costs that accompany the implementation of new
technology.

A variety of building typologies were explored before coming to the conclusion that a residential building was appropriate for Rochester and the housing data suggests that a multi-residential building would fit in well with the existing fabric of the city’s housing stock. It is fair to assert that residential design nation-wide needs to be re-envisioned to achieve a meaningful reduction in carbon emission rates. The demonstration project will explore this assertion through the lens of a common house located in Rochester, NY.

**PRECEDENTS**

Currently the built environment is exacerbating the problem of climate change. Instead it should be part of the solution. This precedents section is an exploration of how this idea could become a reality, touching on proposed concepts, academic inquiries, current research, and established projects.

**ARCHITECTURE 2030**

Ed Mazria, architect behind the Architecture 2030 Challenge also believes that the impact the built environment is having on the climate should be neutralized. Through his challenge he wants “to rapidly transform the built environment from the major contributor of greenhouse gas (GHG) emissions to a central part of the solution to the climate and energy crises” (Architecture 2030 2011). This would be accomplished in two very specific ways. First, Mazria proposes that major reductions in the consumption of fossil fuels and emissions could be achieved by drastically altering
the way we go about planning, designing, and constructing our cities, communities, infrastructure and buildings. Second, we must focus our attention on creating the infrastructure that will allow us to adapt to and manage climate change impacts, preserve our natural resources, and utilize low-cost, renewable energy (Architecture 2030 2011).

Mazria goes on to suggest that global carbon emissions from buildings may be reduced in a number of ways. First, all new buildings, developments, and major renovations to should meet energy consumption, fossil fuel use and emissions standards above and beyond the average values for projects of the same type. Second, as new and renovated spaces come online, an equivalent amount of space in existing buildings would need to be renovated to be brought up to the same standard.

The original goal was a reduction of fossil-fuel based energy consumption by 60% measured against the calculated medians for site energy use by building type. These calculated medians were identified in the Commercial Building Energy Use Survey that was conducted by the United States Energy Information Administration in the 2003. Measuring the Source Energy Use Intensity (EUI) and Site EUI in kBtu/Sq. Ft./Yr, it was determined that for electricity, 1kBtu of site energy was equivalent to 3.34 kBtu in source energy. For natural gas, 1 kBtu of site energy equaled 1.047 kBtu of source energy. For district heating, 1 kBtu of site energy equaled 1.40 kBtu of source energy. For fuel oil, 1 kBtu in site energy was equivalent to 1.01 kBtu of source energy (2030 Inc. 2012). Electricity is shown to be the least efficient by far. The specifics on how the 2030 challenge (or beyond) can be achieved is outlined within the Zeroing in on Net Zero section.

While the challenge started with a reduction goal of 60%, as of January 1st, 2015, it was raised to 70%. By the year 2020 the necessary reduction goes up to 80% and to 90% by 2025. By 2030 designers have been challenged to create built environment that reduces energy derived
from fossil fuels by 100% when compared with their standard counterparts. It is suggested that this goal could be reached through the use of on-site renewables, sustainable design techniques, and by having up to 20% of the building’s energy be offset with the purchase of carbon credits (Architecture 2030 2011).

Mazria’s proposition is an ambitious one and would go a long way toward reducing the overall amount of building-related emissions released world-wide. Unfortunately, the built environment is not the only contributor to global emissions or climate change. Even if buildings are to achieve the goal of “net-zero emissions” as Mazria proposes, we would still have to combat other sources of emissions. Although a strategy for avoiding emissions, Mazria’s challenge is sector specific and does not aid in addressing the release of emissions by other sectors. Even though an individual building cannot be expected to single-handedly reduce a significant amount of atmospheric greenhouse gases, were a large number of projects to adopt a carbon negative design strategy, perhaps the built environment could effectively start to diminish the amount of greenhouse gases in the atmosphere.

**CARBON SEQUESTRATION**

A strategy that does strive to address emissions from multiple sectors is the technique of carbon sequestration. Also known as carbon capture and storage, it is defined by the EPA as “a set of technologies that can greatly reduce CO₂ emissions from new and existing coal and gas-fired power plants and large industrial sources…” (EPA 2013). Sequestration is a multi-step process that includes:
A) the capture of CO$_2$ from power plants or industrial processes

B) the transportation of the captured CO$_2$, compressed, via pipelines to storage sites, and

C) injection of said CO$_2$ underground or into deep rock formations.

The gas would be placed at least a mile below the surface, and be injected into non-porous formations such as sandstone, shale, dolomite, basalt, or deep coal seams. According to the EPA, wide scale implementation could mean a reduction of power plant CO$_2$ emissions of up to 80-90%. This equates to planting 62 million trees and waiting for them to grow for 10 years or erasing the annual electricity consumption of approximately 300,000 homes. Currently carbon sequestration can be applied to coal and natural gas powered electricity plants, ethanol and natural gas processing plants, and has been implemented at over 120 facilities across the United States. There are even some industries that can use the captured CO$_2$ to enhance their production process. Applications include oil recovery, food and beverage manufacturing, pulp and paper manufacturing and metal manufacturing. Because current carbon capture technology is employed at the source of emissions (power generation facilities), all sectors that rely on electric energy see a beneficial reduction of their emissions (EPA 2013). While Mazria’s strategy would be excellent for reducing the emissions of one specific sector, the application of carbon sequestration allows for emissions to be reduced along a much broader spectrum.

“TYPICAL” SEQUESTRATION TECHNIQUES

We have five global “pools” of carbon dioxide. These are the oceanic pool, which has an amount of CO$_2$ fifty-nine times greater than what can be found in the atmosphere; the geologic
pool which is all of the carbon dioxide stored in fossil fuels; the pedologic pool which can be broken into soil-based organic and soil-based inorganic carbons; the atmospheric pool (which is growing by .46% a year); and a biotic pool which is made up by plants. Carbon emissions have been increasing but atmospheric emissions have grown at a steady rate. Carbon is being absorbed by our oceans, forest, soil and other ecosystems through natural sequestration. To avoid the worst impacts of climate change we want to completely stop the addition of carbon dioxide to the atmosphere and find ways to route the carbon into other pools. This would be achieved through the methods mentioned above (through human intervention) or through natural mechanisms (Lal 2008).

Carbon sequestration methodologies can be broken down into two broad categories. The first is abiotic sequestration, or sequestration that relies on physical and chemical reactions alongside engineered techniques. The second method is biotic sequestration, which relies on the “managed intervention of… plants and micro-organisms in removing CO2 from the atmosphere” (Lal 2008).

Abiotic sequestration can take a variety of different forms, including the storage of carbon dioxide in the ocean. It can be liquified, injected at great depths, deposited by a pipe towed behind a ship or pumped into a depression at the bottom of the ocean floor. Unfortunately, all of these methods face the risk of an unstable storage solution. Geologic injection is the terrestrial counterpart to oceanic injection. As described by the EPA, geologic injection involves the placement of CO2 into old oil wells, coal seams, stable rock strata or saline aquifers. Like oceanic sequestration, this methodology raises concerns over the ability to keep the sequestered carbon stable and in the ground. The final method for abiotic sequestration is scrubbing and mineral carbonation (Lal 2008), one and the same with the first step of the carbon capture and storage methodology as outlined by the EPA. Scrubbing and mineral carbonation relies on the transformation of CO2 into other compounds such as calcium carbonate or magnesium carbonate. This is done with a mineral or
amine solvent which the CO2 is passed through. Mineral carbonation deactivates carbon dioxide by passing the particulates through a slurry that ideally reaches a concentration of 15-30%. Then the captured carbon dioxide is removed. Although this methodology can be sped up, becoming more effective with heat, the energy and costs are prohibitive to making it a workable solution (Lal 2008).

Biotic sequestration likewise comes in a number of forms. Oceanic biotic sequestration relies on seeding the ocean with iron, encouraging the growth of phytoplankton and, through their photosynthesis, the absorption of CO2. Land-based biotic sequestration has a number of associated benefits and there are a variety of means to sequester CO2 through land-based techniques. The broad benefits that come along with this methodology include improved soil and water quality, possibility for the restoration of degraded ecosystems, and an increased crop yield. Forest ecosystems are naturally sinks for carbon, whereby the growth of plants absorb CO2. The stored CO2 can then be found in lichens, harvestable timbers, woody debris, wood products, and other woody plants. Afforestation, or the replanting of forests, relies on the fact that forests absorb carbon as they grow. Forest restoration and sustainable management would also help forested lands acts as carbon sinks. While wetlands and peat soils were once a successful carbon retainer, draining and cultivation of wetlands have rendered them ineffective. Restoration would help to re-enable a biotic carbon storage system (Lal 2008).

Soils themselves are an effective means of carbon sequestration through their natural cycling process. Ways to increase the efficacy of soil-based sequestration include land-use conversion, implementing recommended land management practices, the creation of charcoal and biochar and then using it as a fertilizer, integrated nutrient management, manure application, and the reduction of summer fallow fields and using cover crops in place of continuous cropping instead. Growing winter crops is another option to aid in carbon fixing (Lal 2008).
Carbon may also be sequestered in soil as an inorganic compound in the form of secondary carbonates. Secondary carbonates can come in many forms but as of right now, there has been little headway in increasing the secondary carbonate storage rate aside from increasing the activities of soil fauna or speeding up natural biogenic processes. Soils could theoretically benefit from the use of high quality irrigation water which would speed up the process of HCO3 leaching (bicarbonate). The final proposed method of sequestration by biotic means would be through the production of bio-fuels such as bioethanol or bio-diesel using a bio-mass material. The fuel would then help to offset the fuels that are being pulled from the geologic carbon pool (Lal 2008).

Given all of these options, it would be hard to decide upon the “right” approach for carbon sequestration. Each may have its own immediate and relevant applications. Abiotic is useful in that it is able to sequester large amounts of carbon dioxide but many of the techniques are on the horizon rather than being readily available at this moment. Additionally there is a large potential for adverse effects on human health while also requiring the navigation of a complex legal and regulatory system. Even though biotic methodologies sequester at a slower rate, they have a low cost, can be beneficial for the environment, have a low risk of impacting human health, and do not necessarily require new technologies. Additionally, of the five carbon pools, the biotic pool is currently the smallest. Therefore, it has room to grow (Lal 2008). With this information, a biotic approach to sequestering carbon is more appealing today while an engineered, abiotic approach could be just as useful and appealing in the near future.

Outlined above are the general strategies for the implementation of carbon sequestration to decrease the amount of carbon in the atmosphere and, hopefully, lessen the impacts of climate change. How could this be applied to a building or the built environment? The following section will describe four identified strategies.
SEQUESTRATION WITH BUILDINGS

Much of the current research on buildings with regard to carbon emissions has been focused on the investigation of how much carbon is avoided by constructing a building out of heavy timber versus steel or concrete rather than buildings as a means for sequestering carbon (Börjesson & Gustavsson 2000)(Sathre & Gustvsson 2009). That said, there are other techniques which are currently under investigation for future application, or are already beginning to make their way onto the market and into practice. These include the use of concrete to absorb carbon dioxide (Haselbach 2009)(Haselbach & Thomas 2014), the use of algal and vegetative facades (Kim 2013)(Wallis 2013), and protocells for architectural application (Clear 2011)(Spiller 2013). Some researchers have even gone so far as to transform concrete into a growing medium, turning the commonly used building material into a living facade (Brownell 2013). From this, four main categories can be identified: bio-renewables, concrete, living facades, and protocellular. Each will be briefly explored below.

Bio-renewables

Bio-renewables consist of materials that contain carbon compounds derived from either plants or animals and through the process of photosynthesis or consumption, the carbon is removed from the atmosphere by plants and animals. Once removed, the carbon stays embedded in the product until it is either burned or decomposes. Bio-renewable materials typically have a carbon content of around 40-50% with a ratio of about 1 unit of bio-renewable material to 1.83 units of CO$_2$ (Sadler & Robson). Unfortunately, the lifetime of wood products is finite and may be anywhere from a few days to many years. Therefore, carbon dioxide is not permanently stored in woody
products. Only upon regrowth does the carbon become re-captured. To achieve carbon neutrality through the use of bio-based products, the rate of use versus replacement must be a reciprocal relationship. The real strength of wood and other bio-renewables lies in the fact that there is much less carbon emitted in the production process than with concrete or steel products. While storage through the use of woody materials would aid in sequestering carbon, it would not be enough to offset total emissions (Buchanan & Levine 1999). In opposition, Gustavsson and Sathre suggest that “[t]he use of wood building material instead of concrete, coupled with the greater integration of wood by-products into energy supply systems, could be an effective means of reducing fossil fuel use and net CO$_2$ emission to the atmosphere” (2006).

The use of wood materials for building construction is a valid option for a low-carbon alternative. While using wood as a building material is not going to solve the problem of emissions by itself, it is a useful strategy to be employed alongside other techniques.

**Concrete**

There are a couple of ways in which concrete could be used to sequester carbon dioxide. The first way is by focusing on reducing the emissions associated with its manufacture. The California company Calera uses the carbon dioxide captured from electricity production at coal-fired power plants to make cement. The carbon dioxide is transformed into a calcium carbonate cement by taking the stack emissions and passing them through seawater. This process reverses the problem of normal cement production. Cement normally requires extremely high temperatures to be manufactured, the process releasing approximately one ton of CO$_2$ for every ton of cement produced. In this new process, for every ton of cement made, half a ton of CO$_2$ gets sequestered.
as the carbon dioxide is converted into calcium carbonate. The cement they are making could then take the place of Portland cement, which is a large contributor to the \( \text{CO}_2 \) emissions associated with typical concrete production (Biello 2008).

The second method for sequestering carbon in concrete would be accomplished over the lifetime of the concrete itself, after it has already been produced and poured into place. Haselbach and Thomas have found that carbon dioxide can be sequestered in concrete through the natural process of carbonation (2014). Others, such as Biswas et al. and Korake and Gaikwad have investigated methods for improving the carbonation process (Biswas 2011, Korake & Gaikwad 2011). Toshiba Corporation has even developed a ceramic based on lithium silicate which begins \( \text{CO}_2 \) uptake at room temperature versus lithium zirconate which does not become a carbon sink until it has achieved temperatures between 450 and 700 degrees celsius. It is much cheaper than zirconium and absorbs 30% more carbon dioxide (JOM 2001). Perhaps there could be a composite concrete-lithium-silicate material developed which would achieve similar properties. These sample studies suggest that concrete, could be a potential material for the storage of carbon dioxide either prior to or even following building construction but more development is probably needed.

**Living Facades**

Living facades can come in a variety of forms. The first is a what is known as a green facade. With a green facade the living plant either is attached directly to the exterior of the building or to a trellis or cable so that it can climb better. A secondary method for supporting climbing plants is locating a cable or mesh adjacent to the building’s exterior surface but not placing it in direct contact. This is called an ‘indirect’ greening system (Perini et al. 2013).
A more complex approach in establishing a living facade is through the implementation of a ‘living wall system’, known as a green-wall or vertical garden, vertical garden being the blanket term “which refers to all forms of vegetated wall surfaces… as with plants either rooted in the ground, in the wall itself or in modular panels attached to the façade” (Perini et al. 2013). Living wall systems are narrower in scope, defined by their reliance on modular panels, baskets, or boxes that contain a medium in which the plant may grow. In addition to a growing medium such as foam beads, or mineral wool, living wall systems require a supply of nutrients delivered via hydroponics. Typically a living wall system will be employed when there is a desire for a wider range of plant varieties other than climbing plants as the planter boxes and growing medium allows for plants that typically would not grow vertically. Durability is varying between the different styles but can range anywhere from 10 - 50 years. Additionally, when placed externally, living wall systems have the potential to decrease temperature gains in buildings and as a result, save energy (Perini et al. 2013).

An example of a specific living facade system is the Urban Algae Canopy demonstrated at the INTERNI’s Exhibition-Event ‘Feeding New Ideas for the City’ by the ecoLogicStudio in Milan. With this system, algae is cultivated in an umbrella composed of a triple layer ethylene tetrafluoroethylene system allowing for a high level of control over the shape and function of the algae housing. Flows of energy, water, and CO2 were regulated in response to weather and visitors. The core genius of the design is that as the algae grows, it absorbs more CO2 while at the same time,
providing extra shade (ecoLogicStudio 2014). When applied to a building’s facade, this could help regulate a building’s energy demands through the reduction of cooling loads. If the facade were constructed in a manner similar to ecoLogicStudio’s Umbrella system, the amount of algae in a panel could be regulated as well, allowing for regular and on the fly adaptation based on weather conditions.

The BIQ building in Germany is another example of an algal facade, implementing a novel approach to sourcing the building’s energy, the BIQ relies on 129 bio-reactors which take the form of panelized glass housings for algae. These containers are environmentally controlled and the algae relies on liquid nutrients and carbon dioxide for growth. Once enough algae is grown, it is harvested and then broken down in a fermentation reactor. The process results methane gas, which is then used to power a turbine, and in turn, the building (Wallis 2013).

Finally, research scientists at the Universitat Politecnica de Catalunya in Barcelona are developing a concrete that can be utilized as a living wall. Their work involves a panelized concrete system that allows for the growth of mosses, lichens and fungi embedded within the panels. Known as biological concrete, as these plants grow they would reduce atmospheric carbon dioxide and also provide reductions to the urban heat island effect. More promising is that
these panels could be applied to new and existing structures alike (Brownell 2013). Applying a system such as this or the algal system mentioned above could allow for a unique facade system that also is an effective means of sequestering carbon dioxide.

While technically not a facade or a wall, green roofs could also be considered a member of this group. Green roofs are roofing systems that feature live plants as the outermost layer of the roof. A green roof is set up in layers. Moving from the bottom to top these include, structural support, a vapor control layer, thermal insulation, a support panel, a waterproofing and root repellant layer, a drainage layer, a filter membrane, a growing medium, and finally, the live plants. Some advantages to using a green roof include a reduction in the urban heat island effect, absorption of pollutants and greenhouse gases, improved air quality, increased ability to manage stormwater, potential for aesthetic improvement, beautification, and additional communal space. Green roofs can also help to decrease energy costs, and improve the durability of the roof over its lifetime (Green Roofs for Healthy Cities 2014, About and Benefits). Effectively, green roofing are similar in nature to living walls and facades, expect the plants are on the roof of the building rather than the walls.

*Protocellular*

The Advanced Virtual and Technological Architectural Research (AVATAR) Group, based at the University of Greenwich and directed by Neil Spiller, is a diverse group of architectural thinkers investigating “synthetic biology, surreal digital theory, film and animation, interaction design, mixed and augmented reality – all called into service to inform advanced architectural, landscape and urban design” (Spiller 2013).
Of their numerous investigations the application of protocells is of particular interest for its capacity to change architecture. Protocells are artificial cells, or chemistries that exhibit life-like behavior that are not fully alive. A combination of chemicals achieves a life-like activity, creating the protocell (Clear 2011). They can be applied in a wide variety of forms, materials, and scales (Armstrong 2014). One example is the concept of using protocells to shore up the eroding foundations of Venice. Protocells could also be used at much smaller scales. Lee Cronin at University of Glasgow is researching just such an application: using protocells mixed with an oil based paint would be used to “fix” carbon dioxide as it dries (Armstrong, 2014).

While protocells can come in different geometries, allowing for different applications, they are bound by certain criteria. These include temperature, pH balance, the presence of other chemistries and protocells. In effect, their use is very context-specific. Their potential for self assembly and semi-autonomous configurations (Armstrong, 2014) make the introduction of protocellular technology into the architectural field an inviting concept. If work with protocellular architecture advances enough to a stage of applicability, it could be a powerful tool for creating unique architecture that absorbs carbon in an autonomous manner but for now it is only an idea not a reality.

*Thoughts on the current literature*

The concept of using a building to absorb carbon dioxide from the atmosphere is starting to gain momentum to the point where it is an applicable idea. Utilizing wood and concrete in building is currently a standard practice but only certain industrial processes can turn concrete into a material for sequestration. Algal facades are relatively new and protocellular architecture is still a nebulous
idea at best. Given the reality that materiality alone will probably not suffice in making the building carbon negative and protocellular architecture is a still-to-be-realized technology, coupling a net-zero energy program with an algal system seems to be a plausible route to achieving carbon negativity.

How could this be achieved? The next two sections will first investigate how to create a net zero building and secondly, explore typical means of cultivating and supporting algae, which by today’s standards would be considered a “smart material”. Smart materials are “materials, material systems, and products that can be derived from them which behave not in a static but a dynamic way, in contrast to conventional building materials” (Roedel and Petersen 2013).

In short, smart materials are responsive to their environment and can physically change due to items such as sunlight or their natural chemical properties. Algae does both of these things. In fact, Roedel and Petersen mention algae as an example of a smart material. Using algae, or any other smart system, enables a new control over the building’s energy footprint as some smart materials can draw energy directly from the environment (Roedel and Petersen 2013). Coupling this with a design for net-zero energy use will theoretically enable the creation of a building that is not only carbon neutral in its energy use but actively sequesters carbon to the point where the building is carbon negative.

UNDERSTANDING NET-ZERO ENERGY

To achieve a carbon negative design, the first step is designing for net zero energy. Doing so will help to achieve the aim of a carbon negative building, which will be covered further in the section. The front end of this section will deal instead with what it means to be labeled a net zero energy building. U.S. Department of Energy has now released an official definition of what it means
for a building to be net zero. A net zero energy building, A.K.A. zero energy building, A.K.A. zero net energy building, have conclusively been defined as “an energy-efficient building where, on a source energy basis, the actual annual delivered energy is less than or equal to the on-site renewable exported energy” (NIBS 2015).

This definition was arrived at through a dialogue between a number of stakeholders under the common banner of the National Institute of Building Services, or NIBS, and its High Performance Building Council (HPBC). NIBS was founded in 1974 as a non-profit, non-governmental organization by the U.S. Congress and is made up of representatives of all interests that are concerned with the creation of “safe, affordable, efficient and effective structures throughout the United States,” (NIBS 2015) including government officials, design and construction professionals, regulatory agencies and consumer interest advocates. The HPBC acted to organize the process, coordinating input from a multitude of stakeholders including “major standards writing organizations, industry trade associations, nonprofit organizations and federal government entities involved with the built environment… [and] includes representation from all members of the building team, from designers to builders to owners” (NIBS 2015).

For the sake of clarity, there are some additional definitions that are important to outline to fully understand the overall meaning of what really makes up a net zero energy building. Although it may seem redundant, the first term to define within this context is ‘building’. Any reference to a building when talking about a net zero energy means “a structure [that is] wholly or partially enclosed within exterior walls, or within exterior and party walls, and a roof providing services and affording shelter to persons, animals or property” (NIBS 2015). Now that we have working definition of building, it is important to define ‘building energy’ because this will help in understanding ‘source energy’. Building energy is, “Energy consumed at the building site as
measured at the site boundary. At a minimum, this includes heating, cooling, ventilation, domestic hot water, indoor and outdoor lighting, plug loads, process energy, elevators and conveying systems, and intra-building transportation systems” (NIBS 2015). The next term, ‘source energy,’ relies on the previous definition. Source energy is “Site energy plus the energy consumed in the extraction, processing and transport of primary fuels such as coal, oil and natural gas; energy losses in thermal combustion in power generation plants; and energy losses in transmission and distribution to the building site” (NIBS 2015). It is important to note that site energy is synonymous with ‘building energy’ (NIBS 2015). The next string to define is ‘annual delivered energy’, beginning with ‘annual.’ Annual refers to a period of twelve consecutive months during which all energy measurements have been recorded. There is no requirement on when these measurements start as long as they are taken on a monthly basis. The second half of the term, delivered energy, is, “Any type of energy that could be bought or sold for use as building energy, including electricity, steam, hot water or chilled water, natural gas, biogas, landfill gas, coal, coke, propane, petroleum and its derivatives, residual fuel oil, alcohol based fuels, wood, biomass and any other material consumed as fuel” (NIBS 2015). The final piece of the string is ‘on-site renewable exported energy.’ On-site renewable energy can be defined as

“any renewable energy collected and generated within the site boundary that is used for building energy and the excess renewable energy could be exported outside the site boundary. The renewable energy certificates (RECs) associated with the renewable energy must be retained or retired by the building owner/lessee to be claimed as renewable energy…” (NIBS 2015). Finally we come to ‘exported energy.’ Exported energy is any “On-site renewable energy supplied through the site boundary and used outside the site boundary…” (NIBS 2015); essentially if it’s generated on site and then goes elsewhere, it’s exported energy. Separate but not unrelated are Renewable Energy
Certificates, or (RECs), which are purchasable items that represent the “environmental, social and other non-power qualities of one megawatt-hour of renewable electricity generation” and can be purchased ‘untethered’ from electricity itself (NIBS 2015). Essentially, if a project purchases RECs this does not mean that it will receive electricity commensurate with the amount purchased. Rather, it creates an opportunity for that amount of electricity to be generated renewably, elsewhere on the grid. There is no guarantee that this renewably generated electricity will reach the project site.

In all of this, the site boundary is paramount, as all of these definitions hinge upon whether the energy is coming from or being generated within or outside of the site boundary. The site boundary is a ‘meaningful’ boundary that functions as a part of the building. For a single building this typically will mean the property boundary itself but no matter the number of buildings in the project will include the point where the utilities interface. There is some variability on where the site boundary actually falls depending on where the on-site renewable energy sits. If it is within the building footprint it could be counted as surrounding the building itself — otherwise it could be expanded to include the building’s entire site if it is located outside of the building footprint (NIBS 2015).

No matter where the boundary falls, net zero energy buildings are efficient to the point that they produce as much or more energy than they consume on an annual basis. Connected to the electric grid, they then send any excess energy off-site for others to use. Prior to having ‘excess’ energy though, the building will first meet its own energy needs including heating, cooling, ventilation, domestic hot water, indoor and outdoor lighting, plug loads, process energy, and transportation within the building. Energy comes to the building in the form of ‘delivered energy’ and this could include grid electricity, district heat and cooling, and renewable as well as non-renewable fuels. In order to meet the definition of a zero energy building, the energy that is used
to offset any delivered energy must be energy that is generated on-site. This includes renewable resources. Even if they’re sustainably produced, if they are not generated or harvested on site, they will not count toward the total offset of delivered energy (NIBS 2015).

To measure whether or not a building is truly net zero, site energy is the first consideration. This helps to measure how the building is performing overall. To truly measure it though, especially if there are different fuel types being utilized by the building (i.e. solar photovoltaics and gas), the recommended approach is to convert these into raw fuel equivalencies, accounting for the amount that would need to be consumed in order to generate one unit of energy produced on-site. This conversion must also factor in all embodied energy, including the energy it takes to extract the raw fuel, process and transport it, as well as take into account energy that is lost during combustion when it is transformed from raw energy into usable energy, and then again when that energy is transferred to its final destination. When converting from site to the equivalent source energy, the efficiency or inefficiency of a building’s energy provider is out of our direct control. Therefore a national average is used for the conversion factor (NIBS 2015).

To calculate annual source energy balance, the first step is to multiply the delivered energy for a specific type by the source energy conversion factor for the specific delivered energy type. This is done for each delivered energy type and the source energy delivered equivalency for each energy type is totaled. The second step is to go through this process again, but instead multiply the exported on-site renewable energy by the conversion factor for the exported energy type and sum the source energy exported energy equivalency. It is important to note that energy that is renewable, generated on-site, and exported to the electric grid is factored as delivered energy because it is displacing energy that would otherwise be coming from the grid. Once you have both totals, you subtract the exported source energy equivalency from the source energy delivered equivalency. The
mathematical equation is laid out below (NIBS 2015):

\[ E_{\text{source}} = \sum (E_{\text{del},i} r_{\text{del},i}) - \sum (E_{\text{exp},i} r_{\text{exp},i}) \]

With:

- \( E_{\text{del},i} \) = the delivered energy for energy type \( i \)
- \( r_{\text{del},i} \) = the source energy conversion factor for the delivered energy type \( i \)
- \( E_{\text{exp},i} \) = the exported energy for energy type \( i \)
- \( r_{\text{exp},i} \) = the source energy conversion factor for the exported energy type \( i \)

The National Institute of Building Services reports the conversion factors for exported and delivered energy to source energy published in ASHRAE Standard 150 and can be found in the following table:

<table>
<thead>
<tr>
<th>ENERGY</th>
<th>CONVERSION FACTOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>IMPORTED ELECTRICITY</td>
<td>3.15</td>
</tr>
<tr>
<td>EXPORTED RENEWABLE ENERGY</td>
<td>3.15</td>
</tr>
<tr>
<td>NATURAL GAS</td>
<td>1.09</td>
</tr>
<tr>
<td>FUEL OIL (1,2,3,4,5,6, Diesel, Kerosene)</td>
<td>1.19</td>
</tr>
<tr>
<td>PROPANE</td>
<td>1.15</td>
</tr>
<tr>
<td>STEAM</td>
<td>1.45</td>
</tr>
<tr>
<td>HOT WATER</td>
<td>1.35</td>
</tr>
<tr>
<td>CHILLED WATER</td>
<td>1.04</td>
</tr>
<tr>
<td>COAL OR OTHER</td>
<td>1.05</td>
</tr>
</tbody>
</table>

(Source: NIBS 2015)

Although, Renewable Energy Credits may be used in a project, they may not be counted as a part of the “accounting” for net zero energy process. In order for a project to be considered net-zero energy, all annual delivered energy must be offset by on-site renewable energy. The one exception to this is in an instance where the project is unable to provide enough on-site energy
generation due to spatial constraints to accommodate the full scale of the building’s energy requirements (i.e. a large building such as a hospital in an urban environment) (NIBS 2015).

Given these conditions, renewable energy certificates, or RECs may be employed to help balance annual delivered energy but only after on-site renewable energy sources have been utilized. Projects that do make use of such a scheme may be considered a Renewable Energy Certificate Zero Energy Building but only after demonstrating over the course of at least one year’s worth of measurement of annual energy use that the combination of on-site renewable exported energy, plus the energy made up in RECs is equal to or greater than the delivered energy (NIBS 2015).

Our electricity comes from a variety of sources, some more friendly than others (U.S. Energy Information Administration 2015). While a large percentage of that electricity may come from a carbon-neutral source such as hydro-power there is no guarantee and further, there is little to no control over the energy mix that actually gets delivered to a building site. Therefore when the on-site energy is coming from a renewable energy source, establishing a net-zero energy balance between the building and the electric-grid helps to ensure that the building is carbon-emission neutral. If a building is to be carbon-negative, the amount of on-site renewable energy must surpass the non-renewable energy drawn from the grid (including the energy that is lost in transmission).

REALIZING CARBON NEUTRAL AND CARBON NEGATIVE DESIGN

To ease the transition away from the grid to a carbon-neutral or even carbon-negative design, the Society of Building Science Educators in cooperation with the American Institute of Architects (AIA) and the AIA Committee on the Environment has put together the Carbon Neutral Design Project. The Carbon Neutral Design Project was established as a means of helping the architectural
community achieve the Architecture 2030 challenge put forth by Ed Mazria. The guide thoroughly examines the principals of design that need to be considered to achieve a carbon neutral project and while they do not guarantee a carbon neutral project they aim to greatly aid the process (Wasley et al. 2012, Introduction).

The authors are quick to point out that net-zero energy does not equal a carbon neutral building — a net-zero energy building is centered on eliminating a building’s operational energy footprint on the grid through producing as much energy as it uses while a carbon neutral design is meant to reduce carbon emissions across all steps of the project (Wasley et al. 2012, Process). First and foremost, carbon neutral means focusing on the elimination of operational energy related emissions. Then it seeks to account for embodied energy; direct which accounts for the energy expended in the transportation of materials to the building site and the energy expended in the construction process, indirect which includes the energy to procure, process, and produce the materials, and lastly recurring energy which factors in the energy of all of the material and products needed to sustain the building throughout its lifetime. Given the wide range of products and materials that go into a building and then maintaining said building, this obviously complicates the process of accounting for carbon emissions. The final element in defining a true carbon neutral building is also including the carbon emitted in the travel of the building occupants (Wasley et al. 2012, What is Carbon Neutral?).

With the time and financial constraints typically placed upon a project, many designers are probably not going to have the opportunity to look in depth into the emissions footprint of every single item used in their product unless they had a very special client. Some programs such as the Impact Estimator offered by the Athena Sustainable Materials Institute allow for a quick estimate on how different material combinations and building construction types will impact the overall
emissions footprint of the project (Athena Sustainable Materials Institute 2016). While it may not include all products available in the market, it is a good tool to estimate a building’s carbon footprint and optimize the design. Going into this amount of depth may be hard to justify as the next few paragraphs establish that the greatest impact comes from a building’s operating energy rather than the impacts embedded in the building itself.

Two studies indicate that a majority of a building’s impact comes from the operating energy. Kim Bawden and Eric Williams performed life cycle analyses on ten different configurations for an apartment building mixing and matching between construction type and building size, including impact estimates from energy embedded within the construction materials, the energy expended in the construction process (including transport of materials), and operational energy. They chose not to include the energy that comes with repairing the building or the energy expenditure that comes at the end of life. The apartment buildings using wood structure with wood cladding are shown to use the least amount of energy over their lifetime whereas precast concrete buildings with steel structure are shown to use the most. The comparison was then parsed down into energy impact by construction cost, embedded material energy, and operational energy. Out of all the projected energy used, the wood-based apartments had the smallest percentage of their overall consumption going toward material procurement, processing, and building construction. Conversely, the steel structured building with concrete cladding was shown to have a larger portion of the total energy consumed over its lifetime going toward energy embedded in the material and the construction energy. Taking the ten different apartment building configurations into consideration, they found that on average 87% of the building’s total energy usage can be attributed to operational energy, 11% to the embedded energy within materials, and 2% attributable to energy expended during construction (Bawden and Williams 2015).
The second study also looked at the energy use of an apartment building over its lifetime. Unlike the last study, which was broader in context, this case looked at an individual forty-four unit, five-story building in India made from reinforced concrete and brick masonry. Also included in this study was the estimated energy that is associated with building upkeep and demolition. Their findings show that of the building’s total energy usage, 89% of it is attributable to its operational energy, 11% is used by energy embedded in the materials, and less than 1% is consumed during construction and demolition (Talakonukula, Prakash, and Karunesh 2013).

A third study, which Bawden and Williams use to compare to their own analysis, also evaluates the energy consumption of a building of its entire life cycle but instead of evaluating apartment buildings, this piece focuses on the energy of office buildings in Europe and the United States. For the U.S. office buildings they find that a majority of the building’s energy usage over time is dominated by operational energy at 82.8%, with materials taking up the next highest amount at 8.6%. Maintenance is somewhat impactful at 6% of total energy consumed. The last two, construction and end of life energy usage are negligible at 1.5 and 1% respectfully (Junnila, Horvath, and Guggemos 2006).

Effectively, these studies show that because the majority of a building’s energy consumption comes from its operational needs, the biggest gains in reducing the emissions footprint will be realized by focusing efforts on negating these demands. To reduce a building’s emissions footprint further requires an assessment and proper use of materials. Using primarily carbon neutral materials would help accomplish this goal. Gustavsson, Joelsson, and Sathre studied an eight-storey, 33 unit, wood-framed apartment building in Växjö, Sweden which had recently finished construction. Their goal was to understand how using wood as the primary building material would impact the building’s energy consumption over its lifetime. They found that if bio-based energy sources were
used, and construction byproducts were recovered and redirected, the building would not only be carbon neutral, but carbon negative for at least the first half of its lifetime (approximately 50 years). Projecting to a 100 year building lifespan — if the resident’s energy consumption doubled, the building would no longer be carbon negative by the end of its life (Gustavsson, Joelsson, and Sathre 2010). However, this was assuming a worst case scenario in which resident energy consumption continued to increase and efficiencies were not implemented over the building’s entire lifetime.

Combining a reduction or elimination of operational energy with a material that does not have an impact on emissions would effectively create a carbon neutral building.

The task of getting a building to neutral operational energy can be broken down into four steps. These consist of reducing loads and demand, meeting the loads efficiently and effectively, utilizing renewable energy sources and lastly, purchasing carbon offsets (Wasley et al. 2012, Holistic View).

The first step is to reduce loads and demand. This can be done in a variety of ways but what must come first is a close examination of what actually needs to be in the building. The smaller the building, the less amount of space that actually needs to be conditioned (which will reduce energy demands) and with less conditioning, the easier it will be to supply the building with the necessary amount of renewable energy. In essence, the program needs to be finely tuned to fit the needs of the user exactly, no more, no less. Additionally, the characteristics of the site should be taken into careful consideration as the design may be able to benefit from the conditions present (Wasley et al. 2012, Holistic View).

There are a number of items to account for when doing this. The climate zone that the project is located within needs to be determined — the design has to be appropriate for its location. Identifying the climatic trends will help determine whether the project will be more dependent
on cooling or heating for occupant comfort, and whether the locale tends to be arid, humid, or something in between. Wind and sun are also factors. If there is a lot of sun, it could be leveraged to the projects’ advantage, likewise with wind. Vice versa, if there is a cold winter wind, the building could be designed to mitigate the worst of the prevailing winds. This is another item which must be considered (Wasley et al. 2012, Design Strategies).

The sun is useful from an architectural standpoint because at the most basic levels, it can provide a project with both heat and light through solar radiation if the building is positioned to take advantage of these elements. A key component of proper positioning is aligning the size and location of the windows to capture sunlight when its wanted but also avoid sun when it’s not wanted. In addition, certain glass types can help capture thermal energy while others do the opposite by either allowing for transmittance using clear or heat absorbing glass or reflecting the thermal energy back into the environment with reflective glass (Wasley et al. 2012, Solar Geometry). An example of this would be using clear glass on the southern exposure of the building to capture as much heat as possible and then using heat absorbing glass on the northern exposure to allow light in but also prevent the heat that has accumulated on the southern face of the building from radiating back out into the environment.

Heat gain isn’t always desirable, especially during the warm seasons in temperate climates or in climates that are hot year-round. Techniques to avoid heat gain include shading the project with external devices, using internal shading devices, or using specialized windows. An external device could be something that’s affixed to the building such as a horizontal projection or it could be vegetation. Using deciduous vegetation is a versatile solution; it can prevent as much as 80% of the thermal radiation that would enter the building during the summer, but allow in approximately 70% of the thermal radiation in winter when it’s needed because the shielding element, the leaves,
have fallen from the vegetation. Shading solutions for a project are not equal in all respects due to
the fact that in the east and west elevations, the sun hits the building at a different angle than it does
on the southern exposure — particularly at sunrise and sunset, where the sun is too low on the
horizon for horizontal shading elements to be effective. For the southern exposures on a project,
the most effective shading devices are horizontal projections. These can be panels, louvres that
project horizontally, louvres that are stacked vertically, or vertical panels. The first two solutions
block occupant vision the least and the second two solutions block vision more, but all are effective
at preventing thermal gain on the southern exposure. For the exposures that are not south facing,
vertical fins, slanted vertical fins, “eggcrate” fins (a combination of vertical and horizontal fins, or an
egg crate configuration with horizontal louvers in place of horizontal panels all effectively prevent

Passively heating a building relies on retaining as much of the heat gained as possible.
Common methods for this include designing a highly insulted envelope, making sure the building’s
everse is tight, controlling the amount of air that enters and leaves the building, using materials
on the interior of the building that have a high capacity for heat storage that will slowly release the
heat back into the building throughout the day, and specifying windows that have a high R-value to
minimize heat loss. To accomplish passive heating, three general designs dominate. Through a direct
gain system, sunlight hits the floor made from materials such as ceramic tile or stone. Because these
have a high thermal mass they store the heat well and then release it throughout the day. Following
are rules of thumb to consider with a direct gain system (Wasley et al. 2012, Passive Heating):

1. The area of the thermal capture area should be at least three times the area of glazing,
with six times being the preferred amount

2. Typically the mass being used to capture the thermal energy should be thin rather than
thick, and effectiveness drops off after about 4’
3. Dark colors for the flooring will absorb heat while light colors for the walls and ceiling will help reflect light.

4. Insulation over the thermal mass will prevent it from working correctly.

5. Materials should have high thermal mass, such as brick or concrete.

6. For buildings that are constructed out of materials with low thermal mass such as wood, the glazing on the southern exposure should be no more than 7% of the building’s floor area versus 13% for buildings with high thermal mass such as brick or concrete structures.

7. If possible, glazing should be vertical due to ease of constructibility and summer shading. Additionally, windows should face directly south to prevent a drop off in thermal gain. Rotating the face of the glazing up to 15 degrees from due south is permissible but after 15 degrees there is a 10% drop in thermal gain, and after 30 degrees a 20% drop.

8. Low-emissivity glazing can help to reduce loss of heat during the night but can also drive up the cost of the project.

9. The insulating layer should be outside of the thermal mass (inside it will prevent gained heat from radiating into the building).

With a trombe wall, a secondary wall is placed directly behind the building’s outer layer of fenestration but not directly against it. This creates a pocket of air between which heats up. The width of the air pocket is project specific but could be anywhere from 1 inch (Autodesk 2015) to 2 feet (Lea 2010). The secondary wall is made from a thermally conductive material. Two gaps are also created at the base and the top of the wall. As the air warms, it will rise, pushing into the room through the top of the system by the natural stack effect that has been created. This will circulate the warm air throughout the adjacent space.

Much like a trombe wall, a sun space also creates a convective current. The key difference is that a sun space is usually large enough to be a useable space. Typically the floor will also be a heat absorbing material, in addition to the wall that is used to separate the sun space from the rest of the building. Like a trombe wall, as heat is gained and then released into the building through radiation,
a convective current will start, causing the warm air to be circulated throughout the building (Wasley, et al. Passive Heating).

Passive heating leverages heat gain while passive cooling seeks to avoid heat gain because it is easier to mitigate heat gain than to physically lower the temperature and humidity passively. In a sense, passive cooling is a misnomer because a space’s temperature isn’t necessarily being altered. Instead, occupants feel cool when the humidity level is altered, air is moved past the skin, or heat is somehow drawn from the building. Since it is hard to draw heat from a building, the best thing to do is avoid the heat gain all together. This is accomplished by keeping openings small in hot, arid climates, shading openings that are in cold, hot-humid, and temperate climates, using vegetation to provide shade for the building itself, selecting materials that resist heat, encouraging a cool microclimate, and using buildings as shading devices themselves. When heat does build up, it can be shed through ventilation or in hot arid climates, by using the building’s material to work in concert with the temperature changes that occur throughout the day-night cycle (Wasley et al. 2012, Passive Cooling). Materials with high thermal mass will collect heat throughout the day, and then release it at night when it is colder. By the morning they will have cooled and will remain cool to the touch throughout the day even after it has become hot (Wasley et al. 2012, Passive Cooling).

If the “heat sink” methodology is used there are a number of ways to transfer the accumulated heat including ventilative cooling, radiative cooling, evaporative cooling, dehumidification and mass effect cooling. Ventilative cooling or natural ventilation consists of a crossflow of air through the building and is powered by a pressure differential that occurs when openings are strategically placed in the building to take advantage of the local wind patterns. Radiative cooling is broadly used to define the transfer of heat to a sink through radiation. One example of such a sink is the night sky. Evaporative cooling allows sensible heat to be transferred
into moisture. As water evaporates out of warm air, it absorbs the heat, making the air feel cooler. This method only works in climates that are dry. In humid environments, the water content in the air is high enough such that any water that is added would not evaporate, rather, it would raise the humidity levels within the building, and decrease comfort. The converse cooling method involves pulling moisture from the air by cooling it below the dew point — this method is more commonly known as air conditioning. Mass effect cooling relies on the same principals as radiative cooling but in this case, the heat is not only leaving the building but also is being drawn from the mass of the building, where it accumulated throughout the day, and then as cool air moves over the building at night, the heat is drawn from the building (Wasley et al. 2012, Passive Cooling).

Temperate climates necessitate a balance between heating the building and keeping it cool because they experience both hot and cold seasons. In order to accommodate this intermediate state, the building should be well insulated for the winter but have large openings to allow for ventilation. Additionally, these openings should be shaded but only to the degree that it will prevent unwanted heat gain during the summer while still allowing for warmth to penetrate into the building during the winter. Deciduous plantings help keep the building and surrounding environment cool. Providing some sort of thermal massing element in the interior of the building also helps as a heat sink, tempering the day-night shift. Cold climates are similar to temperate in design strategies but will emphasize passive heating over cooling. Despite this emphasis, shading can be utilized to prevent the large areas of glazing used for passive heating from becoming a detriment during the summer. Operable windows in combination with appropriate positioning can also help cool the building with natural ventilation. Although insect screens can cut down on ventilation by around 50% and operable windows can allow unwanted moisture to enter the building if not oriented correctly, with shading also able to double as rain protection, operable windows are still a viable strategy in cold
climates during the cooling season (Wasley et al. 2012, Passive Cooling).

Avoiding heating and cooling loads is a portion of reducing loads and demands. The other is cutting down on the use of artificial lighting through daylighting. Both daylighting and passive heating rely on the sun but instead of requiring direct exposure to sunlight, daylighting works best with indirect light. This helps to prevent glare and provides an even light. In addition to reducing the need for artificial lighting and the associated energy demands, the heat that lights give off is reduced and therefore the cooling load is reduced as well. Additionally, natural light has been shown to be good for mental wellbeing and productivity (Wasley et al. 2012, Daylighting).

Because daylight cannot be directed in the same manner as artificial lights, openings in the project need to be strategic, work in tandem with the building’s orientation, and make use of interior geometries or implement devices such as light shelves to control glare. Light entering the building should be modified as desired by using different types of glazing (Wasley et al. 2012, Daylighting). Additionally, Guzowski argues that in order for daylighting to be truly effective at reducing the impact of artificial lighting, natural light should be approached as a building’s primary light source, rather than secondary (Guzowski 2012).

Creating a tight envelope is fundamental in reducing load and demand, preventing the escape of conditioned air from the building. Air escapes in two manners. Because air wants to move from high to low pressure, it will often get out through openings in the building, where different materials meet, or at points of fenestration. Careful detailing of the design must be accompanied by proper installation and maintenance. This is paramount to prevent unwanted leakage. The second way that air escapes the building is through vapor diffusion. Moisture in the air passes through the walls and often will get trapped in the system. A vapor barrier placed on the conditioned side of the building can help to prevent this from happening (Wasley et al. 2012, Envelope)
Site comes next — where the project is located can have a huge impact on the project’s carbon footprint. Sites in urban settings have the advantage of potentially decreasing or eliminating transportation carbon emissions if they are in walkable locations but on the other hand, often have to contend with shade from nearby buildings and small site boundaries, potentially limiting opportunities for solar and wind renewables (Wasley et al. 2012, Design Strategies).

Typically a building’s interior temperature will be set by its occupants to fluctuate only a few degrees. If the owner or occupants are willing, expanding the customary “comfort zone” to allow for wider swings in temperature can help to remove the necessity of constant space conditioning.

Depending on the passive heating and cooling options available to the project, some or all mechanical systems may be either paired down or eliminated entirely (Wasley et al. 2012, Design Strategies).

As programmatic elements may be able to take advantage of passive heating, cooling, or daylighting, if a gain can be had by making use of the elements, the form of the building should respond accordingly, be it an alteration to the building’s massing, solar orientation, height or internal organization (Wasley et al. 2012, Holistic View).

Once the site has been leveraged to the greatest extent possible the artificial elements that supplement the passive heating, cooling, and lighting need to also be as efficient as possible. Not only should they be efficient, they should also only be used when needed. That is where the effective aspect comes in — artificial lights are not as effective, or even needed, if the room is already lit by daylight. Therefore, sensors should be utilized where appropriate to help the building’s systems in tandem with the passive systems that are functioning autonomously (Wasley et al. 2012, Holistic View).

After the need for mechanical heating and cooling has been reduced as much as possible
and the space conditioning needs have been met with the most energy efficient equipment, the
third step is to provide power to these systems with a solution that does not rely on fossil fuels as
an energy source. These include photovoltaic systems that are either integrated into the building
(attached to the roof or walls) or detached from the building and situated on-site near the building
(Wasley et al. 2012, Holistic View), solar thermal systems which use the sun’s thermal radiation to
preheat water (Wasley et al. 2012, Solar Hot Water), wind turbines, combined heat and power (CHP),
and geoexchange systems. Projects that choose to rely on integrated solar need to ensure that the
building is oriented for maximum exposure to sunlight and that the surrounding context does not
cast too much shade (Wasley et al. 2012, Holistic View). Solar panels will be optimally efficient if
they are oriented to be 90 degrees from the sun’s angle of incidence, or angle that the sunlight strikes
the panel depending on time of year. Solar thermal systems follow the same rule (Wasley et al. 2012,
Solar Thermal). Because the angle that the sun strikes the earth changes throughout the year, the
rule of thumb is that panel’s angle should be equivalent to the site’s latitude plus fifteen degrees to
account for the seasonal shift in the sun’s position in the sky (Wasley et al. 2012, Photovoltaics). Like
solar systems, wind requires the appropriate orientation. Wind suffers from the fact that it creates
noise and its installation can become contentious if those near the project do not like how it looks
and both are subject to variance in output due to changing weather. Therefore, it makes sense to
combine either one or both with geoexchange or CHP systems. Geoexchange and CHP are less
context dependent, they do not rely on the elements, and the amount of space available is not a
detriment to their productivity, therefore they will work in a variety of conditions (Wasley et al. 2012,
Holistic View).

The final step, after all other options have been exhausted is to purchase carbon offsets.
This should theoretically bring your project to a state of carbon neutrality. But again, this is a last
step because the whole idea is to reduce, renew, and then offset (Wasley et al. 2012, Holistic View) — if offsetting were on the table from the start, there would be no incentive to downsize or use renewables.

ALGAE

Achieving a net-zero energy building is the first step in getting to a carbon-negative building. Upon reaching a state of net-energy neutrality, where the building is either producing as much or more energy than it is drawing from the grid through renewable resources, the next step is the introduction of an active carbon-sink. As explained in the earlier exploration of carbon-sequestering techniques, currently the best opportunity for achieving this aim is through the reliance and amplification on an already functioning biotic system. For the purposes of this project, the study and addition of an algal-based sequestration system was selected to fill this role. The following section outlines the different types of algae systems available, and then identifies the best system in the context of this project and how it would work.

In the realm of carbon sequestration, algae has a number of advantages. Through its growth, algae sequesters carbon dioxide (Kumar et al. 2011), with some citing a more efficient photosynthetic process than terrestrial plants (Sudhakar, Suresh, and Premalatha 2011; Patil, Tran, and Giselrod 2008). In fact, some strains of algae can double their biomass in just three and a half hours (Patil, Tran, and Giselrod 2008). It can be used for the production of biofuels (Kumar et al. 2011) and also as a method for the filtration and cleaning of wastewater (Ondrey 2014). Additionally, algae and cyanobacteria (blue-green algae) can thrive in conditions that are dry or wet, and in fresh or saline water (Kumar et al. 2011).
It is estimated that algae can absorb approximately 1.8 g of carbon dioxide for every 1 g of algal biomass produced (Kumar et al. 2011; Sudhakar, Suresh, and Premalatha 2011) with growth rates of anywhere from 5 to 50 g/m²/day depending on conditions (Sudhakar, Suresh, and Premalatha 2011). This is accomplished through photosynthesis — sourcing electrons from water and deriving energy from sunlight, the result is oxygen and sugars (Kumar et al. 2011) in the form of biomass (Slegars et al. 2011). Every sugar mole that results from photosynthesis requires eight mols of photons and each mol of photons contains 218 kJ of energy. With a general efficiency rate of 27%, for every 1744 kJ of solar energy delivered, around 470 kJ of potential energy is stored within the algal mass (Kumar et al. 2011). Not taking into account all of the different growth parameters, algae strains will absorb carbon dioxide at different efficiencies by default. Some strains do better in harsher environments while heterotrophic algae can grow without the input of light (Sudhakar, Suresh, and Premalatha 2011).

There are a number of options available when designing a system for algae growth but all fall under one of two categories. The first category consists of a variety of open systems. These can come in the form of ponds or raceways. Ponds can either be horizontal or circular while a raceway is characterized by a rotating structure which is used to circulate the algae broth (Aresta, Dibenedetto, and Dumeignil 2012, 84). They can come in different sizes with volumes ranging anywhere from 100 to 10 billion liters. The large amount of exposed surface area typically found in pond systems provide the algae with ample sunlight and therefore encourage high levels of biomass growth (Sudhakar, Suresh, Premalatha 2011). These systems typically rely on a mechanism such as a bubbler (Aresta, Dibenedetto, Dumeignil 2012, 84) to feed the nutrients into the system and a paddle wheel to circulate the broth (Sudhakar, Suresh, Premalatha 2011). Nutrients may enter into an open system through runoff or by channeling wastewater into the pond from nearby facilities (Aresta,
Unfortunately, these systems face issues of respiratory loss (carbon dioxide escape into the atmosphere), grazers, and animals falling into and drowning in the water (Sudhakar, Suresh, Premalata 2011).

Alternatively, algae can be grown in closed systems, also known as photobioreactors. These are advantageous over open ponds in a few ways. First, they are closed environments. Therefore they are controllable — contamination is minimized, water evaporation is highly minimized or prevented, and carbon dioxide absorption rates can be controlled (Sudhakar, Suresh, Premalata 2011). Photobioreactors, come in a variety of forms but all are housed in transparent container walls that are typically made from glass or plastic (Aresta, Dibenedetto, and Dumeignil 2012, 85).

Closed systems do have some disadvantages. As algae grows it will form a thick, opaque blanket on the walls of the system, preventing light from reaching the inner layers of algae. Therefore, unless there is regular maintenance and cleaning, they are prone to decrease in production capacity. Like the open pond systems, the closed systems need to be circulated to prevent the problem of collection on the walls. Pumping systems need to be selected carefully as too much aeration or force will damage the algae. Conversely, too low of a flow rate and the algae will suffer from bleaching due to too much sunlight. This will result in a build up of excess oxygen, suffocating the algae and slowing the biomass growth rate. These drawbacks are compounded by the fact that they are more expensive than open systems, requiring as much as ten times the capital investment (Sudhakar, Suresh, Premalata 2011). While an open pond might cost about $100,000 per hectare, photobioreactors can cost as much as $1-1.5 million per hectare. Despite these drawbacks, photobioreactors provide higher yield, achieving growth rates three to five times higher than those of open systems. Additionally, they are much less dependent on land and water than open pond systems (Aresta, Dibenedetto, and Dumeignil 2012, 84, 87).
Photobioreactors come in a number of forms partially because there is still question as to which configuration is the most optimal. Given that algae is grown for different reasons, the most accurate answer would be that there is no one ideal configuration as long as the system has been optimized for its climate. Photobioreactors can be built in the following configurations (Kumar et al. 2011 unless otherwise specified):

1. Vertical tubular photobioreactor

A vertical tubular photobioreactor has a sparger at the base which delivers carbon dioxide and agitates the algae. At the same time this process will also remove oxygen that has built up during photosynthesis.

2. Bubble column reactor

Bubble column photobioreactors are defined by their height and width, with their height being at least twice their diameter. Like the vertical tubular photobioreactor they also rely on a sparging process to deliver the necessary carbon dioxide and mass transfer. They have an advantage in that they have a low surface area to volume ratio, are lower in cost, allow for easy release of oxygen and have no moving parts. In larger systems perforated panels break up the volume of space to ensure that the bubbles released from the sparger avoid agitating the algae too much. Light is provided externally and growth will depend on both this and the rate at which gas is passed through the system.
3. Airlift photobioreactor

An airlift photobioreactor contains the algae within tubes that are split into two distinct zones. The first is the riser and this is where the algae receives sparged gases. The second zone is the downcomer. In this zone the algae is left undisturbed. Airlift photobioreactors are further differentiated by whether or not they are an internal or external loop reactor.

In an internal loop reactor the regions are split by a draft tube or a split-cylinder while in an external loop reactor the two zones are physically distinct, which each zone being self contained within its own tube. Sparging the algae introduces bubbles which helps to mix the broth. Agitation is avoided though, as the algae is fragile. The introduced gas bubbles then move to the top of the riser column. Some of the gas escapes at the top or “disengagement zone” and in the process displaces some of the liquid into the downcomer. Airlift reactors have the advantage in that they effectively mix the algae solution, helping to equalize the amount of light that the algae receives (Kumar et al. 2011). Unfortunately due to the large volume of these systems, the sparging process is energy intensive, sometimes demanding up to 2000 W/m³. Therefore, for the purposes of maximum algae growth, these are not an ideal system (Shi 2014, 37, 39).

4. Flat panel photobioreactor

Flat panel photobioreactors are characterized by having a minimal light path and are cubical in form. They have high surface to volume ratios and rely on an open gas disengagement system. The broth is moved either with air that has been bubbled through the system or through mechanical rotation (Shi 2014, 39). A light path depth of 15mm proves ideal for the
growth of biomass while maintaining an optimal ratio between light and dark zones within
the reactor (Degen et al. 2001).

5. Horizontal tubular photobioreactor

Still relying on a tubular containment system, a horizontal tubular reactor, as the name
implies, is a series of horizontally placed tubes or loops. The advantage over a vertical
system is that horizontal tubular systems that are outdoors will receive more sunlight due
to this configuration, potentially increasing efficiency of the photosynthetic conversion
process from CO2 to sugars and oxygen. CO2 is delivered through a gas exchange system.
The advantage of this system is also its downfall. An abundance of light will result in the
efficient uptake of CO2 but this will also result in the creation of oxygen. If the oxygen
builds up faster than the exchanger can remove it, photobleaching occurs which will reduce
the effectiveness of the photosynthesis process (Kumar et al. 2011).

6. Helical type photobioreactor

Helical photobioreactors are coiled tubes that are attached to a separate degassing unit
which rely on an attached centrifugal pump to bring the algae to the degasser. While carbon
dioxide can be injected from either the top or the bottom of the system, it was found
through trial and error that injection from the base of the system provides the best results.
The efficiency of photosynthesis can be improved by utilizing PVC which will diffuse the
light entering the system but helical photobioreactors are prone to clogging (Kumar et al.
Additionally, helical systems require more energy by a large order of magnitude — while a helical reactor could require 3,200 W/m³ a flat plat reactor would require 100-200 W/m³ (Dillschneider and Posten 2013). In another comparison, a helical reactor is shown as requiring 2000 W/m³ to 15 W/m³ for a flat plat reactor (Duan and Shi 2014).

7. Stirred tank photobioreactors

With a stirred tank system the algae is redistributed using mechanical motion delivered by an impeller. To avoid algae being damaged by vortexes, baffles are installed. With this type of photobioreactor CO2 enriched air is delivered by a bubbler at the base of the system. External fluorescent lamps or optical fibers provide illumination — problematically, these types of systems limit the ability of the algae to absorb light due to a low surface area to volume ratio. Unused spared gas and oxygen is separated by a large disengagement zone. The combination of the low surface to volume ratio and damage due to mechanical agitation limit the capacity of these systems to efficiently sequester CO2.

INFLUENCING FACTORS ON CARBON SEQUESTRATION

A number of influencing factors can be identified as having large impacts on the rate of algal growth and ability of algae to absorb and sequester carbon dioxide. First among these is temperature. Algae can withstand a somewhat high range of temperatures, some up to 60°C. As the solubility of carbon dioxide is dependent on temperature, algae able to fair better at higher temperatures will be able to absorb more carbon dioxide. pH is the second criteria which will influence algal growth — if the algae’s source of carbon dioxide is coming directly from flue gas, the
levels of SOX must be carefully maintained as the SOX will make the broth more acidic, diminishing growth. In addition to SOX, levels of NOX also impact growth of the algae depending on the strain. Therefore the third criteria is the mixture of gas that is fed to the algae. The importance of this lies in the impact that this will have on the pH levels of the algae broth. Of course, how the algae reacts will be dependent on the strain of algae (Kumar et al. 2011).

Light is the fourth factor. The amount of light that the algae has to work with greatly influences its growth rate. The intensity of the light and amount of light distribution are large determinants of the amount of light that the algae can utilize and the biggest contributing factor to this is the design of the photobioreactor system, both in the way that agitates the broth and its depth. Strain of algae is the fifth determinant. Some strains are much more fragile while others, such as Spirulina, are much more resilient to stress. The sixth item, culture density, has a direct impact on the fourth criteria, access to light. In fact, productivity and the extent to which algae can utilize the light that it receives is a direct function of the culture density. The more dense the culture, the less light will be absorbed due to self-shading. Vice versa, if there isn’t enough algae, then some of the light energy that hits the system will be lost because the algae can only utilize a specific amount at any one time (Kumar et al. 2011).

The seventh impactor affecting CO2 sequestration is ironically, levels of CO2. Again, differing based on strain, CO2 levels beyond a certain point can cause stress, reducing the algae’s ability to synthesize and sequester CO2. In part this is due to the fact that the introduction of CO2 reduces the pH level of the broth. Too low, and the algae become inefficient. The levels of ambient CO2 present in the mixture are a result of CO2 absorption rate, which is a function of the volumetric mass transfer coefficient. The volumetric mass transfer coefficient is determined by the flow of liquid within the photobioreactor, and that in turn is highly dependent on whether the flow
rate is being measured at the bubble flow zone, the transition zone, or the heterogeneous zone. The last influencing factor on the growth rate of algae is the level of ambient O2 in the system. Too much oxygen and the algae will experiencing photo bleaching making the photosynthesis process less efficient. To combat this, an effective degassing system (or means of removing excess O2) is necessary (Kumar et al. 2011).

**ALGAE SELECTION**

*Chlorella* sp. and *Spirulina* sp. both seem to be well suited to a wide variety of photobioreactor systems and *Chlorella* sorekiniana seems to flourish in flat panel reactors, with a particularly good volume to productivity ratio (Kumar et al. 2011). Dr. Kyoung-Hee Kim at UNC Charlotte identifies *Chlorella* vulgaris as a promising algae species for use in her research prototyping an algae facade (Kim 2013) and *Chlorella* has also been used successfully in architectural application by Arup (Landers 2013). Additionally, *Chlorella* can withstand a high percentages of pure carbon dioxide (Ono and Cuello 2004) and temperatures of up to 45 degrees Celsius (Shi 2014). This is a significant factor because different strains of algae have unique reactions to carbon dioxide. Some are more tolerant than others. If too much carbon dioxide is added at one time to the broth, it can cause a biological stress in the algae reducing its ability to perform photosynthesis (Sobczuk et al. 2000).

Because it is hardy, *Chlorella* is a good candidate for a flat plate system attached to a building — it can withstand varying levels of carbon dioxide and changes in temperature. Additionally, because *Chlorella* can withstand higher temperatures, utilizing the system secondarily as a thermal PV system would follow as a logical option. While an alternative to *Chlorella* sp. could be *Scenedesmus* sp. which has been demonstrated to have an even higher rate of biomass productivity and ability
to fixate CO$_2$ over Chlorella vulgaris when tested in the same CO$_2$ rich environment (Yoo et al. 2010), given the fact that it has already been used successfully in an algae-producing building facade (Landers 2013) this design will also use Chlorella.

**BIQ BUILDING, HAMBERG, GERMANY**

Designed for the International Building Exhibition Hamburg (IBA) in Germany, the BIQ building is the first of its kind. Completed in 2013, the BIQ contains fifteen apartment units, with a total floor area of 1,600 square meters (5,249 square feet). Each unit itself is anywhere from 48 to 122 square meters (157 to 400 square feet). Where it differentiates itself is that it is a “Smart Material House”. The BIQ building is one of four pilot buildings (Roedel and Petersen, 2013) designed by Austrian based design firm SPLITTERWERK (SPLITTERWERK) for the IBA Hamburg Competition, alongside Arup Deutschland GmbH, SSC GmbH and Colt International GmbH. SPLITTERWERK’s response to this competition was an exercise in utilizing and applying a new technological solution to an already existing, traditional building type (Roedel and Petersen, 2013). In this case, the typical apartment building was re-imagined to showcase a fundamentally new approach to the standard building envelope.

To understand the inspiration and design of the BIQ building, it is important to have some background on the IBA Building Exhibition. The IBA Building Exhibition was organized around the theme of “Smart Materials” and through this theme the design for the BIQ building emerged. Smart materials are defined as being transformative as well as active. More so, they should be environmentally responsive and given the appropriate resources, an informed application of these materials would most likely incorporate an interconnection with building services to produce
optimum energy and material performance (Roedel and Petersen 2013).

Given the capacity and potential of smart materials, it was IBA Hamburg’s position that we need to re-evaluate and re-address our materials categorically — with new ways of measuring material and technological performance, a new means of approaching architectural design arises. Furthermore, this change should not only be occurring at the level of the individual building. With the advent of decentralized water systems, power generators, combined heat and water and means for utilizing waste heat, functions which relied solely upon the urban infrastructure are no longer bound to such large scales. By scaling down these services, we now have an accessible and attainable means for reclaiming and capitalizing on energy which would otherwise be lost. As we move toward the reality in which individual buildings are no longer passive receivers of services but instead a node in a network of interconnected, communicative buildings that can produce and store energy we have the opportunity to transform our cities with this evolving paradigm shift (Roedel and Petersen 2013).

With this shift towards decentralization as described above, the result is a phasing together and blurring of building function and features, with smart materials aiding in this culmination. The ingenuity of the BIQ Building is that through the implementation of the “smart material”, SPLITTERWERK in collaboration with Arup has been able to realize in the BIQ, the practical functionality ushered in by the use of smart materials with a building that produces an energy source, generates heat, and creates shade, all of which is generated from the facade of the building and its interactivity with the surrounding environment (Roedel and Petersen 2013). Not coincidentally, this design perfectly reflects the benefits that can be gained through the use of smart materials.

SPLITTERWERK and Arup began their ideation process for the BIQ building in 2009.
(Roedel and Petersen 2013). At that time, the building was known under a different moniker — the “Smart Treefrog” (SPLITTERWERK). Contained within this early process was a concept for a building that utilized a-typical materials and technology to gather energy and condition air. This took the form of a multi-layered building. The inner portion was to contain private space for living while the outer was to house public and commercial uses. Although this idea was initially met with interest, there was sentiment from the evaluating jury that the idea was not fleshed out enough. Their critique of the project included suggestions for a stronger emphasis on one idea and a retooling of the program due to the prohibitive financial hurdles that the project would otherwise face (Roedel and Petersen 2013).

The idea of a “house-within-a-house”, which focused on both living facilities and commercial operations was explored until 2010 but ultimately cast aside due to its complexity. Despite this setback, the desire to have the building provide for its own energy requirements through the use of a novel technique (Roedel and Petersen 2013), the growth of Chlorella algae (Landers 2013), remained the same. Even though it was conceptually feasible, the algae facade created a technologic hurdle — housing a photobioreactor on the side of a building had never before been attempted. More complicated still was that the design team wanted to integrate it with the building’s services (Roedel and Petersen 2013).

Before any of this could be achieved, an extensive amount of research and testing was conducted by SSC GmbH and as early as August 2008 a working installation had been established in Hamburg Reitbrook. The ability to test the efficacy of large-scale algae production was made possible through collaboration with the City of Hamburg, colleges within Northern Germany, and E.on Hanse AG. This collaboration resulted in the Technologies for Developing the Resources of Microalgae or “TERM” research and development project. Through this research the means for
producing and supporting algae in the varied light and temperature conditions of Northern Europe, allowing for higher than normal cell density (leading to high production rates of biomass, 10-100 grams of dry weight per day), a high conversion of light to biomass at a rate of five to eight percent, prevention of system backup (biofouling), and automating the system to minimize maintenance. All of this ultimately culminating in a working prototype for what would ultimately become the BIQ’s reactor system. Becoming more fleshed out in 2010 via the federally funded Building for the Future program, the system now included a functioning support system, a control system, and a management system. After a successful re-envisioning and design, the BIQ building became a reality in the spring of 2013. What resulted from the original concept, is both a novel spatial design as well as a technological milestone (Roedel and Petersen 2013).

While basic, the cubic shape of the five-storey BIQ building belies its true self. Designed around the implementation of architecturally applied photobioreactors, “Living on Demand”, and the ability to change based on the changing needs of its users, it is composed of two completely separate facade systems. The first being stone and concrete, and the second is its adaptive algae facade, which as a result of direct interaction with the surrounding environment, provides the building with the ability to generate energy, and control light and shade independent of traditional methods (Roedel and Petersen 2013).

The algae system does not comprise the entirety of the BIQ’s facade system but the functionality that it provides is in addition to the regular functions of a facade. Primary features provided by the typical facade or wall system includes the control of thermal radiation, air temperature, humidity, air flow, optimum sight and visual privacy, an optimum audial experience and acoustic privacy, a boundary that keeps out undesired wildlife, structural support, prevents the entry of unwanted water and moisture, and controls fire. Secondarily, facades control the thermal
quality of surfaces, provide useful surfaces, and adjust to movement accordingly and as needed. And lastly, facades play a tertiary role in aiding in providing channels of communication (Allen 2005). Effectively, the facade of the BIQ building accomplishes the standard requirements and then goes above and beyond with its second skin.

The facade operates in a few distinct ways, which is delineated by the two separate layers. The inner layer is a plaster-insulated heating system while the outer layer is the thermally detached algae-generating bioreactor. As the algae grows and changes in accordance with the seasons, the opacity of the building’s outer layer changes as well. This alters the light that enters the building giving inhabitants an oscillating, shifting experience that is a direct reminder of the fact that the building is actively being helped by the surrounding environment to produce energy (Roedel and Petersen 2013).

Any sort of algae-producing system functions through photosynthesis, necessitating an exposure to light of some sort. Therefore the decision to utilize the algae system directly as a facade element was not only the most sensible solution but was also reinforced by the fact that SPLITTERWERK wanted passers-by to be very aware of the unique nature of their project’s ability to produce, store, and directly utilize the energy that is self-generated (Roedel and Petersen 2013).

BIQ’s algae facade is a convalescence of many different forms of energy, including solar thermal energy, geothermal energy, a condensing boiler, and district heating. Not only does it bring different sources of energy together, it generates energy through its synthesis of biomass and the byproduct, heat. This is accomplished through 129 ‘reactor modules’ that are 70cm wide, 270cm high and 8cm thick. This converts to approximately 27 1/2” x 106 1/4” x 3 2/16” (Roedel and Petersen 2013). The module’s walls are composed of a laminated safety glass that have been left clear to let the sunlight through, forming three distinct chambers (Landers 2013). The central chamber
has a 24-litre capacity and is filled with water so that the algae has a medium in which to grow, while the two outer chambers are filled with argon gas allowing for thermal insulation, reducing heat loss (Arup 2015). The module is then mounted in a steel frame. In addition to acting as a support for the weight of the modules, the frame also serves as housing for the necessary wiring (Roedel and Petersen 2013).

The building’s heat source is a micro-CHP or a combined heat and power unit that is powered by bio-gas. The benefit of using this system is that the flue-gas byproduct, which contains CO$_2$, is directly used to enrich the algae. CO$_2$ and nutrient salts are then utilized as a food source for the algae and in turn these act as a catalyst, helping to transform the algae into a useable fuel source. Like the more traditional flat plate photobioreactors explored in the previous section, this system also makes use of an airlift, which runs compressed air through the base of the module creating bubbles and lift, consistently circulating the algae. High flow velocities create a lattice of air beads, called scrappers. These two items in working in tandem help to prevent the buildup of bio-pollution and algae building up on the walls of the reactor (Roedel and Petersen 2013).

In addition to flow occurring within each singular panel, there is a greater flow throughout the entirety of the system as each panel is interconnected. As the algae collects light throughout the day, the water within the panels heats up to approximately thirty-five degrees Celsius — around ninety-five degrees Fahrenheit. While the heat captured from solar radiation aids the efficiency of the facade, because the BIQ building is located in a temperate climate, there also is a requirement for input into the system to prevent unwanted freezing. The algae broth is kept fluid with a thermally insulated stainless steel wire. In the summer, the water is kept below thirty-five degrees celsius and in the winter time it is kept at five degrees celsius or higher (Roedel and Petersen 2013).

Once the liquid solution has made its way through the entirety of the panelized wall system
the algae is collected by way of filtration within the building services center. All of the heat that was gained throughout the day is also captured using a heat exchanger. Built to Passive House Standards, the BIQ building requires a minimal amount of additional heat. The heat that is gathered does not go to waste. Instead, it is used for heating and preheating water which is used seasonally for underfloor heating. Additionally, as spent air is released from the building’s ventilation system, a heat recovery system also prevents usable heat energy from bleeding into the surrounding environment. Any excess heat energy is stored in geothermal boreholes that reach a depth of about eighty meters. Then, when the energy is needed, heat pumps recapture the stored heat. To make a useable biogas from the algae, it is collected and converted in an off-site biogas production facility once a week, and the resulting product is then used as a fuel source for the city as a part of the “Wilhelmsburg Central Integrated Energy network”. When there are gaps in the facade’s ability to produce heat due to colder conditions, the city’s district heat supply makes up the difference (Roedel and Petersen 2013).

Each panel produces 15g TS/m2/day, TS being “total solids.” Utilizing the algae as a fuel for bio-gas, the facade has a production capacity of up to 345 kJ/m2/day. In terms of the biogas that is produced using the facade’s algae biomass, methane gets produced at a rate of 10.20 L/m2/day. But what is that in a year? Accounting for cloudy or inclement weather, it was assumed that the BIQ will produce energy three hundred days of the year, translating to a total of 612 cubic meters of methane per year (Roedel and Petersen 2013). This is with an average of 1,557 hours of sun in Hamburg, Germany. By Comparison, Rochester, NY has an average of 2,298 hours of sun on an annual basis, meaning that the potential for the production of usable energy is even greater (Current Results 2015). In terms of pure numbers, that’s 6,487 kWh of methane-derived energy in a year from the building’s 200 square meters of facade (Roedel and Petersen 2013) or according to Jan Wurm, one of the BIQ’s lead designers, approximately 30kWh per square meter in a year (Landers
While approximately 30% of the produced energy goes back into operating the facade, the system still generates a hefty 4,541 kWh per year in methane based energy and about 6,000 kWh of energy in the form of heat (Roedel and Petersen 2013). That translates to about 150kWh per square meter per year (Landers 2013). At the time of the building’s first operation, the system was running at an energy efficiency of around 48% according to Dr. Martin Kerner, one of the heads of SSC GmbH (Arup 2013), with a 10% conversion ratio of light to biomass and 38% conversion of solar radiation to heat (Arup 2015) — much higher than the estimated 12-15% for solar photovoltaic but lower than the estimated 65% solar energy utilization that solar thermal systems are typically known for (Arup 2013). According to Wurm, the building reduces carbon dioxide by approximately 8 tons per panel per year (Schiller 2014).

The water in the bioreactors is composed of nutrient-enriched tap water, and mixed with a proprietary combination of nutrients including nitrogen, phosphorus, and trace elements. It is then monitored and adjusted to maintain optimum growth through an automated supply system. As matured algae leaves the system, the appropriate ratio of nutrients and CO2 are added back into the growing medium, while the algae is saturated with carbon dioxide using the air-bubbler method. Compressed air containing CO2 is added into the system at about twenty-nine pounds per square inch once every four-seconds. Air and water are ferried throughout the facade with a “carrier” system containing both types of lines. The air enters through a valve that is controlled magnetically. In addition to an inlet and outlet for both air and water, there is also an overflow line and spray nozzle located at the top of each panel. All four air and water lines meet back up in the BIQ’s “energy centre” which is located separately from the rest of the building's mechanical control devices and each floor has its own set of air loops, water loops, and distribution controls that are daisy-chained together into one master control (Roedel and Petersen 2013).
The algae procurement process is completed using a proprietary extraction method developed in partnership with AWAS International GmbH. Once the algae is harvested from its growing solution, the depleted growing medium is deposited into the local sewage line and then lost nutrients are replenished as needed approximately once weekly. While some waste does leave the system, an effort is made to keep as much in-system as possible. Despite the fact that it does require some additional inputs, the fact that the micro-CHP is fueled by algae-derived bio-gas, the waste product of the micro-CHP is flue gas and that flue gas is compressed and fed to the algae-producing facade, the system truly does operate in a near closed-loop with near self-sufficiency. Although not currently installed, there is opportunity to include solar photovoltaic panels as well, further reducing the energy demands of the system. Utilizing the facade in this manner helps reduce the required growth inputs (bioreactors) both lessening the environmental impact of operating the algae facade (Roedel and Petersen 2013) and strengthening the efficacy of the system.

Moving from its technical aspects to the spatial arrangement of the building, just as the facade is in a constant state of flux due to changing environmental conditions, two of these units — titled the Milan and the Hamburg — are adaptable, their design enabling a lifestyle of “Living on Demand.” Made reality by SPLITTERWERK and Arup, this concept was inspired by the likes of architects Mies van der Rohe, Frank Lloyd Wright and Adolf Loos resulting in adaptive apartment units that make use of a function-“neutral” zones and function zones. In this setup, the functions of the apartment (for example the kitchen, bedroom, and bathroom) reside within built-in furniture that can either be in use or stored away into the walls, thus returning the room to a state of function-less neutrality. Essentially, the rooms are blank slates, while at the same time, able to fulfill any number of desired needs (Roedel and Petersen 2013).

Each neutral zone is attached to a reciprocating function-assigned zone. While the interior
decor is simple in these units, color plays a major role in delineation between the individual zones. Additionally the color of the furnishings are directly correlated to the zone within which they reside. A sharp contrast exists between the two units — the Hamburg is blanketed in grey while the functional zones are exaggerated with punches of color. These zones are made more distinct by the black borders around the colored areas that glow with fluorescence in the dark. Conversely, with the Milan’s rooms, “Invisible Cities” and “Breakfast out of Doors”, residents are treated to full-bleed vistas of a “panoramic roof landscape... and a forest backdrop” (Roedel and Petersen 2013), as it presents a foray into the world beyond its upon its walls. It’s third themed room with its blue walls, is aptly named “The Lagoon” (Roedel and Petersen 2013). Despite these differences, no distinction in either unit is made between wall, floor, or ceiling. The rooms uniformly adhere to their theme. Truly, the function of the room is determinant of its boundaries.

Looking at the floor plan and it would seem that SPLITTERWERK is attempting to recreate a modernist design. While inspired by some of the Modernist movement’s greats and their inclination to provide a sense of flowing space, SPLITTERWERK instead deviates. Even though the floor plan reflects an open, seamless connection, their true intention is to provide the user an opportunity to literally capture the space as needed. There is no desire to prevent delineation, but they instead provide a new means of establishing boundaries that are user selected (Roedel and Petersen 2013).

SPLITTERWERK intended to meet the building’s entire energy requirements with its algae facade. The 200 square meters of paneling helps to negate the electricity use of at least one of the building’s units and the 6,000 kWh in heat energy that is generated supplies enough heat for four of the apartments (Rodel and Petersen 2013). It falls short of accomplishing these tasks for the entirety of the building. To put it in perspective, 4,500 kWh could power an average sized home by
itself. At this point it is not certain whether this was the optimal approach for their goal of meeting the building’s entire energy requirements. Perhaps with a different building typology or a larger size system they could have realized their concept. Despite this, the project did succeed in that it tried something new. And, if the main metric for success was to sequester carbon, it was able to accomplish this task.

DEMONSTRATION PROJECT

Two multifamily residential projects in the region emphasize highly sustainable housing. The Ithaca Eco Village in Ithaca, NY and the Flower City Cohousing Community, which is going to be located in Rochester, NY. While the Ithaca Eco Village is already well established, the Flower City Cohousing Community is currently going through the planning process, gaining member support and cultivating general interest. The mission statement on their website describes the Flower City Cohousing Community as

“an intentional cohousing community in an urban setting which values the sharing of resources, sustainability, and simplicity. We are committed to cooperation, consensus building, and diversity. In the larger community, we strive to be a socially and an ecologically responsible neighbor.”

(Flower City Cohousing Community)

Perhaps the most integral part of a co-housing community is its common house. This is the building which brings the community together. Defined by The Cohousing Association of the United States, a common house is:

“A shared facility, often but not always a stand-alone building, that is owned and managed by the community. It typically includes a kitchen, dining area/great room, sitting area, children’s playroom and laundry, and also may contain a workshop, library, exercise room, crafts room.
and/or one or two guest rooms.”

Their desire to create an urban community with sustainability at its core aligns with the imperative that our residential buildings need to be reenvisioned. As the focal point of the community, the common house should embody the culture that the community wants to cultivate — the Flower City Cohousing Community will receive a common house design that is in line with its mission of sustainability in the form of a carbon-negative design that enriches their community and the surrounding environment.

PROGRAMMING THE COMMON HOUSE

This first portion will explore the common house further to establish precedent and basis for the design.

Cohousing is a living style that developed in the late 1960s in Denmark. The movement started when a group of dual-income professional families became dissatisfied with the child care that was available and wanted to share the preparation of evening meals. Today the movement has blossomed into over 300 cohousing projects in Denmark (Scotthanson and Scotthanson 2005). Cohousing made its way to the United States in the late 1980’s and today we have over 100 communities and counting (Kraus-Fitch Architects, Inc. 2014). As the cohousing movement has grown, the movement has become a multi-generational endeavor with all ages and family arrangements enjoying everything that a cohousing community has to offer (Scotthanson and Scotthanson 2005). First and foremost, a cohousing community is meant to emulate the classic village where people live together, share meals, and community (Kraus-Fitch Architects, Inc.
2014). That said, although the common and shared space is a focal element to living within a cohousing community the majority of communities feature private homes with individual facilities (Scotthanson and Scotthanson 2005).

Many cohousing communities thrive on communal decision making, communal care of the grounds, a joint collaboration in the design, and revolve around sharing space and participating in communal activities (Kraus-Fitch Architects, Inc. 2014). Cohousing communities can range in size but they “seem to work best when they contain between 12 and 36 dwelling units” (Scotthanson and Scotthanson 2005). Keeping the communities somewhat small but not so small, makes both the financing as well as community, “right-sized” and manageable. Another central element for a successful cohousing community is an emphasis on member interaction. Unfortunately, a large obstacle to this taking place on an everyday basis among those that don’t living a cohousing community (which is why people might seek out an alternative living style), is the automobile. Automobiles make it too easy to avoid your neighbors. Moving automobiles to the periphery helps to create opportunities for interaction with your neighbors, provides opportunity for alternative site uses such as gardening or natural landscape, and reduces need for pavement. Having pedestrian foot traffic can also make the community a safer environment. Therefore in the layout of cohousing communities there are four “norms” (Scotthanson and Scotthanson):

1. Separate the car from the private residence
2. Create designated pedestrian pathways
3. Active areas of the home (i.e. kitchen) should be adjacent to the pedestrian route
4. Create a centrally located common house.
The common house is the key element because it provides space for shared meals, activities, meetings, and even life events. Spaces within the common house could include a kitchen, guest rooms, a living room, a kids’ room or play room, a shared laundry facility, a community workshop, and often can replace some of the functionality that may not be present in smaller individual units. Large great rooms or living rooms allows for more flexibility in the single-unit design, the kitchen provides space for shared devices that might only be used once in a while, guest rooms can ensure a space for visiting friends and family, and shared laundry and kids’ play rooms create an opportunity to reduce space that may be used intermittently by families (Kraus-Fitch Architects, 2014).

Almost all common homes will include the following items — a dining room, kitchen, kid’s play space, and mail box area. The dining area should be large enough for sixty to seventy percent of the community on a regular basis while having enough space to fit the entire community, or guests on an as needed-basis. The kitchen should have enough capacity to prepare meals for large groups of people, and enough room for there to be more than one cook in the kitchen. The kid’s play space will usually be visually connected so that parents can keep an eye on their children, it usually will have some audial separation from the dining room. Lastly, a place for mail pick up will often have a tack board and personal cubbies for easy communication among community members. Other spaces in addition to the ones suggested by Kraus-Fitch could include an adult lounge, community storage, a craft space, a teen room, a shared office space, a hot tub, work-out room, or even a pool. Larger items (such as a pool) can drive up the cost of the common house (Scotthanson and Scotthanson 2005) so including the more luxurious items can often come at the expense of the common house square footage.

There are a variety of different shapes and sizes to communities. When the cohousing movement began in Denmark homes were typically around 1,500 square feet. Often the common
house was kept around the same size, maintaining a fairly equal relationship between private and social space. As the cohousing experiment was proven to be successful, particularly its communal nature, a shift occurred in the relationship between the private units and the common house. The private units shrank to around 1,000 square feet while the common house ballooned to 5,000 square feet. It is also during this second generation of cohousing where the pedestrian walkways became more institutionalized. The third generation of cohousing brings with it a dramatic shift. Not only does the common house continue to absorb the functions of the personal units, shifting to an average of 10,000 square feet and 750 to 800 square feet respectively, at this stage, some communities have begun to attach the common house directly to the private homes, using an indoor atria to link the buildings together. The fourth generation of cohousing has taken that idea even further with cohousing communities now resembling the archetypal neighborhood (Scotthanson and Scotthanson 2005).

The common house is home to many functions, each requiring a different amount of space and often, there is an optimal size, and arrangement of those spaces. To better understand this, it helps to survey projects that have already been built. The next sections examine four different common houses. The first of four contains an overview of the process that the architects went through to establish the building’s program in addition to a review of the program and spatial allotments itself. The second and third focus on the spatial allotments for the individual spaces as well as a brief description of the communities and homes. The final studies the sustainability features that the residents chose to have implemented into the design of their common house, to provide one example of how sustainable options could be incorporated into the design.
Jamaica Plain Cohousing Common House

The Jamaica Plain’s cohousing community design program was written by Kraus-Fitch Architects in 2001. The design was programmed around serving 30 private living units (Jamaica Plain Cohousing). Examining the program will provide some insight into an example of establishing a successful common house (Scotthanson and Scotthanson 2005).

Kraus-Fitch begins the program with listing the must-have, or priority 1 spaces for the community. These included a porch, patio, or deck, an entry way, a mailroom and coatroom, a great room, a kitchen, a kids’ room, living and sitting space, a couple of guest rooms. “Very, very important” items followed, and were categorized as priority 1.5 spaces. This included a small multipurpose room that could serve as a third guest room, a library, or a table-less meeting space. Decreasing in importance (but still very important), priority 2 spaces included a large multipurpose room which could serve as a gross motor space or a game room, or a general arts and crafts space, an extra pantry, and a meditation room. Priority 2.5 spaces were considered important — these included an exercise/movement room and a sauna or spa. A closely related priority 3 item was exercise equipment and unrelated were rooftop gardens. Community members thought that an art studio would be nice to have but not necessary. Lowest on the list were priority 4 spaces. These were items that community members were indifferent toward having or ultimately felt that they didn't need their own separate spaces. These were music rooms, a teen space, a private entertainment room, a third guest room, a library, game room, gross motor room, crafts room, multi-purpose space, or tv/movie room. Spaces that didn't get included in the prioritization were personal storage or toxic materials storage (Scotthanson and Scotthanson 2005).

Kraus-Fitch then drew associations between the different spaces and what they wanted to
achieve with each space (Scotthanson and Scotthanson 2005) — a key determination in how well each space functions is how much square footage is allocated to it, according to its use. Each use requires a different amount of square footage and plays a large part in the success or failure of a space, therefore it’s important for the space to be right-sized.

Jamaica Plain’s common house entry was designated by Kraus-Fitch as not only a point of entry but a place for verbal and non-verbal communication with a tack board for announcements and a visual connection to the common house’s great room. Off of the entry, the mail room creates a meeting space on the main level to pick up packages, delivered letters, recycle, sit to tie shoes, and pick up or hang coats. Essentially the mail room was considered an extension of the entry way (Scotthanson and Scotthanson 2005).

The Great Room is typically the heart of the common house — therefore Kraus-Fitch planned for it to be a space of many functions, including dining, dance and lounging. To achieve this flexible furniture was desired and as different activities require different lighting conditions, a variable lighting solution was seen as ideal — supplemented with southern daylight that has been controlled for heat and glare, as well as skylights or light tubes. Although an element on the main floor, acoustic separation is considered a must have. Therefore the kids room was physically and visually connected to this space, but it too had to be separated acoustically (Scotthanson and Scotthanson 2005).

As the “great” room, it should be a great space. High ceilings were acceptable under the condition that they don’t create a cavernous, loud environment. To add to the space, Kraus-Fitch suggested the addition of plants, as well as flexible living room furniture to make it a cozy space when it was not being used for larger group gatherings; it should also be comfortable at an individual scale. A fire place was also suggested, to bring warmth into the room. One item that was
under consideration was a separated dining area. Other dining features included a wet bar, bussing area and potential area for condiments. A direct relationship and connection with the kitchen creates a much smoother dining experience. Easy access to storage space for the furniture was also required — and although the great room is the heart of the house, the outdoors is no less important, which is why access to both the entry and outdoor space from the great room was considered a necessity (Scotthanson and Scotthanson 2005).

The kitchen is perhaps just as important as the great room. A connection should remain but the option to close it off should also be in place. Because the kitchen is being used to cook for large groups, there is a push and pull in balancing between commercial appliances and residential appliances. Kraus-Fitch recommend relying on color and material to maintain a homey feel in this space. The space should be large enough to fit three to four cooks, be laid out efficiently, be located on the main floor with the great room, and be easy to clean. The cooking appliances can be commercial or residential but there should be a consideration of at least one accessible counter top and cooking surface. A central island helps create a social atmosphere during food preparation. Storage is also important — there should be room to store pots and pans and a pantry as well. Recycling could also be incorporated into the kitchen space, in addition to the recycling area off of the main entry way. Lastly, like the great room, there should be a connection with the kids’ area and a connection to composting and the outside for easy access to an herb garden (Scotthanson and Scotthanson 2005).

The Kid’s Play Room should be a safe, fun place for kids to play. But different age groups have different ways of playing so creating a separate space for the younger children is important. It is good to accommodate for different types of play, such as an arts and crafts area (wet vs. dry), or a comfortable pillowed space for the younger kids. There should be a bathroom for changing diapers.
and supplies should be kept at a height that is adult-accessible. Like the great room and kitchen, it should maintain a connection with the outdoors, especially an outdoor play space (Scotthanson and Scotthanson 2005).

In addition to a great room, a sitting or living room is suggested to create a more intimate space for smaller gatherings or just as a place to rest and relax. A fireplace could help accomplish this coziness. This room could either be located off of the entry or near the great room. If it is being used for meetings it should be able to be separated acoustically with doors. Vice versa, if it is near the kitchen, it could be used for congregating before or after dinner. Being close to the mail room and entry is also beneficial — this space can help serve as a transition zone (Scotthanson and Scotthanson 2005).

Laundry can be located on any level. The main level or basement is preferred. Multiple washers and dryers should be included, at least three of each. They can be commercial but this isn’t a requirement. Soap should be located so that it is only reachable for adults and a folding area should be included. Indoor and outdoor clotheslines provide a good alternative for drying clothes. A good location would be near the main entry, providing equal access to all community members (Scotthanson and Scotthanson 2005).

Moving away from shared spaces, guest suites provide the opportunity for friends and family to visit — this room should be in a more secluded area of the house. The suite should include two bedrooms, a bathroom (which could be shared with the rest of the common house) and close to the laundry (Scotthanson and Scotthanson 2005).

Other functions that Kraus-Fitch include in the program include a janitor’s closet with mop sink and storage, a storage closet on each level, storage for chairs located next to the dining room, a mechanical room, a sprinkler room, an electrical closet, a trash compaction room, a central vacuum
system, and library shelving. Circulation should make up around twenty percent of the building’s space, including the entry way (Scotthanson and Scotthanson 2005).

Following is an outline of the priority one spaces, the other rooms are included in the program in order of importance, including adjacencies and functions. The table on the next page summarizes the square footages of both the rooms definitely desired by the Jamaica Plain’s community as well as the lesser important spaces, grouped by priority; not all priority items were given a spatial allocation. These will be listed outside of the table (Scotthanson and Scotthanson 2005):

<table>
<thead>
<tr>
<th>PRIORITY 1</th>
<th>ROOM</th>
<th>SQUARE FOOTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENTRY</td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>MAIL ROOM/COAT AREA</td>
<td></td>
<td>100-150</td>
</tr>
<tr>
<td>GREAT ROOM</td>
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<td>1,000</td>
</tr>
<tr>
<td>KITCHEN</td>
<td></td>
<td>300 MINIMUM</td>
</tr>
<tr>
<td>PANTRY</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>KIDS’ ROOM</td>
<td></td>
<td>600</td>
</tr>
<tr>
<td>LIVING/SITTING ROOM</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>LAUNDRY</td>
<td></td>
<td>150 MINIMUM</td>
</tr>
<tr>
<td>GUEST SUITE</td>
<td></td>
<td>100-150 PER BEDROOM</td>
</tr>
<tr>
<td>STORAGE CLOSET</td>
<td></td>
<td>10-20</td>
</tr>
<tr>
<td>CHAIR STORAGE</td>
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<tr>
<th>PRIORITY 1.5</th>
<th>ROOM</th>
<th>SQUARE FOOTAGE</th>
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</thead>
<tbody>
<tr>
<td>SMALL MULTI-FUNCTION ROOM</td>
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<tr>
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<tr>
<td>SECONDARY PANTRY</td>
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<tr>
<td>MEDITATION ROOM</td>
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<table>
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<tr>
<th>PRIORITY 2.5</th>
<th>ROOM</th>
<th>SQUARE FOOTAGE</th>
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</thead>
<tbody>
<tr>
<td>EXERCISE ROOM FOR MOVEMENT</td>
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<tr>
<th>PRIORITY 3</th>
<th>ROOM</th>
<th>SQUARE FOOTAGE</th>
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</thead>
<tbody>
<tr>
<td>EXERCISE ROOM FOR MACHINES</td>
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<td>150-250</td>
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<table>
<thead>
<tr>
<th>PRIORITY 4</th>
<th>ROOM</th>
<th>SQUARE FOOTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUSIC PRACTICE ROOM</td>
<td></td>
<td>50-100</td>
</tr>
</tbody>
</table>
Other functions that were included in planning for the common house but that were not assigned square footages were a porch/patio/main entry porch, a spa or sauna room, a roof garden, and an art studio (Scotthanson and Scotthanson 2005).

In addition to the spaces that were to be incorporated into the common house, Kraus-Fitch also worked with Jamaica Plain Cohousing on spaces that they wanted to be fully accessible to community members but not necessarily incorporated as a part of the common house. On top of the list were home offices, either implemented as an open floor plan or as individual rooms. Both options called for shared office equipment and supplies. There was some desire to have them connected to the common house but only if it did not interrupt other elements of the common house nor reduce security (as the offices could potentially be leased to the public). Attached to the office would be a communal office area to house the shared office resources and if the office is indeed separate from the main common house, a meeting room would be included as well (Scotthanson and Scotthanson 2005).

Also included as a priority one space (although not necessarily attached to the common house) is bicycle storage. While storage for a specific number of bikes was not specified, Kraus-Fitch suggested at least enough space for two bicycles per residence. Vice versa, the workshop which was counted as a priority 2 item, should be a separate building unless there is proper ventilation and adequate sound isolation provided. The following table summarizes spatial locations for the functions that could either be connected or separate from the common house (Scotthanson and Scotthanson 2005):
Ultimately the community opted to include some but not all of the spaces in the final design. These include a courtyard, patio, garden, playground, great room, kitchen, kid’s room, living room, lobby, mail room, and lending library, rumpus room (multipurpose tv/game/exercise space), laundry room, storage, and office. Also included were two guest rooms with a shared bathroom, a woodworking shop, bike storage, and common storage (Jamaica Plain Cohousing). Final square footages for these spaces were not given but could be estimated based on the programming process that Kraus-Fitch went through. Knowing the final space selections, the common house can be estimated to be roughly 5,200 square feet if the spatial allocations by Kraus-Fitch were utilized.

The Jamaica Plain’s Cohousing Common House is a good case study in that there is an in-depth exploration of both the programming process and approximate spatial allocations readily available. Doing some additional research yields a number of cohousing communities that have not made their programming process as transparent, but do provide floor plans from which spatial allocations can be determined.

_Yulupa Common House_

The Yulupa Cohousing community is located in Santa Rosa, California. They were
established in 2005 with 29 residential units. Fifty-four members make up Yulupa representing both young and old (Yulupa Cohousing “Welcome”). The common house which draws all of its power from solar energy features a kitchen, multi-purpose room, library, kid’s play room, dining lounge and laundry room. Additionally, there is a shared workshop, laundry, exercise room, an outdoor play structure for the kids, and a guest house (Yulupa Cohousing “Welcome”).

The common house has a gross area of 2,873 SF. Doing take offs from the first floor plan, the spaces on the main level have been assigned the following square footages (Yulupa Cohousing “Features”):

<table>
<thead>
<tr>
<th>ROOM</th>
<th>SQUARE FOOTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENTRY</td>
<td>113</td>
</tr>
<tr>
<td>MULTIPURPOSE ROOM</td>
<td>1,047</td>
</tr>
<tr>
<td>DINING LOUNGE</td>
<td>333</td>
</tr>
<tr>
<td>KITCHEN</td>
<td>245</td>
</tr>
<tr>
<td>PANTRY</td>
<td>66</td>
</tr>
<tr>
<td>LAUNDRY</td>
<td>147</td>
</tr>
<tr>
<td>LAVATORY</td>
<td>36</td>
</tr>
<tr>
<td>TOILET</td>
<td>44</td>
</tr>
<tr>
<td>KID’S PLAY ROOM</td>
<td>204</td>
</tr>
<tr>
<td>STORAGE</td>
<td>132</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>2,367</strong></td>
</tr>
</tbody>
</table>

The rest of the common house is occupied by enclosed mechanical spaces and area for circulation.Disconnected from the common house is the guest house which contains a guest room and exercise room which share storage space and an adaptable bathroom. This area has the following spatial assignments (Yulupa Cohousing “Features”):
Although the workshop does not have a floor plan available, it is shown on the site as being located on the northern side of the campus, somewhat removed from the rest of the buildings (Yulupa Cohousing “Features”). This is probably to account for potential noise issues.

*Pleasant Hill Common House*

The Pleasant Hill Cohousing community is also located in California. Similarly sized to Yulupa at 32 residential units, their common house is slightly larger to account for a greater number of community members. Their webpage indicates that there are 47 adults and 191 children living in the community, for a total of 238 community members (Pleasant Hill Cohousing 2014) — whether or not that is the total count of community members or current residents plus community members abroad is unknown. Their common house consists of a kitchen, dining room that doubles as a great room, sitting room, kids room, teen older room, crafts room, guests room, and bathroom. While the spatial allotments for each individual room is not given, the common house totals 3,835 square feet (Pleasant Hill Cohousing 2014, Our Homes). This project was selected as a case study because even though it does not list square footages for individual rooms, it does provide some insight into sustainable design options, which the community opted to emphasize — to the point that the
common house is the only building on their campus that has air conditioned cooling (Pleasant Hill Cohousing 2014, Our Homes).

To reduce the need for conditioning, the common house relies on stack ventilation during the evening time. A cooling tower in the center of the building uses fans to draw out the warm air that has accumulated during the daytime and pulls in the cooler night time air. Additional energy saving features include shading devices and awnings on the southern and western exposures for passive heating and cooling. The buildings are wood frame construction with a stucco weather barrier. To aid the passive heat gain and cooling, the construction consists of polar ply radiant barriers, low-e windows, and a gypsum board that is thicker and denser than typical gypsum. Wet-spray cellulose insulation is used to bring the walls up to a rating of R-22 and the ceilings up to R-38. To prevent excess air exfiltration, fire places were left out of the design. Radiant baseboard heating, coupled with shared hot water heaters is used to provide warmth instead. Low flow fixtures were used to save water and efficient fluorescent lighting minimizes the energy requirement for lighting. Operable windows, fans, and shallow spaces were included to allow for cross-ventilation. Lastly, interior shutters that are opaque and reflective aid in the night time cooling and ventilation process described above (Pleasant Hill Cohousing 2014, Our Homes).

Environmental impact also came into consideration for the material selection. All concrete that was used in the project contains at least fifteen percent fly-ash. Advanced framing techniques were used to erect the campus, all of which was built with FSC-certified wood. In addition to Forest Stewardship Council (FSC) certified wood, flooring was also built using bamboo and natural linoleum. This meant that no wood treated with CCA (Chromated Copper Arsenate) was used. To further prevent issues of toxicity, low VOC materials were used throughout the project. (Pleasant Hill Cohousing 2014, Our Homes).
Daybreak Common House

Transitioning to a somewhat colder climate, the Daybreak Cohousing Community is located in North Portland Oregon within the Overlook neighborhood. This project is located close to a light rail stop and are three miles from central downtown. Of note is the fact that their common house is not a stand alone building. Unlike the previous common homes that have been included in this review; the Daybreak common house also contains living units above the shared spaces (Daybreak Cohousing 2012, Site and Design). In total, they have 30 homes within their community and the living units consist of 1, 2, or 3 bedroom configurations that are either 700, 900, or 1100 square feet. (Daybreak Cohousing 2012, FAQs)

While living spaces are above, the common house occupies the first floor and basement totaling around 7,000 square feet. While there were no scaled drawings available, there were floor plans provided on the website — spatial allocations were obtained by scaling the available plans to the same scale, irrespective of their original size. Then, the square footage of the individual rooms were measured and totaled by room type and added together for a grand total. The allocation for each room type was divided by the grand total to find the percentage of total space that the room type occupies. Once that percentage was identified, a ratio was applied to establish how many square feet each room type uses out of the approximate seven thousand square feet that comprises the Daybreak Cohousing Community’s Common house. The square footages are shown in the table on the next page (Daybreak Cohousing 2012, Site and Design):
Like Pleasant Hill, sustainability was an important factor for Daybreak’s residents. The community opted to save on building materials in a few ways. They reduced the size of their private spaces, FSC certified wood was used for advanced framing, and they dismantled the existing buildings on site, salvaging materials when possible. Each of these decisions helped to reduced the overall impact of the building. Additionally, many common household tools were made available to the whole community, emphasizing the use of common space and sharing resources. With reduced living spaces comes a smaller building footprint — as such they have room for plenty on their site. The landscaping relies on native plantings, as well as items that can be eaten, adding texture to their grassy play area, kid’s playground, and outdoor terrace. On-site storm water management helps to
feed these plants and prevents water from running off-site (Daybreak Cohousing 2012, Site and Design).

Inside the building, a ductless split system allows the temperature of the common house rooms to be regulated as needed and is used in tandem with radiant floor heating. Coupled with a rain screen to limit the entry of moisture, and an adequate amount of formaldehyde-free insulation, the building is tight and energy efficient. While tight, it still allows for fresh air with operable wooden-framed windows. While the heating system is not in use, the common house and apartments make use of a southern orientation to passively warm during the winter and sun shades to prevent too much heat gain in the summer. The building conserves energy through its design and selection of energy efficient appliances, lights and plumbing, and should Daybreak choose to reduce its energy footprint further, the common house roof was also designed to accommodate solar panels (Daybreak Cohousing 2012, Site and Design).

The final piece to understanding the common house is to compare the three examples side-by-side where similar data across projects was available. Looking at them individually gives insight into the communities for which they were designed but the real usefulness in examining these spaces is understanding not only the trend in function selection but also to identify an approximation of appropriate spatial allocations for programming purposes. The table on the next page shows a comparison of the features that are the same between the common houses and provides an average for spatial allocations.
The common house can vary widely depending on what is desired by the community and the four examples are evidence of this. Despite their differences, there are many common elements no matter the community. These factors were taken into consideration when establishing a program for Flower City Cohousing.

**PROGRAM**

Two meetings with the Flower City Cohousing Community were held, one was an informal opportunity to get a better idea about the organization and the second was a formal meeting to discuss the specifics of what the community would like to see in their common house.

The driving concept behind the community is it wants to be a village in the city, with an emphasis on sustainability both in the communal structure and facilities. The community’s buildings
will consist of 20 housing units and a common house for shared activities.

A portion of the community’s units will be town-houses, while the remainders will be apartments, located within the common house. The common house will reflect its sustainability through material selection and effective use of daylighting.

The common house will be the heart of the community. The 13 town houses will be in the vicinity of the common house although it has yet to be determined whether they will be located on the same site. The location of the common house in relation to the other housing units will be determined once a final site selection has been made by the Brick and Mortar Committee. No matter the final location, it was requested that the design encourage walking, helping the community to be active within the neighborhood. On-site parking will be limited and kept to the periphery of the site. The idea is to have the common house footprint be no larger than it needs to be, maintaining space for a garden and a children’s play area next to the common house.

Initial investigations by the building Brick and Mortar committee revealed that a building four stories or taller requires an elevator that is large enough to fit a hospital gurney. This is not an investment that Flower City CoHousing wants to make so the building will be no taller than three stories.

Ultimately, the common house is meant to be enjoyed and lived in by people of all ages and life stages. Therefore, the design will ensure that it is accessible by visitors and residents alike. Following this logic, acoustics will be tuned to prevent excess noise. Other desires for the common house include a shared kitchen, dining room, library, play room, meeting space, guest rooms, co-working space, workshop, studio and art space, bicycle storage, and a shared laundry room.

As a community focal point the common house will feature pleasant and inviting spaces that allow for gathering and social interactions, helping foster a vibrant community. This will start at the
entrance which will feature mail boxes for the residents of the building and a place for visitors to hang up coats and take off shoes. From here, guests and residents will be able to access both the shared communal space and the building’s apartments.

The meeting room will also double as a living room and will be connected to the main gathering space, which will be used for group meals or other functions such as exercise, movie screenings, or large group meetings. Storage for chairs and tables will be kept off to the side of this space. The kitchen will be next to the main gathering space and have an attached pantry. This will make the large group dinners a smoother process as the food will not need to travel as far. The play room will also be in the vicinity of these functions, featuring a visible connection while also maintaining some sound isolation. The second floor of the communal space will house the shared co-working space, library, and art studio.

The residential portion of the common house will be kept separate from the shared communal spaces but will still be physically linked with an indoor connection. This will accommodate movement throughout the entire building, even during inclement weather. The common house will have six apartment units and two guest suites. The apartments will be located on the second and third floors. Although there is an opportunity for multi-level units, they will be restricted to a single floor, making the apartments more livable for residents of all ages.

The building will be oriented along the east-west axis with the broader faces of the building being the north and south elevations. This orientation will allow for the greatest southern exposure, providing sunlight for the algae facade’s photosynthesis and heat generation. This orientation will also allow for ample use of photo voltaic panels and natural ventilation.

The common house will accommodate the above mentioned functions with the following spatial allocations:
FLOWER CITY COHOUSING COMMON HOUSE SPATIAL ALLOCATIONS

<table>
<thead>
<tr>
<th>BASEMENT</th>
<th>SF</th>
<th>SECOND FLOOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAUNDRY</td>
<td>200</td>
<td>LIBRARY</td>
</tr>
<tr>
<td>BICYCLE STORAGE</td>
<td>400</td>
<td>CO-WORKING SPACE</td>
</tr>
<tr>
<td>GENERAL STORAGE</td>
<td>800</td>
<td>KID’S PLAY ROOM</td>
</tr>
<tr>
<td>MECHANICAL ROOM</td>
<td>2,600</td>
<td>APARTMENTS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2,400</td>
</tr>
<tr>
<td>FIRST FLOOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ENTRY</td>
<td>200</td>
<td>APARTMENTS (3)</td>
</tr>
<tr>
<td>WORKSHOP</td>
<td>400</td>
<td>GUEST SUITE (2)</td>
</tr>
<tr>
<td>LIVING ROOM</td>
<td>400</td>
<td>STUDIO / ART SPACE</td>
</tr>
<tr>
<td>MULTI-PURPOSE ROOM</td>
<td>1,000</td>
<td>BATHROOM</td>
</tr>
<tr>
<td>KITCHEN</td>
<td>600</td>
<td></td>
</tr>
<tr>
<td>BATHROOM (2)</td>
<td>140</td>
<td></td>
</tr>
</tbody>
</table>

| THIRD FLOOR                 |     |
| APARTMENTS (3)              | 2400|
| GUEST SUITE (2)             | 800 |
| STUDIO / ART SPACE          | 400 |
| BATHROOM                    | 50  |

Summarized, the programmatic goals include:

- Orientation and siting for an algae facade
- Preserving site space for other features such as a playground and gardening space
- Creation of an indoor-outdoor connection
- Sustainable material selection
- Accommodation of individual apartments and shared spaces for residents of the common house and the greater FC3 community
- Use of daylight to illuminate interior spaces
- Use of passive cooling and ventilation techniques
- Sound attenuation between major spaces
- Facilities for multiple age groups
- Ample storage for building residents and overflow storage for community members
- Opportunities for flexibility in space usage
For a review of the City of Rochester's applicable zoning regulations please see the below charts. These charts show how the common house would meet the city's zoning guidelines.

Membership within the cohousing community is multi-tiered. There are associate members and equity members. Equity members are those that have committed to making financial investment as needed and are intending to be a part of the community. Associate members attend meetings and make a small financial contribution but it is not applicable toward their equity fee.

All equity members are equal in terms of decision making and ownership. Membership is kept up with monthly dues but for those joining the first time, there will be a fee that is established by the finance committee. For those that are equity members that decide they no longer want to be a part of the community, they may receive a refund but it is not guaranteed (Flower City Cohousing).
SITE ANALYSIS

At this time the Flower City Cohousing Community is still being planned. A number of locations that are being considered by the Brick and Mortar Committee — the body in charge of making the (consensus-based) decisions surrounding the physical infrastructure and location of their community. The following section will explore the site that has been selected hypothetically for this project, and examine the surrounding context and environmental factors.

80 Charlotte Street, Rochester, NY 14607 was selected as the site for a variety of reasons which will be explained below. For a visual reference, a site location map can be found on the following page.

According to Walk Score, the selected project location gets a score of 90 out of 100 — by their definition it is objectively a, “Walker’s Paradise” but daily errands do require a car. The score of 90% is an average between seven categories including Drinking & Dining, Groceries, Shopping, Errands, Parks, Schools, and Culture and & Entertainment. As expected one of the lower scorers are errands, while the other is parks. The score is based on the distance to nearby places and pedestrian access. It receives a transit score of 68 out of 100, with “many nearby public transportation options.” This was based on how well the location is served, with the measurement factors being distance to transit options and types of options available. The site received a bike-ability rating of 69 out of 100, with the area being described as “Bikeable”. This rating is based upon access to bike lanes, trails, whether there are hills, connection with roads, and destinations that can be reached by bike. Although it is “Flat as a pancake”, it is also wanting for bike lanes. In terms of transit time to the center of Rochester from the site, by car it is a 3 minute commute, by bus it is 15 minutes, by bicycle 5 and walking it is 19 minutes. Overall the location is quite central (Walk Score 2015).
Not only is it centrally located within the context of the city fabric, there are also a number of destinations within a short walking distance. This includes thirty-eight restaurants within a quarter mile, four coffee shops, five bars, five grocery stores, four schools, six shopping venues, and four entertainment venues (Walk Score 2015).

Delving deeper into how the score is actually determined and where the percentage rating comes from, a team of researchers from Harvard and University at Buffalo independently verified the validity of Walk Score’s scoring system using GIS. Part of this research was to unpack their scoring process. Walk Score pulls its data from Google, Education.com, Open Street Map, and Localeze. The distances to five facility types, including educational, retail, food, recreational, and entertainment, are measured in straight line distance. The nearest of each of these facility types is then used to determine a score through a combination based on facility type priority and a function of diminishing distance. The outcome is then put on a scale of 0 to 100. Any destination that requires the use of a car to reach automatically gets a rating of zero. Vice-versa, any walkable location starts at a score of 100 and then diminishes. If the location is within a quarter mile it receives a 100 with the rating decreasing until the distance from the site location reaches one mile. At that point, if the nearest of any of the five facility types mentioned above is a mile or further from the site, that category will receive a rating of zero (Duncan et al. 2011).

While the site is quite walkable this does not mean that vehicular transportation will not occur to or from the common house, vehicular or otherwise. In putting together a study of the surrounding area, the diagram located on page 89 charts a variety of destinations within a half mile radius as opposed to a quarter mile. What we can see is that there are a wide variety of destinations all within walking distance, corroborating the Walk Score rating that the site received. Locating the building here would diminish the need to drive due to the number of locations reachable by foot.
The site itself is accessible by both foot and bicycle which can be seen in the diagram on page 91. At the present time there is no pedestrian way running along the north side of the site although there are plans for improved pedestrian infrastructure in the Charlotte Square development project, which will establish a connection with the walking path that already runs along the western side of the site.

If walking is not an available option, then there is ample connection to many of the city’s main roadways as well as highway access all within a half mile of the site, shown in the diagram on page 92.

At 26,397 square feet (less than an acre) 80 Charlotte St is not a small site but it is not huge either. Maintaining the desire for a garden and a playground, it will only conveniently fit the common house program. The advantage to this location is that with the City of Rochester’s Inner Loop East Transformation Project (City of Rochester) there will be ample room for expansion once the sunken roadway is brought back to grade with the surrounding street grid. A diagram of potential places for expansion is located on page 93.

The site is surrounded by buildings on the South, West, and North. Therefore, a shade analysis was done to determine the areas of the site that will receive the most sunlight. This was done in three stages and the analyses are on page 94. The first shade analysis simulated the wintertime conditions that would be present on December 22nd taking snapshots at every hour over the course of the entire day. These were then overlaid to show the greatest and least areas of shadow. The second shade analysis followed the same procedure and simulated the summer time conditions that would be present on June 21st. These two dates were chosen to identify what the shade would be like when the sun is both at its highest and lowest points in the sky. The third analysis is a compilation of the winter and summer conditions, with an overlay that highlights the
ROAD AND HIGHWAY ACCESS
OPPORTUNITIES FOR EXPANSION
WINTER SHADE

SUMMER SHADE

AREA OF MAXIMUM SOLAR EXPOSURE

SHADE ANALYSIS
areas on the site which will receive the most sunlight. The results show that the area that receives the most sunlight throughout the year is the eastern half of the site with a bias towards the northern end. This understanding helps inform the placement of the building.

Sunlight will be utilized for both electrical production and heat gain but other techniques were also studied. The psychometric chart on page 96 generated using Climate Consultant 6, shows the best strategies for maximizing occupant comfort. Large comfort gains can be made by using natural ventilation and flushing excess heat gain during the evening. With our cold climate, heating the building provides the largest comfort gains.

To utilize natural ventilation, the common house needs to be oriented to maximize wind exposure so that air will move through the building. To capture the wind, the building will be oriented with its broadest side facing the windward direction, southwest. Page 97 shows a windwheel placed over the site map, also generated using Climate Consultant 6, reaffirming that for optimal wind capture, the common house needs to face a south westerly direction for natural ventilation to be effective. Creating a perpendicular exposure to the wind allows for the best airflow through the building. On days that there is not wind, the stack effect can be used to encourage air movement throughout the building — as the hot air rises and escapes from the building, cooler air will rise up to take its place, creating a cooling sensation.

How all of these elements come together in the building’s final form will be explained in the Design portion of the demonstration project section.
PRODUCED USING CLIMATE CONSULTANT 6 AND ADOBE PHOTOSHOP
DESIGN

The two driving factors behind the design were making accommodations for the algae wall and fulfilling the programmatic goals.

To reiterate, the programmatic goals include:

• Orientation and siting for an algae facade
• Preserving site space for a playground and gardening space
• Creation of an indoor-outdoor connection
• Sustainable material selection
• Accommodation of individual apartments and shared spaces for residents of the common house and the greater FC3 community
• Use of daylight to illuminate interior spaces
• Use of passive cooling and ventilation techniques
• Sound attenuation between major spaces
• Facilities for multiple age groups
• Storage for building residents and overflow storage for community members
• Opportunities for flexibility in space usage

Designing the building to meet the needs of the Flower City Cohousing Community as well as accommodate the algae wall proved challenging. In the prior section on achieving a net-zero, carbon negative design, it was established that a 15 degree departure from due south would not impact the amount of solar gain, and therefore efficiency of the algae and solar systems. Unfortunately, the
site is not parallel with the east-west axis. Instead, it is rotated 22 degrees to the east. The decision was made to keep the building in-line with the existing infrastructure but if the algae wall and solar panels were parallel with the structure, they would see a drop in efficiency and power output. The solution to this problem was to rotate the building but keep the algae facade aligned south. Doing so meant that the facade had to be pulled away from the building but resulted in a number of advantages. The diagram below illustrates this decision and an explanation follows.

By pulling the facade away from the building, it maintains an optimal exposure to the sun. This would allow for the highest potential of biomass production. The more biomass, the more available fuel for energy production to meet the building’s energy demands. The algae would be suspended in water, and the water would act as a heat sink. Therefore, as the biomass production process is unfolding, heat capture would be occurring simultaneously. The double advantage of this setup is that as more heat is gained, the less energy the common house would need to sustain
occupant comfort during the winter. This heat would be captured and used to help maintain the desired temperature in the building. Although the heat gain would be beneficial during the winter, it would be less-so during the summer. Some of this issue is avoided by having the algae facade pulled away from the building. As the biomass grows and densifies within the algae panel, it would provide shade. Because the shading element is on the exterior of the building, it would prevent the thermal radiation from going directly into the building and by extension, heat build up. Instead, excess heat could be transferred into an underground geo-thermal well via a heat exchanger. Moving the facade away from the building helps promote biomass production, and by relying on the principals of passive heating and cooling, helps to regulate internal conditions and maintain occupant comfort.

Conveniently, by moving the facade south, the common house becomes exposed to the south-western wind across the entire length of the building. Operable windows would be placed along this side of the building, allowing air to flow through. The operable windows would also allow the building’s occupants to adjust their indoor environment on an as-needed basis. To make the most of this funnelling effect, the algae facade was curved toward the building, guiding air into the common house’s interior. To avoid efficiency loss the facade is rotated no more than 15 degrees away from a direct southern exposure.

Lastly, there is an aesthetic advantage to moving the algae facade away from the building— one of the concerns that the Flower City Cohousing’s Brick and Mortar Committee had was that the green color of the algae would completely take over the internal visual experience. While some of the light that enters the building is green, a majority of the interior spaces do not have a green hue as can be seen in the renderings further on in the section.

Due to all of the advantages mentioned above, pulling the wall away from the building was the most practical and sensible option. Also, doing so helped to accomplish the programmatic goals
of establishing the proper orientation and siting for the algae wall, and designing for passive cooling and heating. This was the first step though. Other design decisions also contributed to this goal, which will be explored further on.

The site plan is on the following page. Referencing back to the solar study that was conducted, orientation and location of the building still provided ample room on the site for a playground and raised garden beds, another programmatic goal. Plus, keeping the common house on the north-eastern side of the site, the common house would be closest to the potential sites for expansion outlined in the site analysis. This was the sensible approach given that the common houses is the heart of the community. Therefore, the spatial layout of the building followed the notion that while only some of the cohousing community’s residences are within the common house proper, all residents of the community should have equal access to the shared spaces of the building. As a result, the shared portions of the building also occupy the northern and eastern portions while the residents are on the southern side of the building (which occupy the second and third floors). This can be seen in the space type diagrams shown on page 103 and the floor plans, pages 104-108, which shows how the goals of accommodating both the residential and community functions was achieved as well as providing ample storage space. The parking was also placed on the northern side of the site, to meet the city’s minimum requirement of shading the parking lot by at least 40%. This was greatly exceeded by an additional 40% by placing the parking underneath the building, which can be seen to the left.
Just as the algae facade informed the building’s layout, it also informs the parti. The algae are individual but each absorbs carbon dioxide, photosynthesizes and as a whole, provides the common house with an energy source. Within the panels, they act as one. The common house is made up of a variety of functions, which each can be separate but are most impactful when brought together into one being. Each interior space is wrapped by a frame on the exterior that mimics the locations of its boundaries. While the spaces are separate, the exterior frames are smooth and organic with one space seeming like it could slide right past the other, just as the algae would in its watery suspension. The organic nature of the building shows up again on the interior spaces through circular fixtures (alluding to the algae) and spatial elements that are either wooden or curved.

Elevations for the common house are located on pages 110 and 111. Materiality is also shown in the elevations. Just as the interior spaces are reflected by the building’s exterior, the interior elements are reflected on the outside as well, with the majority of the building being clothed in wood, accented by aluminum wraps. This was done to fulfill Flower City’s desire to reflecting the building’s sustainability through its materiality. Although not verified, the notion is that in building using wood as the main material, like the building studied by Gustavsson, Joelsson, and Sathre (2010), the carbon impact of the building would be reduced overall.

Sectionally, the common house works toward the programmatic goal of enabling passive cooling and also works toward the aim of enabling light to penetrate into the interior of the
FIRST FLOOR
1' - 6"

SECOND FLOOR
13' - 6"

THIRD FLOOR
25' - 6"

ROOF
37' - 6"

0'
5'
10'
20'
40'
80'

1/8" = 1'-0"

NORTHWEST ELEVATION

SOUTHWEST ELEVATION
building. This would help reduce electricity needs for lighting the facility during the day.

The sections found on pages 113 and 114 show how the large atrium that brings together the community functions, and light wells that run from the roof through to the first floor corridor, allow light to enter and heat to be expelled through operable windows and skylights.

Acoustic performance of the space was also considered as some residents are or may be hard-of-hearing. To ameliorate the issue of sound traveling between spaces and provide sound attenuation, as requested by the Brick and Mortar Committee, the proposal is to use the AucoustiGuard Genie Clip to reduce sound transmission through wall and floor assemblies. The section below shows what a typical wall assembly would look like -- a double stud construction with insullation filling the cavity and Genie Clips acting as a buffer between the gypsum board and wood studs. Half of this assembly would provide a Sound Transmission Class of 57. This number is based on AcoustiGuard’s lab results -- it may be higher with the thicker, double stud wall that is shown. All major spaces comply with the necessary aisle widths for a wheelchair bound resident in addition to the private residences, shown on page 115. This in combination with the sound attenuation helps to
provide an environment that is comfortable for all ages and types of people.

The building’s heat would be distributed by hydronic in-floor heating and coupled with the geothermal well that would serve as a heat sink for the algae wall’s excess heat energy. The algae wall would rely on 180 panels. These would be fed from the base with algae and carbon dioxide and then heated by warming lines that run along the top. The panels would not drop below 35 degrees, allowing them to remain active year-long. A breakdown of the algae panels is below. Diagramic cutaways of the geothermal system, algae network, and in-floor heating are on the next page.
ALGAE FACADE NETWORK AND IN-FLOOR HYDRONIC HEATING

CLOSED-LOOP GEOTHERMAL WELL
(700 FT DEPTH, 10 wells)
Moving from the technical to the experiential, the common house is entered through either the parking in the back or the main entrance on the southeast side of the building. Upon entering, there is a mail pick-up for the community members and building's residents.

Once through the main entry, guests are presented with the living room as well as the main vertical
circuit by way of a three-storey atrium. Splashes of color each highlight a different communal function.

Directly opposite the living room is the monitoring station. This is where residents, community members and guests can see a live status report on the building’s algae wall and energy systems.

Further down the corridor is the great room. This multi-purpose space can be used for a variety of activities such as group meals or exercise sessions. It is through this space that the goal of programmatic flexibility is achieved. Additionally, if extra space is needed the doors separating the
Great room from the patio outside can be opened during nice weather.

Through the great room is the communal kitchen. This space features two ovens as well as two sinks, making it easy to cook together and prepare large meals. Additionally, counter tops at different heights make it easier for someone in a wheelchair or a child to participate in the festivities.
The last communal space on the first floor is the bike storage, easily accessible from the entry.

Journeying through the atrium provides a bold view of the building's algae return lines. These tubes bring the algae into the mechanical space in the basement for processing. The second level hosts the shared office space, playroom and library. Like the level below, each of these spaces are emphasized from the corridor with a different color paint.

While some common houses feature separate rooms for children of different ages, the playroom in this design is a singular space with the potential to be broken up into smaller rooms. At
the time of design the demographics of the community are still in flux.

The library and office shown below are both on the south eastern exposure. To compensate for glare in the mornings, the windows feature horizontal louvres and lightshelves to bring more
afternoon light into the spaces. Wood soffits reflect that light back down and give the spaces a warm feel. The office’s northern wall features an image of a forest to inspire a calm working environment, with a nod to the common house’s materiality. The space is does not feature built in computer work stations, people would use their laptops or other mobile workstations instead. The idea is that the space could be used for a variety of types of work, or could even be used as an impromptu meeting space. Therefore the work tables and chairs are movable, if need be.

Moving into the residential wing of the building, the apartments feature a large light well that is used to separate the kitchen and dining room from the living room area, bedroom, and bathroom. Despite this separation, there is still a visual connection, making the apartment feel larger. For a comparison, the two images of the apartment are shown on the next page. The first is shown with the dining room light turned on while the second shows the kitchen without any lights on. Despite this, the room is still bright, showing that the strategy of daylighting is successful. As
mentioned earlier, if the space is too warm, operable windows would be installed on either side of the apartment, allowing air to flow from one end of the apartment to the other while also allowing heat to escape up through the lightwell.

The third floor features an art studio and two guest suites. The art studio was purposefully placed on the north side of the building to prevent glare that is common in rooms on the southern exposure, creating better lighting conditions for making art. Additionally, track lights ring the perimeter of the room, highlighting pin-up space which could turn the art studio into an improvised gallery for the cohousing community.

The guest suites are available to those living in the common house and the greater cohousing community as a place for out-of-town guests or family members to stay when they come to visit. While there is room in the apartments for a pull-out couch, these suites provide a private space and a small kitchenette in addition to a place to sleep.
Both floors also provide access to the communal deck spaces outside. Also outside, the playground provides an outdoor area for cohousing members as well as those in the surrounding neighborhood to play. A grassy hill that provides access to the second floor of the common house provides the perfect spot to relax and watch the activity during the summer, or go sledding during the winter.
The basement level is not shown but this floor includes storage, the mechanical room, laundry facilities and the workshop. Both the workshop and laundry were placed in the basement to minimize sound travel to the rest of the building.

The design invokes the communal aspirations of the Flower City Cohousing Community by providing a central, accommodating space that provides a live example of sustainable principals in action through the algae wall, use of sustainable construction materials, passive cooling, and flexible spaces that can be used for different purposes. Exterior visualizations of the building as a whole are located on the next three pages.
PERSPECTIVE - WESTERN ELEVATION
The BIQ’s uniqueness is reinforced by the fact that there was infrastructure already in place to utilize the algae that was being produced by the building. In fact, were it not for the existing biogas production program in Hamburg, the BIQ building would have only been able to make use of the heat energy that it was able to capture through solar radiation. While it was advantageous that the design was able to utilize both the heat captured and the energy generated, there are a couple of drawbacks to the system that was ultimately put into place.

First, while the algae procurement process is able to take place at the building, there was still a need for it to be processed into a usable power source. This requires the algae to be transferred to the nearby biogas production facility with a truck, expending energy. Then after the algae is converted into a bio-gas, this bio-gas is used for electricity generation. The electricity then has to be transferred back to the building (Roedel and Peterson 2013). In order for the algae to be used as a power source, energy has to be expended along the way. Essentially, each step erodes the potential energy of the algae, lessening its efficacy as a fuel.

Despite the fact that the building loses energy in the system of extraction, it is still fortuitous that the BIQ has been able to form a symbiotic relationship with the existing bio-gas generation facility and city-wide power plants that came first. Rochester does not present the same opportunity, unfortunately. This creates the need for an alternative solution to utilize the algae that the common house would produce.

Grow Energy Inc. is currently developing a system that would function much like a typical residential solar photovoltaic system, except it will use algae panels to generate power instead of solar panels. It will come in two iterations -- Verde for home installation and Hydral for larger scale
implementation (much like what is currently used by the BIQ Building). Their system is unique in that it not only produces but also processes the algae on-site, relieving the need for a dedicated city-wide biogas plant and methane-powered turbine to generate electricity. Not only does it reduce infrastructural requirements, it also avoids the need to expend energy transporting the algae to the refinery.

The system for transforming the algae into bio-fuel that Grow Energy Inc. proposes is not unlike the one that is used by the BIQ building, albeit scaled back for small commercial or residential application. After reaching a harvestable state, the algae is moved into the generator where it becomes separated from its broth and is prepared for combustion through a drying process. Excess algae gets cycled back into the panels while the dried algae gets burned to produce electricity. The usable power is then transferred into the building’s power grid with the excess going back to the utility company. Any byproducts including the carbon dioxide that gets released in the combustion process gets recycled back into the system to support the next batch of algae. Grow Energy Inc. proposes that the algae would be nourished using their Nutripack (Grow Energy 2013), although given the potential for algae to be utilized as a waste water treatment solution, a cost-effective way to add nutrients to the algae would be to utilize the common house’s waste water. Any excess electricity that is produced could be stored in batteries. A schematic layout is shown on the next page. Granted, it is assumed that the extraction and electricity production method that Grow Energy Inc. proposes would actually function as described. There is no way to know this at the current moment because their technology has not made it to the market yet. Additionally, the sizes of the devices shown in the mechanical room diagram are estimates as Grow Energy Inc. does not provide any information on the scale of the two systems that they are developing.

While the feasibility of the proposed algae extraction and electricity production are
debatabile, estimates for the amount of energy consumed and produced by the common house are laid out below.

To re-state from the examination of the algae facade, according to Roedel and Peterson, the BIQ’s algae facade produces 15g of total solids/m²/day, 345kJ/m²/day, and 10.2L of methane (biogas)/m²/day. Over a year’s time, that converts to approximately 4541 kWh of electricity derived from methane and 6000 kWh of heat generation (2013). These numbers were arrived at by taking the global radiation for Munich, Germany, 1150 kWh/m²a and assumes that about 50% of the energy penetrates into the facade system, while the rest is lost due to orientation, exposure and reflection. The water within the panels captures about 40% of this energy and the 10% is converted into biomass by the algae.

Doing the same with Rochester, NY, the average annual amount of solar radiation from 1998 to 2005 for our region was 4.0 - 4.5 kWh/m²/day. (National Renewable Energy Laboratory for the U.S. Department of Energy 2008). Let’s assume the middle range of 4.25 kWh/m²/day would be reaching the facade. We also have to account for loss to due orientation (the panels are vertical), reflection, and exposure.

\[ 4.25 \text{ kWh/m}^2/\text{day} \times .5 = 2.125 \text{ kWh/m}^2/\text{day} \]

An individual algae panel has the dimensions of 2’ - 3 1/2” x 8’ - 10 1/4”, or an area of 18.38 square feet. 60 panels are planned per facade section, with 3 sections total. This comes to 180 panels when multiplied. The total area of the algae facade is:

\[ 180 \text{ panels} \times 18.38 \text{ sq. ft} = 3,308.4 \text{ total sq. ft.} \]

\[ 1 \text{ m}^2 = 10.7639 \text{ sq. ft.} \]
The next step would be to take the area and multiply it by the average energy delivered by solar radiation.

\[
307.36 \text{ m}^2 \times 2.125 \text{ kWh/m}^2/\text{day} = 653.15 \text{ kWh/day}
\]

Next, we have to factor for losses.

Biomass energy = 653.15 kWh/day \times 0.10 = 65.315 kWh/day

Heat energy = 653.15 kWh/day \times 0.40 = 261.26 kWh/day

Extended over a year, or 365 days of operation (this is of course assuming optimal conditions),

Biomass energy production = 65.315 kWh/day \times 365 days = 23,840 kWh

and

Heat energy gained = 261.26 kWh/day \times 365 days = 95,360 kWh

Total Energy Production = 119,200 kWh

This estimate is the maximum amount of energy that could potentially be produced by the algae facade. In reality, it would probably be less; Colt International GmbH, sites that via the energy extraction method that they have established in Hamburg, they are able to capture around 80% of the energy contained within the biomass (2013).

On the matter of carbon sequestration, approximately 1.8g of carbon dioxide is sequestered for every 1g of algal biomass produced (Kumar et al. 2011; Sudhakar, Suresh, and Premalatha 2011).
Using the BIQ’s daily biomass generation estimate of $15g/m^2$/day, the facade would sequester approximately:

$$1.8g \times 15g/m^2/day \times 307.36m^2 = 8,298.72g \text{ of } CO_2 \text{ / day.}$$

Annually Sequestration = $8,298.72g \text{ of } CO_2$/day $\times 365 \text{ days} = 3,029,032.8g$

This is equivalent to approximately 3 metric tons.

In addition to the energy generated by the algae panels, the 84 SunPower E20-327 photovoltaic panels would also produce energy. Based on SunPower's cut sheet, these panels have a nominal power rating of 327 W and an average efficiency of 20.4% (SunPower 2016).

To calculate the estimated production, the National Renewable Energy Laboratory's online calculator was utilized. It takes into account system size, the type of solar panel, array type, estimated system losses, degree of panel tilt, and orientation to the south. Utilizing 84 panels rated at 327W, a 27.4 kW system would be created. A premium panel type was selected. This gives an efficiency rating of 19%. Other options included a standard or thin film module type but both are listed as only having 15% and 10% efficiency respectively. The premium was chosen because it was the closest to the listed 20.4% efficiency rating. The system lost was kept at the suggested average of 14%, which takes into account soiling, shading, snow, manufacturing imperfections, poor wiring and connections, photovoltaic cell deterioration, performance variation, system age, and system outages. The panels are tilted at 43 degrees but are rotated approximately 22 degrees north of due south. The result was an annual production of 31,081 kWh per year. While this is just an estimate, the calculation takes into account over thirty years of location specific solar and meteorological data (NREL 2016).

To answer the question of whether the common house is actually carbon negative we have
to look at the estimated usage of the building. According to the Residential Energy Consumption Survey an apartment building with 5 or more units will typically use 76,200 Btu per square foot in a year (United States Energy Information Administration 2009, CE1.2). The estimated usage calculation is below:

\[
1 \text{ Btu} = 0.293 \text{ W}
\]

\[
76,200 \text{ Btu} \times 0.293 \text{ W} = 22,326.6 \text{ W} = 22.327 \text{ kW/sq. ft.}
\]

Common house occupied space = 19,406 sq. ft.

Total usage/year = 19,406 sq. ft. * 22.327 kW/sq. ft. = 433,278 kW

Assuming building usage of 16 hours a day, this totals:

\[
16 \text{ hours} \times 433,278 \text{ kW} = 6,932,448 \text{ kWh on a yearly basis}
\]

Passive cooling could reduce this by 1% (this is based on the typical amount of energy that is used for cooling in New York State).

New total building consumption = 6,863,125 kWh

Using Climate Master’s Geothermal Saving’s Calculator (ClimateMaster 2009), 49% of the energy load could be eliminated using a geothermal system. North East Geo states that an average 2,000 square foot home would require a 4-ton system (North East Geo). This means that the system would need to be approximately 40 tons. Green Building Advisor recommends 175 ft of depth per ton. This means that the well would need to be 7,000 feet deep cumulatively (Briley 2010). With this
reduction, the new annual demand for the common house is:

\[ 6,863,125 \text{ kWh} \times .51\% = 3,500,193 \text{ kWh} \]

The onsite energy production = 

119,200 kWh (from the Algae facade) + 31,081 kWh (from the solar panels) = 150,281 kWh

Compared against the building’s consumption, only 4% of the common house’s energy demands are accounted for. This was calculated by dividing the estimated production by the estimated consumption.

**COST**

Given the experimental nature of the project, and the fact that it is using technology that is still very much evolving, the cost estimating for a project of this type is not as straightforward as a typical stick-built, wood or steel framed home, or multi-residence building. That said, there are some known elements using the BIQ building as a jumping off point.

The BIQ building was priced at approximately 5 million euro (Roedel and Petersen 2013), or $5.66 million when converted to U.S. currency. At around $2,300 to $3,200 per square meter of bioreactor (dependent on the size and scope of project according to Jan Wurm), when compared with the total cost of the BIQ building, the cost of the panel system was less than 10% of the building’s budget, including both the facade components and necessary hardware (Landers 2013).

The Flower City CoHousing Community expressed a desire to keep the cost at around $180
per square foot. Using RSMeans Online square footage calculator, the total cost of the base building would be around $4,053,508.62 million at $180 per square foot (The Gordian Group 2016).

The SunPower E20-327 solar panel sells for approximately $1,827.93 per panel at $5.59 per watt. (freecleansolar.com 2016). At 84 panels, this comes to $153,546.12

The panels according to would cost between $2,300 to $3,200 per square meter. Less if the production increases on the panel system but at today’s value, but using a middle value of $2,700 the system would cost an approximate $829,872 if there are a total of 180 installed panels (Landers 2013).

Geothermal installer North East Geo quotes a geothermal system for a 2,000 square foot home costing around $6,000-$8,000. Assuming a multiplier of 9.7 to bring the square footage to the 19,406 square feet of conditioned space, the cost would be at most approximately $77,600 (North East Geo).

With electricity currently costing around 16.5 cents/kWh in New York, the combined energy production of the algae facade, and solar energy comes to a savings of approximately $24,796.37 a year (NYSERDA 2016). This money could help to pay off the algae facade over a 33 year period.

Totaling all of the figures, the building costs an estimated:

\[
$5,114,526.74 = $4,053,508.62 + $153,546.12 + $829,872 + $77,600.
\]

This estimate does not include site work.
CONCLUSION

As a primary driver of climate change, we must reevaluate how we develop our built environment and how it functions. If we do not, we are on track to expand the root of the problem -- an excess of greenhouse gas emissions, primarily carbon dioxide. These excess emissions are caused by our demand for energy. Failure to curb and reduce these emissions will exacerbate the litany of complications that are tied to climate change and if left fully unchecked, they could severly diminish the habitability of our planet.

Ed Mazria suggests that buildings should aim to become carbon neutral by 2030 via a multi-phase step down of building greenhouse gas emissions. To reach this milestone we would have to slow and eventually phase fossil fuels out of our energy ecosystem. This project used this idea as a jumping-off point to question the viability of a building that is not only carbon (dioxide) neutral but also carbon negative. Designing buildings to be carbon negative would slow the release of greenhouse gases into the atmosphere and with increased adoption rates of applied carbon negative designs, could actually decrease the amount of carbon dioxide that is currently being emitted in excess.

Theoretically, buildings could reduce the amount of carbon in the atmosphere by producing more renewable, non fossil-fuel energy on-site than they actually need to function. Currently the two largest consumers of energy in the United States are the residential and commercial sectors. Of the two, the residential sector consumes a greater amount of energy. A majority of this energy comes from the combustion of fossil fuels, releasing emissions in the process. If we are going to radically adjust the way our built environment is designed and functions, the residential sector is an excellent place to start.
This is not a small proposal -- it calls for open minded people that are willing to challenge business as usual and the status quo of residential design. Fortunately, there are already people that have done this through the cohousing movement which originated in Denmark and has expanded to countries all over the world. Cohousing emphasizes a focus on community and a reduction of personal environmental footprint. The anchor point of all cohousing is the common house, which serves as a hub for the community members, creating a place to share meals, resources, and foster an extended family and support network.

The disparate elements of needing to reduce building emissions and requiring a drastic shift in housing conceptually, coalesced around a cohousing community that is forming in Rochester, NY, the Flower City Cohousing Community. At the heart of this new sustainable community, will be their common house. The intention behind this project was to develop a carbon negative common house that also suited the needs of the cohousing community. It is a well suited match as the heart of a sustainable community should also embody their sustainable ideals.

The end resolution deviated from the initial intention but that does not mean that it was a lost opportunity. In addition to proposing that the common house be a carbon negative building, the suggested pathway to achieving this goal was non-traditional, namely to implement an algae facade alongside the more common elements of geothermal heating and a solar panel array. The algae within the facade would draw in carbon dioxide from the air and light from the sun. After performing photosynthesis, the resulting biomass would be combusted as a fuel source, producing energy. Additionally, the water that the algae grows in would be used a heat source and used to supplement an in-floor heat distribution system. Coupled with geothermal wells, any excess heat could be stored within these wells when not needed. This system has been proven applicable in an architectural setting although it was not applied with the premise of a carbon negative building in
mind. If the building to which it was applied started off as being carbon neutral (the common house in this case), any excess energy created by the algae facade would cause the building to be carbon negative while sequestering carbon (due to photosynthesis) at the same time. In theory, this is how a carbon negative building with an algae facade would function.

In application this method proved untenable due to the scope of the program, the available solar resources, and scale of the facade. While the geothermal system greatly reduced the energy demand of the common house, the energy produced by the facade and solar panel system did not compensate or surpass the building's energy demands. Although the intended result was not realized, if the program were smaller or the facade larger, an application of this method may successfully achieve a carbon sequestering building. Especially if the system were scaled up beyond the extents of a single building to a neighborhood scale.

It would also be worth noting that the technology is in its infancy. The results of this project should not be taken to suggest that an impactful application is impossible -- the BIQ building has been able to leverage its algae facade to generate enough heat for the entire building. There is no way to tell yet if this success was an aberration but further testing could reveal promising results. If algae facades become more widespread, costs will come down. As algae facades better the environment and provide a unique architectural design approach, they contain the potential to be a powerful tool in the necessary fight against climate change and ballooning energy demands.
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