ALGAE BIO-REACTOR BUILDING ENVELOPE:

ENERGY SAVING AND CO2 SEQUESTRATION INFORMATION DISPLAY SHADING SYSTEM

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NOMENCLATURE

Algae Bioreactor – Algae bioreactors are designed for cultivating microalgae. There are open-system bioreactors and closed-system bioreactors. Algae bioreactors provides a water environment for algae with light and nutrients.

Carbon Sequestration – Carbon Sequestration is a process that removes carbon dioxide from the atmosphere. Carbon is naturally fixed. This process can mitigate the greenhouse problem.

Nannochloropsis Oculata – Nannochloropsis belongs to six genera of algae and usually is found in marine environments. This alga is widely used in industry because of its high percentage of oil.

Haematococcus Pluvialis – Haematococcus Pluvialis is found in freshwater and is used to produce Astaxanthin. The Astaxanthin will accumulate when there is living stress.

Energy use intensity (EUI.) – Energy use intensity indicates a building's energy efficiency. A building's annual energy usage divided by its gross square footage is EUI.

Greenhouse Gas (GHG) – Greenhouse gas absorbs and stores energy, cause the global temperature rise. 80% of GHG is made of Carbon Dioxide.

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ABSTRACT

In recent years, several algae-based facade systems have been integrated into buildings. They have high ecological performance, working as a multi-functional system to reduce energy use and capture carbon dioxide (CO_2). Compared with other dynamic building envelopes, the algae bio-reactive building envelope (ABBE) is unique to other dynamic building envelopes because it contains a bio-driven dynamic building skin rather than the traditional mechanically driven skin. Although algae bioreactor building systems have the potential to replace existing mechanical dynamic shading, their implementation has been limited due to the high costs associated with their research, development, and implementation. Much of ABBE research has focused on early concept exploration and feasibility discussions rather than the development and testing of actual implementations. The only real-world built project, the Bio Intelligent Quotient, investigates an algae bioreactor building envelope's energy gain and biomass harvest. However, solely using ABBEs' ability- to harvest energy to justify its usefulness may not be enough to support ABBE research and development at scale. This thesis discusses how algae bioreactors react to buildings' environments and demonstrates the significance of bio-driven dynamic shading in buildings in addition to the energy perspective.

This research aims to bring algae into cities using algae bioreactors on building envelopes. Algae bioreactors that respond to CO2 concentration, lighting, and temperature can be used as information display that show environmental conditions. Using algae's extraordinary properties, this study establishes a connection between environmental information and building appearance while also capturing CO2, generating electricity, storing thermal mass, and providing shading for indoor environments. Moreover, shading has enormous potential to help to reduce buildings' CO2 emissions and energy use.

How algae bioreactors respond to people's living conditions, such as lighting, air (CO2), or temperature, are also examined through using built prototype experiments and computer simulation. To accomplish this, I use a prototype that focuses on creating algae façade color variation, which means creating interaction between algae appearance and environmental conditions. Additionally, I use digital simulations to test how much energy the bioreactors receive from solar on a whole-scale building and speculate about how environmental factors influence algae bioreactor building envelope appearance.

An algae bioreactors building envelope is an environmentally reactive two-layer building skin that can indicate environmental conditions. Combining environmental data visualization and a bio-driven dynamic shading strategy gives designers a new design for building envelopes.

1. INTRODUCTION

Advanced algae cultivation technology inspires architects and designers because of its efficient energy production and ability to improve the health of the environment. In the last ten years, closed algae bioreactors have been designed with building façades to harvest biomass and gain heat from solar energy.

Compared with other dynamic building envelopes, a bio-reactive building envelope is a multi-functional system that improves indoor environment qualities and reduces energy use. Dynamic facades and shades are advanced exterior window systems that can be managed according to environmental conditions, such as light, air, and solar energy. The outdoor natural environment determines the geometry of a dynamic façade system to maximize occupants' comfort and conserve energy. Solar energy and lighting are under control and transmitted into buildings for other uses. A bio-reactive building facade is based on these dynamic facade systems, but it adds a natural element, algae, to provide a passive control method that improve the system's performance. In winter, algae's growth rate is low, and less dense algae make the façade more transparent, allowing more sunlight to enter the interior of the building. The ABBE also contains water that can transform sunlight into thermal energy, keeping the interior warm. In summer, a denser algae solution transforms the facade into a shading system that reduces irradiation and excess sunlight. Integrating this kind of bio-reactive envelope into the building facade has another advantage: that the high-concentration indoor CO_2 air can be input into the building surface. CO_2 is a good nutrient for algae growth, and, after the algae solution, the air will contain O_2 produced by algae photosynthesis. Such air is equivalent to undergoing purification and then returned to a room, thereby improving indoor air quality. Harvested biomass and biofuel could supply the building energy that has been generated onsite.

However, ABBE is not widely used in architecture. The technology has not been thoroughly developed, and there are certain problems associated with it, such as monotonous colors, heavy vertical load, complicated system operation, and metal frame corrosion. This research tests algae's reaction to solar or CO_2 within an urban context by exploring the inseparable relationship between algae and cities' environmental conditions through prototype experiments and computational simulation.

1.1 Background

1.1.1 Algae Bloom Indicates Environment Change

Algae are important in our ecological environment because they produce 50% of all oxygen[1] and ocean-based algae contribute 45 to 50% of total carbon dioxide absorption.[2] Algae bloom occurs in polluted lakes or rivers and indicates environmental change. Some people believe algae are useless or even undesirable when they grow in private yards or swimming pools. In contrast, scientists in the industrial field work to study all kinds of algae to find new raw materials or value in them. For example, algae can produce biofuel in a short time, and it is more productive than other forms of biomass. In addition, it is an efficient method of carbon sequestration.

This project seeks to interest architects or designers in the potential of algae in the architectural area. One strategy to achieve this goal is to make the advantages of ABBEs explicit; in addition to developing techniques, nothing is more persuasive than increasing people's awareness of what is taking place in our environment and what algae can do for our cities. This research leverages algae's extraordinary properties to establish a connection between

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[1] Russell L. Chapman, "Algae: The World's Most Important "Plants"—an Introduction," *Mitigation and Adaptation Strategies for Global Change* 18, no. 1 (2010): 5, doi:10.1007/s11027-010-9255-9.
[2] Haoyang Cai, "Algae-Based Carbon Sequestration," *IOP Conference Series: Earth and Environmental Science* 120(2018): 4, doi :10.1088/1755-1315/120/1/012011.

environmental information and building appearance.

1.1.2 Urgent Need for Renewable Energy

The US Energy Information Administration (EIA) published a report on US energy consumption by sector. According to their findings, in 2019, residential, and commercial energy accounted for 16% and 12% of gross US energy consumption, respectively, when energy losses were excluded. When energy was included, the residential and commercial sectors showed to comprise approximately 39% of total US energy consumption in 2019. Despite shortages, fossil fuels, such as coal, petroleum, and natural gas –accounted for about 80% of total US primary energy production. Many industrialized countries have made switching from fossil energy to sustainable energy a major priority.[4]

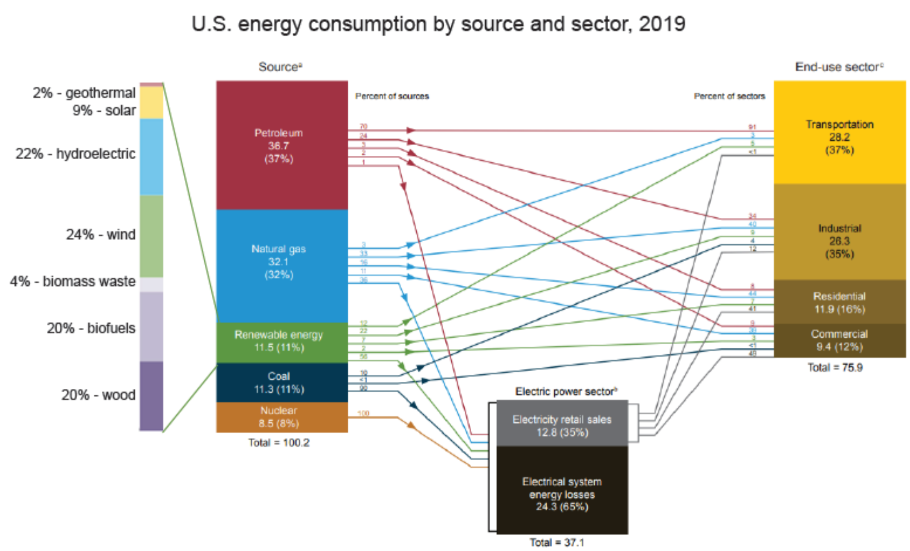

Figure 1-1: U.S. energy consumption by source and sector[3] (open-source image)

[3] "U.S. Energy Consumption by Source and Sector, 2019," U.S. Energy Information Administration, 2019, accessed June 22, 2021, https://www.eia.gov/energyexplained/us-energy-facts/#:~:text=Download%20image%20U.S.%20primary%20energy,natural%20gas%2034%25%20petroleum%2035%

[4] "U.S. Energy Facts Explained - Consumption and Production - U.S. Energy Information Administration (EIA)," U.S. Energy Information Administration (EIA), accessed December 7, 2021, https://eia.gov/energyexplained/us-energy-facts.

The transformation of resources in the industry, residential, and commercial sectors can positively impact today's energy-scarce society. Renewables include energy that comes from water, wind, and solar radiation. Biomass and geothermal energy are other options for sustainability. The decisive factors required for a successful switch to renewable energy are availability and efficient distribution of energy sources. Using renewable energy resources reduces the overwhelming force of the energy crisis and helps reduce greenhouse gas emissions.[5]

1.1.3 CO_2 Sequestration

Buildings' CO_2 emissions cause a greenhouse effect and negatively impact occupants. Greenhouse gas traps heat and warms the planet. Though greenhouse gases are part of ecology, human activity is most responsible for increasing emissions. The most significant source of greenhouse emissions is the burning of fossil fuels to generate electricity, heat, and transportation.[7] There are two ways to reduce CO_2 in the atmosphere: reduce CO_2 emission by reducing energy use or capture and store atmospheric carbon dioxide, which we call carbon

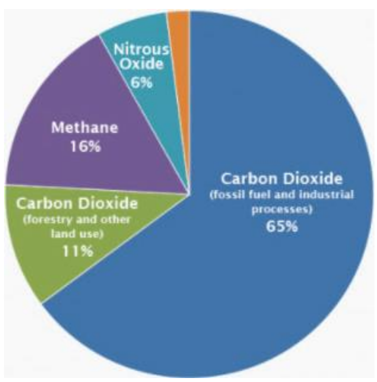

Figure 1-2: Global greenhouse gas emissions by gas[6] (open-source image)

[5] "AR5 Climate Change 2014: Mitigation of Climate Change — IPCC," IPCC — Intergovernmental Panel on Climate Change, accessed December 6, 2021, https://www.ipcc.ch/report/ar5/wg3/.
[6] "Global Greenhouse Gas Emissions by Gas," US EPA, accessed June 22, 2021, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.
[7] "AR5 Climate Change 2014: Mitigation of Climate Change — IPCC," IPCC — Intergovernmental Panel on Climate Change, accessed December 6, 2021, https://www.ipcc.ch/report/ar5/wg3/.

sequestration.

1.2 Research Structure Summary

Introduction: this thesis relates to renewable energy and CO_2 sequestration. Moreover, information delivery regarding the interior environment and how the building simultaneously handles renewable energy and CO2 sequestration could become crucial.

Literature Review: This part expands on the techniques involved in this thesis project, providing characteristics of algae and basic knowledge of how to cultivate algae and explaining how to design algae bioreactors by referring to Germany's Bio Intelligent Quotient's example bioreactor prototype design. A second layer of a building envelope, algae bioreactors are like many dynamic shadings in that they require basic knowledge of dynamic shading. This project not only includes a design of bioreactor but an evaluation of its performance. The literature review overviews existing evaluation and simulation research on algae bioreactor systems.

Motivation and Research Questions: this section explains the motivation for conducting this research, outlining the research questions and goals.

Proposed System: this section proposes a revised system based on the BIQ house. It details how it works and gives general rules for the design.

Methodology: This section reviews the two research methods involved in this project, prototype experiments and computer simulation evaluations.

Results and discussion: this section provides results from the prototype experiment and computer simulation, indicating what results were expected and what were not expected.

Future direction: This section discusses what has been accomplished within the scope of this thesis as well as provides suggestions for further studies.

1.3 Scope of Present Thesis

ABBE has the potential to replace existing mechanical dynamic shading. However, much of ABBE research has concentrated on early conceptual exploration and feasibility discussions without developing and testing actual implementations. The German Bio Intelligent Quotient finished construction in 2013, and the research team conducted experiments on the algae bioreactor building envelope's energy gain and biomass harvest. However, solely using ABBE’s energy harvesting capabilities to justify its usefulness may not be enough to support ABBE research and development at scale. This thesis discusses how algae bioreactors react to building environments and an innovative bio-driven information shading system.

This research seeks to bring algae into cities using algae bioreactors. This would facilitate the building of new envelopes and would convince the industry and academia to investigate and fund similar project through environmental information. Algae bioreactors that respond to CO_2 concentration, lighting, and temperature can potentially become information displays for the city that show how environmental conditions change over time. Additionally, they can also capture CO_2, generate electricity, provide thermal mass for energy storage onsite, and provide interactive shading that could reduce CO_2 emission, generate energy, and improve indoor air quality.[8] This project's main task is to test an algae bioreactors’ feasibility to become an information display medium integrated within a building envelope. Furthermore, computer simulation provides a speculative scenario of using algae bioreactors on an existing New York City building. New York City is a typical large metropolis that has energy and CO_2 emission problems. Many similar structures there could be used as testing objects.

This research studies how ABBE reacts to light and CO_2. Although there is extensive

[8] Maryam Talaei, Mohammadjavad Mahdavinejad, and Rahman Azari, "Thermal and Energy Performance of Algae Bioreactive Façades: A review," *Journal of Building Engineering* 28 (2020): 3-4, doi:10.1016/j.jobe.2019.101011.

literature in biology that characterizes the relationship between growth and light, this thesis emphasizes the use of ABBE in the built environment in the built environment and therefore addresses the visual and communicative aspects of those reactions.

1. How do algae bioreactors respond to people's environmental conditions, such as light, air (CO_2), or temperature? The research methodology explores solutions to these questions by building a functional, small-scale prototype.

2. Assuming that an algae bioreactor is installed on the surfaces of a high-rise building in New York City, how much heat and biofuel can be generated by the building envelope in different seasons? The energy generated by this biofuel accounts for a certain percentage of the total energy consumption of the building. Computer simulation helps to answer this question. A digital model built with Rhino software is tested through a simulation in Ladybug software with estimated CO_2 production.

3. An algae-bioreactor can play a role in a building's carbon neutralization. How much CO_2 can be absorbed from a chosen building? This speculation is based on the literature review.

4. What are the color and transparency variations of the algae, and what variables control these changes? Prototype bioreactors are given environmental variables to observe color changes.

The prototype focuses on creating algae façade color variation, which means creating interaction between algae appearance and environmental conditions.

Digital simulations test the bio-reactor performance on a whole-scale building and speculate on the algae bioreactors' appearance.

2. STATE OF THE ART

2.1 Technologies Applied in the Proposal and Research Approach

The literature review includes three closely related themes: algae and algae bioreactors, dynamic building envelopes, and algae bioreactor building envelope simulation and evaluation. The German Bio Intelligent Quotient building is used in this thesis as a case study to explain these three topics.

The first topic requires a general understanding of algae and algae bioreactors and the application of bioreactors in the built environment. This research investigates the conditions required for proper algae growth. The case study shows how the bioreactor in the BIQ project was designed.

As a second skin of a building, ABBE presents building and construction systems characteristics like those in dynamic shading systems. The bioreactors placement on the facades of a building can be based on the construction and technical or structural process of dynamic building skins. In this literature review, several types of dynamic building skin are introduced in relation to these topics.

In this thesis, computer simulation is used as a tool to visualize and test bioreactors' thermal and light regulating performance in a building. In particular, this research investigates how a bioreactor system, when incorporated on a building facade could change over time. Can they improve the comfort of people living indoors? An overview of relevant topics is necessary to refine this project's conceptual proposition, development, and evaluation.

Germany Bio Intelligent Quotient was constructed in 2013. The research project was conducted from 2010 to 2013. The research group includes Arup Germany GmbH, Strategic Science Consult GmbH, and Colt International GmbH. Prototypes of the developed system were tested in January 2012. The research has sought to maximize biomass and heat gains. Their technical report recorded conceptual design, operational dilemmas, energy, and occupant experience.[9]

2.2 Algae and Algae Bioreactors

2.2.1 Algae Species and Values

Algae are defined as “oxygenic photosynthesizers other than embryophyte land plants”[10] Algae have the most potential to be sources of renewable biofuels in the future. Unlike fossil fuels, algae can be harvested in a very short time, and can live under unfavorable environmental conditions. Algae are everywhere within the biosphere, generating a large amount of Oxygen.[11] Both its use as a source of energy fuel and its ability to capture CO2 have also attracted considerable attention.

There are 160,509 species of algae, and infraspecific names are listed in the AlgaeBase.[12] The classification of algae remains controversial. Two different algae: Nannochloropsis Oculata and Haenatococcus Pluvialis, are used for this project. Nannochloropsis grows widely in saltwater. Some Nannochloropsis species are suitable for algal biofuel production because they can accumulate high levels of fatty acids. Haenatococcus Pluvialis is a freshwater unicellular alga that is sensitive to its living condition. When the living condition is not suitable, it forms Astaxanthin, making this green alga appear red.

Algae absorb carbon dioxide and produce oxygen. The chemical equation for

[9] Jan Wurm et al., *Monitoring Fassadenkonstruktion aus Photobioreaktoren am Pilotprojekt BIQ auf der IBA 2013 in Hamburg. Abschlussbericht* (2016), 57-58.
[10] T. Cavalier Smith, “Evolution and Relationships of Algae: Major Branches of the Tree of Life,” in *Unravelling the Algae: The past, Present, and Future of Algal Systematics* (Boca Raton: CRC Press, 2007), 21–55.
[11] Marc Y. Menetrez, "An Overview of Algae Biofuel Production and Potential Environmental Impact," *Environmental Science & Technology* 46, no. 13 (2012): 7073, doi:10.1021/es300917r.
[12] "Genus Search: Algaebase," Algaebase: Listing the World's Algae, accessed June 22, 2021., https://www.algaebase.org/search/genus/.

photosynthesis as follows:

$$6\ CO_2 + 6\ H_2O \longrightarrow C_6H_{12}O_6 + 6\ O_2 \qquad (1)$$

2.2.2 Basic Requirements of Algae Cultivation

Based on existing research and early experimentation with Algae, two types of algae were chosen for experimentation. Algae that easily grow were prioritized in this experiment. The choice of algae species also coordinated with the experimental goals of density and variation change. Nannochloropsis oculata was chosen as a density changing type because of its adaptability and fast growth rate. Hanatococcus Pluvialis is ideal for seeing color variation because it is sensitive to elements of the environment, such as sunlight and nutrition.

Nannochloropsis oculata is single-celled green algae and prefers brackish to saltwater. Its ideal PH is nine, and its ideal temperature is 30 Celsius degrees. As the algae has Chlorophyll -a and -b, its color ranges from yellow green to dark green. It easily adapts to the environment and grows extremely fast. Culture salt and nutrition media for this project came from ALGAE RESEARCH AND SUPPLY[13] Culturing salts are a modification of the media from Aiba, S. and Ogawa, T.[14] and Schlösser.[15] Nannochloropsis Oculata likes nitrogen and phosphorus sources such as sodium nitrate ($NaNO_3$) and sodium phosphate ($NaPO_4$). To initiate its growth, it must be exposed to dim light for the first few weeks, followed by brighter light but no direct sunlight for bottled cultures. Algae nutrient media is F/2, which is the perfect nutrient media for algae. F/2 was slightly modified and adjusted for freshwater and seawater algae. It originally comes from Guillard

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[13] "Algae Research Supply: Algae Culture Salts, Marine Algae," Algae Research Supply, accessed June 22, 2021,https://algaeresearchsupply.com/collections/algae-culture-salts-and-medias/products/algae-research-supply-algae-culture-salts-marine-algae.

[14] Shuichi Aiba, and Takahira Ogawa, "Assessment of Growth Yield of a Blue-green Alga: *Spirulina Platensis* in Axenic and Continuous Culture," *Journal of General Microbiology* 102, no.1 (1977), 179 – 182, doi:10.1099/00221287-102-1-179

[15] U.G. Schlosser, "SAG-Sammlung von Algenkulturen at the University of Göttingen Catalogue of Strains X." *Botanica Acta* 107, no.3, (1994): 111 – 186, doi:10.1111/j.1438-8677.1994.tb00784.x.

and Ryther (1962).[16]-[17]

Lighting is one of the most critical factors influencing N. Oculata metabolic activities. N. Oculata shows high adaptation to changing lighting, and algae's growth rate highly depends on growth stages and living conditions. Bicarbonate limits photosynthesis processing.[18]

Haematococcus Pluvialis is a type of freshwater green algae. It is one of the producers of astaxanthin, the production of which is promoted by light. A lower cost way to harvest astaxanthin is under high light intensity and nitrogen starvation. When its living conditions are not ideal, the species can produce high concentrations of the antioxidant astaxanthin. It lives in PH 7-8 freshwater and contains Chlorophyll-a, -b, and astaxanthin. Its growth rate is slow and will react to bright light and high salinity. Culture media for this project comes from CAROLINA Biological Supply Company.[19] Its optimal temperature for living is 22 Celsius, and optimal light should be low, ranging from 50 to 100 foot-candles (540 Lux to 1076 Lux). This project uses freshwater media Alga-Gro Freshwater Medium as Haenatococcus Pluvialis start media. The CAROLINA

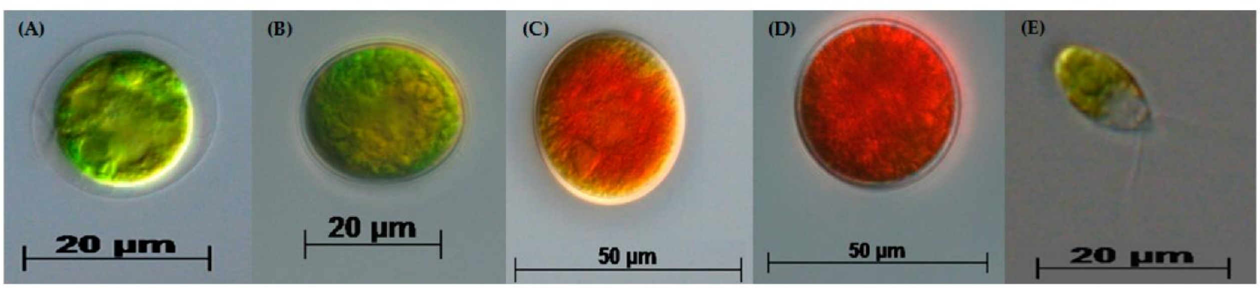

Figure 2-1: Life stages of H Pluviali[20] (open-source image)

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[16] Robert R. Guillard and John H. Ryther, "Studies OF Marine Planktonic Diatoms: I. Cyclotella Nana Hustedt and Detonula Confervacea Cleve," *Canadian Journal of Microbiology* 8, no. 2 (1962): 229-239, doi:10.1139/m62-029.
[17] Robert R, Guillard, "Culture of Phytoplankton for Feeding Marine Invertebrates in 'Culture of Marine Invertebrate Animals.'" *Culture of Marine Invertebrate Animals*, 1975, 29-60, doi:10.1007/978-1-4615-8714-9_3.
[18] Yussi M. Palacios, Avigad Vonshak, and John Beardall, "P-hotosynthetic and Growth Responses of Nannochloropsis Oculata (Eustigmatophyceae) During Batch Cultures in Relation to Light Intensity," *Phycologia* 57, no. 5 (2018): 492, doi:10.2216/17-100.1.
[19] "Haematococcus Pluvialis, Living," Carolina.com, accessed June 22, 2021, https://www.carolina.com/catalog/detail.jsp?prodId=152282&s_cid=ppc_googleproducts&utm_source=google&utm_medium=cpc&scid=scplp152282&sc_intid=152282&gclid=Cj0KCQiAyoeCBhCTARIsAOfpKxiCRCMF17EmmWCpbsVQ0bJMJFfZlhXvYybnL0viOZ5AxBi4CyfNHnEaAplXEALw_wcB#.
[20] Thomas O. Butler et al., "Media Screening for Obtaining Haematococcus Pluvialis Red Motile Macrozooids Rich in Astaxanthin and Fatty Acids," *Biology* 7, no. 1 (2018): 2, https://doi.org/10.3390/biology7010002.
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Culturing Algae Booklet provides additional details about Medium.[21]

2.2.3 Bioreactors

An open raceway pond and closed photobioreactor system are used to cultivate algae. Algae photosynthesis in turn produces biomass and oxygen. The open raceway pond is the oldest and easiest method of algae cultivation. However, this system faces problems like low biomass density, and water is easily contaminated and evaporated. A closed photobioreactor system ameliorates these problems by providing a closed system that renders algae cultivation more controllable than in an open system. Tubular and flat photosynthesis bioreactors are commonly used in industry. A Christmas-tree-shaped bioreactor is a modified version of a tubular bioreactor with a tapered geometry that maximizes its exposed area to solar energy.[22] In addition to common bioreactors, some others, such as the algae waterbed done by algaePAR, act as experimental prototypes. With algaePARC the algae tubes are immersed in large plastic bags filled with water. This system requires far less cooling and heating because the water adjusts temperature for algae.[23]

2.2.4 Bio Intelligent Quotient - Bioreactor Prototype Design

The photobioreactor panel is more than simply a container for algae culture. The Bio Intelligent Quotient algae bioreactor is a secondary façade system that makes use of flat closed bioreactor system technology. Many details such as necessary supply lines, substructure for removing the loads, and material choices were considered during the initial design stage.

One fundamental consideration is that the bioreactor must be designed to bear extreme weather. It is necessary to operate and maintain it on a building envelope with specific longevity.

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[21] "Culturing Algae," Carolina.com, accessed December 7, 2012, https://www.carolina.com/teacher-resources/Document/culturing-algae-instructions/tr29112.tr.

[22] "Microalgae Become Resistant to Biological Contamination through Targeted Cultivation," GICON-Group, accessed December 7, 2021, https://www.gicon.de/aktuelles-546/artikel/items/microalgae-become-resistant-to-biological-contamination-through-targeted-cultivation.

[23] "Bekijk: Touren Door Een Park Vol Algen," NEMOKennislink, accessed June 1, 2021, https://www.nemokennislink.nl/publicaties/touren-door-een-park-vol-algen/.

For energy harvest efficiency purposes, energy converters are fitted in bioreactors. If this technology is marketed, costs, and benefits would also have to be considered.[24]

In thermal and solar energy, have to be controlled in algae bioreactors in order to prevent it from overheating jeopardizing as a consequence its energy yield. In addition, it is imperative to minimize cooling loads and ensure daylight.[25]

An airlift system cooperates with the plate-shaped photobioreactor. Gas bubbles are generated at the bottom part of PBR and rise to produce turbulence, maximizing the algae's metabolic activity. A German algae bioreactor design uses Chlorella Vulgaris.[26]

Bio-photoreactor is used in BIQ. The building consists of a slab where panels are going to be attached, a C-profile element under the panel to conceal the supply and return system, a durable frame of the sealed space against wind and dead load, and a sealed space/container made of safety glass for algae solution. Vertical bars at the bottom diffuse any air bubbles.[27]

2.3 Dynamic Building Envelope

2.3.1 Dynamic Shades Introduction

Dynamic facades and shades are advanced exterior window systems that can be managed according to natural conditions, such as light, air, and solar energy. Their geometry is determined by the outdoor natural environment to maximize occupant's comfort and achieve the goal of energy saving. Solar energy and lighting are under controlled and transmitted into building for other uses.[28] Compared to other dynamic building envelopes, a bio-reactive building envelope is a multi-functional system that improves indoor environmental qualities and reduces energy use. Bio-

[24] Jan Wurm et al., *Hinterlüftete Fassadenkonstruktion aus Photobioreaktoren. Abschlussbericht* (Stuttgart: Fraunhofer IRB Verlag, 2013), 22.
[25] Ibid, 23.
[26] Ibid, 24-26.
[27] Ibid, 40-41.
[28] Ihab Elzeyadi, "The Impacts of Dynamic Façade Shading Typologies on Building Energy Performance and Occupant's Multi-comfort," *Architectural Science Review* 60, no.1, (2017): 316, doi:10.1080/00038628.2017.1337558.

reactive building façades add the natural element of algae based on the dynamic envelope, which is more intelligent and passive control method. In winter, the algae's growth rate is low, and less dense algae make the façade more transparent, which brings more sunlight into the indoor building; the photovoltaic tech façade contains water that can transform sunlight into thermal energy. In turn, this maintains indoor warm. In summer, a denser algae solution makes the facade a shading system to reduce irradiation and excess sunlight. Adding this kind of bio-reactive envelope to the building facade has another advantage: the indoor high-concentration CO_2 air can be transferred into the building surface. CO_2 is a good nutrient for algae growth, and after the algae solution, the air will contain O_2 produced by algae photosynthesis. When returned indoors, such air has effectively been purified, thereby improving indoor air quality. In addition, harvested biomass and biofuel could be generating energy onsite and supplying the building with it.

2.3.2 Effects of Dynamic Shading on Indoor Environmental Quality (IEQ)

To improve the quality of indoor environment, a dynamic shading system is expected to be "intelligent," "adaptive," or "responsive." Typical operations of dynamic building envelopes aim to regulate daylighting, reduce heating or cooling loads or improve ventilation. Some could even provide energy to the building. In other occasions, an adaptive building envelope measures and processes outdoor or indoor environmental conditions and adjusts itself according to the occupants' preferences.[29]

In 2017, Elzeyadi evaluated six types of dynamic shading: automated movable screens, automated exterior blinds, stretched fabrics/weaved panels, optical elements panels, egg-crated/fins, and thermal change planes. Energy utilization intensity is reduced with an average savings of 20-30%. Reductions were observed in solar thermal loads. The thermal and vertical

[29] Maria Konstantoglou and Aris Tsangrassoulis, "Dynamic operation of daylighting and shading systems: A literature review," *Renewable and Sustainable Energy Reviews* 60 (2016): 269-283, doi: 10.1016/j.rser.2015.12.246.

blinds systems are the most effective strategy to reduce thermal loads, lowering them by 75-92%. Most of these shading systems met the standard of – 55% floor area achieving or exceeding the 300 Lux threshold for 50% of the year. In conclusion, the most consistent performance among these six dynamic shadings is egg rates/blinds and thermal elements. The best approach for reducing glare is 3D parametric screens.[30]

2.3.3 Dynamic Shading as Information Facade

Dynamic shading technologies are not only able to contribute to energy efficiency and human comfort; they could also be used as information displays. In other words, because algae change color over time, a building façade composed of this organic material could be designed as a screen that projects information. Intelligent shading can respond to thermal, lighting requirements, and individual engagement. Krietmeyer's 2008 thesis proposed combining dynamic shading and media display, accepting the information to be presented on the building façade and using context and environmental conditions to adjust the facade light and information. The most common information we presented on the facade is its reaction to daylight. In addition to the presentation of light information, environmental information can be presented on the facade, adjusting to affect indoor performance. Indoor human participation can also play a decisive role. According to the activities and needs of the people in a room, the facade pattern can be adjusted and customized to improve the comfort of indoor light. This is a kind of information exchange between building facades and users.[31]

2.3.4 Environmental Control and Information Exchange through Responsive Building Membrane Technology

[30] Ihab Elzeyadi, "The Impacts of Dynamic Façade Shading Typologies on Building Energy Performance and Occupant's Multi-comfort," *Architectural Science Review* 60, no.1, (2017): 322, doi:10.1080/00038628.2017.1337558.
[31] Elizabeth Krietemeyer, "Environmental Control and Information Exchange through Responsive Building Membrane Technology," (Master thesis., Rensselaer Polytechnic Institute, 2009),10.

Krietemeyer's research introduced a new type of material: electroactive polymers (EAP). This material is controlled by an electromagnetic field, which changes its size and shape. It is applied on the building facade to control the amount of light transmission and display image information. In her research, Krietemeyer discussed how single-layer, double-layer, and three-layer EAP can be applied to the building facade and outlined how to improve the indoor light environment. This kind of smart facade controlled by a tiny electromagnetic field can sense and respond to light to adjust its conditions. This control is a response to seasons. It can also be set according to the user's preference through indoor occupants. In this project, the effect of adjusting light through EAP technology is used as an essential piece of information to define the boundary of a building. Both the lighting control of the facade and people’s preferences are considered influential on the facade effect. In algae bioreactors research, similar ideas have been used, but the regulation of bioreactor's opposite is based on algae's metabolic activity. This also shows environmental information, and the amount of human activity also has some influence on the facade.

2.3.5 Vertical Algae Farm 2014

The Vertical Algae Farm 2014 is a project by Cesare Griffa designed for the 2015 expo in Milan. Its façade was designed for algae cultivation as well as an interactive smart building skin. The algae-growing modules are composed of transparent plastic film. The architectural envelope system provides algae necessary living conditions such as a suitable temperature and is equipped with a programming control system. The active façade consists of more than a thousand algae modules. Each of the modules can be filled or emptied. The whole system circulates algal solutions and is reconfigured by full or empty modules. Additionally, the system creates interaction between people and the facade by using motion sensors that can detect people’s movements and a programming system that remaps the façade’s appearance.[32]

2.4 Algae Bioreactor Simulation and Evaluation

2.4.1 Algae Bioreactor Simulation and Evaluation Introduction

Algae bioreactors integrated within building facades are designed to be exposed to solar radiation and to harvest biomass. Beyond their ability to obtain solar energy, algae bioreactors also work as daylight regulators and possess an average shading co-efficient of 67%.[33] Evaluations of areas such as heat production rates, biomass production rates, lighting control, and energy consumption reduction have been executed. Many of the evaluations were based on small-scale prototype experiments and computer simulations. As the only one built and monitored for scientific study purposes, the BIQ empirical building provided many informative data such as solar radiation to heat conversion rate, solar radiation to biomass conversion rate, and ability to sequester CO_2. This section goes over the existing evaluation research of algae bioreactors used as building envelopes. Data and experience from previous studies have been engaged in this thesis research. This thesis built upon a previous study and develops a unique way to design algae bioreactor building envelopes.

2.4.2 Algae Bioreactor as a Shading System that Reduce Energy Consumption

The implementation of algae bioreactors in buildings is often challenged by technical planning or financial problems. As a result, much research has focused on conducting evaluations through computers. One approach is using a closed-loop simulation analysis integrated with BIM, which provides a framework for exploring the performance of algae façades within a dynamic

[32] "Vertical Algae Farm 2014," Cesare Griffa, accessed December 7, 2021, https://cesaregriffa.com/2015/03/16/vertical-algae-farm-2014/.
[33] Amira Elnokaly and Ian Keeling, "An Empirical Study Investigating the Impact of Micro-algal Technologies and Their Application within Intelligent Building Fabrics," *Procedia - Social and Behavioral Sciences* 216 (2016): 721, doi: 10.1016/j.sbspro.2015.12.067.

system model. The preliminary system dynamics model in the study clearly illustrates what factors influence the workings of an algae façade. The simulation framework based on BIM provides a methodology for evaluating an algae façade.[34] This research is ongoing but does provide a framework for evaluating algae bioreactors integrated with BIM.

Algae has incredible potential to reduce the embedded CO_2 emissions embedded in buildings' life cycle by reducing energy consumption and capturing CO_2. Umdu's 2017 study indicated that algae bioreactors act as insulative building envelope components. They studied the thermal transmittance (U value) of different material combinations using. Box-Behnken experimental design methods as an optimization tool. Their best result was an algae bioreactor with a reservoir wall and an air layer, and the lowest U value they recorded was 3.84W/m^2 K.[35]

Daylighting comfort is another potential advantage of algae bioreactors. Pagliolico's research of plastic prototypes examined light transmittance and visual comfort. Three types of plastic photobioreactors were designed to be test subjects. They used a variety of shapes such as circular cubicles/square packing, rectangular cubicles, and aerated circular cubicles/hexagonal packing. Light transmittance was recorded, and the value was highly variable in time due to algae growth and sun positioning. The study drew an average light transmittance of, 0.76. Their algae system limited users' the view to the outside, so it is possible that the presence of green algae would influence the occupants' normal activities if the windows' transparency really mattered.[36]

2.4.3 Bio Intelligent Quotient – Monitoring Report

The ARUP group monitored heat transfer rate and bio-mass production. In one of their

[34] Soowon Chang et al., "Framework for Evaluating and Optimizing Algae Façades Using Closed-loop Simulation Analysis Integrated with BIM," *Energy Procedia* 143 (2017): 237, doi: 10.1016/j.egypro.2017.12.677.
[35] Emin S. Umdu et al., "Optimization of Microalgae Panel Bioreactor Thermal Transmission Property for Building Façade Applications," *Energy and Buildings* 175 (2018): 113, doi: 10.1016/j.enbuild.2018.07.027
[36] Simonetta L. Pagliolico et al., "A Novel Photo-bioreactor Application for Microalgae Production as a Shading System in Buildings," *Energy Procedia* 111 (2017): 152, doi: 10.1016/j.egypro.2017.03.017.

reports, they found that 40% of heat gain expected, while the actual conversion efficiency factor is 21%. The conversion of sunlight into biomass was found to be 4.4%, which is 50% lower than the expected production. Social acceptance has also been studied in the case of green panels and possible olfactory influence. Users were all open to this new type of building envelope even though small problems existed such as system acoustic issues.[37]

The existing diagram is based on the BIQ's building system and energy diagram. The heat

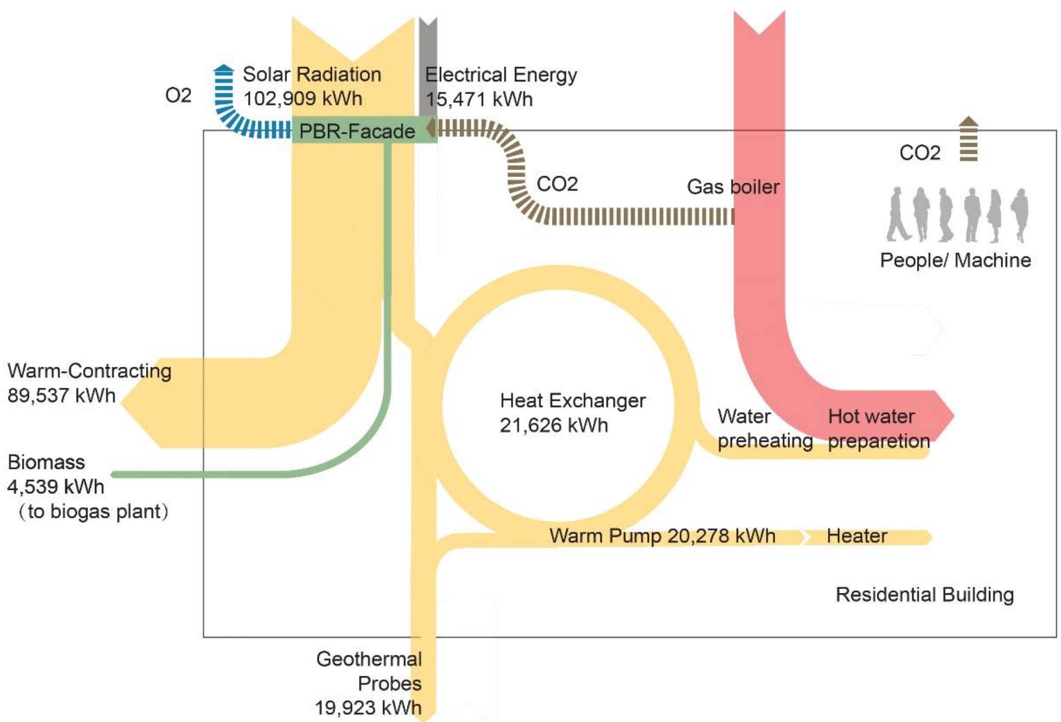

Figure 2-2 Bio Intelligent Quotient Building system diagram

obtained from bioreactors is redistributed for use in the BIQ's house building system. In summer, there is no high heating demand, so the heat energy could either be stored in the building or delivered to the district of Hamburg. In spring and fall, a heat pump supplements the temperature of the harvested heat to ensure that it reaches the required building level. Some electrical energy

[37] Jan Wurm and Martin Pauli, "SolarLeaf: The World's First Bioreactive Façade," *Architectural Research Quarterly* 20, no. 1 (2016): 1, doi:10.1017/s1359135516000245.

is used to maintain the bioreactors. Natural gas combustion generates hot water for the building, and CO_2 from combustion is delivered to bioreactors.[38]

Despite the great contributions of the BIQ system, this project has failed to address several areas. First, the system has not generated biofuel energy onsite. Second, the building has a natural gas boiler. CO_2 produced from combustion is transported to solarleaf, and the gas feeds algae, but it does not use indoor exhausted, containing high CO_2 concentrations. Third, from an aesthetic standpoint, is it necessary for the façade to be green; is there any other value of the algae bioreactor building envelopes?

[38] Jan Wurm et al., *Monitoring Fassadenkonstruktion aus Photobioreaktoren am Pilotprojekt BIQ auf der IBA 2013 in Hamburg. Abschlussbericht* (2016), 44.

3. MOTIVATION AND RESEARCH QUESTIONS

3.1 Motivation

Although the algae bioreactors' building system has the potential to replace existing mechanical dynamic shading, its implementation has thus far been limited due to the high cost and difficulty of its research and manufacturing. The German Bio Intelligent Quotient is the only implemented project and has been demonstrating the an algae bioreactor building envelope's energy gain and biomass harvest. Much of ABBE research has focused on early concept exploration and feasibility discussions without developing and testing actual implementations. This thesis discusses how algae bioreactors respond to a building's environment and examines the significance of bio-driven dynamic shading in buildings in addition to energy.

This research aims to find a way to bring algae into cities by using algae bioreactors on building envelopes and algae bioreactors to show environmental information. Algae bioreactors that respond to CO_2 concentration, lighting, and temperature can act as information displays showing environmental conditions. Algae's growth rate highly dependent on environmental conditions, so if the living environment is ideal, they will grow better. Conversely, if conditions are less favorable the growth rate is low. On building facades, for instance, the façades in sun light or shadow will have different rates of algal growth. Over time, the algae solution in each bioreactor has a different density, so they look different- while this is happening, algae bioreactors capture CO2, generate energy, store thermal mass onsite, and provide interactive shading that all have great potential to reduce CO2 emission and, energy consumption and improve the quality of indoor environments.

3.2 Research Questions

The primary objective of the project is to explore the following questions：

1. How can algae bioreactors respond to different aspects of people's living conditions, such as lighting or air (CO2)? Are they going to change in density, color, in a sustained manner or are they going to be damaged by uncontrollable environmental conditions? Both prototype experiments and computer simulations are involved.

2. Assuming that an algae bioreactor is installed on the surfaces of a high-rise building in New York City, how much energy can they gain from solar radiation? How much CO_2 can be absorbed by the system? How much biofuel can be generated? What percentage of the building's total energy consumption can be generated does energy generated by this biofuel?

3. Algae bioreactors can play a role in controlling the lighting and thermal gain of a building; how, then, could it improve indoor lighting and thermal environments? In different seasons, how do algae bioreactors adjust the indoor environment, and to what extent do they improve it?

In terms of question 1, small-scale experiments help to establish a connection between algae and environmental conditions. The prototype focuses on creating color variation in the algae façade. This variation can be used as an aesthetic element on the facade and as a way to display environmental conditions.

Regarding question 2 and 3, the built model helps to understand the changing process on a building. Digital simulations test how much energy bioreactors will attain from solar on a whole-scale building and speculate about light and CO_2's impact on bioreactors.

4. PROPOSED SYSTEM

This research focuses on ABBEs, bioreactor systems that (1) work as an environmental indicator (2) harvest biofuel onsite and (3) absorb indoor CO_2. This approach covers areas unexplored in previous projects like the BIQ. Exterior second skins display environmental information by changing the algae bioreactors' appearance. Biofuel is a renewable fuel resource with the potential to become a next-generation fuel for our daily life. In addition to converting sunlight into heat energy, the proposed system suggests using biofuel originating from the algae

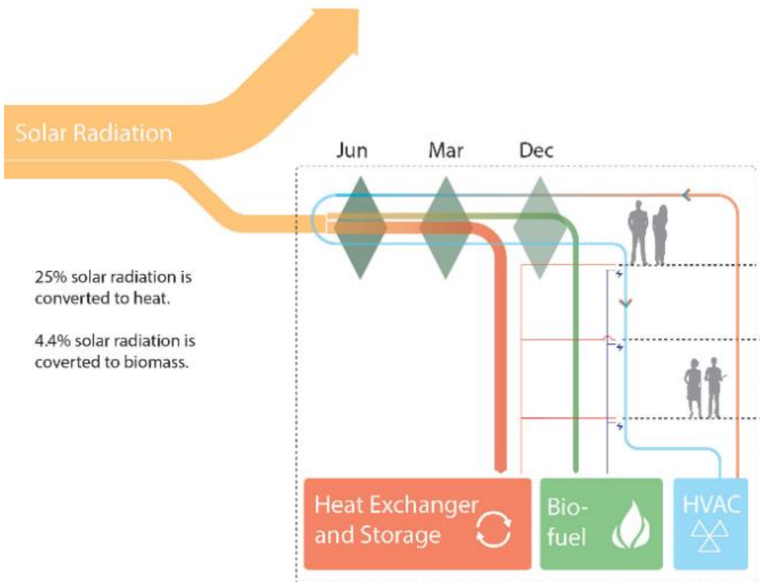

Figure 4-1: Proposed building system

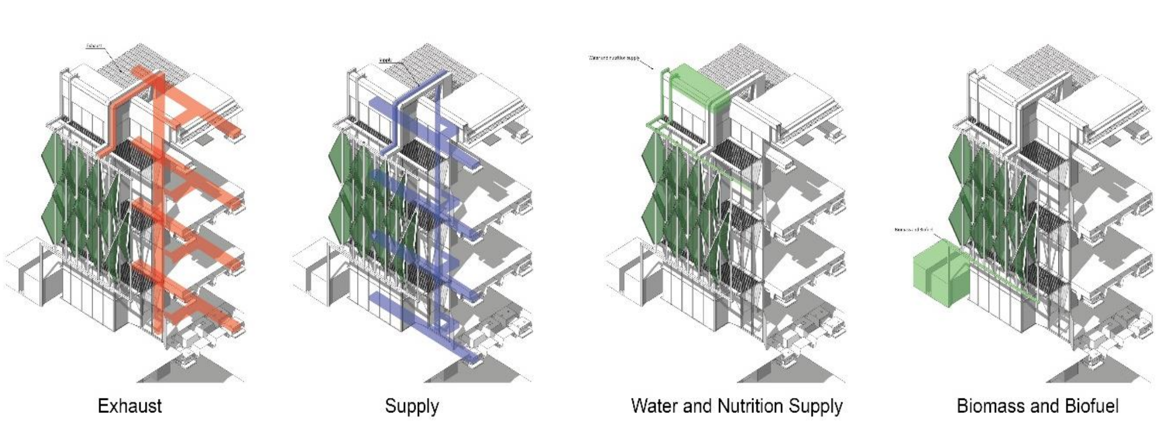

Figure 4-2: Proposed system diagram

generated onsite as one of the building's energy sources. In addition, the bioreactor system is connected to the HVAC system, and the CO_2 generated by indoor human activities is transported to the bioreactors. As a green photosynthesis element, algae can absorb CO_2 indoors, generate O_2 and improve indoor air quality.

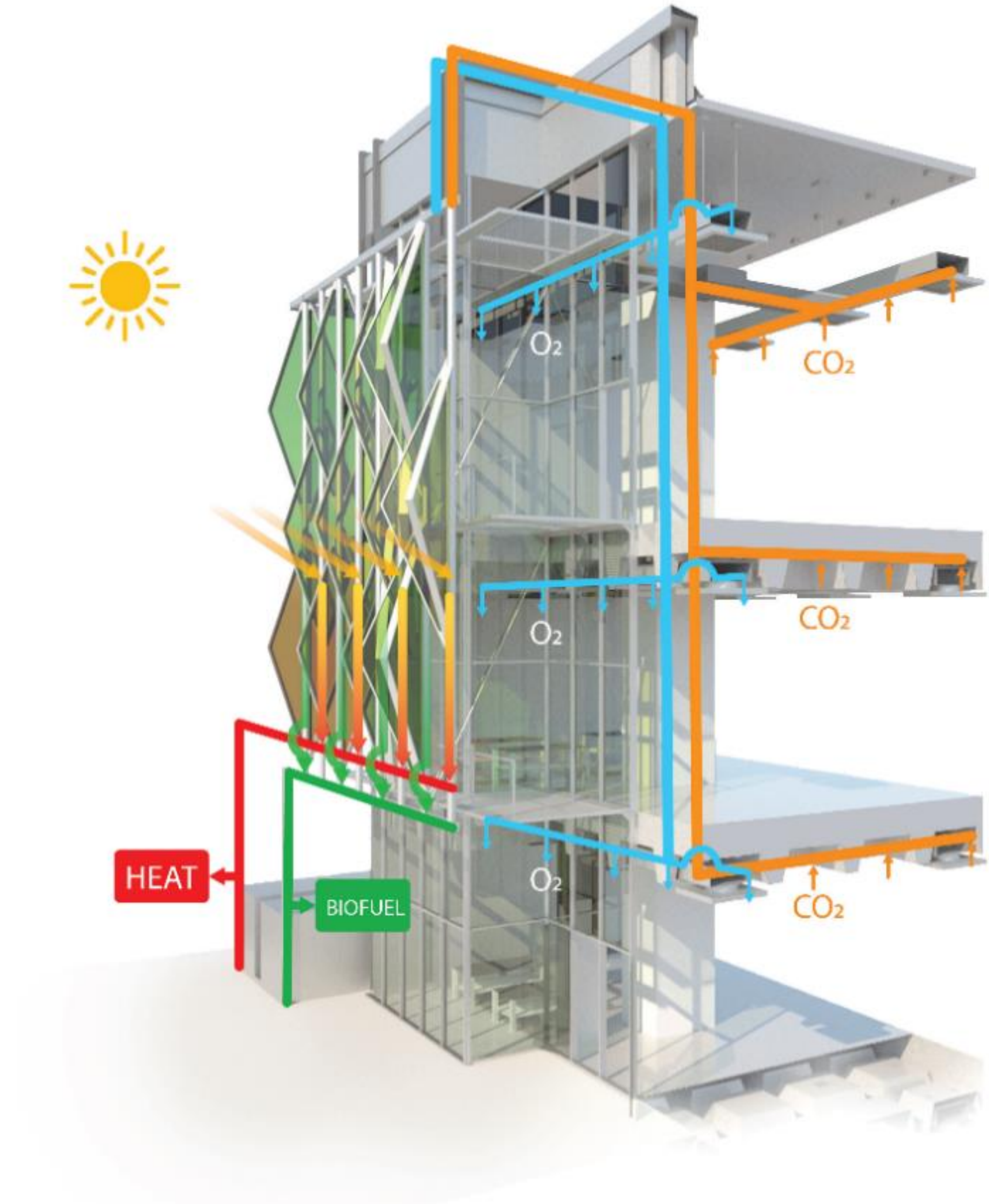

Figure 4-3 Proposed system axon detail

5. METHODOLOGY

This research addresses problems with the algae's reaction to the environment through two complementary techniques: prototype and digital simulation.

First, I performed algae bioreactor prototype experiments with the hypothesis that algae bioreactors can work as adaptive shading systems for buildings. A second layer of building envelope with denser algae could potentially provide shading on warm days. Furthermore, algae density and color would be change based on varying environmental conditions, such as lighting, temperature, and the concentration of CO_2 in air. As the proposed system can respond to environmental factors, this shading system can also display information about environmental changes. Prototype experiments examine algae changing process responses to environmental variables.

Digital simulation is used to mimic a whole building envelope's yearly changing process. A rectangular and glazing-covered building was chosen to be simulated in two aspects: the full scale of building envelope appearance based on surface solar radiance and indoor CO_2 estimation.

5.1 Prototype

5.1.1 Introduction and Objective

Prototypes were built to observe how algae grow and react to solar radiation and indoor CO2 concentration. The experiment was executed in Brooklyn, and three months of data were collected for observation and analysis between March 14 and May 24, 2021.

The experiment or prototype design focuses on observing algae color variation, which means studying the interaction between algae media appearance and environmental conditions. Two main aspects of the living index affect algae growth as input data: envelope solar radiation, and indoor CO_2 concentration.

5.1.2 Bioreactor Prototype Design

The key elements required for bioreactors to function are those that guarantee algae life by providing the required conditions for its growth. As stated in the literature review, algae require a water environment, lighting, proper temperature, nutrition, and constant air supply. This experiment was conducted at my apartment due to COVID-19 restrictions, so experimental tools were extremely limited. Some deviations happened inevitable. Therefore, some deviations were expected and accounted for.

In general, experimental equipment was prepared as needed:

Algae living environment: containers for algae and algae nutrition solution, aquarium pipe, and air pump.

Algae culture transparent container were selected to ensure that algae receive enough sunlight (Figure 5-1). LED lights were embedded at the bottom of the containers to provide distinct colors of light. A stream of water was produced by a motor inside to prevent algae

Figure 5-1 Algae culture pods

settlement. The container volume was 1.5 liters with a movable cap. The size was 4.5 x 4.5 x 12 inches.

Air pumps were connected to algae culture pods via tubes. The air supply rate could be controlled by valves. At the end of each tube, a bubble diffuser diffused large bubbles into small, dispersed ones to make the algae contact air as often as possible (Figure 5-2).

Figure 5-2 Air pump (with valves and air bubble diffuser)

<u>Measurement equipment:</u> in addition to the above elements for cultivating algae, this experiment required, other devices, such as an aquarium heating element, a lighting meter, and

Figure 5-3: Digital light meter (LUX)

Figure 5-4: Temperature meter

a thermometer were used to record relevant data from the algae environment. (Figure 5-3, Figure 5-4, Figure 5-5). A Secchi stick, a common liquids optical density analytical device, was also used to measure algae density. The algae solution's transparency was determined by the depth shown on the ruler scale at which the disc is no longer visible. This measurement is called the Secchi depth and indicates to the turbidity of any liquid solution. The greater the depth, the clearer the liquid. A smaller depth, on the other hand, signifies low transparency (Figure 5-5).

Figure 5-5: a. Secchi stick measurement method b. Secchi stick depth

<u>Variable creating and controlling</u> CO_2 generator, lighting, and aquarium heater.

A CO_2 generator used at home for the aquarium. The Rhinox D.I.Y. pressurized CO_2 system, generates CO_2 from a chemical reaction of baking soda and citric acid (Figure 5-6 a).

The reaction equation is $3NaHCO_3 + C_6H_8O_7 \rightarrow C_6H_5Na_3O_7 + 3CO_2 + 3H_2O$.

The CO_2 mix tank is a closed system that produces a certain concentration of CO_2. It was sealed with hot glue and was tested for airtightness in water until no bubble appeared when squeezing the plastic bottle. The mix tank was supplied with air from the air pump and CO_2 generator. To achieve a certain concentration of CO_2, the air pump supply rate and CO_2 generator supply rate had to be adjusted. A CO_2 detector inside measured CO_2 concentrations (Figure 5-6 b).

Figure 5-6: a.CO_2 generator b.CO_2 mix tank with CO_2 detector inside

5.1.3 Experiment Design

The experiments' goal was to see how algae react to the indoor or outdoor environment and change their appearance to show environmental conditions. This experiment focused on variables of CO_2, lighting, and temperature. There were six bioreactors and four groups of comparison. The density variation experiments used Nannochloropsis Oculate. The color variation experiment used Haematococcus Pluvialis.

5.1.3.1 Density Variation

The start density of bioreactors A, B, C, and D is the same, and the Secchi depth was around 185 mm.

Bioreactor A was controlled (a standard bioreactor), provided with 450ppm CO_2 (indoor air, around 400 to 500, not precise because of variation). Ordinary room lighting, present largely, during the day, provided natural lighting; at night, ending around 10 pm, provided electric lighting.

B, C and D were variable experiments, as shown in Figure 5-9. First, bioreactors B and A were tested whether different CO_2 concentrations cause different growth rates of algae, which are supposed to be observed algae density variables. Bioreactor B was provided air with a higher concentration of CO_2 when compared to bioreactor A. Other conditions like lighting, and temperature were at the same levels.

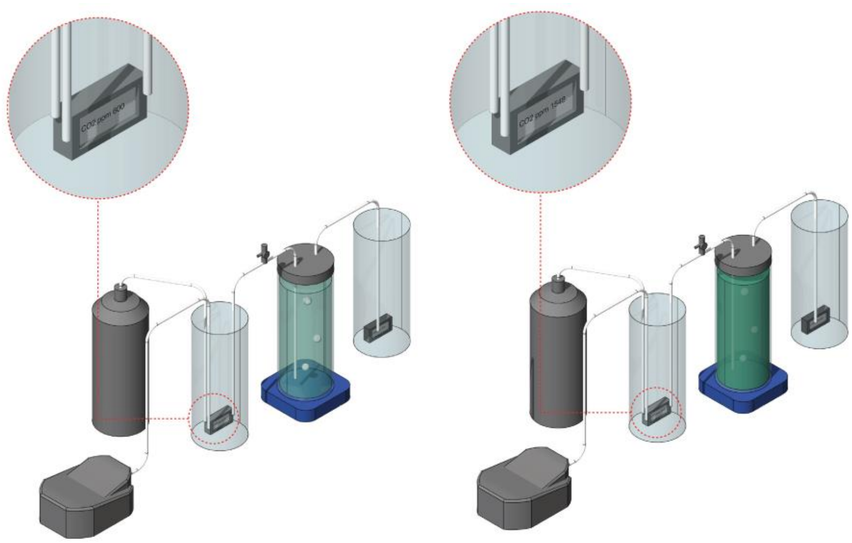

Figure 5-7: Bioreactor A and B

Second comparison, bioreactors C and A was intended to determine whether different temperatures cause the different growth rates of algae. During experiment time, specifically between March and April, the indoor average temperature was approximately 22 Celsius degrees. Group C was heated to a consistent temperature of 25 Celsius degree (Figure 5-10).

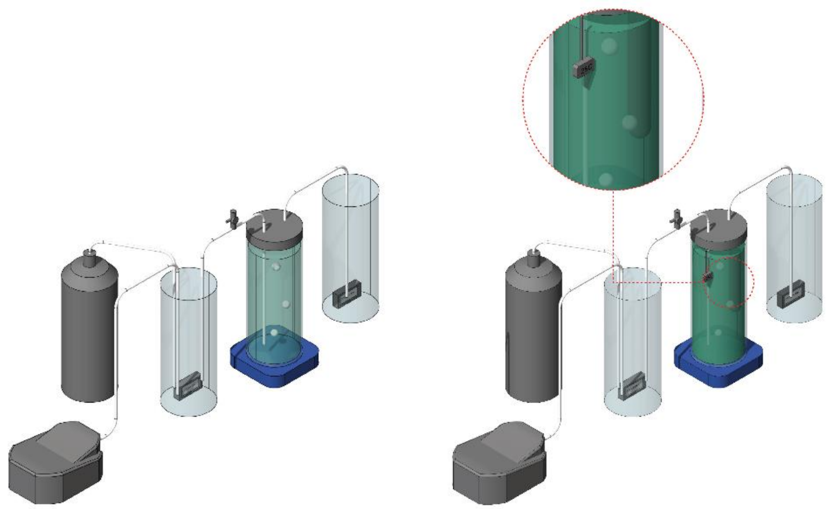

Figure 5-8: Bioreactor A and C

In the third comparison, bioreactors D and A explored whether lighting conditions change growth rate. D was provided with higher lighting and bioreactor A with typical indoor lighting. (Figure 5-11)

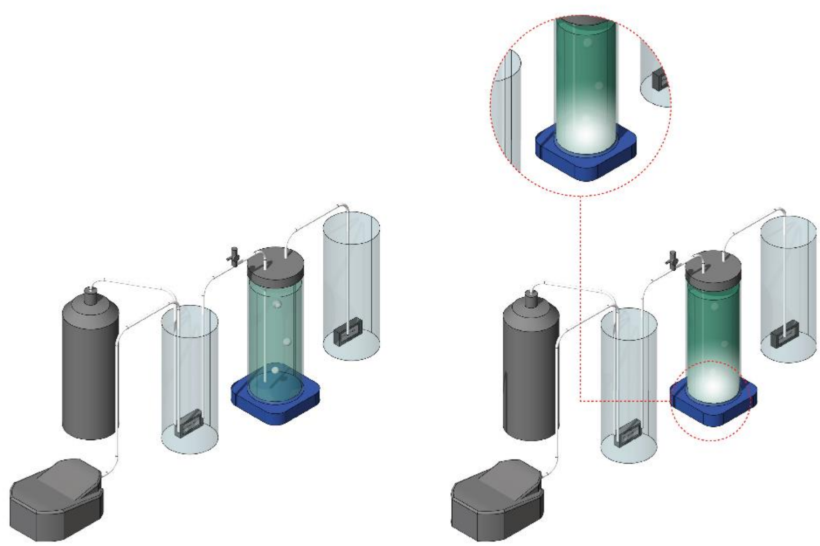

Figure 5-9: Bioreactor A and D

5.1.3.2 Color Variation

This project planned to have bioreactors F and E of Haematococcus Pluvialis in the experiment design phase to see how they reacted under different lighting conditions. A fourth comparison comprised bioreactors E and F, providing different lighting conditions. Bioreactor E was exposed to normal indoor lighting and bioreactor F to bright lighting.

Haematococcus Pluvialis grows exceedingly slow. Three tubes of this algae were strategically placed within an apartment based on the amount of light they would receive. One tube was placed in a darkly lit located far from any window, another at a location next to a window, and the third on an outdoor terrace with considerable direct sunlight. The start density of the three tubes was the same. The experiment lasted for about two weeks. Although a two-week period is not ideal, some results were drawn from this short period experiment that are discussed on the results chapter that follows.

5.2 Computer Simulation

5.2.1 Introduction and Objective

To further demonstrate that the algae bioreactors play an essential role in conveying information about a buildings' external and internal environment, digital simulations were used to emulate the bio-reactor appearance variation when influenced by solar radiation and indoor CO_2 concentration. The software used for radiation simulation was Ladybug of Grasshopper in Rhino 6. The CO_2 estimation was based on ASHRAE 62.1 and ASTM D6245. New York City's climate was chosen as input data, and the test building was located in middle Manhattan. Based on the data collected from the Germany building BIQ and prototype experiments, digital simulations were conducted along 3 aspects:

1. full-scale building envelope solar radiation simulation and how it influences algae bioreactor appearance.

2. full-scale building plan, CO_2 distribution estimation, and how it influences algae bioreactor appearance.

3. When solar radiation and CO_2 are affected at the same time, guess the appearance influenced by two factors simultaneously.

The building 1345 Ave of Americas was chosen as a test building. This building is located at 1345 6th Ave in Manhattan. It is a fifty-story office building with glazing that covers 90% of the envelope. Because of its simple shape it was an ideal case study for simulation.[54]

5.2.2 Solar Radiation Simulation

The building and context were built in Rhino. This project's goal was confirming that algae bioreactors can be used as information panels to display environmental information. Consequently, the simulation was not performed to maximize solar energy or carbon sequestration but to explore the potential expression of the system as a display. Solar radiation and CO_2 affect algae’s metabolic activity and then alter algae bioreactors' appearance through change either density or color variation. Algae growth rate, density, and appearance are positively related to the amount of solar radiation.

Panels shape design: First, the building envelope retrofit was designed in as way that would not affect the existing structure of the building and indoor space. The new bioreactor panels were designed as a second skin with an attachment to the existing exterior facade of the building. The panel was designed as a parametric modular system that could take different shapes. For this exercise, the design considered a diamond shape to show that other shapes rather than rectangular panels could be developed in further applications. New panels are diamond shapes, as shown in Figure 5-12. The panel is double the floor height regardless of load. The bioreactor panel's upper and lower corners would be mounted on floor slabs, and the load would be transmitted to the load-bearing part.

Façade radiation simulation: Ladybug was the main tool of simulating solar radiation. The simulation was established to calculate heat gains on the east and south façades of the

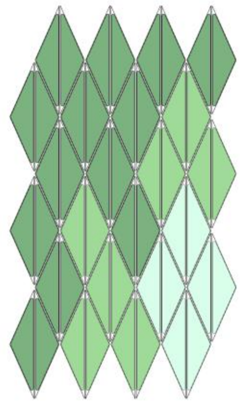

Figure 5-10: New panel's design

building. Climate data on New York City was obtained from the Energy Plus website. Each month, solar radiation was run and recorded. A script to determine solar radiation was written in grasshopper, as Figure 5-14 shows.

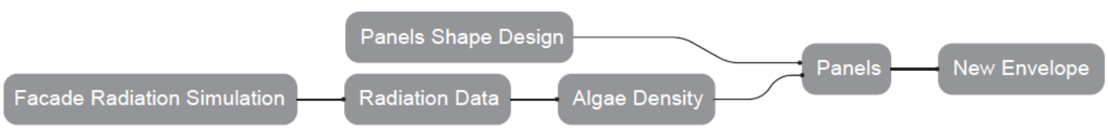

Figure 5-11: Solar radiation simulation and impact on bioreactor building envelope workflow

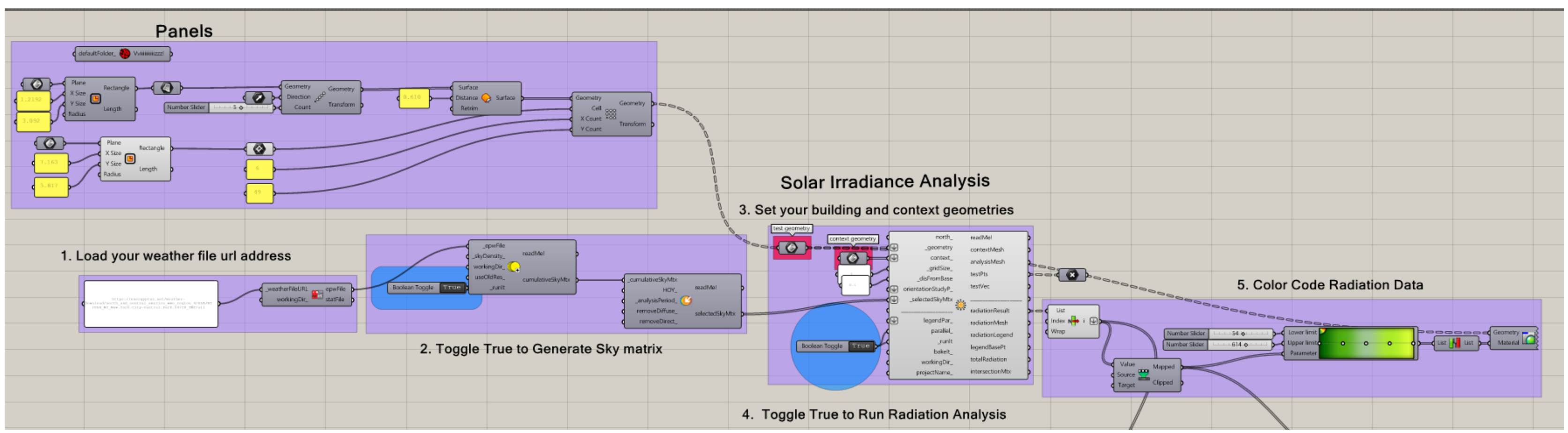

Figure 5-12: Solar radiation grasshopper script

5.2.3 CO_2 Estimation and Simulation

5.2.3.1 Standards

Standard ASTM D6245 – 18 (standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation) and ASHRAE 62.1 or 62.2 (Ventilation for Acceptable Indoor Air Quality) were adopted to help evaluate and determine indoor CO_2 concentration.

ASTM D6245 – 18: this is a standard guide for evaluating indoor air quality by analyzing indoor CO_2 concentration levels. Occupants' body size and level of physical activity determine CO_2 generation rates. The CO_2 generation rate was calculated based on the standard and the functions of buildings, and a room's CO_2 concentration was subsequently determined according to ASHRAE.[39]

Indoor CO_2 concentrations are a representative indicator of indoor air quality. Algae

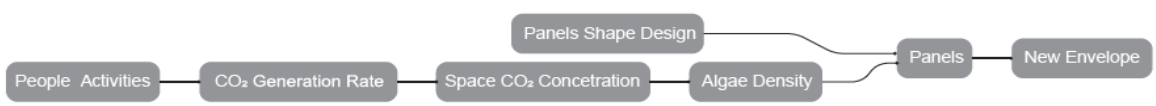

Figure 5-13: CO2 impact on algae bioreactors workflow

absorb CO_2 indoor and improve indoor air quality. This standard illustrates how to use CO_2 concentrations to evaluate indoor building air quality. This standard will help determine a CO2 supply rate. The rate of carbon dioxide generation of an individualVCO2 in L/s per person, at an air temperature of 273 K and an air pressure of 101 kPa is as follows:

VCO2 = RQ BMR M 0.000569

RQ = respiratory quotient, dimensionless (equals about 0.85)

[39] "ASTM6245-18：Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation," ASTM International – Standards Worldwide (2018), accessed December 17, 2021, doi: 10.1520/D6245-18.

B.M.R. = basal metabolic rate, M.J./day. The tested building is an official building, so the BMR value picked from ASTM D6245-18 Table 1 with an, from age group ranging from 18 to 60 males and females.[40]I used a fixed value of 2.

M = metabolic rate per unit of surface area, met (dimensionless). This value was picked from ASTM6245-18 Table 2 and Table 3 are based on human activities of space, so metabolic rate was the only variable in this equation. In other words, a space CO_2 generation rate was determined by metabolic rate.

After arriving at the CO_2 generation rate, the next step was using ASHRAE 62.1(2016) to calculate CO_2 concentration in a room.

ASHRAE 62.1 - Ventilation for Acceptable Indoor Air Quality is the standard "to specify minimum ventilation rates and other measures intended to provide acceptable indoor air quality and that minimize adverse health effects."[40]

The equation used in this CO2 estimation is below:

$V_0 = N / (Cs - C_0)$

V_0 = outdoor airflow rate per person. This was a fixed value of 15 cfm (7.5 L/m)

N = CO_2 generation rate per person, which was Vco2 in the last equation.

Cs = CO_2 concentration in the space, which was the value this part attained from the calculation.

[40] "ASHRAE 62.1: Ventilation for Acceptable Indoor Air Quality" ASHRAE, accessed December 2021, https://ashrae.iwrapper.com/ASHRAE_PREVIEW_ONLY_STANDARDS/STD_62.1_2019.

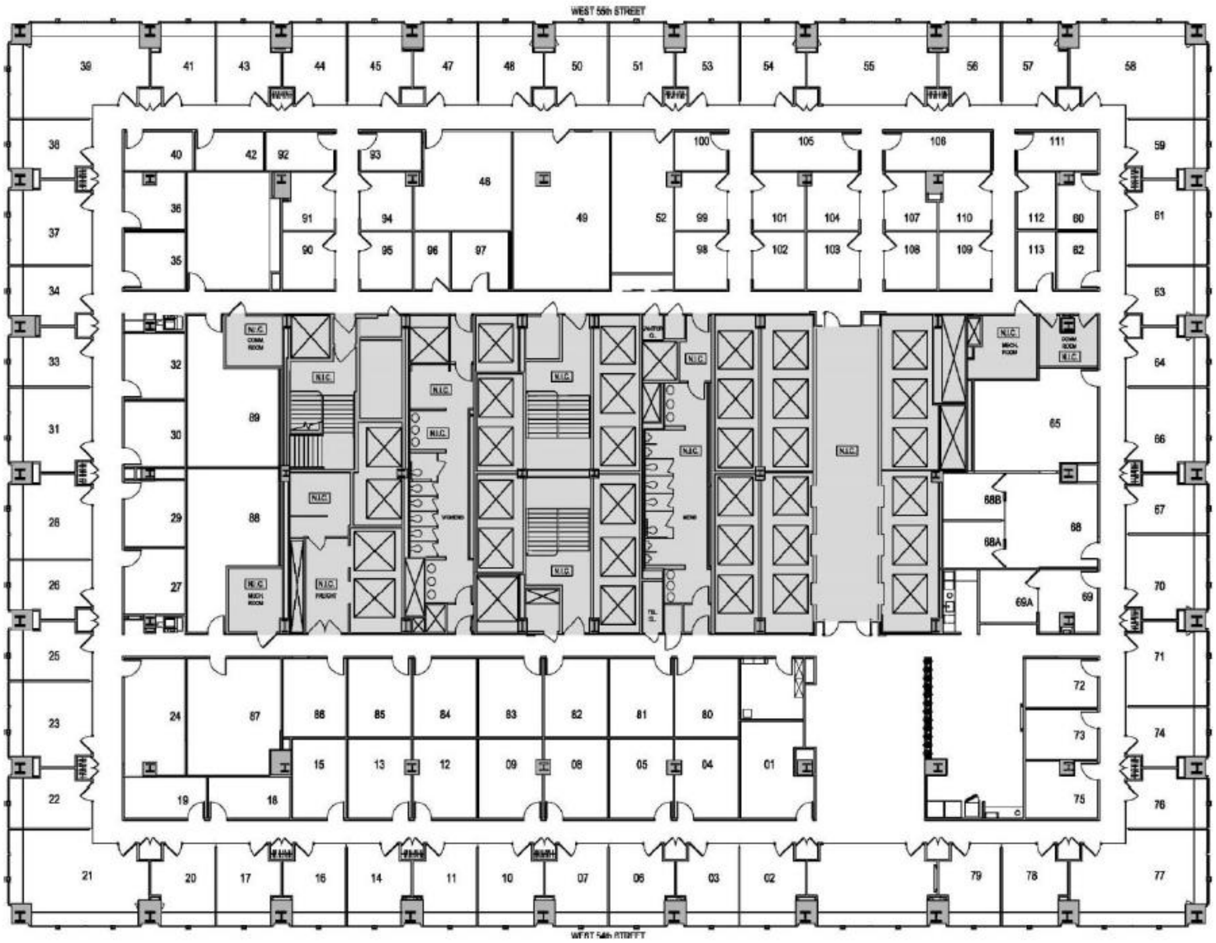

Figure 5-14: Typical plan of 1345 Ave of Americas[41] (open-source image)

[41]C_0 = CO_2 concentration in outdoor air, which was meant be a fixed number of 400ppm.

Figure 5-17 depicts the plan to calculate each room's CO_2 concentration. Because CO_2 concentration in the rooms on the periphery would influence algae bioreactor panels' envelope appearance, this study examined the south and east facades, meaning rooms 02-21 and 58-79 were considered as those that would influence the envelope. In addition, due to the limited information of 1345 Ave of Americas, we only that know this building is used for offices. Hence, each tested room was assigned a function. Four types of rooms are defined as follows:[42]

[41] "1345 Ave of Americas Typical Plan," VIRGO, accessed December 7, 2021, https://www.virgobc.com/midtown/#gallery-5.

Type A: sitting task, light effort. Metabolic rate: 1.5

Type B: standing tasks, light effort (for example, store clerk, filing). Metabolic rate: 3

Type C: mixed room, sitting and standing, light effort. Metabolic rate: 2.2

Type D: Fitness room. General exercise. Metabolic rate: 5

Rooms 02-03, 11-20, 59, 64, 67, 74, 76, 78, and 79 are type A, and they are offices in which, people are performing sitting tasks. Rooms 06, 07, 10, 61, 66, 70, and 71 are type B, and they are offices wherein people performing light standing tasks. Rooms 21 and 58 are type C, and they are meeting rooms in which, people sitting and standing. The room between room 02 and 70 is a pantry, type C also. Room 77 is a fitness room, and type D, according to different type rooms, calculated the CO_2 generation rate and CO_2 concentration of each room.

5.2.3.2 Calculation

Step 1: CO_2 generation rate every person:

Type A: metabolic rate M = 1.5

VCO_2 = RQ BMR M 0.000569

= 0.85 x 2 x 1.5 x 0.000569

= 0.00145095 L/s

Type B: metabolic rate M = 3

VCO_2 = RQ BMR M 0.000569

= 0.85 x 2 x 3 x 0.000569

= 0.0029019 L/s

Type C: metabolic rate M = 2.2

VCO_2 = RQ BMR M 0.000569

= 0.85 x 2 x 2.2 x 0.000569

= 0.00212806 L/s

Type D: metabolic rate M - 5

VCO_2 = RQ BMR M 0.000569

= 0.85 x 2 x 5 x 0.000569

= 0.0048365 L/s

Step 2: CO_2 concentration in every room

Original equation: $V_0 = N / (Cs – C_0)$

$Cs = N / V_0 + C_0$

Type A:

$Cs = N / V_0 + C_0$

= 0.00145095 / 7.5 x 10^6 + 400

= 193.4 + 400

= 593.4 ppm

Type B:

Cs = N / V0 + C0

= 0.0029019 / 7.5 x 10^6 + 400

$= 386.92 + 400$

$= 786.92$ ppm

Type C:

$Cs = N / V_0 + C_0$

$= 0.00212806 / 7.5 \times 10^6 + 400$

$= 283.74 + 400$

$= 683.74$ ppm

Type D:

$Cs = N / V_0 + C_0$

$= 0.0048365 / 7.5 \times 10^6 + 400$

$= 644.87 + 400$

$= 1044.87$ ppm

6. RESULTS

6.1 Prototype Experiment Record and Discussion

6.1.1 First Round of Experiment – Density Change

The first round of experiments commenced on March 14. Bioreactor A was supplied with indoor air. A CO_2 meter was not used for this experiment, so there were, no CO_2 concentration records. Bioreactor B was supplied with pure CO_2 produced by a CO_2 generator (baking soda and citric acid). On the first day of installation, the two bioreactors' algae density was at the same level. For both, the Secchi disk depth was 185mm. Air was not supplied every day, and only the experiment note indicates that there was air supply. On the fourth day of the experiment,

Table 1: CO2 concentration experiment 1 records

3/14/2021 10pm	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	first day set up. Video took in the evening
A (indoor air)	19.9	139	185(Secchi Stick Maximum)	
B (Carbon Dioxide)	19.9	139	185(Secchi Stick Maximum)	
3/16/2021 8am	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	Air supply 8am-1pm; Led lighting 8am-1pm
A (indoor air)	21.2(8am)	350	185	
B (Carbon Dioxide)	21.2(8am)	350	185	
3/17/2021 10am	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	Air supply 9am-1pm
A (indoor air)	22.6	127	185(totally can not see pattern)	From observation. A is denser than B. CO2 side e
B (Carbon Dioxide)	22.6	127	185(can see the black and white pattern vaguely)	need to cap after supply air, the evaporation is f
3/19/2021 2pm	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	
A (indoor air)	21.8	170	180(totally can not see pattern)	
B (Carbon Dioxide)	21.8	170	185(can see the black and white pattern vaguely)	
3/21/2021 10am	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	should be recorded at the same time
A (indoor air)	24.7	262	170(totally can not see pattern)	
B (Carbon Dioxide)	24.7	262	185(can see the black and white pattern clear)	
3/22/2021 2pm	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	
A (indoor air)	22.6	95	145(totally can not see pattern)	
B (Carbon Dioxide)	22.6	95	185(can see the black and white pattern vaguely)	
3/29/2021 9am	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	
A (indoor air)	22.2	305	105	
B (Carbon Dioxide)	22.2	305	180	
4/5/2021 6pm	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	
A (indoor air)	23.3	228	80	
B (Carbon Dioxide)	23.3	228	130	

observation indicated that bioreactor B became less dense. After a week of the experiment, a major difference in transparency could be observed. These results were not expected. Because of insufficient research into CO_2 supply for algae, after the experiment showed differently, it was noticed that media PH influenced algae growth. The PH of bioreactor B dropped due to pure CO_2 supply. Nannochloropsis Oculate prefers to live in an alkali water environment. After the first five days, this experiment stopped supply both air and pure CO_2. Bioreactor B became accustomed to the solution and gradually grew. From the first to the last day of the experiment, bioreactor B's density dropped first because of excessive CO_2 and then increased after stopping CO_2. The other one, bioreactor A started to bloom after ten days with indoor air supply and grew quickly.

The first round of experiments, then, indicated that too much CO2 will prevent algae growth or even damage algae. The specific CO2 concentration value that threatens the growth of Nannochloropsis Oculate requires more accurate experiments or literature.

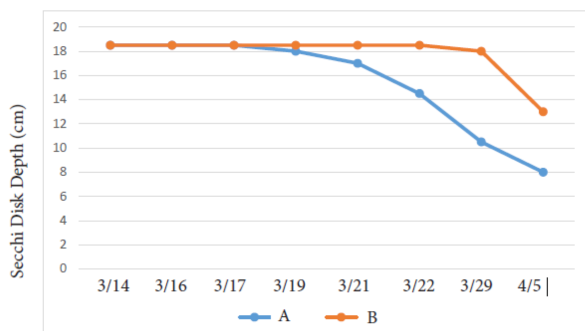

Figure: 6-1 Secchi stick depth records

Figure 6-2: CO2 concentration experiment photo records, 3/14 3/17 3/19 3/26 4/5, 2021

6.1.2 Second Round of Experiment – Density Change

Figure 6-3: CO2 and air mixing container and CO2 concentration measuring

The second-round experiment started on April 18. When three algae bioreactors were installed. This experiment was equipped with a CO2 mix tank. Bioreactor A was the standard bioreactor, supplied with indoor air, room temperature, and room lighting. Bioreactor B was the variable one, supplied with indoor air mixed with CO2, room temperature, and room lighting.

Table 2: Experiment 2 records

4/18/2021 11:30am	Co2 concentration (ppm)	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	Air supply time 11:30-12:00
A (indoor air)	434	22.2	225	100	
B (Carbon Dioxide)	539	22.2	225	100	
C (Lighting)	434	22.2	2020	100	
4/21/2021 10:00am	Co2 concentration (ppm)	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	Air supply time 10:30-11:00
A (indoor air)	456	21.5	378	90	
B (Carbon Dioxide)	587	21.5	378	90	
C (Lighting)	456	21.5	1841	60	
4/23/2021 8:30am	Co2 concentration (ppm)	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	Air supply time 8:30-9:00
A (indoor air)	429	21.5	247	85	
B (Carbon Dioxide)	586	21.5	247	80	
C (Lighting)	429	21.5	4150	45	
4/25/2021 9:30am	Co2 concentration (ppm)	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	Air supply time 8:30-9:30
A (indoor air)	477	21.1	125	80	
B (Carbon Dioxide)	537	21.1	125	75	
C (Lighting)	477	21.1	308	40	
4/28/2021 9:00am	Co2 concentration (ppm)	Temperature (C)	Lighting (LUX)	Algae Density (Secchi Disk Depth)	Air supply time 9:00-9:30
A (indoor air)	477	20.5	283	70	
B (Carbon Dioxide)	585	20.5	283	70	
C (Lighting)	477	20.5	2160	30	

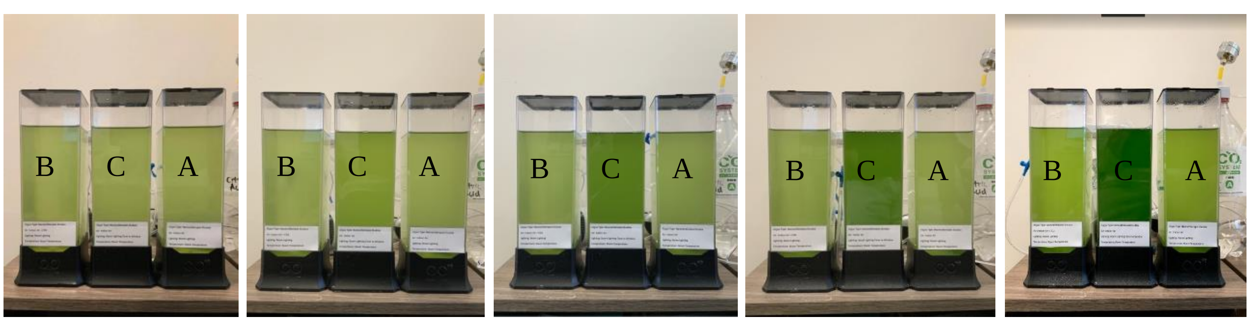

Figure 6-4: Lighting and CO2 reaction experiment 4/18 4/21 4/23 4/25 4/28, 2021

Bioreactor C was the variable supplied with indoor air, room temperature, and room lighting close to the window which means more sunlight than the other two bioreactors. Three bioreactors' start densities were the same; their algae density increased at different levels after ten days. The most obvious was C with more sunlight. The density of the one with a slightly higher CO_2 did not markedly change. On the fifth or sixth day of the experiment, bioreactor B's density was slightly higher than that of A. On the last day of the experiment, they looked very similar. Their densities both changed from 100 to 70 from Secchi Stick records. Measurement method, the way mixed CO2 or photos might cause inaccurate results, it's hard to tell the different impacts of CO2 concentration on bioreactor A and B. However, group C's algae density increased dramatically. The Secchi disk depth changed from 100 to 30, which means its algae grew faster than those in the other groups.

6.1.3 Third Round of Experiment – Color Change

The third-round experiment began on May 15, 2021 when three tubes of Haematococcus Pluvialis were installed. The literature states that bright light could cause this algae's color to change. Consequently, for this experiment group, three tubes were placed under different lighting conditions, the one with the dark label was in the room far from the window, the one with the normal label was in the room close to the window, and the one with bright label was

Table 3: Experiment 3 records

5/15/2021 10:00am	Co2 concentration (ppm)	Temperature (C)	Lighting (LUX)	Algae Color
Bright	452	30.5	89400	
Normal	464	24.7	1352	
Dark	464	24.7	135	

5/20/2021 10:00am	Co2 concentration (ppm)	Temperature (C)	Lighting (LUX)	Algae Color
Bright		25.1	22100	
Normal		27.5	1622	
Dark		27.5	237	

5/25/2021 10:00am	Co2 concentration (ppm)	Temperature (C)	Lighting (LUX)	Algae Color
Bright		24.6	82500	
Normal		26.5	1622	
Dark		26.5	215	

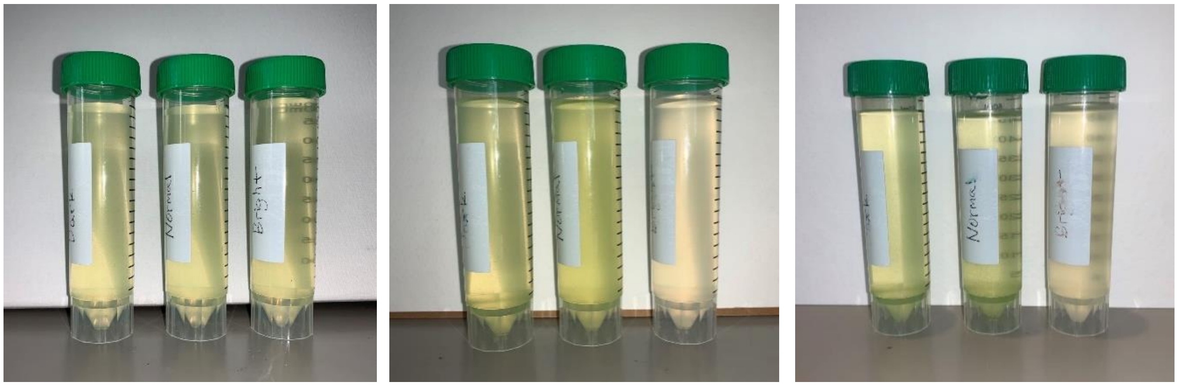

Figure 6-5: Experiment 3 photo records 5/15 5/20 5/24,2021

outdoors exposed directly to sunlight. In addition to light conditions, more sunlight also caused the media temperature to increase, so both the light intensity and the temperature were recorded. Initially algae had the same color and density. The one in the dark environment did not change considerably. The normal sunlight promoted algae growth and became denser than the dark one. The one provided with bright sunlight became less dense than the other two, and the color became warm. Further experiments are needed in future research that would take place at longer timer intervals.

6.2 Computer Simulation Record and Discussion

Figure 6-6 is the result of the simulation of monthly solar radiation of 1345 Ave of Americas' north and east facade. For all simulation results, more radiation was visible on the top part of the south and east façade because they lacked shading influence. At the bottom portion of the south and east façades, it was possible to observe less radiation because the surrounding buildings prevent direct sunlight. According to the prototype experiment, algae will grow faster if there is more sunlight. Thus, in the upper part of the building, algae density change was more obvious, and density was higher. Figure 6-7 predicts algae bioreactors' appearance based on the

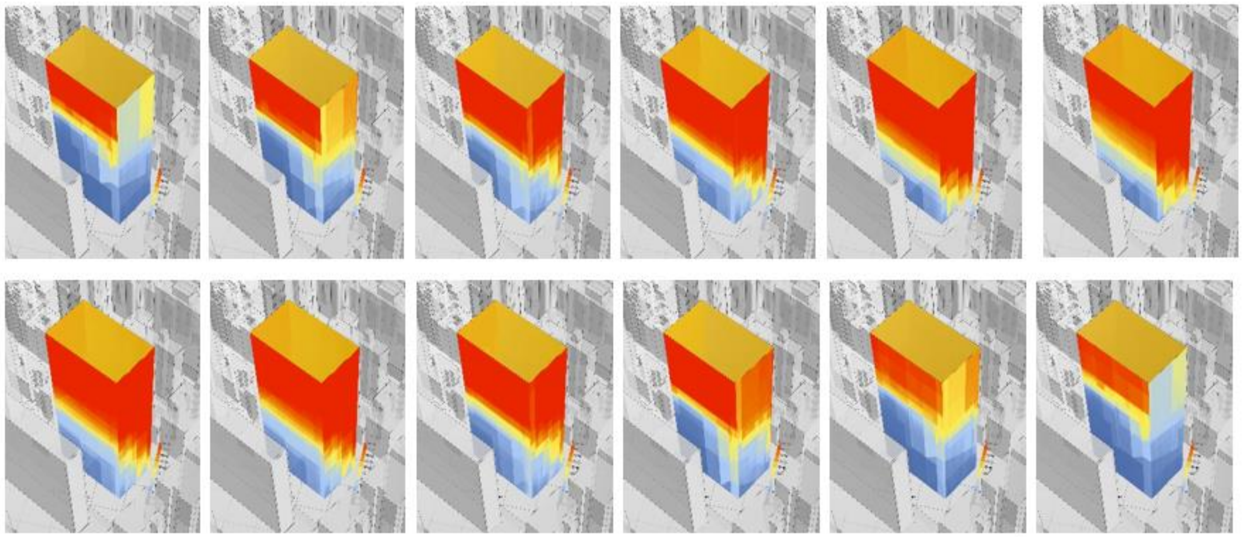

Figure 6-6: Solar radiation from January to December in sequence

amount of solar radiation. In January, February, November, and December, there was less radiation solar radiation on the east façade, so the algae color was less green than on the south façade during these two months. The building envelope can attain more solar energy from March to October, and algae will be remapped according to different solar conditions. In addition to solar radiation, temperature also influences the growth of algae. As a result, on cold days, algae will not grow quickly because 25 Celsius Degree is the preferred temperature for Nannochloropsis Oculate.

Regarding CO2 estimation, more accurate experiments should be conducted in future research. In this experiment, the inaccuracy of the measuring instrument and the air leakage of the equipment affected the results. The change of CO2 concentration level was not stable, and

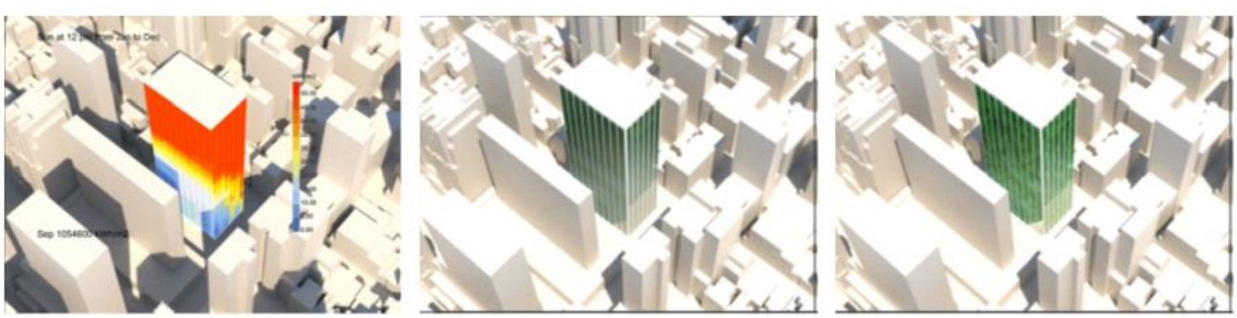

Figure 6-7: a. September radiation map b. Solar impact speculation c. CO2 impact speculation

it could only be controlled in a range. Some kinds of the results could be predicated from the literature review. For example, the literature showed that we could draw that 400-ppm air to make algae grow better. The inference was within the 0.04 - 2% CO_2 concentration range, where increasing the carbon dioxide, without changing the PH of the solution will promote algae growth. Under normal circumstances, the CO_2 concentration would not exceed 2% (equal to 20000ppm) unless in unique mechanical spaces.

The solar simulation showed that the total energy the algae bioreactors get from solar was 1.0076e+7 kBTU. The energy use intensity at1345 Ave of Americas was 269 kBTU/sqft in 2017. This demonstrates that 2% of energy could be attained from algae bioreactors. In terms of CO_2, the building's greenhouse gas emission intensity was 9.66 kgCO2/sqft in 2017, and the algae envelope can absorb 37.5% of CO_2 from indoor sources.

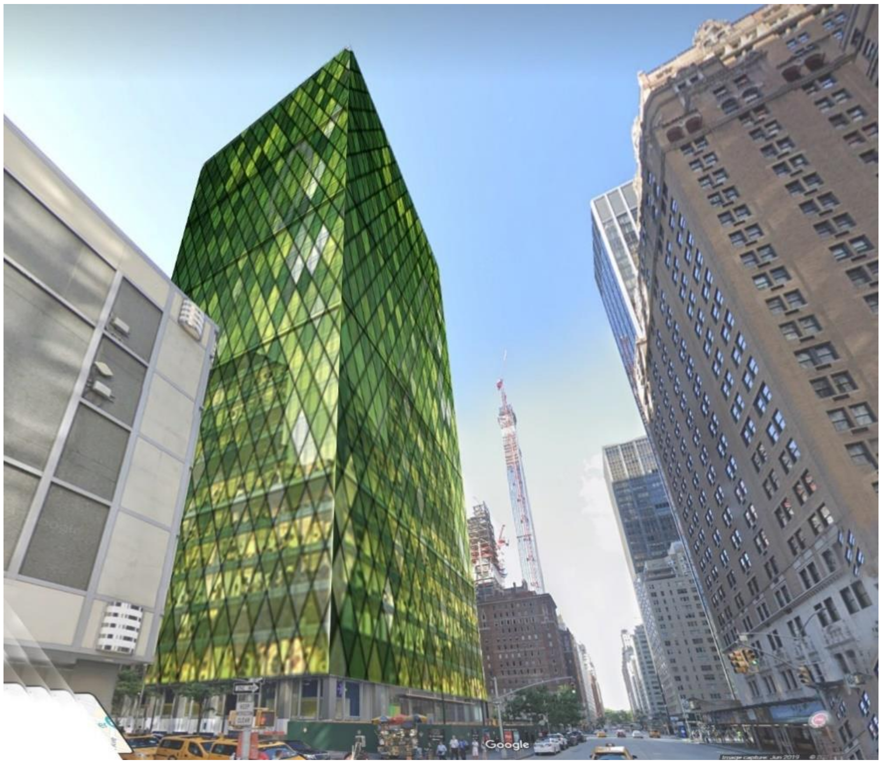

Figure 6-8: A street view of retrofitted 1345 Ave of Americas

6.3 Conclusion and Future Research

In this project, the algae bioreactor using Nannochloropsis was better able to display light energy information. This shows that more lighting strengthens the algae’s ability to grow. For another type of algae, Haematococcus, excessive lighting generated red coloration. Therefore, in the design of the building facade, the designer could choose the first algae to change transparency and the second one to change the colors. The designer's choice of algae type would be based on both environmental and aesthetic requirements. This study proved that using algae to show natural conditions is feasible to a certain extent, but more research is needed. Human beings need to improve their living conditions in close relation to their natural environments. Algae panels use the properties of algae to bring the city one step closer to nature. Regarding the reaction of algae bioreactors to CO_2, more research is needed as the influence of CO_2 on it is uncertain.

Regarding CO_2, we need to take it one step closer. If the concentration difference is small, there will be no significant difference in the short term. More precise and long-term experimentation is needed. However, the appearance difference can be realized.

There are many future directions researchers could take to examine algae bioreactors in the future. If it is based on this research, a more precise relationship between algae and people's living environment could be explored. For example, researchers could explore further how the algae's ability to grow when integrated within a building façade can be controlled in order to regulate the amount of sunlight and heat gains for the building.

The algae bioreactors’ ability to absorb the carbon used in buildings, generate oxygen and purify the air should also be investigated for its overall environmental benefits.

Regarding the building performance of a double skin facade, cold and heat loads reduction as well as improvement of people's comfort are additionally worth studying.

This study suggests simplifying the production process and reducing the production cost and the weight of the panel itself. In general, it is important that researchers realize that production at scale is significant hurdle to overcome for such technology to produce amplified impact.

In addition, an algae bioreactor life cycle would have to be simplified, eliminating the need for algae experts to maintain and operate it.

Algae bioreactor building envelopes can potentially become adaptive building skins that indicates environmental conditions. Moreover, combining environment data visualization with a bio-driven dynamic shading strategy, would provide designers and engineers with a new way to re-design urban building envelopes.

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APPENDIX A

Figure A-1: The retrofitted building indoor scenario 1

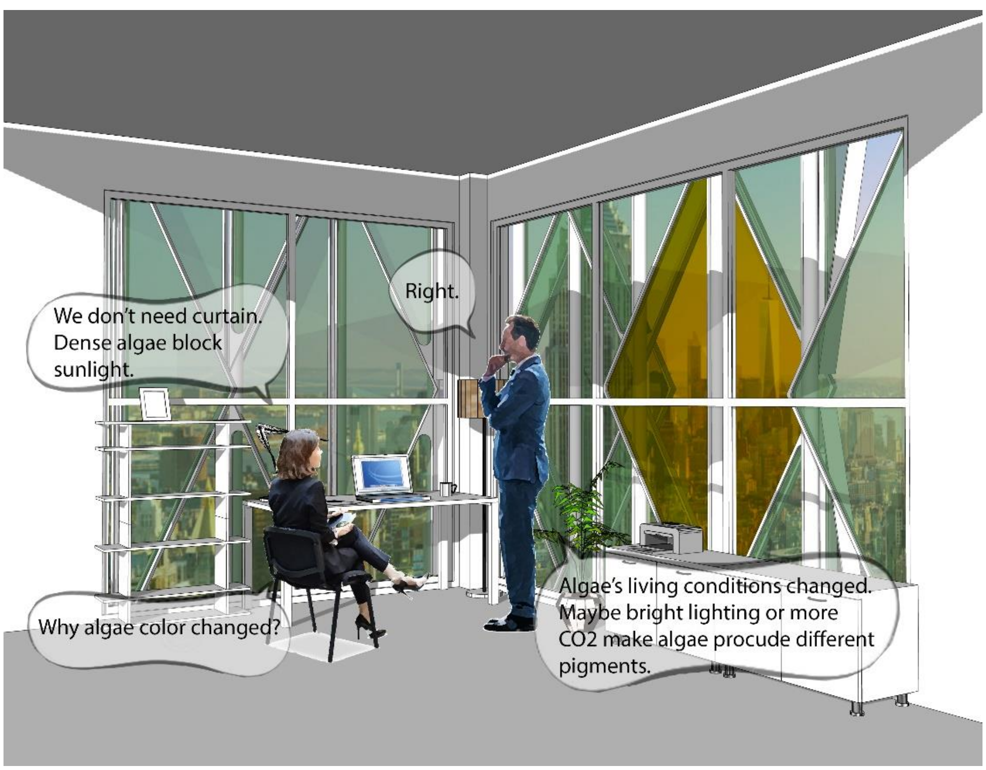

Figure A-2: Retrofitted building indoor scenario 2

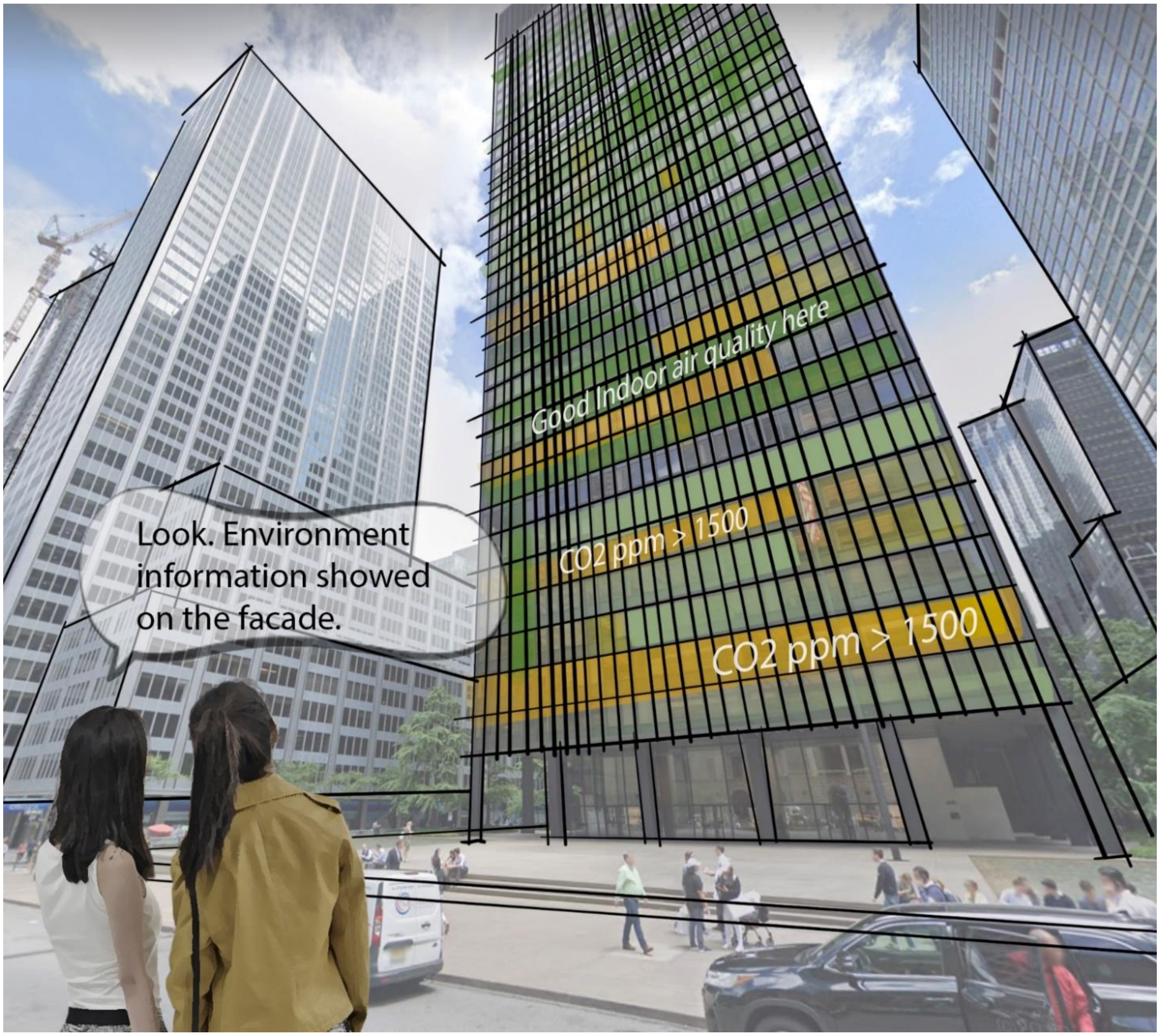

Figure A-3: Retrofitted building outdoor scenario

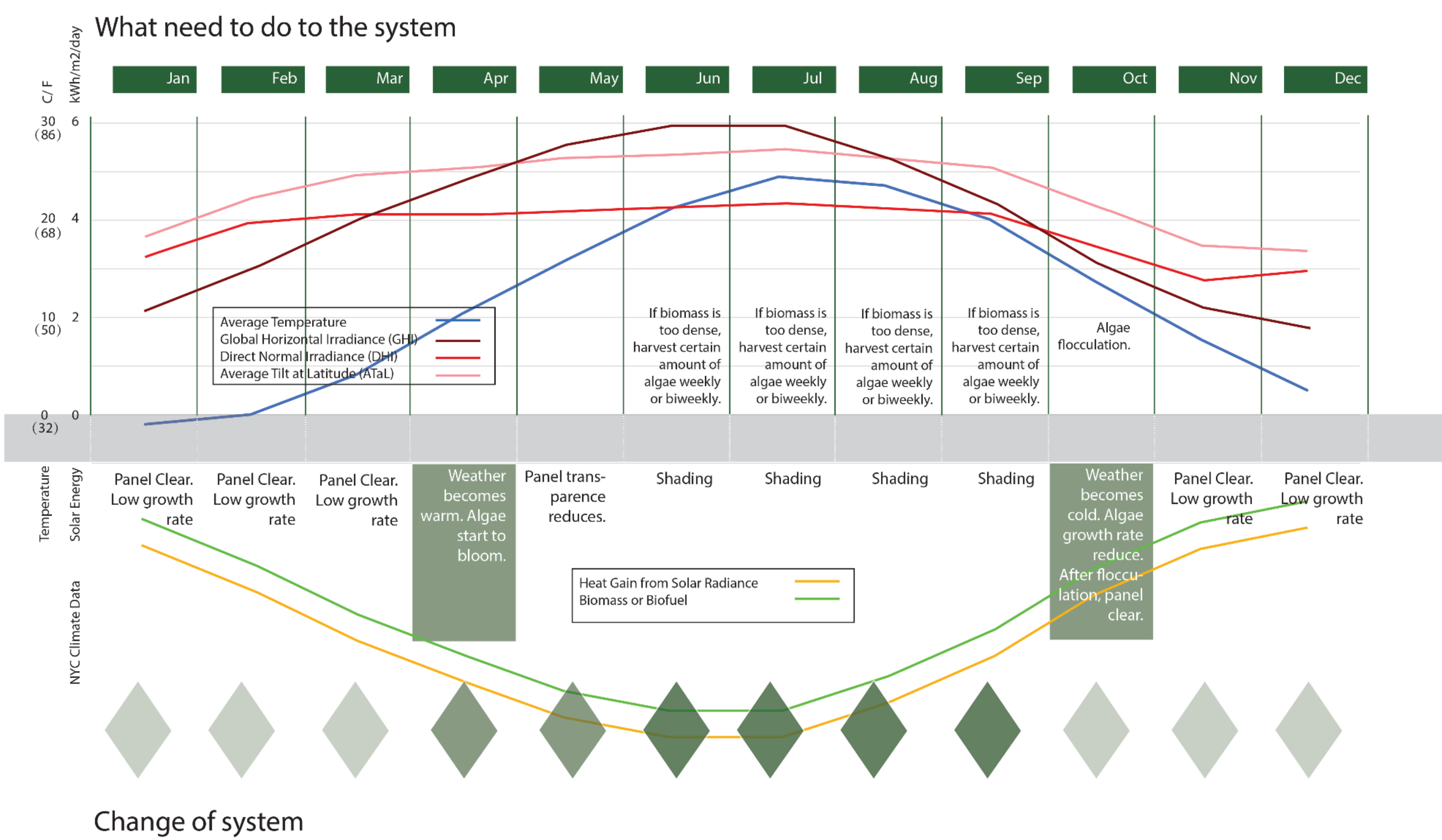

Figure A-4 Retrofitted building yearly timeline