# SUSTAINABLE TALL BUILDINGS: MICROALGAE FACADES FOR CITY'S ENERGY PRODUCTION, WATER CONSERVATION, AND GOOD AIR QUALITY

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**Abstract** - This research project addresses a looming crisis – the potential consequences of anthropogenic climate change – by investigating microalgae facades and their impact as an innovative and sustainable building technology for tall building enclosures. Microalgae facades offer a solution toward reducing this future strain on human population centers and dense urban sites by creating the built environment that offer good indoor air quality, better occupant satisfaction, and produce carbon-free energy. The research addresses the technical design of a novel microalgae facade design process that aims for net-zero architecture practice, with a holistic integrated approach toward the effective fabrication, optimal operation strategies, maintenance, retrofit, and repair of these facades. The preliminary research indicated that the microalgae facade has both long- and short-term benefits that are significant. The microalgae façade's successful utilization of the natural biologic process of absorbing $CO_2$ and releasing $O_2$ provide good indoor air quality with reduced dependence on energy-intensive mechanical equipment. Additionally, the research also explored user perceptions of the use of microalgae, the results of which can be used to improve the awareness of this technology.Preliminary analysis indicated that an office building retrofitted with microalgae facades results in reduced energy consumption by 20% compared to the original building due to its improved energy and daylighting performance. The retrofitted microalgae façades also cut down on annual operational costs by $80,000 and lowers the annual $CO_2$ emissions by 6 tons which equates to $2.4M energy cost savings and 200 tons of $CO_2$ reduction over a 30-year period. Further, additional $CO_2$ reduction and $O_2$ generation as a result of photosynthesis are estimated to be 250ton per year respectively whereas biofuel potential was estimated to be 1100gallons per year.

**Index Terms** - Climate change, microalgae facades, net zero building, sustainable building technology.

## I. INTRODUCTION

The world's urban population has grown rapidly from 746 million in 1950 to 3.9 billion in 2014 with 54 percent of the world's population living in urban areas[1]. It is expectedthat additional 2.5 billion people will reside in cities by 2050, totaling over six billion of urban populations[1].As a result, fast growing citieshave been faced numerous challenges in meeting the needs of their growing urban dwellers, including housing, infrastructure, transportation, energy, and employment and so on. These demands led to the increase in environmental issues in cities such asincreased energy usage, air pollutions, and water shortage. US is one of top energy consumers in the world, wherethe building sector accounts for approximately 75% of electricity use, 40% energy use, and 40% greenhouse gas emissions, making it essential to tackle environmental challenges[2].According to the data from WHO, air polluted cities cause a higher risk of respiratory and cardiovascular sickness and death rates compared to non-polluted areas[3].The air quality in cities is becoming worse due to the increase in energy demands in building, industrial and transportation sectors. Scientific data indicates that $CO_2$emissions due to anthropogenic activities has been drastically increased compared to the pre industrial era, and as a result, climate changes such as flooding, drought, sea level changes are evident.

Over the past few decades, microalgae have been cultivated for various uses in agricultural, aquacultural, pharmaceutical, and food industries due to its fast growth rate and a wide array of biodiversity growing in a wide range of habitats. Microalgae offers ecological sustainability by improving soil quality, water quality, and air quality while encouraging biodiversity and minimizing greenhouse gas emissions. Furthermore, it serves socioeconomic sustainability by offering social well-being (e.g. employment, food security), energy security, and resource conservation[4]. Algae's photosynthesis with its fast growing rate could offset human $CO_2$ emission. Its potential to generate biofuel can reduce our dependence on non-renewable resources and offer ecological and economic benefits. Currently the algae biofuel industry is growing with remarkable investment from government and private companies.

Recently, building-integrated microalgae façades have also drawn the attention of architects and designers in the field of net zero architecturedue to its effective role in enhancing building energy efficiency, producing on-site biofuel as well as reducing air pollutions and water contaminants[5].These innovations have led to a need for more study of the various design and technical challenges of building integrated microalgae façades. The research, therefore, focuses on the feasibility of a microalgae façade system for tall building enclosures in dense urban sitesas a way toaddress climate change adaptation in built environments. A prototyping of an initial concept of a unitized microalgae façade system is undertaking. Preliminary assessment of building

energy consumption and ecological benefits have been carried out and are included in this paper.

## II. LITERATURE REVIEWON MICROALGAE SYSTEMS

As the carbon levels in the world increases, the need for reducing $CO_2$ increases. US is the largest country to produce the most CO2 emissions by capita with 1.6metric tons of $CO_2$per capita. As most amount of $CO_2$ is produced by buildings, vehicles, and non-renewablepower plant production, the need for green energy production and $CO_2$reductionis significant. The precedent projectsin this section act as a reference of feasibility of a microalgae system in various applications in four main areas: (1) infrastructure intervention, (2) urban intervention, (3) building intervention, and (4) product intervention.

### (1) Infrastructure Intervention

The project Carbon T.A.P. designed by PORT Urbanism aims to use the $CO_2$ absorption released by the vehicles. The Carbon T.A.P. project is a large-scale hybrid design project that converts $CO_2$ as an economic and ecological resource. The project is strategically placed at locations, which re-configures its position to absorb the $CO_2$ emissions at different locations. It consists of the $CO_2$ storage vessels, which connect the tunnel and the algae bioreactor. This storage vessel traps the $CO_2$ emitted by the vehicular air pollution and releases to the algae bioreactor for consumption. The idea of man-made ecology utilizes the algal agriculture to produce energy by consuming the $CO_2$ levels and producing oxygen and biofuel to offset energy consumption by the transportation sector (Figure 1).

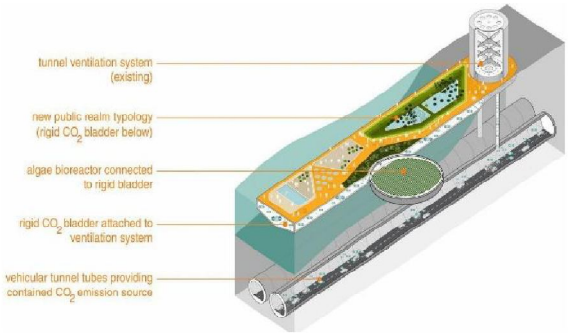



**Figure 1. Microalgae bioreactor system as green urban infrastructure**
**Source: http://porturbanism.com/work/carbon-t-a-p/**

Another project at the infrastructure intervention level is wherealgae farms can beintegrated with power plant facilities.$CO_2$ contained in coal plant flue gases is utilized for cultivating algae and the remaining heat energy from flue gases is used for drying algae biomass (Figure 2).Dried biomass is then usedas fuel stocks,offering good energy conversion efficiency compared to other biomass counterpart. The research data estimated that microalgae integrated power plants could offer a promising green energy technology that reduces CO2 emissionsand economic return [6].

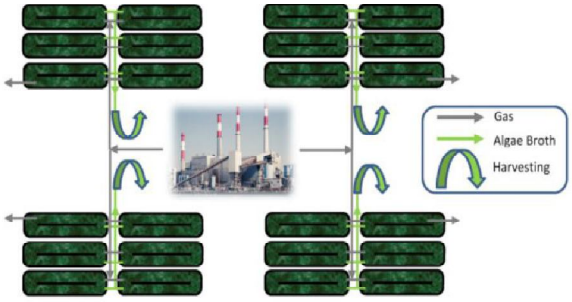



**Figure 2. Power plant integrated with algae pond to reduce $CO_2$ emission and produce biomass for co-firing**
**Source: A. Giostri, M.Binotti, and E. Macchi, "Microalgae cofiring in coal power plants: innovative system layout and energy analysis", Journal of Renewable Energy, 2016**

(2) Urban Intervention

The Milan EXPO 2014 featured the Urban Algae canopy project,a bio-digital canopy that synthesizes the urban algae farming and architectural bioreactor systems to reduce city's carbon emissions and green energy production. This system consists of the four-layered ETFE cladding with automatic valves for controlling algal cultures, $CO_2$, and water.Visitors and solar intensity actuates the electro valves to regulate the growth and the density of algae culture within the ETFE panel,offering the solar shade potential. It was estimated that the algae harvest produces oxygen equal to 4 hectares of forest area and an estimated 150 kg of Biomass/Day.



**Figure 3. Urban Algae Canopy to provide shades and foods for urban goers**
**Source: http://www.carloratti.com/wp-content/uploads/2014/05/20140430_Domus.pdf**

Another microalgae system in urban intervention is the Algae Dome displayed at CHART art fair in Copenhagen in 2017 (Figure 4). The project aims to raise awareness of the innovative biotechnology to reduce environmental impacts and in the meantime showcase the sustainable nutritious food of the future that can be grown in cities. The project was able to grow up to 450 liters of microalgae for three days and encourage interaction with visitors through improved air quality and spirulina algae foods.



**Figure 4. Algae Dome to grow super foods within cities while reducing environmental impacts**
**Source: https://space10.io/algae-dome/**

### (3) Building Intervention

The BIQ building is located in Hamburg, Germany, and is the first algae powered building in the world. Designed by Splitterwerk architects and Arup engineering, the BIQ isa 4 story high building with 15 apartments and a penthouse in a site area of 839m$^2$. The algae facade consists of the photobioreactors (PBRs) which are embedded in a steel frame and flat panel glass. The total number of PBR's are 129 and cover 200 m$^2$ of the southeast and southwest façade for maximum sun exposure. Each PBR is sized at 70cm x 270cm X 8cm which are filled with microalgae and 24 litres of nutrient rich water in 18mm thick cavity. The biomass produced within the RBR panels is supplied to another location for biogas extraction for heating heating purpose and to create heat energy for generating domestic hot water. These operations are controlled by a centralized building management system (BMS), which forms a closed loop for energy generation and reuse. The annual electricity production is approximately 4500 kWh with 6 tons per year $CO_2$ reduction.



**Figure 3. Bio Intelligent Quotient (BIQ) multi-story housing building in Hamburg, Germany**
**Source: https://www.iba-hamburg.de**

In response to growing population demands and the construction of new glass high rise buildings, Dr. Kim at University of North Carolina at Charlotte (UNCC) explored the challenges and feasibility of microalgae facades as the primary skin of a building. Precedentsinvolving algae have only used it as an external shading device such as the one in BIQ house. The UNCC team carried out a prototyping and preliminary performance assessment using simulations and lab testing under the building life-cycle assessment framework. The UNCC's microalgae façade system aims to meet an assembly value of R-5, summer SHGC-0.2, winter SHGC-0.6, and minimum 40% VLT. Lightweight micro photobioreactor and cost-effective fabrication method aims for material cost reduction compared to a conventional window counterpart with similar energy attributes such as a triple IGU with low-e coating(s). With these innovative technical improvements, the microalgae facades in tall buildings is expected to reduce primary energy use of typical commercial buildings in North Carolina by 0. 25 Quads, energy use intensity (EUI) by 80%, and peak loads by 20% by year 2030 while enhancing occupants' comfort.

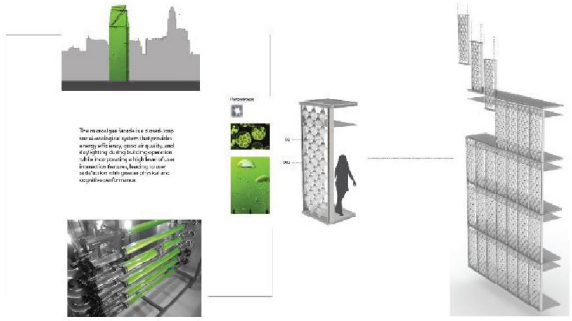


**Figure 4. Unitized microalgae facades for tall building enclosure application**
**Source: Author (produced with Shika Patel)**

(4) Product Intervention

The Living Things is photosynthetic furniture installation at a domestic level that explores symbiotic living with beneficial micro-algae through a series of three vignettes of a home environment. This installation contains furniture and furnishings that cultivate Spirulina algae in custom glass bioreactors designed as household furnishings (Figure 5). Living Things recycle light, heat, and $CO_2$ from buildings and their inhabitants into biomass, biofuel or agricultural fertilizer. The morphologies of glass bioreactors function as both lighting and heating elements for the human occupants, and they offer appropriate heat, light, $CO_2$ supply, nutrient inputs to the living algae inside. A centralized control system is connected to the glass bioreactors, that monitor the cultivation of algae and harvesting of Spirulina.

The Algae Curtain is another example of product intervention. Located in Lille, France, it is made of transparent polymer tubes and suspended like anarchitectural drape on the interior. Microalgae are pumped through these knotted tubes and absorb summer sunlight to produce biomass while reducingsummer solar penetration into the space.The microscopic algae used for this project is

Nannochloropsiswhich grow ten times faster than trees and produce biofuel through photosynthesis. The micro ecologies form a network within the architectural built environment where the natural conditions are used in the curved geometry to grow algae and produce biomass. These bioreactors consist of Phyto nutrients and Nannochloropsisalgaes which are pumped through the algae curtains. The biomass produced is estimated to yield 75000 liters of biodiesel per acre/yr. The transparent tubes forming the curtain are hand weaved by using the "Archilace" technique to form a curvilinear homogenous composition which informs the constant transformation within the complex network of ecologies.



**Figure 5. Microalgae light fixtures for symbiotic living in home environments**
**Source: http://www.ethanfrier.com/living-things/**



**Figure 6. Microalgae curtain for summer solar reduction, biofuel production, and good air quality**
**Source: http://loop.ph/portfolio/algae-curtain/**

## III. MICROALGAE FACADES FOR TALL BUILDING ENCLOSURES

Building enclosures have enormous significance to provide good indoor environment and energy management of energy flow between indoor and outdoor. Glass enclosures have been preferred in contemporary buildings by architects and owners due to design opportunities such as daylighting, view-out and aesthetics. Aesthetic appeal of transparency and lightness of glass is unique attributes that no building materials can offer. The innovation in glass technology over the past decades has pushed the boundary of design opportunities and technical advancement with new development an sophisticated approach. The glass buildings has often been associated with green building or sustainable buildings with good indoor climate and low operational energy. Optimization of façade functions in building energy conservation can be expressed as to synthesize different energy attributes of heat transfer, solar energy and daylighting potentials.

In addition to energy attributes, constructability of building enclosure system is important in that the high-rise buildings and the dense urban site have additional construction challenges such as access to the site, building material storage and space for installation equipment.The prefabricated unitized façade integrated with microalgae system is a factory installed façade unit that provides the necessary functions of structural integrity, water/air tightness, thermal insulation, daylighting, ventilation and maintenance. Depending on the project conditions, the prefabricated façade unit could be hungfrom the primary structure typically concrete slab or bottom supported by sitting on the bracket embed to concrete slab.Since microalgae façade system is a photo-bioreactor integrated into a glazing system, assembly details between these two systems are critical. The assembly must resist environmental loading and external and internal impacts, and be durable under dynamic outdoor environments. A further challenge is to establish material compatibility and jointing methods between the photobioreactormicroalgae façade system and the glazing system. The microalgae façade system is a preassembled unitized façade system that serves as a primary building enclosure with additional benefits such as better occupant response, good indoor air quality, and biofuel production. Specific design strategies of microalgae facades should be employed depending on building massing and site location, façade orientation, building program needs (view, daylight, solar gain, ventilation etc).

Our microalgae facadewas newly configured to provide a sustainable alternative to a high performance glass enclosure that provides a good daylighting potential while offering adequate insulation from its thermal mass potential and the addition of CO2 circulation [7].The new development builds on earlier results with the aim of further developing the microalgae panel into a prefabricated curtainwall unit with cost-effective constructability and long-term durability for tall building application in a dense urban site. Results of the previous work also informed us that the presence of microalgae in constructed environments was often perceived negatively. We examined specific user perceptions to determine how we can better promote our design, with an emphasis on interactive features that can reduce negative perception, enhance creativity and cognitive performance, and improve occupant's well-being. While the prior microalgae façade utilized domestic water and additional nutrients to cultivate microalgae strains, we consider system design strategies to use

rainwater and urban wastewaters for the microalgae biomass and lipid yield for biofuel production.

The microalgae facades in this research are for tall building application in urban cities where construction challenges much exist due to dense construction sites and on-site storage issues. Therefore,our microalgae faced systemwas configured as a cost effective lightweight prefabricated unit with longevity and quality control that ensures the compliance of building codes and national industry standards for scalable industrialization in building industry.The microalgae façade system is supported by metal frames typically extruded aluminums on four edges, which are thermally broken to prevent cold bridging and condensation during winter time. The aluminum extrusion incorporate cavity to run algae growing hose lines as well as stiffening nibs, screw races and pockets to receive gaskets to provide waterightness. In order to prevent heat built-up within the microalgae system layer, the inner glazing panel has ability to allow air circulation as well as maintenance access. Furthermore, the photobioreactor of the microalgae façade offers heat storage capacity and adaptable utilization of solar energy across a day and seasons (low SHGC in summer and high SGHC in winter). Figure 7 shows preliminary system development of the proposed microagle façade.

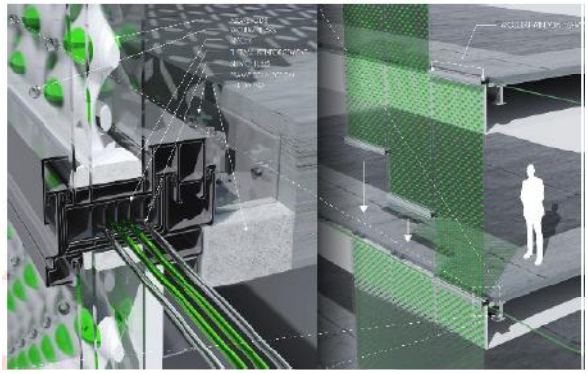


**Figure 7. Lightweight prefabricated microalgae façade unit for tall building application**
**Source: Author (produced with BekimSejdiu)**

In order to understand the energy conservation potential from the retrofitting using microalgae facades, we carried out an energy performance simulation for both the existing building and the retrofitted building with microalgae facades [8]. The case-study building, located in Climate zone 4 (New York City) and built around 1950, has a conditioned floor area of 85,000$m^2$ and a volume of 11,200,000$m^3$ within 46 floors. The original building was cladded with low performance windows and veneer bricks with batt insulation behind it. In order to measure the energy efficiency of the microalgae façade, only variable between the original building and the retrofitted building in building energy simulation is the window system. The remaining variables such as the specification of the opaque wall, window-to-wall ratio, air infiltration rate, and building operational schedules remained same between two scenarios [9,10].

The energy simulation results clearly show that it is possible to significantly reduce a building's energy consumption and environmental impact by upgrading the façade using microalgae facades. These high-performance façades result in substantial reductions to both electricity consumption and thermal energy use. The life cycle impact assessment indicates that during a 30-year operational period, the existing building produces approximately 12,100 tons of carbon emissions while the retrofitted building with microalgae facades would generate 11,900 tons of carbon emissions. As a result, the retrofitted building with microalgae facades would reduce the $CO_2$ emissions by 200 tons over a 30-year period (Figure 8). The 30-year life cycle energy cost was estimated to be $52,500,000 for the existing building and $42,200,000 for the retrofitted building with microalgae facades, based on the unit energy cost of $0.17/kWh and $0.98/Therm in New York City, leading to a net saving of more than $10M over 30 years.

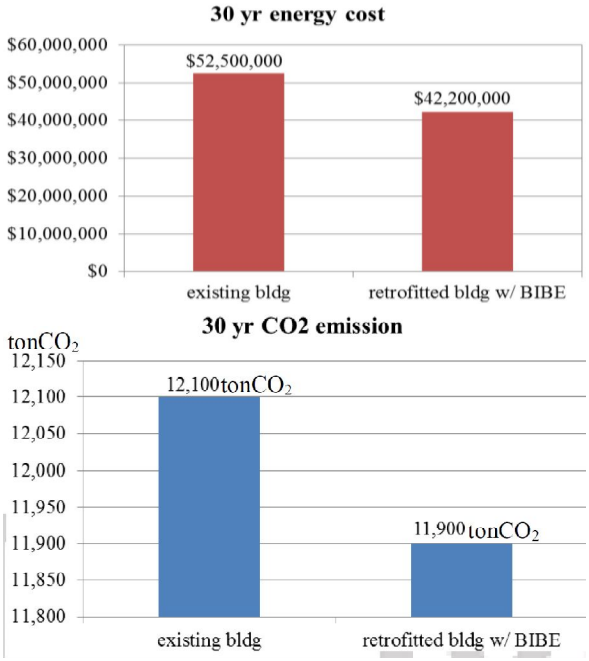



**Figure 8. Thirty-year life cycle analysis of energy cost and CO2 emission**

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## CONCLUSIONS

The research indicates that microalgae facades significantly advances a building's sustainability through improved energy performance of building envelopes, including carbon capture and renewable energy generation. Innovative application of microlage

facades in tall buildings harnesses natural or nature-inspired processes for a carbon-neutral building and sustainable energy systems in urban areas. Microalgae facadescan be applied to a wide range of building programs and typologies that promote awareness of sustainability and reduce environmental impacts. Algae biofuel development would contribute to the development of regulatory or the creation of policies that can encourage biofuel production and secure natural resources, leading to sustainable pathway to energy independence. The economic benefit to the building industry, especially to high performance buildings and consumers, will be immense.

The development of the microaglae system was carried out toidentify energyattributes that minimize heat transfer and unwanted solar heat gain while maximizing daylighting penetration. To encourage user interaction and positive perceptions, colored light emitted through microalgae facades can perhaps have potential applications in children's museums, K-12 schools or children's hospitaland so on where tocreate healthy and safe environments. Microalgae facades can achieve more energy efficient office buildings with good indoor air quality while enhancing workers' health and performance. This will also allow for diverse aesthetics in built environments, resulting in more aesthetically evocative and energy efficient buildings.

The algae façade system is a social-ecological building system that poses complex biotechnical application issues for tall building applications. We will explore the use of other innovative technologies, ultimately leading to scalable industrialization of microalgae facades toward net zero architecture practice and sustainable renewable energy system. These outcomes, along with increased user satisfaction, cost effective constructability, energy efficiency, on-site power production, life-cycle cost savings and aesthetics, will mark the success of this project.

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