Growing Sustainability - Integrating Algae Cultivation into the Built Environment

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ABSTRACT:

Designers are expanding the definition of Sustainable Design by incorporating biological processes and systems directly in their projects. Systems like green roofs and living machines have proved themselves invaluable for reducing a project's overall environmental footprint. More recently, advanced algae cultivation technologies – some still in the testing phase – inspire architects and designers. With its efficient energy production and potential for improving the health of the environment, algae cultivation is the next photosynthetically driven system primed for architectural integration.

This paper examines the various methods of algae farming, their roles in cyclical systems, their design implications, and their potential for integration into urban space. Algae can effectively sequester carbon dioxide and treat wastewater while increasing its growth efficiency. These properties give it great potential for integration with other infrastructural systems. Synergies can be developed into closed-loop systems within the built environment, resulting in lower CO2 emissions, O2 production, nutrient reuse and efficient energy generation.

These multi-layered benefits of algae cultivation have strong potential for sustainability methods to utilize algae-integrated systems. Algae's high ecological performance generates a multi-fold contribution towards improving the health of the environment. With its combination of carbon neutral energy production and recycling of environmental pollutants, the integration of algae cultivation into the built environment opens a new dimension in sustainability design.

EAR Volume 33, 2013
Edinburgh Architectural Research Journal
The Edinburgh School of Architecture and Landscape Architecture
Edinburgh, UK
http://sites.ace.ed.ac.uk/ear/home

INTRODUCTION

Microalgae promises a new era of sustainable energy production as the next biofuel source. Its potential is attracting hundreds of millions of dollars for research into viable algae cultivation methods. Although the US Department of Energy (DOE) has invested over $200 million in research, development and the construction of pilot projects over the last two fiscal years, private industry and venture capital lead the field. One oil company alone invested $600 million in algae oil production and a related advertisement campaign. Other companies are making multimillion-dollar investments in algae production, often in conjunction with DOE grants. Overall, hundreds of start-up companies, university projects and other efforts now exist in algae biofuels in the US and other countries (Hall and Benemann, 2011).

This narrow focus on only one purpose – biofuel production – neglects the multiple environmental benefits that algae cultivation itself provides. The autotrophic process of sunlight-driven photosynthesis in algae production reaches beyond renewable energy production; it sets up a co-dependency between energy transformation and ecological recycling (Hall and Benemann, 2011). Besides delivering lipids for fuel production, microalgae are capable of actively improving the health of the environment through the sequestration of carbon-dioxide (CO2) and production oxygen (O2) while recycling nutrients and potentially cleaning waste water in this process. These multiple benefits are actually the strength of algae production. Experts suggest that algal cultivation is primarily indicated where algae performs multiple functions and cultivation and harvesting expenses do not have to be adequately offset by fuel production alone (Benemann, 2009). Architects and designers are currently highlighting this underutilized potential. Advanced algae cultivation technologies – some still in the laboratory and scientific testing phase – inspire them on speculative projects, design competitions and prototypes. Many recent, innovative design proposals and competition entries feature the integration of algae cultivation and lead the way to new potent sustainability methods.

This paper accesses the current state of algae farming methods, reviews emerging architectural applications and cases on how architects, engineers and designers start to integrate those as sustainability strategies in the built environment. Algae cultivation and its architectural integration promises to revolutionize ecological design and become a powerful tool to address the causes of climate change.

ALGAE CULTIVATION

Humans have been harvesting algae for food and medicinal purposes for over 2500 years, and have been cultivating it for approximately 300 years (Tseng, 1981). Currently, microalgae are commercially grown worldwide (Morton, 1998). One of the earliest mentions of algae as fuel occurred in 1953 in Algal Culture: From Laboratory to Pilot Plant. In his introduction to the edited volume, John S. Burlew – inspired by MIT research into rooftop micro-algae production – recommends harnessing algae's extremely efficient photosynthesis process to produce oils, effectively accelerating the natural process through which fossil fuels are formed (1953). In the 1960s, Stanford University scientists Oswald and Golueke released their paper "The Biological Transformation of Solar Energy," documenting their studies on a closed-looped algae-to-fuel production process (1960). US government-supported research into the potential of algae as a biofuel surged during the energy crisis of the 1970s (Benemann, 2008). Funding dwindled in the 1980s, and government funding has only recently resurged again in response to the growing interest in alternative energies, leading to an expansion of testing and innovation in algal fuel production and wastewater processing (Pienkos and Darzins, 2008). According to biologist Peer Schenk, international awareness of climate change and the need for reduced CO2 emissions has focused scientific attention on the potentials of algal biofuels (Schenk et al., 2008). Charles Hall and John Benemann confirm which dimension the research in algae oil production has developed over the last three years (2011). Since algae farming can occur without disrupting domestic agriculture, some governments and food industries are directly invested in its success (Fishman et al., 2008).

PRODUCTIVITY

Microalgae, autotrophic organisms often living as single cells and floating as plankton, are among the fastest growing, most efficient and adaptive organisms on the planet. They can produce 3,000-15,000 gallons oil/acre/year (Goldenberg, 2010). This makes them up to 60 times more productive than soybean, 15 times more productive than jatropha and about 5 times more productive than oil palm in producing oils that can be converted to biofuels per acre of land per year (U.S.DOE, 2010). Their high energy content of 18.5 - 35 MJ/kg rivals coal (averages at 24 MJ/kg) and exceeds the energy density of wood, wastewater sludge, and agricultural by-product, making them an excellent energy source (IMechE Report, 2009). Algae have a fast reproduction rate; some strains of algae are able to grow exponentially, doubling in mass in less than a day. That leads to a quick harvest cycle of only 1-10 days and the possibility of harvesting batch-wise nearly all-year-round, providing a reliable and continuous supply (Schenk et al., 2008). Besides energy in the form of biofuel, commercial algae cultivation has numerous uses. These include production of food, nutritional supplements, fish feed, bioplastics, chemical feedstock, pharmaceuticals, fertilizer, and soil enhancements.

RESOURCE EFFICIENCY

Algae can tolerate salt and wastewater streams and thereby greatly reduce freshwater use. In nutrient-rich, eutrophic water some strains thrive even more abundantly, consequently, wastewater can be considered a resource in some circumstances (Schenk et al., 2008). As a positive by-product, algae clean the water as a means of pollution control. Algae farming couples CO2-neutral fuel production with CO2 sequestration and O2 production. Physical sequestration of atmospheric CO2 is technically challenging, photosynthetic organisms have however mastered this process (Schenk et al., 2008). Numerous studies confirm that photosynthesis performed by algae significantly contributes to a reduction of atmospheric CO2 levels. It is possible that a one-hectare (2.5 acre) algae pond sequesters one ton of CO2 per day. If the captured CO2 could be transformed into a more stable form for long term storage (for more than 100 years) the process would start to lower the alarmingly high CO2 levels in the atmosphere (Schenk et al., 2008). As by-product algae produce 70-80% of the atmospheric oxygen we breathe (Hall, 2011). Increased CO2 concentration in the growing medium will further increase the rate of algae growth as long as there is an abundance of other limiting nutrients (IMechE Report, 2009).

CULTIVATION METHODS

To achieve maximum yields, algae production strives for strain-specific cultivation. Their optimization depends on interrelated factors that can each be limiting. These factors include temperature, mixing, hydrodynamics, gas exchange and bubble size, mass transfer, light cycle and intensity, water quality and pH level, salinity, mineral and carbon regulation, cell fragility, density and growth inhabitation (Schenk et al., 2008). In respect to the integration into the built environment, the different possible cultivation system designs for algae farming are of special interest. They range from low-tech ponds to high-tech bioreactors, with each design varying the balance of economics, environmental impact and operational factors. Today the feasibility assessment of algae cultivation systems is often reduced to economic factors alone. A more holistic assessment of these methods would include economic viability – high yields with low initial and operating costs, low environmental impact – low water, land, and energy usage, and low operational input – low resource use and low maintenance.

OPEN POND SYSTEM

The open pond system is the most commonly employed growing technique today. It utilizes shallow lakes, constructed or raceway ponds that usually operate at water depths of 15–20cm (6-8”) (Schenk et al., 2008) and are circulated by gravity or paddlewheels (Figure 1A). The major advantages of open ponds are their low construction and operation costs, but their economic margins are also lower than more controlled systems. Open ponds require large areas of land and are susceptible to contamination, evaporation losses, poor light utilization, temperature swings, and bad weather (Schenk et al., 2008). To minimize many of the problems associated with an open system, the pond can be enclosed with a transparent or translucent barrier that effectively turns it into a greenhouse. Currently several large-scale manufacturers of algae are using the raceway pond method (i.e. CyanoTec in Hawaii and Earth Rise Farm in Southern California) to produce food supplements and vitamins for human consumption (Hall and Benemann, 2011).

CLOSED, VERTICAL GROWTH SYSTEMS

Various vertical algae growing systems offer increased productivity per areal footprint. All of these are primarily capitalizing on the fact that most algae thrive best in diffuse light. To optimize the photosynthetic reaction, most algae species require indirect, middle-intensity light levels, which equal a light intensity of 1,000-10,000 lux. Direct sun light causes lower efficiencies, photo-inhibition, or even photo-bleaching (Schenk et al., 2008). As a consequence algae can be grown in three-dimensional space rather than on a surface (like terrestrial plants), as long as the light can penetrate into the depth of the volume. These vertical, closed systems consist of two main components: a feeding vessel and a solar array. The algae solution, along with the necessary nutrients and CO2, is introduced into the system through the feeding vessel. After the solution is mixed, it is pumped into the solar array where the solution is circulated and exposed to sunlight. In these closed systems, the yield is higher and algae is not vulnerable to contamination.

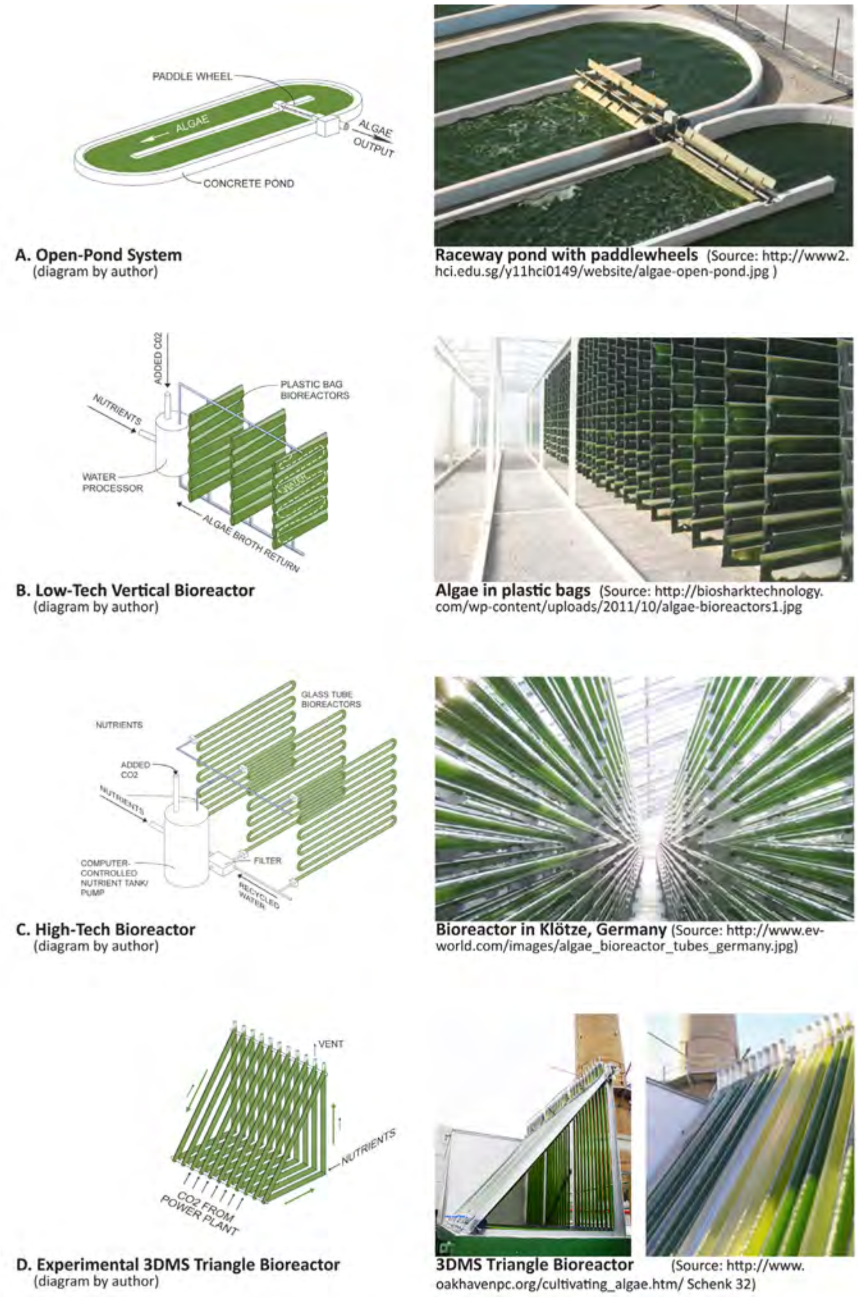
The most simple vertical systems, or low-tech bioreactors, cultivate algae in clear, poly-ethylene plastic bags hung vertically from racks to expose all sides to light (Figure 1B), as for example Vertigro, a bio-fuel oil/ CO2 sequestration system developed by Valcent Products in El Paso, TX. The algae solution is mechanically pumped through a continuous series of bags. The use of simple materials keeps the construction costs low, but might also require additional structure and enclosure to protect the cultivation from weather fluctuations (Kizililsoley and Helvacioglu, 2008).

CLOSED PHOTO-BIOREACTOR SYSTEMS

Closed bioreactors are initially up to 10 times more costly than open pond systems but have 5 to 10 times higher yields per areal footprint than conventional methods. They achieve this by maximizing the absorption of nutrients and energy in a minimal volume of water under controlled conditions. The algae are typically grown in glass tubes through which water is continuously pumped. This mixing is necessary to prevent settling of the algae cells and to support even distribution of CO2 and O2. The design goal of all growing structures is to maximize the surface-to-volume ratio and provide light saturation at optimal light intensities (Schenk et al., 2008).

Currently, AlgoMed, a company that focuses on food and medical supplement production operates the world's largest photo-bioreactor in Klötze, Germany (Figure 1C). It consists of 500km of glass tubes in

Figure 1: Algae Cultivation Methods



a 12,000m2 green house; the total volume of the system is ca. 600m3 (AlgoMed) and produces up to 100 t algae biomass per year. A very recent bioreactor variation, the 3D Matrix System increases the photosynthetic active area per areal footprint even further (Pulz, 2007). This system is currently in a test phase conducted by GreenFuel Technologies in Cambridge, MA at the Cogeneration Plant at MIT. This “airlift reactor” consists of triangular-shaped bioreactors from poly-carbonate tubing (Figure 1D). Flue gases are introduced at the bottom of the hypotenuse and flow up while the algae solution flows in the opposite direction. The ascending bubbles and downward current generate vortices that intensify the matter exchange (assimilation), which determines the growth rate. Even when tested under sub-optimal lighting conditions, the reactor is one of the most productive algal cultivation systems ever built (Schenk et al., 2008).

EVALUATION OF ALGAE CULTIVATION METHODS

Despite the development of more advanced bioreactor technology, the open-pond system is still the predominant commercial system because it is initially cheaper and produces a profitable yield, even if it is not nearly as productive as controlled systems (Figure 2). The environmental impact from open-pond systems is high due to its resource need for water and land. This land-intensive operation however can be installed on marginal and non-arable land and therefore opens up new economic opportunities for arid or coastal regions (Schenk et al., 2008). The system's vulnerability to contamination and higher land cost limits the possibility for its integration in cities.

When integrating algae cultivation in cities or areas of higher density and land cost, bioreactors are the resource friendly technology of choice to minimize the area needed, while increasing the yields by 5-10 times. Closed systems minimize evaporation and therefore control resource input and biochemical reaction rates carefully. Depending on the construction system used, from low-tech plastic bags to high-tech fiberglass bioreactors, controlled systems require a higher initial investment. Simultaneously, the necessary structure and compactness makes them more applicable for architectural integration. Bioreactors can potentially be connected to urban infrastructures and even building systems for resource recycling and pollutant sequestration at its source, as well as energy production where it is needed.

HARVESTING METHODS

Regardless of the growing method, the growth occurs over the course of 1-10 days depending on the algae strain. After this the algae mass is extracted. Algae's high water content makes the harvesting and processing a challenging task. Currently the most common harvesting processes are microscreening, centrifugation and flocculation. To develop a cost-effective and energy efficient harvesting method, the strain selection is important.

Large and filamentous microalgae can be easily harvested using microscreening and filtration. This process works well on small scale, but is difficult to scale up for large applications because it suffers problems like membrane-clogging, that result in high maintenance costs. Centrifugation and sedimentation are methods that can be also applied for harvesting also small algae. Pure sedimentation or settling is time and space consuming for biofuel production. Centrifugation is too cost- and energy intensive for the primary harvesting of microalgae, but is considered a very useful secondary method to concentrate the initial algae slurry. Flocculation, the aggregation and sedimentation of algal biomass is a common primary step to concentrate algae. Inorganic chemicals and organic flocculants can be added to the algae medium to increase the particle size and lead to faster sedimentation. The method of choice for cheap and sustainable production is currently self-flocculation,

Figure 2: Comparison of Algae Cultivation Methods (chart by author).

Algae Cultivation Methods

	Economic Factors		Operational Factors		Environmental Impact		
	Yield (g/m2/day)	Initial Cost	Operating Costs	Contam. Threat	Water Use	Energy Use	Land Use
Open Pond System	Low 10-25	Low*	Low*	High	High	Low*	High
Bioreactor Vertical Low-Tech	Mod. Up to 50	Mod.	Low*	Low*	Low*	Mod.	Low*
Bioreactor High-Tech	High* 50-60	High	Mod.	Low*	Low*	Mod.	Low*
"3DMS" Triangle Reactor	Very High* 80-100	Mod.	Mod.	Low*	Low*	Mod.	Low*

*= positive

initiated by carbon limitation or pH value shifts. Bioflocculation is currently the cheapest harvesting process available (Schenk et al., 2008).

If cultivated for biofuel, the algae are pressed for oil, after they are extracted from the growing medium. Common extraction processes involve mechanical crushing and squeezing. The cell disruption can be either carried out by high-pressure or electroporation, a process in which a high electrical field leads to the perforation of the cells and better extraction (Schenk et al., 2008). The oil is then refined into a useable form, typically biodiesel. With other forms of energy exploitation such as biogas, methane, ethanol, and biobutanol, the economic payback is lower. (Schenk et al., 2008).

SYNERGIES AND BUILDING INTEGRATION

Algae's nutritional and chemical requirements offer opportunities to integrate them in holistic sustainability methods. Their integration creates synergies between algae production and industrial, urban, and building utilities for a more holistic use of urban resources. Commonly, connections of algae cultivation with industrial plants or large infrastructure projects that produce CO2 or nitrogen-heavy by-products establish benefits and higher yields. Architecturally, the integration of algae farming with urban centres, infrastructure, and building systems is equally promising. The unused resources here are solar energy, CO2 -rich building exhausts, excess heat and wastewater.

Accordingly, current case studies and investigations emphasize four different aspects and benefits of algae farming. (1) Building Integration and Solar Energy Harvesting: Instead of remaining a hidden, utilitarian amenity, speculative design projects have started to weave the infrastructures of algae cultivation with cities and building systems. Algae bioreactor façades harness solar energy and reveal the new technology.

(2) CO_2 Sequestration: Controlled systems can be installed as effective CO_2 filters and additional power sources for buildings or neighbourhoods, which utilize CO_2-rich exhausts. (3) Wastewater Treatment Support: Other pilot projects utilize algae's ability to thrive in nutrient-rich wastewater to improve ecological wastewater treatment practices. (4) Closed-Loop Systems: Integrated in complex, closed-loop systems, algae cultivation helps to establish net-zero, or perhaps even carbon-negative, building performance.

BUILDING INTEGRATION AND SOLAR ENERGY HARVESTING

In 2009 the Institute of Mechanical Engineers recommended integrating algae cultivation into the existing building stock as a strategy to deal with climate change. Building-integrated photo-bioreactors would be designed to efficiently collect solar radiation on the surface of buildings. Prefabricated bioreactor panels would present a manageable form for algae farming on the domestic and small commercial scale (IMechE Report, 2009). These units would be more accessible from the commercial point of view and would be an ideal bolt-on solution for a retrofit scenario. In addition to lowering the atmospheric CO_2 level and providing a natural source of energy, the algae growth infrastructure can act as thermal buffer (if integrated in a double skin façade), lead potentially to reduced energy demand, and improve building performance.

Process Zero: Retrofit Resolution, the winner of Metropolitan Magazine's The Next Generation 2011 Design Competition, translates this vision into a design proposal. It uses energy-generating algae to power a 1960s-era General Services Administration office building in Los Angeles (World Architecture News, 2011). A 25,000 sq ft microalgae bioreactor system generates 9% of the renovated building's power supply. A modular system of algae tubes wraps the building and absorbs solar radiation while reclaiming CO_2 and building wastewater to produce lipids for fuel production on site (World Architecture News, 2011). The bioreactor tubes are protected from intense sunlight through a thin-film photovoltaic shading system to avoid overexposure (Figure 3A) (HOK and Vanderweil, 2011). They are part of a full-scale closed system of holding tanks and filtration ponds to complete the bio-energy network (Hales, 2011). The panelised, tubular algae skin expresses the alternative energy production and environmental system architecturally and equips the building with more than a "metaphoric green cast" (Hales, 2011).

The emerging technology of bioreactors has not yet been installed on the side of the building nor integrated with high-performance double-skin facades. Both case studies suggest this innovative step. It is only a matter of time, judging from the success of other alternative energy systems, like solar thermal, photovoltaic, and living machines, when this technology will be integrated into buildings. Currently the main concern for realizing this step is a question of scale, in terms of efficiency, harvesting, and processing of the biomass.

CARBON DIOXIDE SEQUESTRATION

Carbon-absorbing algae cultivation and existing carbon-emitting power plants or building exhausts can be combined to both clean emissions and increase algae yield. Several pilot programs have found that small concentrations of algae can be used to "scrub" gas emissions from power plants, absorbing as much as 85% of CO2 content. A test system run by the Swedish energy company Vattenfall absorbs greenhouse gas emissions from a coal-fired power plant in Germany. Flat-panel airlift reactors cultivate an algae solution through which gas emissions are pumped. The resulting biomass is used for biofuel or fish feed (France-Presse, 2010).

An innovative architectural application of this synergetic affect is Carbon TAP by port, the winner of UCLA's WPA 2.0 Competition. Carbon TAP (Tunnel Algae Park) advocates taking advantage of concentrated CO2 resources from underwater vehicular tunnels and urban infrastructures in cities. With the CO2 exhaust of the Brooklyn-Battery Tunnel as primary case study, Carbon TAP develops a new eco-landscape/ algae farm in the Upper Bay north of Governor's Island. The algae feed off underwater "bladders" of CO2 collected from the tunnel in sealed large-scale bioreactors on the surface of the bay. The farm is integrated into a public park, which doubles as an operable bridge between Manhattan and Brooklyn (Port, 2009). The project is notable for its integration with existing urban infrastructure, utilizing an "out of sight" source of CO2, and generating an index for the otherwise invisible tunnel below. It imagines algae cultivation as part of a functional urban landscape, while taking advantage of substantial CO2 sources for algae production as well as its "cleaning" effect through carbon dioxide sequestration (Figure 3B).

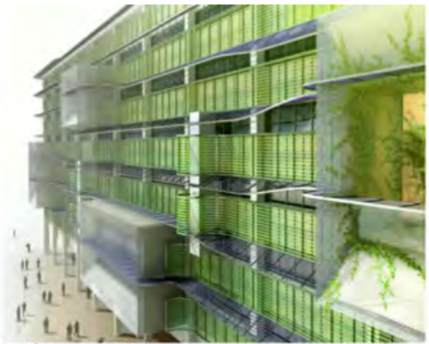
This case study also takes the established growing method of a bioreactor and establishes an urban scale algae farm. The farm uses two underutilized resources, CO2 created in traffic infrastructure and the unobstructed solar access of the large water bodies in the city.

WASTEWATER TREATMENT SUPPORT

Algae's ability to utilize the nutrients in wastewater calls for integration with water treatment processes. Solar Aquatic is one of the first living machines to use algae in translucent, light-transmitting tanks for wastewater treatment. This ecologically engineered system has operated continuously since 1989 at Ocean Arks International in Rhode Island. More recently, many municipalities are announcing plans to integrate algae technology in their wastewater treatment facilities while harnessing their additional benefits.

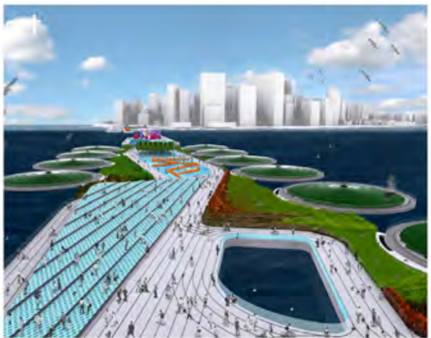
Rotating Algal Contactors RAC's, also referred to as Algaewheels, are algae-based applications for wastewater treatment currently in the testing phase in several American cities (Algaewheels). RAC technology employs a series of rotating photosynthetic algal contactors, which are propelled by a constant airflow and are designed specifically to grow large amounts of algae. Each wheel employs a miniaturized and intensified version of the pond growing system with paddle wheels. It provides optimal conditions for algal growth while removing nutrients from the water and increasing the energy efficiency of the treatment process (Figure 3C). Algae and bacteria grow in a symbiotic relationship, even though algae metabolize sewage far more rapidly than bacterial treatment by converting organic matter to plant life. This natural growth process of algae removes nutrients, such as nitrates and phosphates, from the treated effluent water, which therefore can no longer harm lakes and streams. The process helps to eliminate greenhouse gas emissions by sequestering CO2 and eliminating N2O as a by-product of conventional water treatment methods. The photosynthesis process also generates oxygen, which replaces the need for costly mechanical oxidation of the wastewater. In addition, Algaewheels significantly improve the energy efficiency of water treatment; they use 50 to 75% less energy than other biological processes and generate 95% fewer waste solids. The valuable

Figure 3: Case Studies

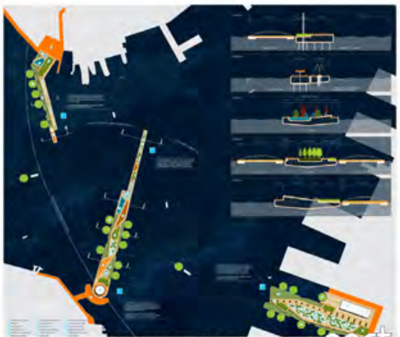


A. Algae as a Facade System - *Process Zero: Retrofit Resolution* (Source: http://www.process-zero.com)

Facade System Detail - *Process Zero: Retrofit Resolution* (Source: http://www.process-zero.com)

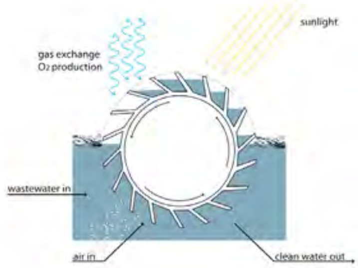


B. Algae Farming as Landscape - *Carbon TAP* (http://wpa2.aud.ucla.edu/info/index.php?/theprojects/winners/)



Carbon Dioxide Transport Diagram, (http://portarchitects.com/profile/carbon-tap--tunnel-algae-park/TAP4.jpg)

C. Algae Wastewater Treatment System - *Algaewheel Technology* (http://www.todaysfacilitymanager.com/facilityblog/wp-content/uploads/algaepac-1-1024x768.jpg)



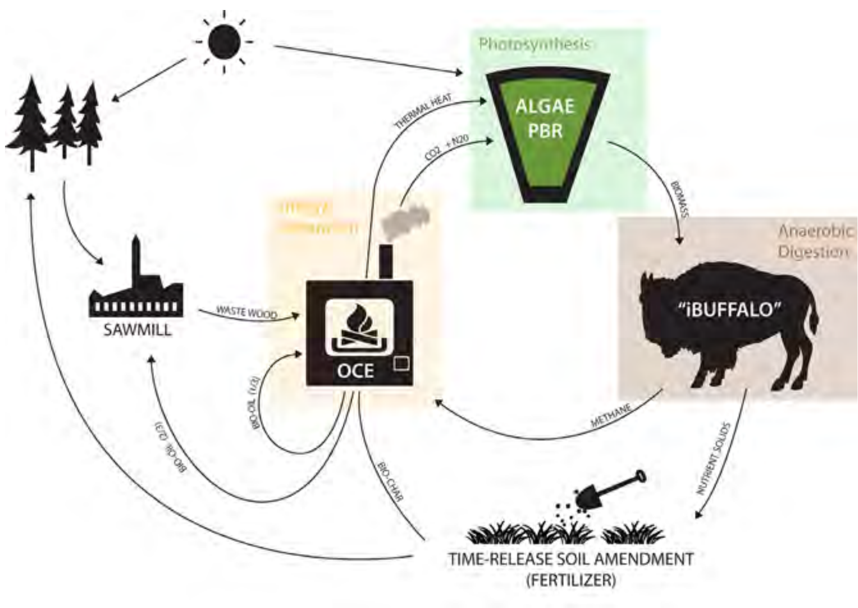
Algae Wastewater Treatment (diagram by author) by-product of algal biomass is an alternative energy source, which can improve the energy balance even further. Overall, RAC technology provides one of the most environmentally friendly solutions to wastewater treatment available today (Bishop, 2010).

CLOSED-LOOP SYSTEMS

Algae's ability to sequester CO2, produce energy, and absorb pollutants can be integrated into a sequence of processes that build on each other by using the by-product of one cycle as the resource for the next. Multiple interlocking cycles can create a self-sustaining, net-zero system. The Green Power House (GPH) uses newly-developed Algae Aquaculture Technology (AACT) within a system that inputs two resources abundant in Montana: sunlight and woody debris waste from a lumber mill. The Green Power House is located at F.H. Stoltze Land and Lumber Co. near Columbia Falls, Montana. The system uses three separate-but-interrelated processes to create two important outputs: nutrient-rich soil amendment and energy, both of which are necessary components of a successful, resource-efficient timber operation (Figure 4).

Eight algae ponds of the AACT cover the floor of the GPH greenhouse. Sunlight, CO2 and N2O from the Organic Carbon Engine (OCE) provide nutrients for algae growth. Ponds are managed and harvested separately for maximum yield and contamination control. The anaerobic digester breaks down algae sludge harvested from ponds inside the greenhouse by using a process similar to that found in a buffalo's stomach to produce methane and nutrient-rich solid matter (digestate). The methane is used in the OCE to start gasification process. The Organic Carbon Engine (OCE) converts waste wood into biochar, bio-oil, CO2, and N2O through gasification (pyrolysis). Waste gases are pumped into the algae ponds to accelerate algae growth and increase yields while simultaneously managing CO2 emissions and creating a carbon-negative cycle (Melcher, 2011).

Figure 4: Green Power House - Closed-Loop Systems (diagram by author)



CHALLENGES AND LIMITATIONS

The primary challenge research in algae cultivation faces is that all efforts go toward algal oil and biofuel production, which have to be optimized for very large scale production (Benemann, 2009). For these large operations, the availability of all resources in one place – a concentrated CO2 source, water, infrastructure, and land – is critical. The currently predominant open pond growing method is especially land-intensive, which limits the locations where it can be implemented. Oil production requires also a monoculture of one algae strain with high oil content, which can be threatened through pest-infestations in the open ponds.

Even so, algae can be grown in waste and seawater for resource efficiency, problems can occur through the varying quality of both sources. Especially, wastewater varies dramatically in quality over time and from one source to the other (Schenk et al., 2008). Contaminants can either be valuable nutrients or heavy metals (that can be inhibitory or even lethal at high levels). The pH value has also to be carefully monitored. The maintenance of an acceptable pH range is of upmost importance in high performance cultures (Schenk et al., 2008).

Other important factors in this context are the high costs of harvesting and processing the algal biomass (Benemann, 2009). Algae can be produced in large quantities, but at the same time efficient harvesting needs to be available on site. Many tons of biomass must be harvested, processed, and refined daily. A selected location needs to be able to handle both, the production of algae as well as the processing of the end product. Cost-effective harvesting is still a major limiting factor (Schenk et al., 2008).

The Institute of Mechanical Engineers suggests the large-scale introduction of algae cultivation into the built environment by integrating growth facilities into the urban fabric (IMechE Report, 2009). While the growing is dispersed on available vertical and horizontal surfaces in discrete photo-bioreactors, a local, combined energy centre contains and coordinates all processing and energy generation. The centre is linked up to a district heating/cooling network, as well as the electrical grid for surplus production. Mixed-use developments with an energy demand profile sufficient to merit running a combined heat and power unit for more than 5,000hrs/year are ideally suited for this scheme. The implementation of this concept is scalable, but larger processing plants and systems will benefit most from economies of scale (IMechE Report, 2009).

Experts suggest that algal cultivation is primarily advantageous where algae perform multiple functions, such as CO2 sequestration, wastewater treatment, and nutrient recovery. Expenses for cultivation and harvesting do not have to be adequately offset by increased fuel production alone (Benemann, 2009). This is also a good argument for moving away from algae cultivation for fuel production alone. Given the growing architectural interest in algae integration, more research needs to be conducted on the efficiencies and scale of algae farming. An interesting question remains in how far algae cultivation could happen on smaller scale and as a component in smart networks, following the trend of other alternative energy production toward decentralization.

CONCLUSION

The architectural integration of algae cultivation opens a new dimension to sustainable design by combining carbon neutral/negative energy production with ecological recycling of environmental pollutants. With its high ecological performance, algae production invites introduction into sustainable projects and generates a multi-fold contribution toward improving the health of the environment.

On the infrastructural scale, algae cultivation improves the environmental footprint and CO2 emission of power plants, industrial processes and large urban infrastructures. As demonstrated in design projects for innovative parks, it can become part of the urban landscape. Through urban and building integration, it can be connected to the waste and exhaust streams of the existing urban infrastructure. On the smallest scale, algae cultivation can potentially improve the performance of individual buildings, for example, through the integration of novel façade technologies.

Besides sequestering CO2, algae also mitigate other environmental challenges. It treats wastewater by using the pollutants as nutrients for its own growth. Algae can grow in waste and salt water and can be cultivated on marginal land (Schenk et al., 2008). Therefore, it does not contribute to the strain on freshwater resources or compete for arable land with other crops. On the contrary, as a source for fertilizer and soil amendment, it helps to re-establish the nutrient cycle, improve depleted soil, and reduces the energy intensive petrochemical fertilizer production.

These unique benefits of algae cultivation initiate an innovative approach to sustainability methods by integrating sunlight, alternative energy and material recycling. Although currently monopolized by industrial-scale operations focusing on the efficiency of biofuel production, the recent interest by architects and designers in algae technologies shows that these new methods have strong potential for future development of algae-integrated buildings, closed-loop systems and innovations in the building industry to mitigate climate change.

ACKNOWLEDGEMENT

This investigation of current algae cultivation methods builds in part on research previously published in "Photosynthetic Energy and Ecological Recycling: The Architectural Potential of Algae Cultivation" as part of the conference proceedings for “Digital Aptitudes,” the 2011 ACSA 100th Annual Meeting.

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