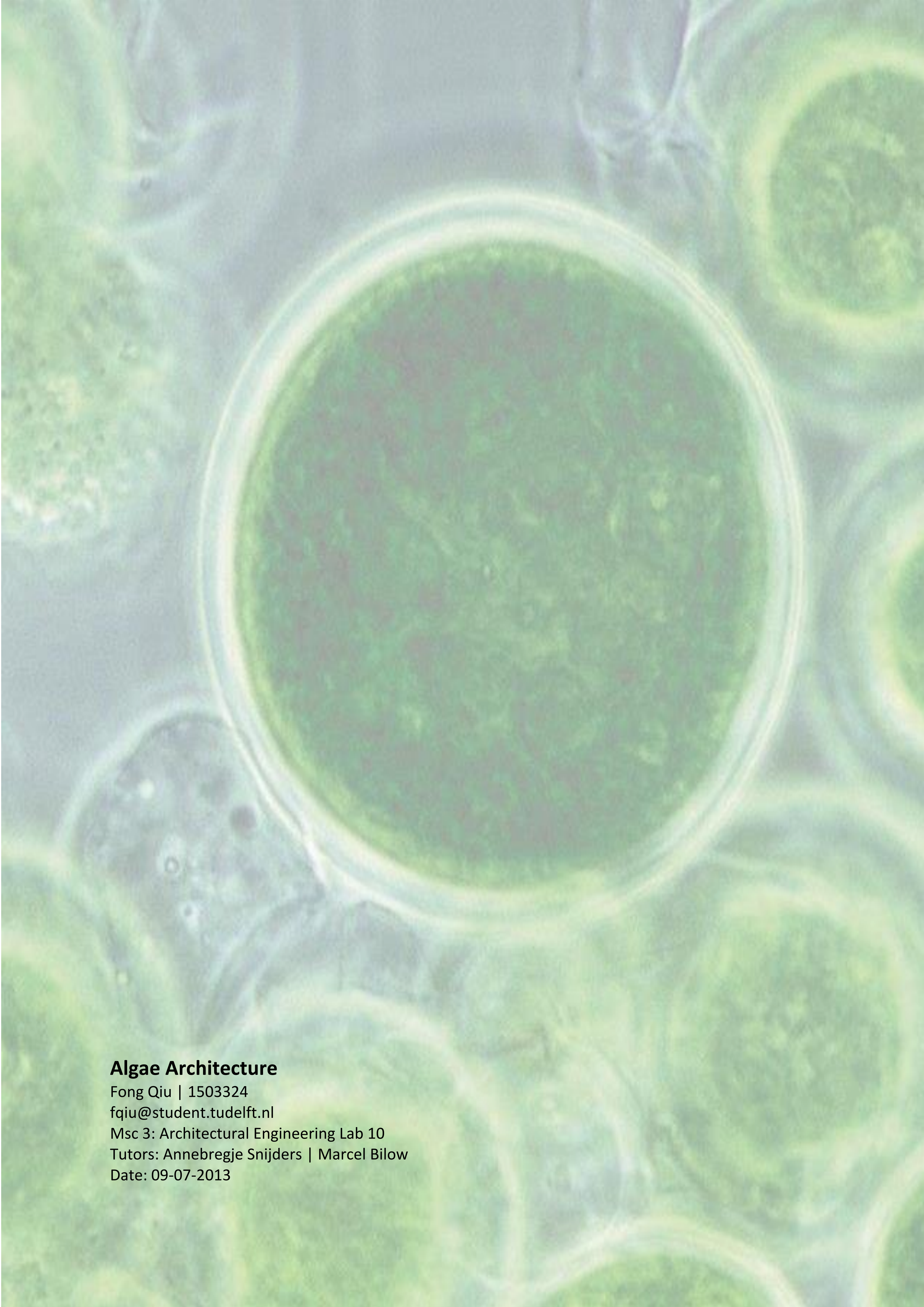

Algae Architecture

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Integration of algae in architecture

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Keywords: algae, sun shade, sustainable energy, biofuel, green building, bioreactor

Abstract

With rising energy consumption in the world and the depletion of fossil fuels in the near future, we have to make sure that energy security is guaranteed when conventional energy sources are depleted (BP, 2012). Nowadays, the energy we use is from fossil fuel sources and the generation of energy releases the greenhouse gas CO_2 and energy is transported over large distances. The energy needs to be generated locally and from a sustainable source to have energy security. Buildings contribute 30% to the total energy consumption in the Netherlands (Rijksoverheid, 2011) and therefore, if buildings can generate their own energy, it will have a large impact on the total energy consumption. Currently popular sustainable energy harvesters are windmills and photovoltaic panels. These systems can sustainably generate electricity, but it cannot take up CO_2 to support the goal of meeting the value of 20% below the 1990 level by 2020 (European Union, 2012). Microalgae can mitigate the CO_2 and produce energy at the same time.

The focus of this paper is on the use of algae as a building component that reduces the external energy demand in existing and new buildings. Especially the use of algae in façade design in closed photo bioreactors can be implemented as components in buildings. These closed photo bioreactors appears in many shapes and have to meet specific conditions for microalgae cultivation. Conditions for microalgae to survive and grow is dependent on (sun)-light, nutrients, pH, CO_2 and temperature (Tampier, Alabi, & Bilbeau, 2009). Closed photo bioreactors needs to be designed with these conditions in mind. During the cultivation process, the appearance of the building will change in color and become less transparent with increasing biomass concentration. The building will have a dynamic appearance with a liquid façade that also works as an adaptive sunshade. However, microalgae cultivation on buildings is not usual. Most of the results documented about the productivity of microalgae are measured in laboratory conditions. So designing a building with the main focus on microalgae as element is quite new in the world of architecture.

The results provided by this paper will give you an insight of the possibilities of algae when used in architecture in comparison to industrial applications. Algae is seen as one of the most promising sustainable way to produce energy in the future but it is still under development to increase its energy output (Wijffels & Barbosa, 2010).

This paper can only provide insights of the current algae technologies. So future developments and breakthroughs can change the way we think about cultivating microalgae and application in buildings. Algae technology has yet a long way to go to reach its full potential. But the development of algae technology has just been started and the potentials are high (Wijffels & Barbosa, 2010). In comparison to fossil fuels, biofuels are not profitable yet in terms of costs and low harvesting efficiency. That's why we search for new applications as in components in buildings to find new ways to use algae in the build environment.

Introduction

In the world we know today, it is unimaginable that we can live without (electrical) energy. The energy we use is so integrated in society that it has become part of our lives. Energy brings us joy, comfort, mobility and productivity and the energy hunger is still going on (Goldemberg, 2000). Most of the energy comes from a non-renewable source and harvesting these energy sources are affecting the environment at local, regional and global levels. Also, these energy sources are not evenly spread around the globe. This causes import and export of energy from one country to another and because energy is important in modern life, energy security is an issue for countries without own energy sources. They are totally dependent on other countries for energy which is not ideal in times of economic crisis or energy crisis when the countries keep the energy for themselves or increase the price (Huang, Chen, Wei, Zhang, & Chen, 2010). There are wars fought about oil and oil is mostly found in dangerous and unstable countries (Dillon, 2010). With the current energy consumption generated by fossil oils, natural gas and coal takes about 54.2 years, 63.6 years and 112 years respectively before the resources are completely depleted (BP, 2012). With this prospect in mind, we cannot live the way we do now after the fossil fuel sources are depleted without finding ways to harvest energy sustainably.

Sustainable energy can be generated or grown in a renewable way that can support the human development over the long term in social, economic and environmental dimensions (Goldemberg, 2000). Sustainable energy is not just energy security for the future, but also a way to secure human well-being and prevent environment issues caused by current energy consumption (Goldemberg, 2000). Combustion of fossil fuels causes atmospheric pollution and is the major source of greenhouse gas (GHG), which is accepted that it causes climatic changes (Ahmad & Wyckoff, 2003).

Producing bioenergy is an important strategy to mitigate greenhouse gas emissions and become a substitute for fossil fuels as energy source (Goldemberg, 2000). The biomass can fix CO_2 from the atmosphere or from concentrated sources through photosynthesis. Biomass is one of the better sources of energy that can be turned into bioenergy. The energy harvested from biomass is nontoxic and biodegradable, obtained from a renewable source (Hossain & Salleh, 2008). If the biomass is grown sustainably, combustion will release the same amount of CO_2 as it has nourished when grown with photosynthesis and results in a carbon neutral energy source (Hossain & Salleh, 2008).

Fuel energy is important because it supplies for 66% of the global energy consumption. Biofuels are the sustainable counterpart to fossil fuels (Stephens et al., 2010). Biofuels are extracted from crops and plants with lipid contents in their cells and can be used as liquid fuel as bioethanol or biodiesel, and can also be in a gaseous form as biogas, syngas an bio-hydrogen (Koh & Ghazoul, 2008). Growing biomass with photosynthesis is the most efficient with algae compared to other biomass sources (Shay, 1993).

The possibilities of growing microalgae as a renewable energy source on a local scale is discussed in this article. Local energy production becomes more important for future energy security with fossil fuel scarcity. Energy saving and energy production in buildings becomes more important. The cultivation of algae can take place in a much smaller area than crops and can be applied to buildings in an existing urban context. Using algae as a building component is something that is fantasized about, but almost never build in practice. When algae are grown on buildings, it transforms the static building in a living and dynamic building. The building will be able to recycle its own wastewater and purify the atmospheric air.

Algae in general

There are two kinds of algae: microalgae and macroalgae. Macroalgae is better known as seaweed and is left out of this article, because for fuel energy generation, microalgae are more suited due to their high lipid content and fast growth rate (Hossain & Salleh, 2008).

Algae are microscopic plants in Its most primitive form and lacks the defined parts of plants like shoots, roots, leaves, seeds and fruits (Lee, 1980). Microalgae cannot be seen with the naked eye, but if it grows in water with enough nutritions, the color of the water will change in green, brown, blue or orange liquid due to the massive amounts of microalgae (Hemming, Sapounas, & Voogt, 2012). They have relatively high surface area-to-volume ratio, which let them absorb nutrients and carbon dioxide much faster than agricultural plants (Tampier et al., 2009, p. 1). Microalgae are responsible for 1/3 of the world's carbon fixation and produce at the same time for about 70% of the atmospheric oxygen (Chinnasamy, Hanumantha, Bhaskar, Rengasamy, & Singh, 2012). Algae are already cultured for their high value oils, chemical, pharmaceutical products, fertilizer, bio plastics and cosmetics, and have been as supplement in human food, fish food and livestock food (Levine, 2010; Tampier et al., 2009). There are a lot of different microalgae species, some say its between 200.000 to 800.000 different species (Wolkers, Barbosa, Kleinegris, Bosma, & Wijffels, 2011, p. 9). However, only about 30.000 species are studied and analysed (Hemming et al., 2012).

"Microalgae are considered one of the most promising feedstock for biofuels" (Wijffels & Barbosa, 2010, p. 796).

The productivity of microalgae in converting CO_2 into oils far exceeds that of agricultural oleaginous crops without sacrificing arable land for fuel production and therefore doesn't compete with local food production (Wijffels & Barbosa, 2010). The smaller scale means that it can be implemented in smaller areas like in urban areas or buildings (Chinnasamy et al., 2012). The gathered sun energy is stored in a natural way in the form of sugars or oils (neutral lipids or triglycerides) (Wijffels & Barbosa, 2010, p. 797). Microalgae can not only create clean renewable fuels, but also remediate wastewater and create bio chemicals (Chinnasamy et al., 2012). There are many advantages over land crops by using microalgae. The high growth rate of microalgae makes them a perfect candidate to satisfy the energy need in the future with limited usage of land resources (Chinnasamy et al., 2012).

Cultivation methods of microalgae

The main techniques developed in Japan and the United States in 1970s are still viable today like the open raceway ponds and principles of a closed photo bioreactor (bringing light inside the bioreactor with fiber optics), which are still being developed today (Wijffels & Barbosa, 2010). The reason they started to get interested in algae was because of the oil shock in 1970s (Waite, 2011).

In contrast to land based crops for biofuel production, microalgae biofuel production is only a small percentage of the total biofuel production. The reason is that microalgae production is still done in a small scale (Wijffels, Barbosa, & Eppink, 2010). Researchers all over the world are developing technology to scale up algae production for oil extraction and other applications to an industrial scale (Wijffels & Barbosa, 2010). Developments in systems biology, genetic engineering, and bio refining can grow microalgae at larger scale and in a sustainable and economical way (Wijffels & Barbosa, 2010). The first goal is to reduce the production costs and energy requirements while at the same time increase the lipid productivity of algae and make use of all the other possibilities of biomass (Wijffels & Barbosa, 2010).

Open photo bioreactor systems

Open raceway pond (RWP)
The oldest and most commonly used cultivation system for microalgae is the raceway pond (Jiménez, Cossio, Labella, & Xavier Niell, 2003). This system have been in use since the 1950s (Borowitzka, 1999). Mass microalgae cultivation using RWP requires a lot of ground area, are susceptible to contamination, have bad light utilization, susceptible to pollution, have bad temperature control, diffusion of CO_2 concentration, less algae species can be cultivated and water loss through evaporation (Pulz, 2001; Ugwu, Aoyagi, & Uchiyama, 2008). The advantage of open systems are the low cost to operate and build, easy to clean and good for mass cultivation of microalgae (Ugwu et al., 2008).
The open raceway ponds are shaped like raceways (figure 1) with a shallow layer of minimal 0.2m water (Norsker, Barbosa, vermue, & Wijffels, 2010). For mixing, a paddlewheel is rotating at a velocity of 0.25 m/s to circulate the water. The paddlewheel has to operate constantly to prevent temperature difference in the pond and prevent microalgae from settling on the bottom (Wolkers et al., 2011).
The biomass density is low for this system (0.3 g DW/liter/day). Most industrial microalgae production is done this way with Spirulina and Dunaliella as microalgae strains (Norsker et al., 2010). RWPs are easy to build and are simple to operate (Hemming et al., 2012). Disadvantages of this system is to control the climatic conditions and keep the microalgae pure and free of contamination (Wolkers et al., 2011). Furthermore, only limited amount of microalgae species can be cultivated in temperate climates in the Netherlands (Tampier et al., 2009). RWPs seems to have reached their technological limit, so nowadays lots of research is done in photobioreactors to increase the productivity (Hemming et al., 2012). Therefore the main focus is on closed photo bioreactors that in size and applications is more suited for urban areas and in buildings.

Figure 1: open raceway pond algaePARC (van Sprundel, 2012)

Closed photo bioreactor systems

Photo bioreactors (PBRs) were created to overcome the problems that RWPs suffer from as contamination, uncontrollable environments, evaporation, limited species suitability, low volumetric productivity and use of large land areas. Cultivation can take place inside a building or outdoor with artificial light or sun light (Tampier et al., 2009). More microalgae species can be cultivated in photo bioreactors than in an open pond system due to their heat retaining capabilities. Because the temperature are better controlled in a closed photo bioreactor, microalgae can be cultivated longer periods in temperate climates. However, overheating can quickly occur with photo bioreactors during daytime, intensive mixing and pumping is required to cool the photo bioreactor down to a temperature in which the microalgae is the most productive (Tampier et al., 2009, p. iii).

Tubular photobioreactor
In this system, the microalgae are cultivated in transparent tubes (figure 2). The tubes can be in a single layer of horizontal tubes. The productivity in the tubular PBR is higher per square meter compared to an open system, but due to the high light intensities on the surface of the tubes, the growth rate can be limited. The advantage is that it is scalable by adding more tubes to make it longer (Wolkers et al., 2011). A more effective way to use tubes is to stack them vertically on top of each other and place several of these reactors next to each other. The reactors will cast shadows on the reactor next to it and therefore light intensities are lower and a higher productivity can be achieved. Also more biomass can be created per square meter (Wolkers et al., 2011). The culture is circulated by a centrifugal pump and passes through a degasser that blows off the accumulated oxygen (Norsker et al., 2010). The tubes can be made from different transparent materials but the choice of the material have influence on the life-time of the photobioreactor. Soft polyethylene tubing is cheap, but have a life-time of one year. Acrylic tubing and stacked layers of glass are also possibilities with a longer life expectancy. The centrifugal pump have to create a turbulent flow of 0.5 m/s to mix the cells from the illuminated surface and the dark core of the tube (Norsker et al., 2010). Biomass densities of 1.7g DW/L are obtained with Haematococcus, Chlorella and Nannochloropsis production (Norsker et al., 2010).
(Norsker, Barbosa, Vermue, & Wijffels, 2011) says that the practical maximum photosynthetic efficiency of an outdoor tubular PBR system is 6% while 9% is possible in theory. This is due to environmental factors that influences the productivity of the microalgae. For Dutch climatic conditions, cultivating microalgae in tubular photo bioreactors is the most economical (Sierra et al., 2008).


Figure 2: tubular photobioreactors algaePARC (van Sprundel, 2012)

Flat panel photobioreactor
The flat panel system is in fact a flat transparent container in which the microalgae are cultivated in the space between two glass plates or polyethylene film. The mixing is done in the panels itself with use of pressurized air with a volume of 1 liter of air per liter reactor volume per minute (Sierra et al., 2008). Flat panel photobioreactors can be placed close next to each other for higher photosynthetic efficiency due to the fact that the panels provide shade, and dilute the solar light. Lower light intensities results in less overheating and more efficient solar harvesting (Sierra et al., 2008). Biomass concentrations of 2.1 g DW/l is obtained with this system.
The first algae building is delivered with a flat panel photobioreactor, developed by Colt international GmbH, ARUP Deutschland GmbH and SSC Strategic Science Consult GmbH. “The prototypes are 2.60m high and 60cm wide and consists of four panes of monolithic glass. The panes form a central cavity of 18mm for the circulation of the medium and 16mm insulating cavities on either side” (Wurm, 2012). At the bottom of the photobioreactor are all the pipes and valves integrated to service the photobioreactor (figure 3).

Figure 3: Solarleaf bioreactor facade (Wurm, 2012)

Vertical bubble columns and airlift reactors
These photobioreactors are cylindrical shaped in which the microalgae are grown. The PBR is injected with gas bubbles from the bottom and causes mixing due to turbulence and supply nutrients for the microalgae. The areal productivity measured for P. tricornutum in a bubble column in summer is 2.02 g/L/day (Mirón, Gomez, Camacho, Grima, & Chisti, 1999). The mean annual productivity is 1.535 g/L/day because the high productivity is only in the summer (Mirón et al., 1999).

Figure 4: tubular photobioreactors (Schwartz, 2012)

Helical PBRs
This PBR is made of parallel flexible translucent tubes coiled around a cylindrical frame (Pattarkine, 2010). The light source can be in the cylindrical frame or solar light can be used. Productivities up to 113.7 g/m2/day (0.9 g/L/day) can be achieved (Tredici & Zittelli, 1998).

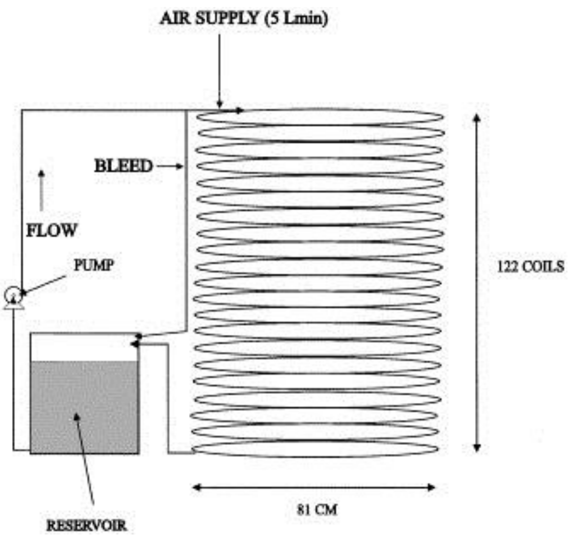


Figure 5: left (Vizcarra, 2012), right (Scragg, Illman, Carden, & Shales, 2002)

The microalgae culture is pumped from the reservoir to the top of the bioreactor and it will flow with gravity to the bottom of the bioreactor. It will be mixed with air at the top of the bioreactor and the whole bioreactor is illuminated from the inside. Energy is needed for the artificial light and pumping the culture (Scragg et al., 2002).

Figure 6: Diamond PBR (Vic, 2009)

The diamond PBR in figure 6 is a variation on the helical PBR and is used outside on the roof or in open field. The microalgae reservoir is at the top and with the helical design, no energy is needed for the microalgae culture to flow from the top to bottom. Energy is only needed for pumping the culture back up into the reservoir.

Orig*inoil Helix photobioreactor*

Originoil developed a new kind of photobioreactor (figure 7) that grows with precisely tuned frequency of LED light which allows microalgae to absorb light more efficient. The light uses low energy and the bioreactor is small in size and can be stacked (Pattarkine, 2010). The system is a big transparent tube with a central axis with lights attached in a helical pattern. The tube will be filled with water, microalgae and nutrients. The tuned light will rotate on the central axis for mixing and expose microalgae with different frequencies of light. The light used are red, blue and white frequencies. The biomass in the reactor can be harvested daily and scale-up possibilities are being tested.

Figure 7: left (Iyovo, 2009), right (Wesoff, 2009)

Algae waterbed algaePARC

Figure 8: Waterbed AlgaePARC (van Sprundel, 2012)

This photobioreactor is the algae waterbed (figure 8). It is like a big plastic bag filled with water with integrated algae panels. With this design, it is easier to keep the temperature at a certain level due to the mass of the water. The advantage is that less energy is needed for cooling or heating the photobioreactor and less material usage. Seawater with nutrients and CO_2 will be pumped through the panels with the microalgae. The thickness of the plastic bag is only 2mm thick and it is vulnerable to leakage and can be damaged easily (van Sprundel, 2012).

Plastic film bioreactor

Figure 9: plastic film bioreactor at Floriade Venlo (Qiu, 2013)

Microalgae can also be cultivated in plastic film panels. The bioreactor can have many different shapes. The panels in figure 9 shows a curved pattern to fill the whole plate surface area with the bioreactor. However, for architectural reasons, there can be different shapes with areas of the plates without microalgae cultivation and therefore creating a transparent part in the plate.

Conditions for microalgae cultivation

Light

Light is for phototrophic algae the base source of energy, but light can also vary in intensity and wavelengths and these parameters can affect the success and failure of algae cultures (Tampier et al., 2009).

There are two destinct points in light intensities that each phototrophic algae culture has. The one is at zero light intensity (night) in which algae don't grow at all (the compensation point). The growth rate increases with increasing light intensities and the photosynthesis increases until a point of maximum light absorbtion is attained. The algae becomes saturated and can't absorb more light (the light saturation point) (Tampier et al., 2009). If the light saturation point is exceeded, algae will not grow faster, but instead it will degrade its growth rate by photo oxidation. Photo oxidation is damage caused by light to light receptors which results in a decrease in photosynthetic rate and productivity (Tampier et al., 2009).

Microalgae have light harvesting antennas that are so efficient that it will absorb all the light that hits them, even if it can't be used for photosynthesis, it will be dissipated as heat (U.S. Department of Energy, 2010). The heat is considered as a waste energy, but in architecture, this heat can be used for heating the building when needed. If the algae are not mixed, the top or outer layer of the algae culture will be absorbing all the light and become saturated which results in shading the rest of the algae (mutual shading), which causes an overall decline in productivity. Thus mixing the algae is required to have evenly distribution of light inside a bioreactor or pond.

So there are two problems if we want to cultivate algae biomass. The saturation point of algae is about 20% of the solar light intensities. The surface algae may get saturated and photo oxidation may occur. The developments in microalgal strains with smaller antanna sizes will decrease the chance of oversaturating the microalgae cells (Wijffels & Barbosa, 2010). The algae below the surface have the opposite and can't harvest solar light by photosynthesis because the light is blocked by the surface layer of algae (Tampier et al., 2009, p. 9).

The challenge to overcome these issues is to keep mixing the algae and expose as much as possible the algae cells to solar light. The cell densities must be kept at a point at which mutual shading is minimal for optimal growth of algae. This can be achieved by proper mixing of the cells and don't have stationary cells which resides only in light or dark (Tampier et al., 2009, p. 9).

Temperature
Increase in temperature results in general in exponentially increased growth of algae until it reaches an optimum growth temperature. If the temperature exceeds this critical point, growth will decline. It is important to maintain a certain temperature level or have control over temperature. Outside in shallow open ponds it is difficult to control temperature due to climatic conditions (atmospheric temperature, solar irradiance and humidity) (Tampier et al., 2009). Diurnal shifts in temperature have an negative effect on the productivity of algae. The optimal temperatures for most microalgae to grow is between 20-30^{o}C, and stop growing with sustained temperatures below 5^{o}C and above 35 ^{o}C (Lavens & Sorgeloos, 1996).

Water in great amounts will remain mostly at a stable temperature due to the long response time to air temperatures. Excessive warmth can be stored and used again in colder weather conditions. In this way we can keep the temperature stable at a certain temperature in which optimal growth of algae is achieved. Tampier and co-researchers thinks that the long response time to air temperatures is a negative aspect for optimal algae growth and only parts of the day it will achieve the optimal culture temperature (Tampier et al., 2009). The other problem stated by Tampier and co-researches is that light intensities increase very rapidly in the morning when the temperature of the algae cultures is below optimum levels. The optima of both conditions are not in sync and it affects the overall productivity of algae growth (Tampier et al., 2009).

Temperature control and solar light must be in sync to overcome the difficulties in cultivating algae in outdoor spaces. While algae will survive temperatures below optimum levels (not freezing conditions), sustained temperatures above this level will kill the algae (Tampier et al., 2009). A high temperature at night have shown increased loss in biomass (Tampier et al., 2009). The goal is to reach optimum levels of solar light and temperature in the morning and rapidly decrease temperatures after sunset. These are the optimum condition in which algae grow rapidly and maintain its biomass (Tampier et al., 2009).

Gas exchange
The biomass of grown algae roughly contains 45-50% of carbon which is absorbed through photosynthesis (Tampier et al., 2009). The concentration of CO_2 in the air (0.033%) is the limitation for a quick algae growth if additional CO_2 is not supplied to feed the microalgae. For maximum growth rate, concentrated CO_2 supply is necessary. This can be captured from industrial exhaust gases or from soluble carbonates (NaHCO3 and Na2CO3) (Chinnasamy et al., 2012). Also the CO_2 from the atmosphere can be collected with a carbon scrubbing device with carbon capture resin. When the resin is saturated, water vapor is released to increase the humidity and the resin will release the CO_2 (appendix J). The supplement CO_2 is usually injected via gas exchange vessels in PBR's or with sumps in open raceways (Tampier et al., 2009, p. 10).

To produce 1 ton of algal biomass, 1.8 tons of CO_2 is needed (Wijffels & Barbosa, 2010). Transporting the CO_2 over large distances to the bioreactors is not a good solution in producing biofuels (Wijffels & Barbosa, 2010). Carbon sources can be captured from flue gasses at (coal) power plants. Large amounts of gases are emitted every day in these power plants with concentration of CO_2 up to 13%. This concentrated CO_2 can be used to cultivate microalgae in open pond systems or photobioreactors (Huang et al., 2010, p. 42). Here we use a waste stream of CO_2 from coal combustion and transforming it in usable fuel.

The supply of CO_2 must be reliable for the photobioreactor. When unsufficient CO_2 is supplied, algae biomass decreases and pH levels will change (Hemming et al., 2012). Also a high concentration of CO_2 is no problem for microalgae, in fact they grow faster (Chinnasamy et al., 2012).

The concentration of O_2 created by the algae itself must not exceed the saturation point in algae cultures. The effect of exceeding the saturation point is photo-oxidation damage to the algal culture and reduce the productivity of algae (Tampier et al., 2009). In open systems it is not a problem, but in closed PBR's it will become a problem if the excessive O_2 isn't removed form the algae culture. O_2 can be removed by adding gas exchange chambers (Norsker et al., 2011; Tampier et al., 2009).

Nutrients

Typical inorganic elements needed for algae to grow are phosphorus, nitrogen, potassium, sulfur and silicon (Chinnasamy et al., 2012; Tampier et al., 2009, p. 10). The optimum levels of nutrients required isn't much documented for mass algal cultures. The ratio of phosphorus and nitrogen is generally considered to be 1Phosphorus : 16Nitrogen (Tampier et al., 2009). Usually because the numbers are not known, they add excessive nutrients to be sure that nutrients are not the limiting factor in algal growth (Tampier et al., 2009). The use of excessive nutrients have not shown any negative inpact on the growth of algae. Typical trace metals as nutrition for algae are chelated salts of iron, zinc, cobalt, manganese, selenium and nickel (Tampier et al., 2009, p. 10).

The biomass of algae consists of 7% nitrogen and 1% phosphorus (Wijffels & Barbosa, 2010, p. 798; Wijffels et al., 2010). Recycling and use of waste streams is the most sustainable production method. These organic loads can be found in the waste streams from municipal, industrial or agricultural sources (Chinnasamy et al., 2012). The municipal wastewater of Amsterdam contains about 6-8 mg/L phosphorous and about 40-60 mg/L nitrogen (van Nieuwenhuijzen, Havekes, Reitsma, & de Jong, 2006). Microalgae with a productivity of 1.9 g/L/day, requires at least 2.37 L wastewater to provide enough phosphorous to maintain the productivity of 1.9 g/L biomass (appendix I). Microalgae with a productivity of 0.62 g/L/day requires 0.778 L of wastewater to feed the microalgae (appendix I). Excessive nutrients will not influence the productivity of microalgal growth. Therefore it is better to use more wastewater and produce nutrients in abundance than using too less wastewater and slowdown the productivity of the microalgae.

Water

For photosynthesis approximately 0.75 liter of water is needed per kg of concentrated algae biomass (Wijffels & Barbosa, 2010). If the lipid content of the microalgae is 50%, then for 1 liter of biofuel is 1.5 liters of water required. If we compare it to fuel crops, approximately 10000 liters of water are needed for 1 liter of biofuel (Wijffels & Barbosa, 2010). In open pond systems it will require more water due to the evaporation of the water, but in closed photobioreactors this is not an issue.

Water can be used in closed photobioreactors for cooling, but cooling can also be achieved with an heat exchange system (Wijffels & Barbosa, 2010). The same can be achieved with heating the PBR and heat can also be extracted from the PBR for usage in the building. The way of regulating the temperature is different in the Netherlands than in Algeria (appendix H). The photo bioreactor in the Netherlands requires heating in the winter, in contrary to Algeria where cooling is needed (Slegers, Wijffels, van Straten, & van Boxtel, 2010).

The optimal pH levels for microalgal growth is different for each species, but for most cultured microalgae it ranges between 7 and 9 (Lavens & Sorgeloos, 1996). A culture can collapse when the pH levels aren't right for the microalgae. This can be prevented by controlling the pH levels with injection of CO_2 which decreases the pH levels. This is needed in high density algal cultures when the pH is rising (Lavens & Sorgeloos, 1996).

Stress conditions
Microalgae under stress conditions decrease the growth rate and therefore also the productivity. Stress conditions are nutrient deprivation, high light intensities, and too high concentrations of O_2, too low pH (Hemming et al., 2012, p. 10).
When microalgae are non stressed (comfortable conditions), it will store the lipids in the form of phospholipids. However if the conditions aren't right for the microalgae (nutrient deprivation or high light intensities), then it will accumulate the lipids in the form of triacylglycerols (oil bodies) (Wijffels & Barbosa, 2010, p. 797). The accumulation causes a decline in productivity and in growth rate. Microalgae will be grown to a certain density and then starved from nutrients. In this way the microalgae stop growing and produce more lipids (Wolkers et al., 2011).

Energy production

For energy security in the future, energy needs to be produced regional, local and national scale. Energy security means that the energy is always available at all times in various forms, in sufficient quantities and with affordable prices (Goldemberg, 2000). Microalgae can produce energy at a local scale and can survive harsh conditions. This makes it possible to cultivate microalgae anywhere in the world. Energy production with microalgae is dependent on the amount of sunlight, the chosen microalgae strain, the type of cultivation and type of energy. In a tubular system with P. tricornutum with a volumetric productivity of 1.5 g/L/day and 40% lipid content in the biomass will produce 2.19 kWh/L/year, (appendix H). These are calculations with optimal growth conditions of microalgae. Different scientific sources reports different productivities with the same microalgae. The values ranges from 1.15 to 1.90 g/L^3/day and is dependent on the day of the year (van Beveren, 2011). The real life test in Wageningen University with changing lighting and temperature conditions in the Netherlands results in a productivity of 227.8 g/L/year (van Beveren, 2011), which gives a daily productivity of 0.62 g/L/day or 0.905 kWh/L/year (Appendix H). Microalgae in a flat panel PBR with a productivity of 1.9 g/L/day and 40% lipid content, will produce 49,92 kWh/m^2/year. The Solarleaf (figure 3) produces 50 kWh/m^2/year from biomass with a solar conversion of 8-10% into oils. With the biogas, 40 kWh/m2/year of electricity is generated (Colt International GmbH, 2013b).
If the same dimensions as the Solarleaf is used for a tubular PBR system with a tube diameter of 50 mm in the Netherlands, then the panel system with tubes (figure 14 & appendix G-H) will produce 35.54 kWh/m^2/year. The volumetric productivity of a flat panel PBR is higher than a tubular PBR. Also the energy usage of a tubular system is higher compared to a flat panel. This is caused by the continuous pumping of microalgae through the tubes. With a flat panel, the microalgae are in the panels and the panels are not connected in a loop. In a vertical tubular PBR, energy usage of pumping the culture (LGem system) is 105 W/m^3 without an air pump and 229 W/m^3 with air pump (Hemming et al., 2012). Usually the power supply of tubular bioreactors ranges between 2400-3200 W/m^3 (Acién, Fernández, Sánchez, Molina, & Chisti, 2001). In a flat panel PBR, only an air pump is needed and consumes therefore 53 W/m^3. In a bubble column, the energy consumption is 40 W/m^3 (Sierra et al., 2008).

Energy production with hydrogen from green algae, a theoretical production of 20 g/m^2/day can be achieved. The theoretical maximum of hydrogen is 284,7 kWh/m^2/year, but in practice the number is much lower. Growenergy is developing the Hydral system that can produce 67,6 kWh/m^2/year (Growenergy, 2013). The technology is developing since 2001 and higher yields are now possible. However, major breakthroughs are needed to optimize the technology and achieve higher yields.

Seasonal productivity changes occur for countries with higher latitudes. The fluctuations in the Netherlands are higher than in France, in contrast to Algeria where the production is stable throughout the year (appendix H). In the Netherlands and France, days occur with negative biomass production. This is the result of dark respiration in the night and overall low light intensities on that day. This phenomenon is more likely to happen in winter days in the Netherlands and France (Slegers et al., 2010).

Algae in architecture

For a more effective and productive system of growing algae, a bio refinery infrastructure is needed that can take care of all the requirements needed for algae to grow. The bioreactor must be designed, the supply of nutrients and resources must be efficient and the logistics of water is also part of the bioreactor (Wijffels & Barbosa, 2010; Wijffels et al., 2010), harvesting and extraction should be on site to prevent transport energy loss. Breakthroughs in microbial fermentations, strain modifications and technological improvements (bioreactor design, process control, harvesting and extraction) are needed (Wijffels & Barbosa, 2010).

Light source
Some microalgae have the ability to light-up under certain circumstances. Biologist at UC San Diego have succeeded in creating colored algae with the use of fluorescent proteins in the algae cells. The colors of that they can make at the moment is blue, cyan, green, yellow and orange all with fluorescent protein. The algae will glow light and it can be implemented in façade design with different colors and as a small light source (Sciencedaily, 2013a).

Artificial light with LEDs like in the Originoil helix photobioreactor can be used as light for microalgae, but it can also be interesting as a public furniture where people can sit and see the microalgae grow and in the night, it could serve as lighting for the public space and grow the microalgae by night (figure 10). Also Pierre Calleja is working on algae street lamps. His design for a street lamp is a big tube that stands as a light column. The column can absorb CO_2 from the atmosphere and use it as nutrient for microalgae to grow (Scholtus, 2012). The batteries in the bioreactor is charged during daytime with photosynthesis. At night, the stored energy in the batteries is used for lighting.

Figure 10: energy flowers (BLUA, 2010) and Algae street lamps (Calleja, 2012)

Microalgae cultivation with artificial light in the night is possible and prevents dark respiration and keeps the productivity high. Energy is needed for artificial lighting, but for a public building that always keeps the light on at night, its free energy for the microalgae. Part of the energy from lighting can be used again for energy production since the grown biomass can be converted into energy again.

Colors of microalgae

Figure 11: colors of microalgae (Wolkers et al., 2011)

Microalgae can have different colors. This is dependent on the microalgae species and the density of the microalgae in the water. A higher microalgae concentration results in a darker color with no transparency, while less dense cultures have more transparency with lighter colors. If the concentration of the microalgae is very low, then it just looks like water and is totally transparent.

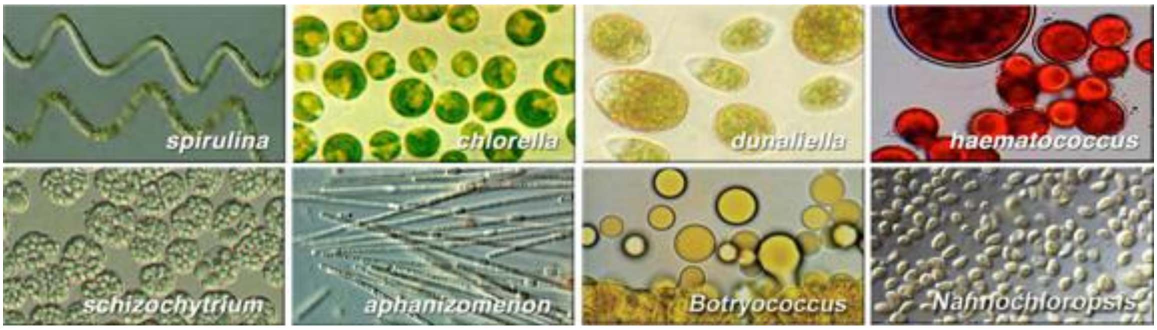


Figure 12: commercial microalgae (Hendrikson, 2012)

Sun shading with microalgae

Fast growing microalgae can be used as a dynamic sun shading. Microalgae have a harvesting cycle of 1-10 days (Chinnasamy et al., 2012). The photobioreactors of the B.I.Q. building also acts as an adapting sun shading. The biomass concentration dictates how much light can pass through the panels and it increases with higher solar intensities. The shading can be doubled within a day when continuous harvesting is suspended. The system is interactive and transmission of light can be controlled by increasing or decreasing the harvesting process (Wurm, 2012). Also seeing the microalgae grow in the PBRs is interesting with changing colors do a darker tint. The building is always changing in appearance.

Sun shading can be made from any form of PBR cultivation and be applied on the surface of the building. It can be made with tubes, panels and plastics. Different setups will influence the experience and the effectiveness of the sun shading. It can be integrated in the façade or acts as a second skin façade. If there is a glass roof, it can also be shaded with the same techniques as for a façade.

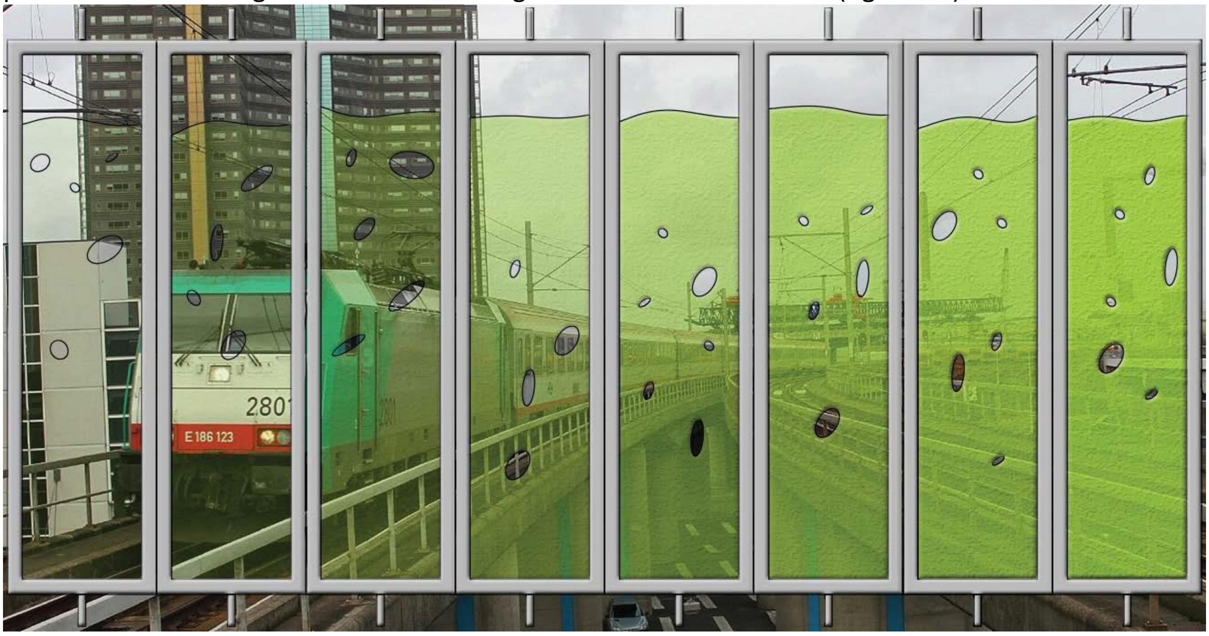
Figure 13: left (Bouck, 2010b), right (Bouck, 2010a)

For a window configuration, tubular PBRs can be placed in different arrays and shapes. In figure 13 are tubes with different diameters. The big tubes creates more colorful shading and light up with intense sun light. The smaller tubes have denser culture and creates darker shadows, but it also allows for more sun light to enter the building. Also more tubes can be added for more shading. These tubes are arranged in a vertical setup, but also horizontal applications is possible. The vertical standalone tubes are bubble columns. The horizontal tubes have to be tubular continuous cycle to function.

Flat panels can be used the same as with solar panels. It can and should track the sun for maximum efficiency and at the same time shade the space behind the flat panels.

Transparancy and panel volume

The concentration of microalgae in the bioreactor influences the transparency of the panels. With higher concentrations of microalgae, more light is absorbed and the panel will be darker in color with less transparency (figure 14). However, in practice the water will be more turbid and it will not be possible to see through the medium and a gradient of color will occur (figure 15).



Figuur 14: different stages of transparency (Qiu, 2013)

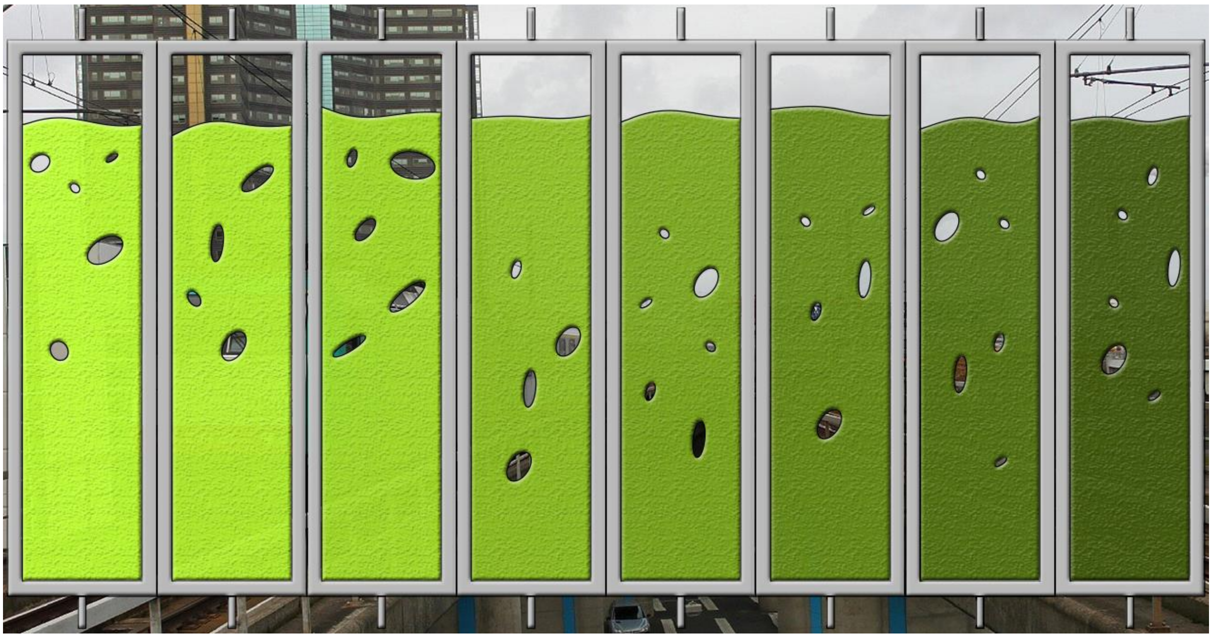


Figure 15: turbid microalgae panel gradient (Qiu, 2013)

The volume of the microalgae medium can be varied individually, because each panel is a closed system. The productivity will increase or decrease when the volume is changed, but in this way, the transparancy and light penetration can be influenced for more comfort when needed (figure 16).

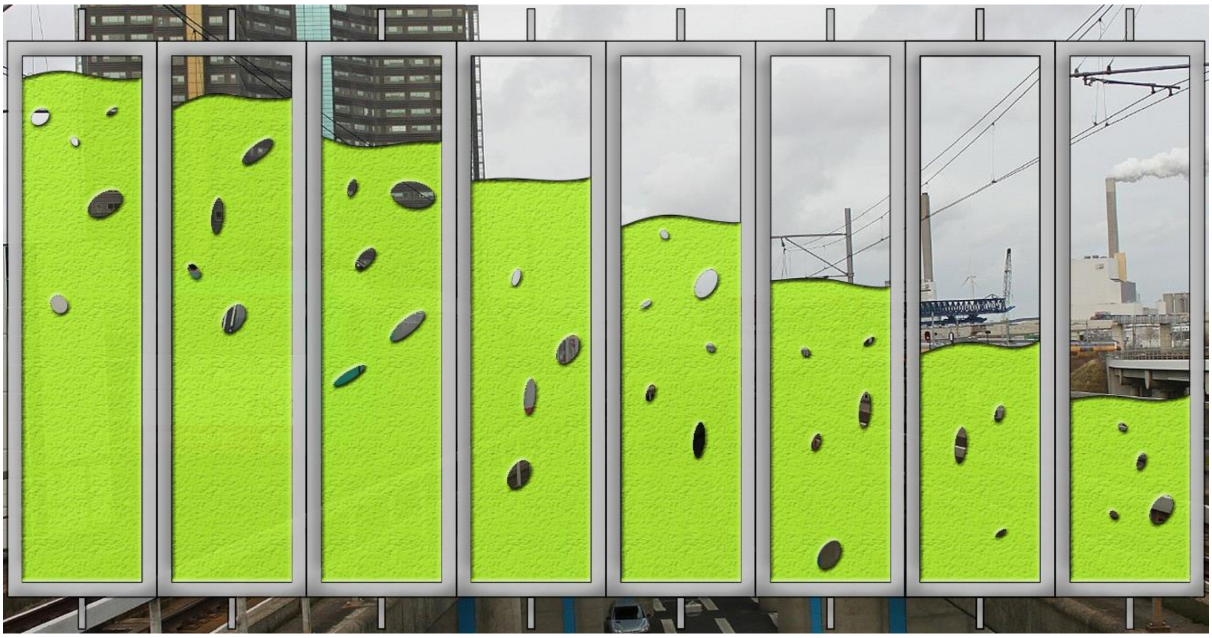


Figure 16: adaptable water levels for transparency (Qiu, 2013)

Air bubbles

Figure 17: B.I.Q. building (Colt International GmbH, 2013a)

In a Flat Panel Uplift bioreactor, nutrients and carbon dioxide are mixed with the liquid in the panels to stimulate a fast growth rate. Pressurized air is used to mix the microalgae in the bioreactor and at the same time the turbulence is scrubbing the inside of the glass panels clean to keep up the productivity of the microalgae (Wallis, 2013). Air bubbles also adds interest to the façade and makes it more dynamic.

Maintenance

Microalgae under stress conditions (low pH, low CO_2, low N) tend to stick to the inside of the transparent tubes (figure 18). Due to the layer of microalgae in the bioreactor, less light can penetrate into the culture medium and therefore production of the whole bioreactors was lower (Hemming et al., 2012). To clean and decontaminate the photo bioreactors, (Hemming et al., 2012) adds Baskal (KOH + K_2CO_3) in low concentrations (1ml/l) into the cultivation water. The Baskal dissolves within a day the majority of the sticky microalgae and brings it back into the water (Hemming et al., 2012). Baskal in low concentrations seems to have no influence on the productivity and the sticky microalgae also starts to grow again. The photobioreactors can be cleaned during production by using Baskal and does influence the productivity in a positive way (Hemming et al., 2012).

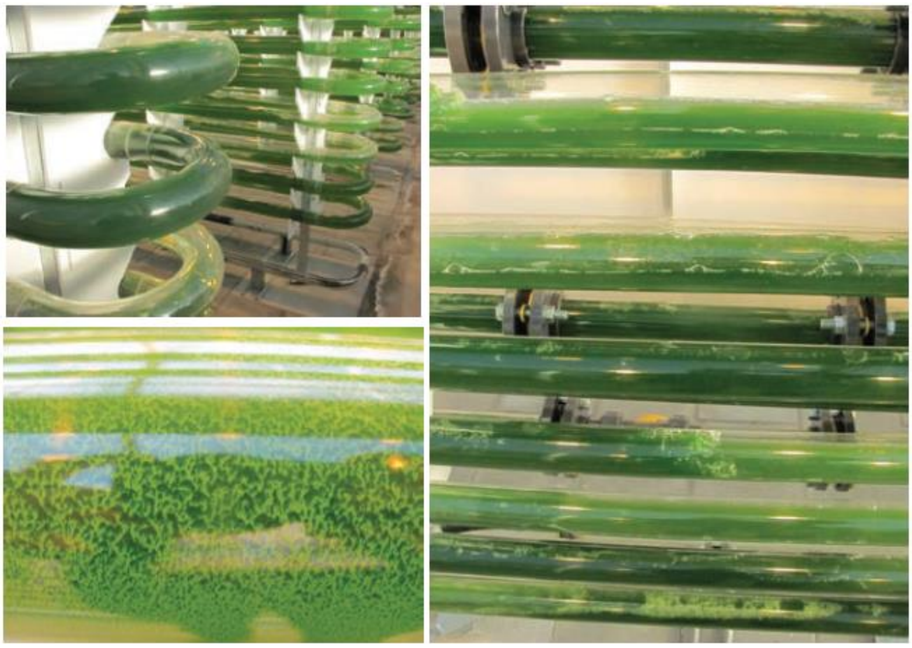


Figure 18: microalgae growing on the inner surface of the tubes (Hemming et al., 2012)

Parameters
The parameters of the PBRs are the diameter of the tubes. The dimensions of the diameter influences the appearance on the building and light transmission for microalgae cultivation. Space between the tubes can create a line of sight from the inside and see the outside world as it is, which is not possible through a PBR at full production. These lines of sights are important for the experience of the space and the building itself. It changes the ambience of the space inside. Also, the density of the microalgae can be so high that no light will pass through the PBR. Functions with need for daylight should get the daylight from somewhere else or the façade should be designed with openings in the PBRs.

The tubes can be extended to the length needed or provided in context. However, if it is a long continuous loop, the whole cultivation system should be shut-down when something is wrong. It would be wiser to make smaller loops to keep it more manageable.
Orientation at the sun is important for biomass production, but microalgae also grows in diffused light. When PBRs are placed next to each other, the light will be diluted and production per panel is lower, but overall production will be higher on the same ground area (figure 18) (Hu, Fairman, & Richmond, 1998). Also too high light intensities will slow down the productivity of the microalgae. The difference in efficiency can be up to 20% compared to an optimal horizontal reactor (Hu et al., 1998).

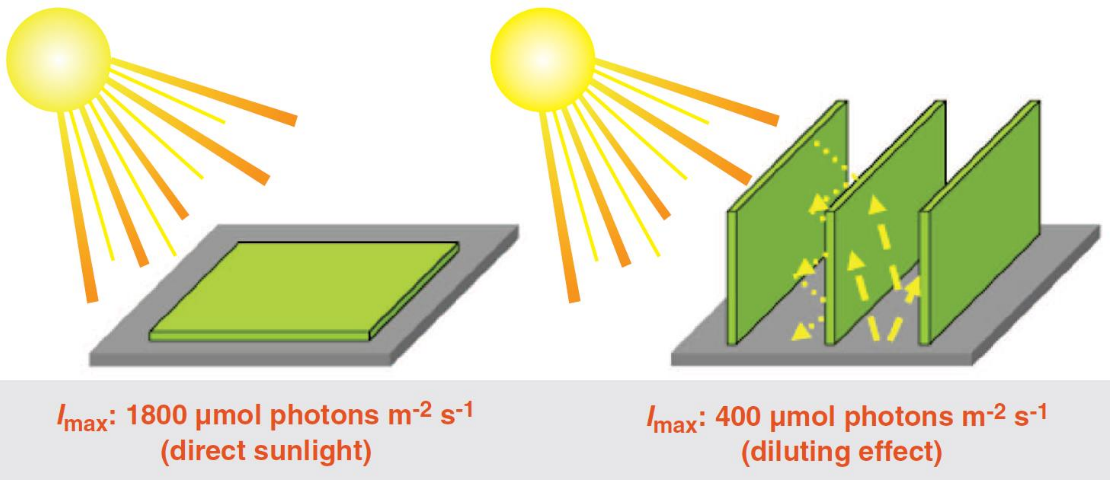


Figure 19: horizontal versus vertical flat panel photobioreactor (Wijffels & Barbosa, 2010, p. 796)

A flat panel can be placed on the façade and on the roof. The orientation and amount of sunlight influence the productivity of this system. This is dependent on the location of the PBR (appendix A). For locations with latitudes above 35°N, an east-west facing flat panel is more efficient than an north-south facing flat panel and intercepts more solar radiation (5% annual) than a horizontal PBR (Sierra et al., 2008).

Temperature control is an important factor the PBR to be productive. Placing the PBRs outside will expose it to atmospheric temperatures and shifts in temperature during the day. To keep the temperature stable will require cooling and heating. Heating and cooling can be achieved by controlling the temperature of the culture water. Warm or cold water can also be used in combination with a heat exchanger and this energy can be stored underground and can be used when needed for the building. For indoor cultivation, the temperatures does not shift as much as outside and it is easier to control the temperature in the PBR. Cooling or heating can be provided in the water itself. To keep the temperature more constant, PBRs can be submerged in water and due to the thermal mass of the water, the temperature will remain more constant

Design tools

The diagrams from appendix B, C and D provide a small overview of what is possible with the different cultivation techniques. The configuration will dictate the appearance of the building and can influence the experience and the line of sight from indoor spaces. The most flexible system is the tubular PBR that can be made longer by attaching new tubes to it, but it can also change direction and angle depending on the connector in between the tubes (figure 20). Plastic film bioreactors can have any shape but it has limitations on how large one panel can be. Also the shape inside the panel can be designed and create transparency and closed parts with microalgae. The system with the least flexibility is the flat plate bioreactor and contains the microalgae in between two glass plates. However different setups are possible which creates different ambiences inside the building and appearance from the outside (figure 21).

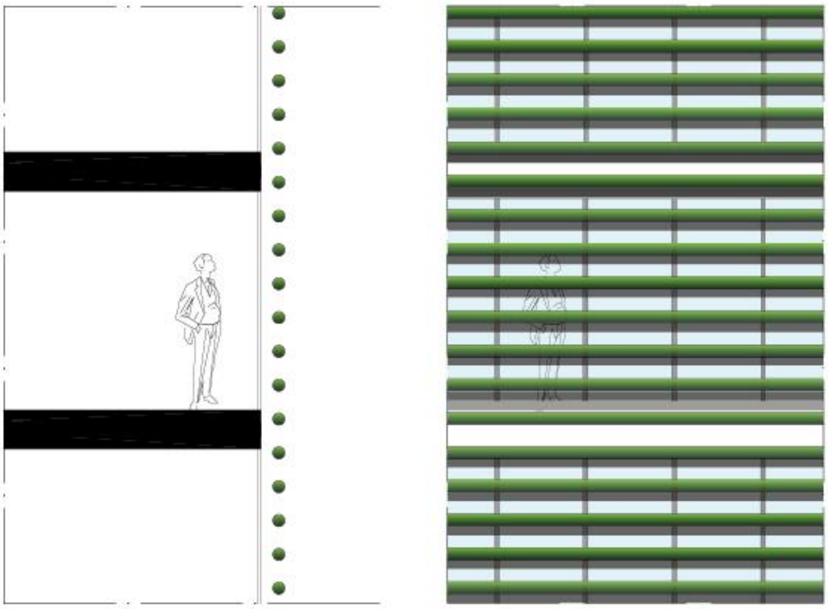


Figure 20: tubes diagram (Qiu, 2013)

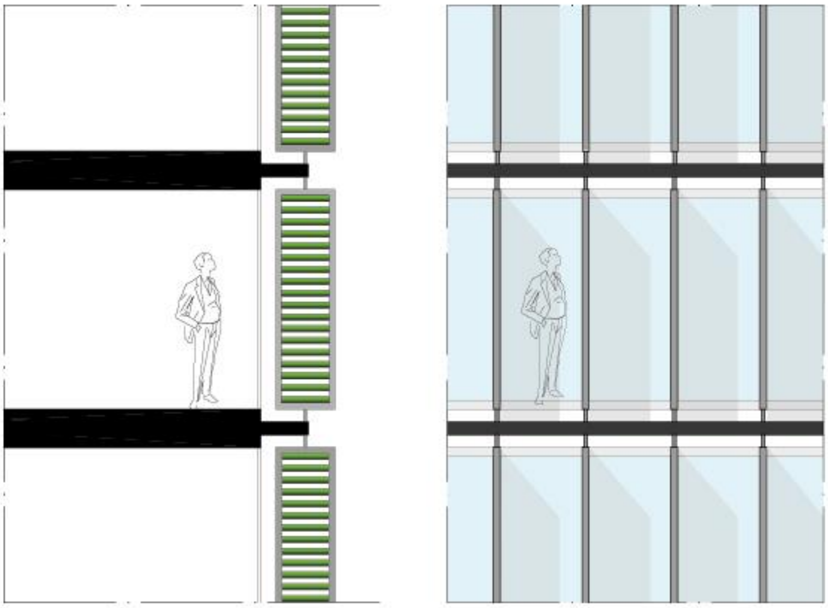


Figure 21: tubes in panel diagram (Qiu, 2013)

Integrate harvesting and product extraction in the building

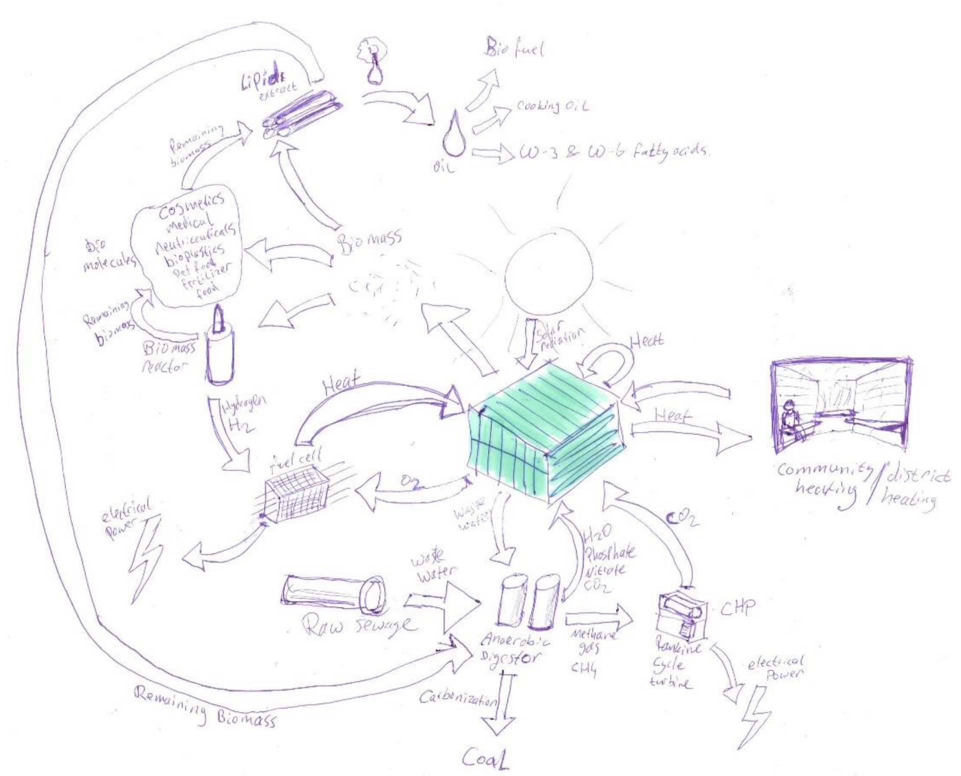


Figure 22: the algae factory (Qiu, 2013)

To create a functioning microalgae building, it will need input from the outside for nutrients. The wastewater from the sewage and the railway station can be used in an anaerobic digester and produce CO_2, methane, coal, phosphate and nitrate. The methane can be used in a rankine cycle turbine and produce electricity and CO_2 that will be used for the algae. The microalgae will consume the phosphate, nitrate and CO_2 and with photosynthesis, it will produce biomass. The biomass will be used for biomolecules for the production of high value products and hydrogen. The remaining biomass will be used for lipids that can turn into biofuels or high valuable oils. The hydrogen is used in a fuel cell combined with the produced O_2 from microalgae cultivation to generate electricity. Heat produced with the fuel cell can be used for the building. Excessive heat energy can be used for district heating or stored under the building.

Experiment and experience

Figure 23: left- the algae room (StudioJonandNina, 2009), right – growing microalgae with CO_2 from your breath (EcoLogicStudio, 2011)

See how microalgae are cultivated up-close and growing microalgae yourself. Seeing is part of the experience and getting involved in the production of microalgae. Educate people about the possibilities of these microscopic plants and show them that green energy can be created locally in an interesting way. The community cultivated microalgae can be turned into product that can be sold or given away to the contributors.

Context

The location of the project is situated in the Teleport area of Amsterdam (figure 19). It is a public transport connection point with very dominating infrastructure. The infrastructure and industry causes that the air in the area is very polluted.

Figure 24: Amsterdam Sloterdijk area (Google., 2013)

The railway station is located at the center of Teleport and is the public motor of the area. It is easily accessible due to all the infrastructure by car and public transport. The monotonous office functions in this area causes that the area is not used after office hours. Railway station Amsterdam Sloterdijk is used as a transportation hub for these offices. Before and after office hours, are peak moments when there are a lot of people at the station to leave the area, with the result that Teleport is deserted by night. There are no functions or points of interest that keep the people in the area or attract visitors. The railway station is suitable to be more than only an infrastructural hub. The existing structure of the railway station is suited for microalgae cultivation in different forms. Microalgae can be cultivated by using wastewater, (sun) light and CO_2 for biomass production and releases O_2 that can be used lower the pollution concentration in the atmospheric air. This new technique of energy generating creates a different look and ambience that can make people curious. The appearance of the building is dynamic and changes each day. The area need more functions, with the addition of living, working, shops (algae products) and facilities to educate people about algae production and energy production, it can become a point of interest in Teleport.

Integration in the existing structure
In the existing Sloterdijk railway station can be retrofitted with microalgae photo bioreactors. Bioreactor tubes can be integrated in the existing roof of the platforms construction. The supporting construction have holes in the beam where tubular PBRs can pass through and functions as sun shade and microalgae cultivation. The space frame construction over the railway station can also be used for microalgae cultivation. PBRs can be custom made in the shape that fits into the triangles of the space frame. Microalgae tubes at the top of the new glass façade shade the new created space, but does not disturb the lines of view on ground level.

Figure 25: Impression railway station Amsterdam Sloterdijk with algae bioreactors (Qiu, 2013)

Flat panel PBRs can be mounted on a roof and on the façade. It is possible to make the panels rotate and track the sunlight to increase the productivity and shade the inside from the sun light.
Helical PBRs can be shaped like street furniture and creates spots where people can rest and cultivate microalgae with sunlight at the same time. At night, these furniture will light-up with the integrated LED lighting system and acts as streetlights and maintain microalgae cultivation at night. Also the banisters can be used as light source to create a special ambience around the stairs (figure 26). Also big elements can be placed inside the building that shows the production of microalgae to the public (figure 27), which sets the ambience inside.

Figure 26: impression east entrance (Qiu, 2013)

Figure 27: impression central hall (Qiu, 2013)

Conclusions and recommendations

Concerns about global warming, increasing CO_2 emissions and environmental pollution caused by fossil fuels, combined with energy security and fossil fuel depletion in the future, are important factors in the development of alternative energy sources that is renewable, clean and environment friendly. Fuel energy is 66% of the global energy consumption and it is important to solve the biggest contributor to CO_2 emission and environmental pollution first. Recent developments in biofuels are showing results that you can create biofuels with microalgae and be more productive on a small scale than agricultural crops and can grow in non-arable land and does therefore not compete with food production and guarantee land for food production in the future. The created biofuels nowadays are mostly from agricultural crops with high lipid contents like oil palm, coconut, jatropha, canola, soy bean and maize (Chisti, 2007). However, this is not the best solution for the future, because biofuels release as much CO_2 when combusted as when we they are grown. These biofuels are carbon neutral and but not negative. The best way is to capture the CO_2 in biomass and make other valuable products of it like cosmetics and beauty products, pharmacy and medical applications, neutriceuticals and dietary supplements, packaging and bio plastics, pet food and fertilizers, food and snacks.
The energy production potential of bio-hydrogen is much higher than with biofuels and can be from the same microalgae that also contain lipids. This clean and renewable source of energy (H_2) can be found in green algae (Skjanes, Lindblad, & Muller, 2007). The microalgae are grown with solar radiation and fixate CO_2 with photosynthesis. When grown, the microalgae will be starved of sulfur and causes that the photosynthesis will stop producing biomass and use solar radiation for H_2 production (Skjanes et al., 2007). After H2 extraction from the biomass, the remaining biomass can be used for valuable products and CO2 stays fixed and can be stored safely. In this way, energy production with H2 is carbon negative and reduce the greenhouse gas globally and does not cause harmful and polluting byproducts with the advantage that it also creates high valuable products. This can all be done in photo bioreactors that can be attached to buildings and generate energy on a local scale.

Phototropic microalgae needs light to grow and produce biomass. This means that without artificial lighting, the growth of microalgae will stop or biomass will decrease due to dark respiration that can occur in the night and with low light intensities (Slegers et al., 2010). The productivity in the Netherlands is higher in the summer and lower in the winter compared to locations closer to the equator (appendix H). Also by using artificial light in the dark hours will stop the decrease of biomass due to dark respiration. For a building with a public function that requires lighting at all times is beneficial for the microalgae to grow in dark hours. This forms a perfect combination of microalgae growth and architecture. With application of algae as a building component will lead to a new appearance of buildings. The microalgae can be grown on the building façade, on the roof and as public furniture. The building will be literally alive with living organisms that can produce energy and other useful products. The growing microalgae can provide dynamic sun shading, controlled by the harvesting rate of the panels or tubes. The new appearance of the building will be dynamic and is constantly changing. The technique of cultivating microalgae is new and exciting on buildings and can make people curious. The current Amsterdam Sloterdijk railway station is a public transport hub with the function of moving people as fast as possible into and out of Teleport (Gemeente Amsterdam Dienst Ruimtelijke Ordening, 2008). The railway station can become a new meeting point with the addition of living, new commercial functions, catering and education. The dynamic environment of the Teleport area with public transport is perfect for the dynamic appearance with microalgae cultivation. The new technique combined with new functions added to the railway station will create liveliness at the place where people enter and leave the area.

The cultivation and harvesting microalgae biomass requires energy input. The energy usage of the system is for pumping and degassing. The different cultivation methods have different energy requirements. If the energy demand can be lowered by designing a more efficient system, then the total energy output will be higher. Also cultivating microalgae outdoors in the Netherlands will not have a constant biomass production throughout the year. The peak production will be in the summer and in the winter there is very little biomass production. In the future, when more productive microalgae are found or developed, the energy output can be higher with the same system. The energy output with the current microalgae is low, but the maximum potential is not achievable yet. The by-products are now more valuable than the energy generated with microalgae. In the cycle of using the microalgae biomass, the priority is extracting the valuable first and energy will be extracted from the remaining biomass.

Recommendations

The energy production of both biofuels and H_2 can be improved and gives at the moment a low energy output. Improvements can be made in exploring more microalgae species, genetic modification, more productive PBRs and simplify harvesting. The theoretical maximum energy output is not reached yet and it will take breakthroughs in genetic modification of the microalgae strain or find new microalgae species that are more efficient in harvesting solar light. The ideal microalgae will have high yield on high light intensity, large cells with thin membranes, is insensitive to high oxygen concentrations, is stable and resistant to infections, grow and produce lipids at the same time, oils are excreted outside cells and the cells can automatically flocculate when a certain concentration is reached (appendix M). All these characteristics can be found in natural microalgae, but never in all of them in one strain (Wijffels & Barbosa, 2010). Searching for new microalgae species and genetic modification is needed to further improve the energy output of the microalgae.

Also an interesting development is the concept of biomass milking. This is extracting lipids from the biomass without destroying the cell, which will increase the lipid production and only sunlight, CO_2 and saltwater is needed for growth (Wolkers et al., 2011). The development of nano-cellulose from microalgae is promising and can be used if further developed as construction material that is stronger than steel and stiffer than Kevlar (appendix N). If this material can be produced on industrial scale, it can become the building material in the future.

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Appendix A: parameters for orientation

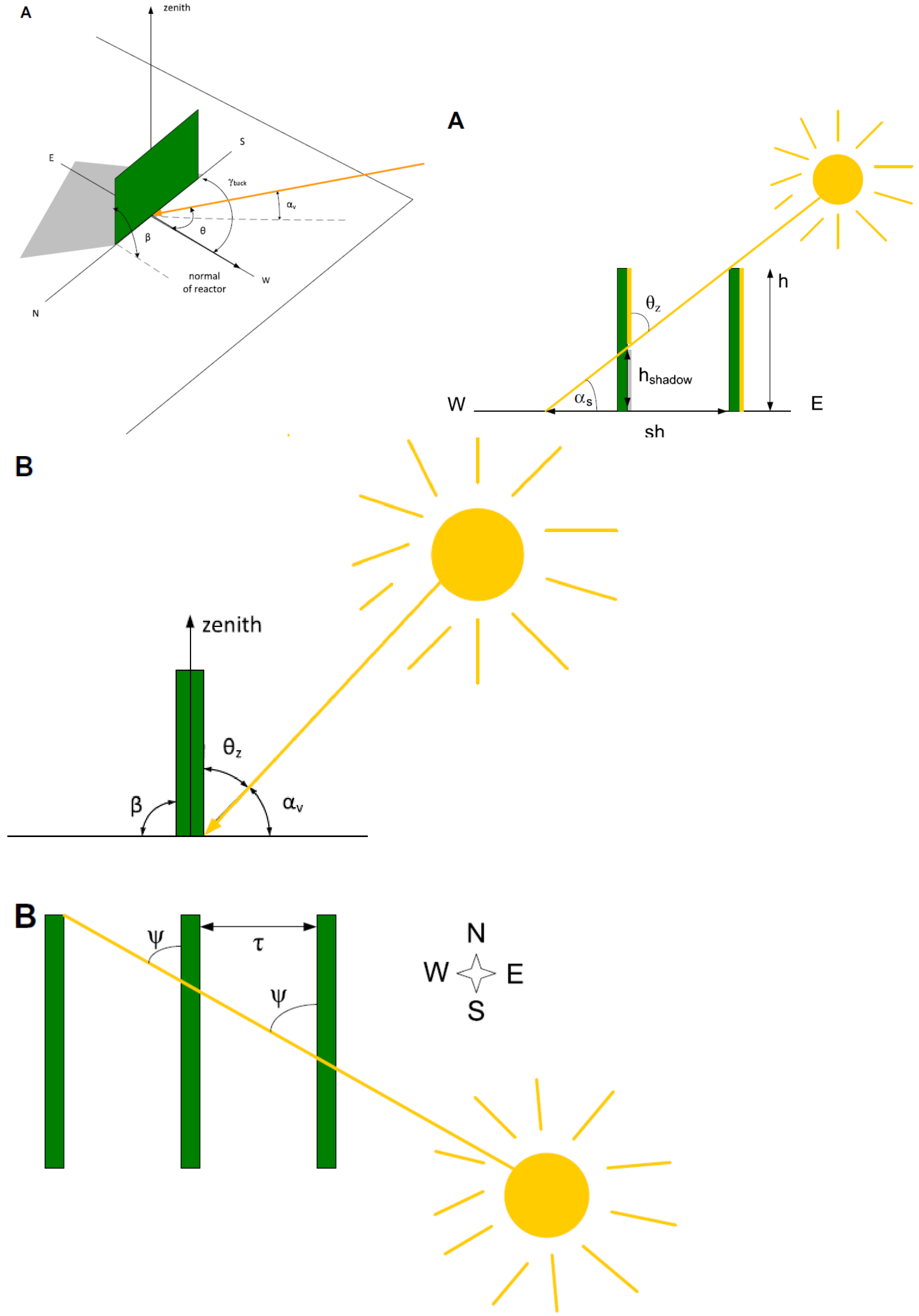


Figure 28: flatpanel parameters (Slegers et al., 2010)

Appendix B: sunshading facade
Panels

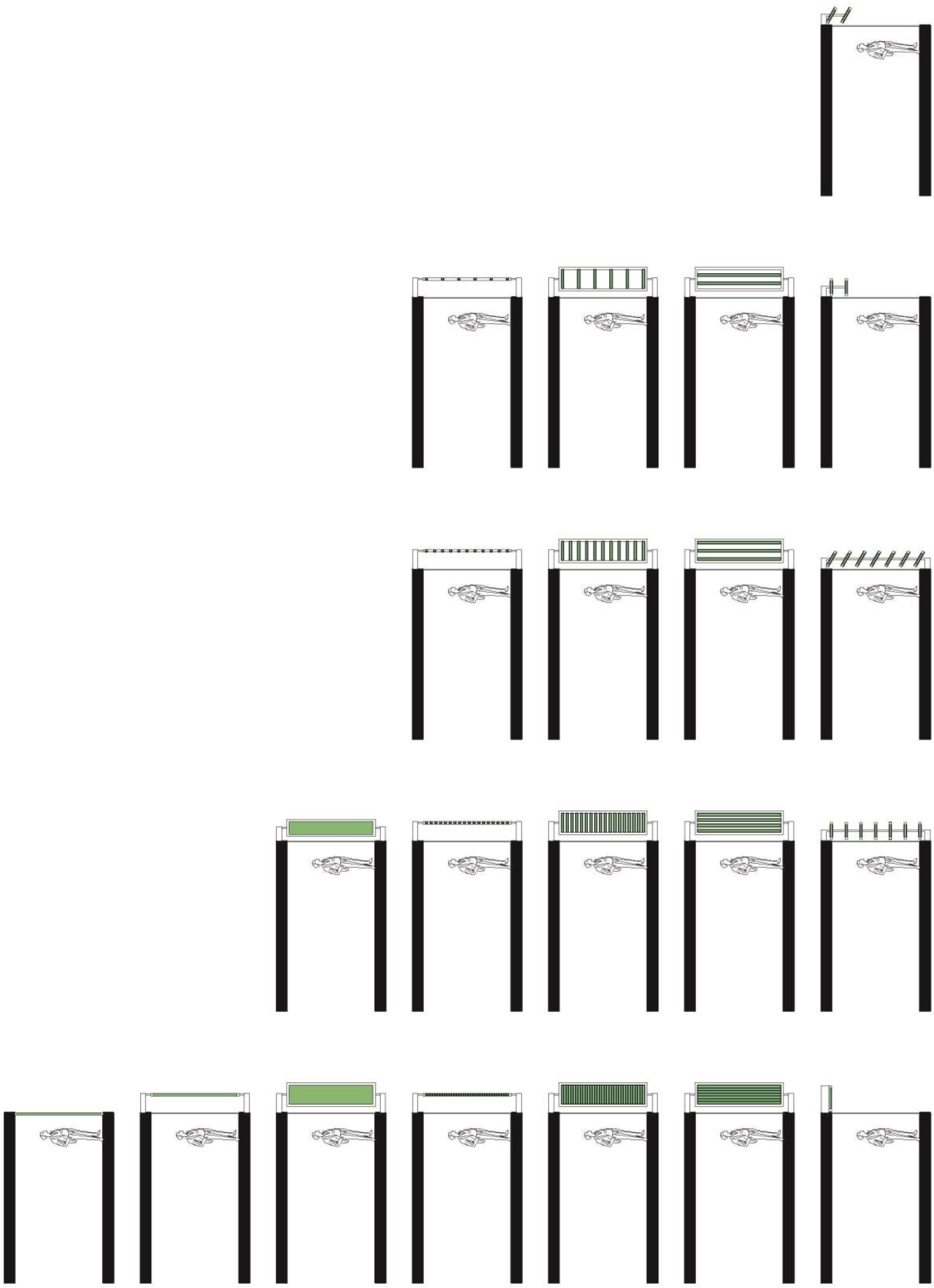


Figure 29: panel bioreactor diagrams (Qiu, 2013)

Tubes

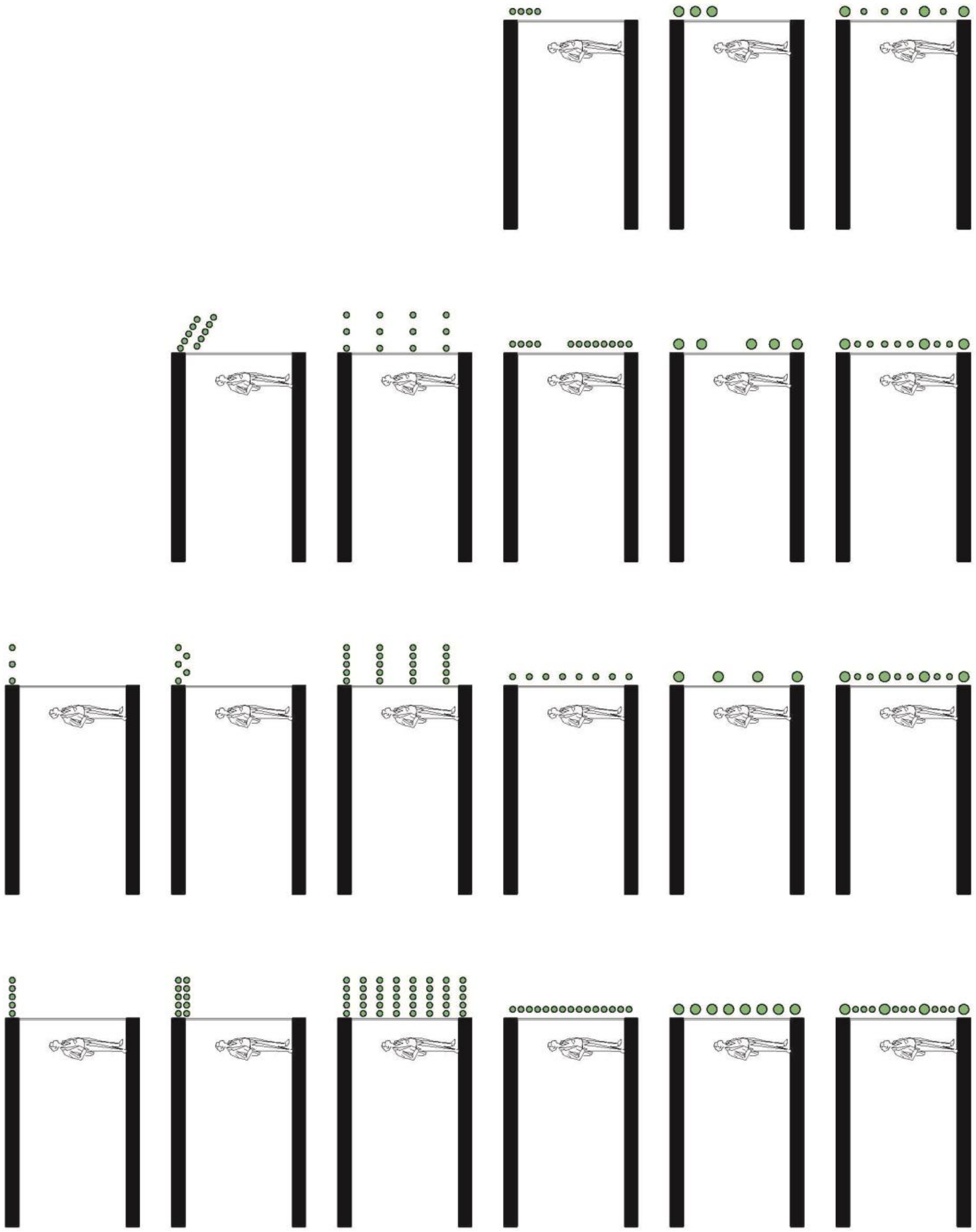


Figure 30: tubular bioreactor diagrams (Qiu, 2013)

Appendix C: sunshading glass roof

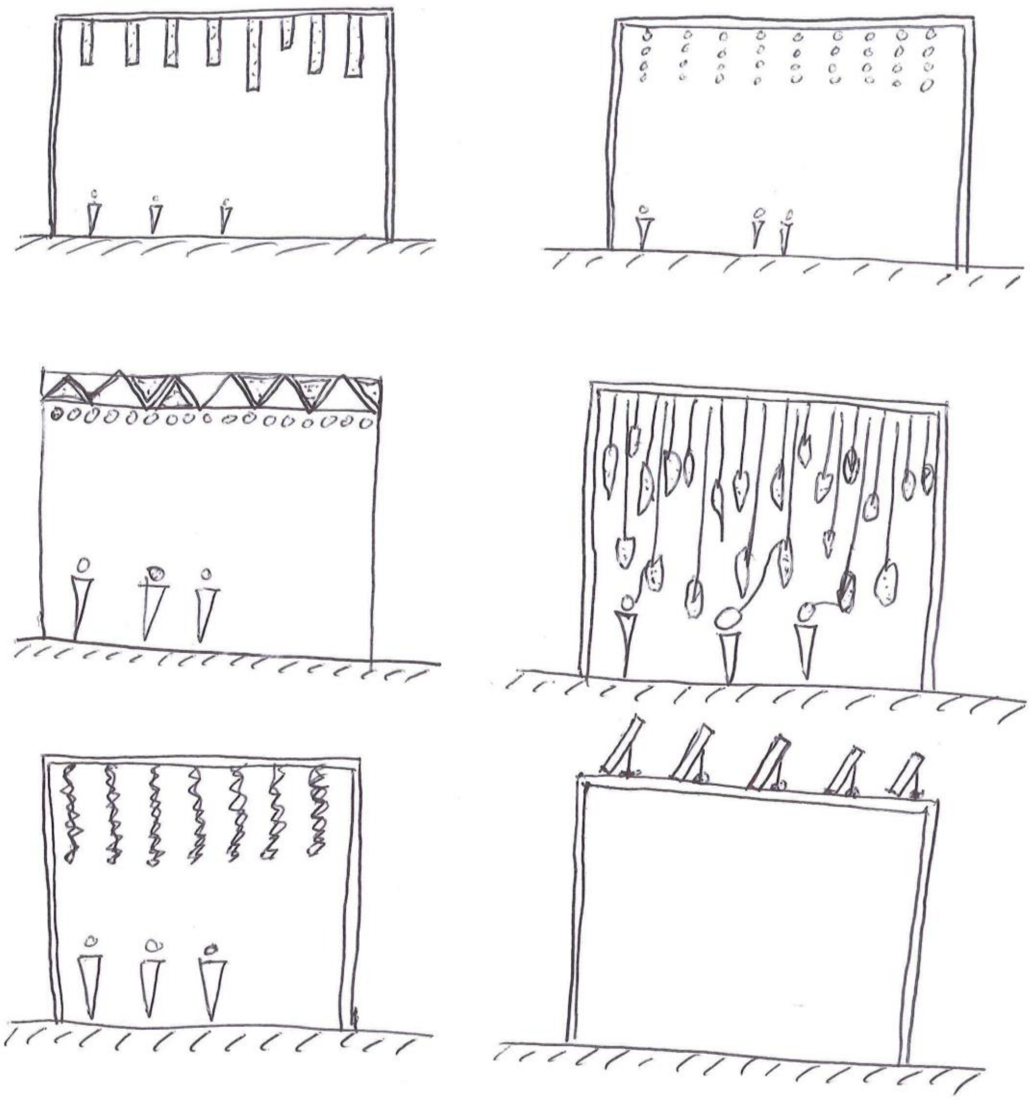


Figure 31: diagrams roof sun shading (Qiu, 2013)

Appendix D: thin film (poly bag) photo bioreactor

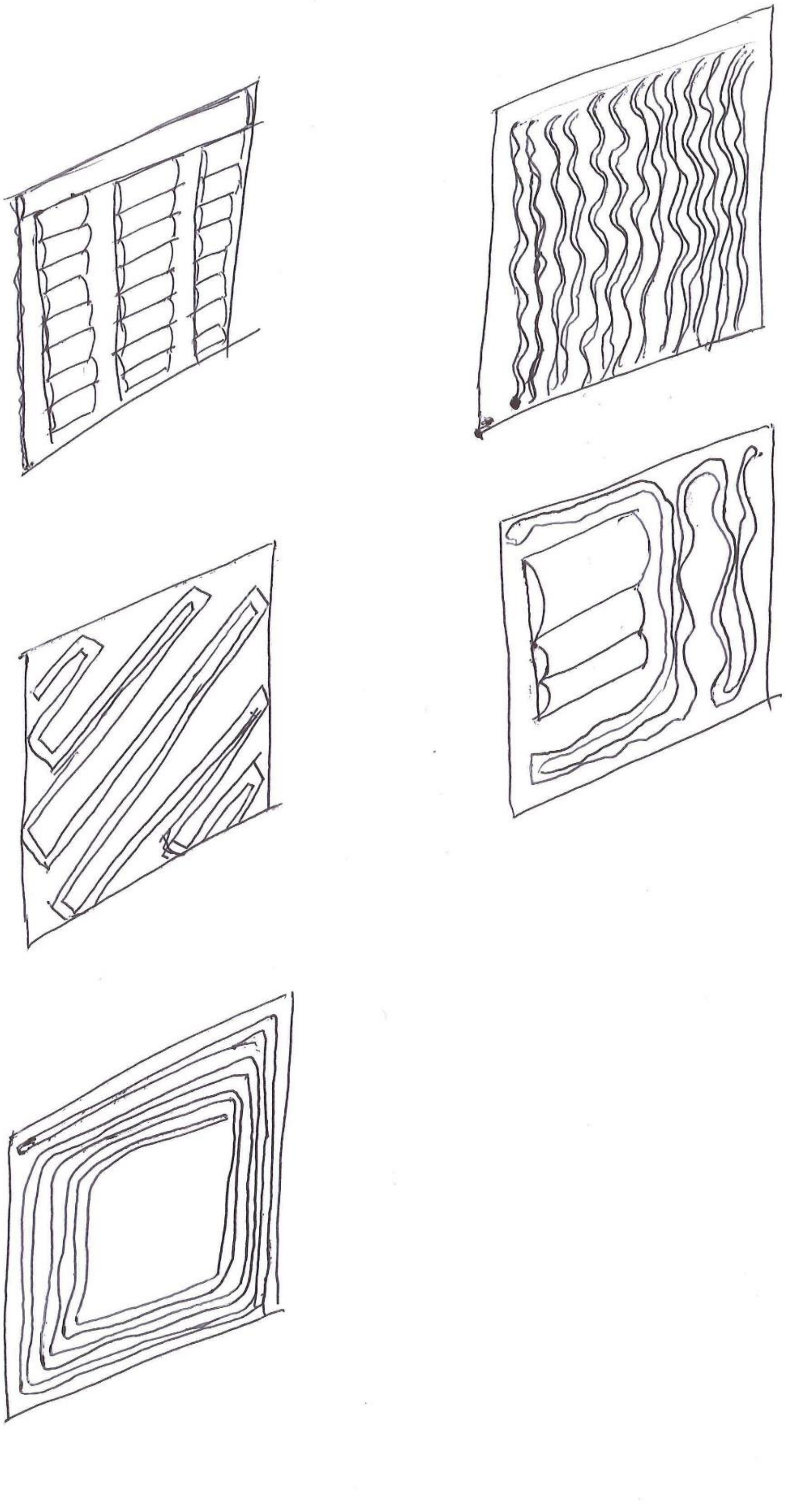


Figure 32: poly bag thin film bioreactor (Qiu, 2013)

Appendix E: sketch impression with street furniture

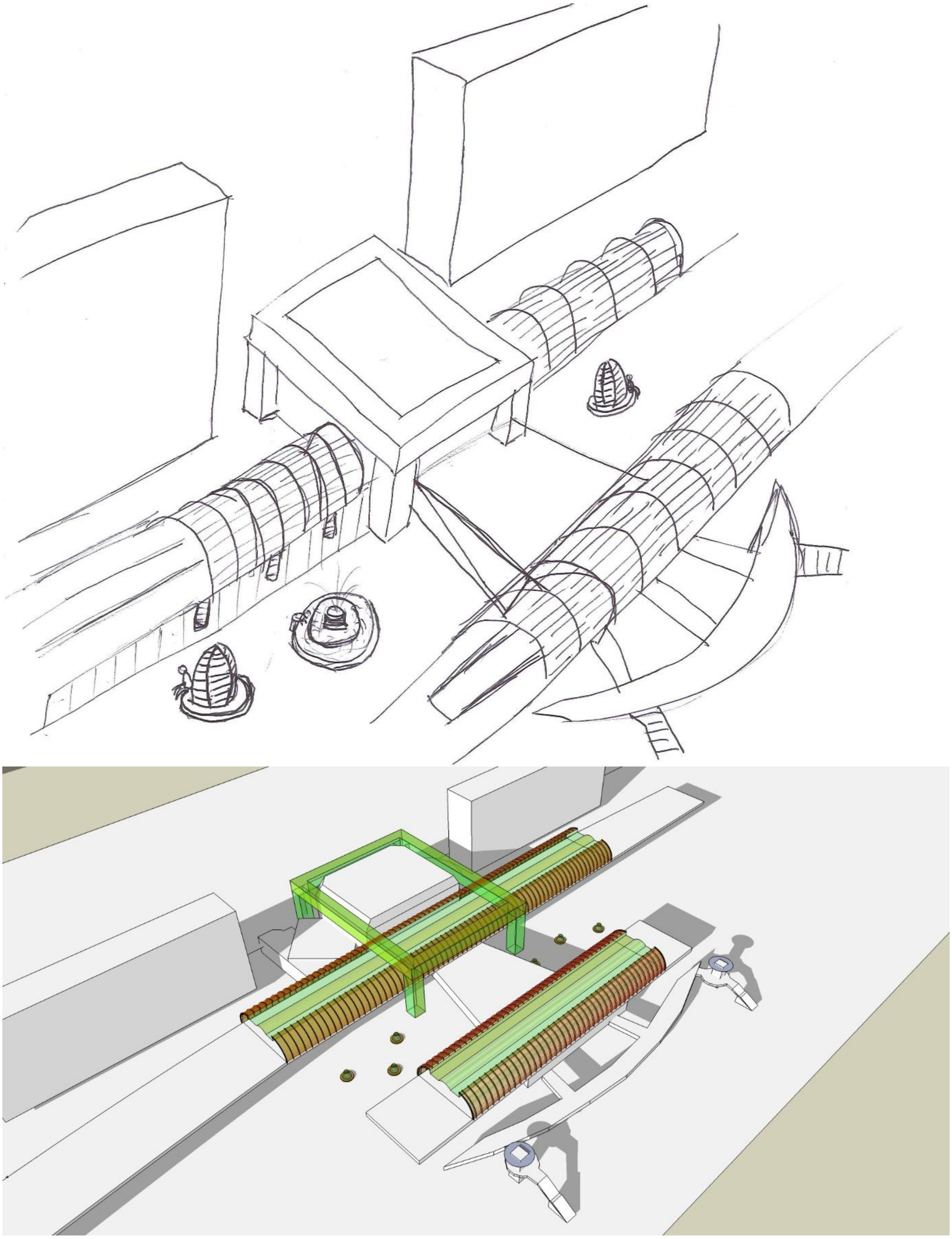


Figure 33: sketch existing structure with bioreactors (Qiu, 2013)

Bio Intelligent Quotient building (B.I.Q. building)

Figure 34: B.I.Q. building (Wallis, 2013)

In Hamburg, Germany, an apartment building complex is constructed with a high-tech façade that works like a vertical algae farm. The algae façade provides renewable energy for the building in the form of biofuel, heat and sunshade by harvesting fast-growing algae (Wallis, 2013). Jan Wurm describes the algae façade as a transparent container that creates a controlled environment for photosynthesis (Wurm, 2012). Jan Wurm and his team followed the recent developments in the Flat Panel Uplift Bioreactor (Wurm, 2012). In a Flat Panel Uplift bioreactor, nutrients and carbon dioxide are mixed with the liquid in the panels to stimulate a fast growth rate. Pressurized air is used to mix the microalgae in the bioreactor and at the same time the turbulence is scrubbing the inside of the glass panels clean to keep up the productivity of the microalgae (Wallis, 2013). The productivity of this kind of bioreactor is estimated to be ten times higher than tubular glass reactors (Wurm, 2012). The panels are also used as thermal collectors to turn the excessive heat of the sunlight to usable energy. For a stable production rate, the temperature of the bioreactor must not exceed 40^{o}C (Wurm, 2012). The heat can be recovered through a heat exchanger and used for heating in the building or stored in the buildings geothermal system beneath the building.

Figure 35: machine room from the B.I.Q. building (ALJazeeraEnglish, 2013)

The photobioreactors also acts as an adapting sun shading. The biomass concentration dictates how much light can pass through the panels and it increases when the sun is shining. The shading can be doubled within a day when continuous harvesting is suspended (Wurm, 2012). The system is interactive and transmission of light can be controlled by increasing or decreasing the harvesting process (Wurm, 2012).

"The prototypes are 2.60m high and 60cm wide and consists of four panes of monolithic glass. The panes form a central cavity of 18mm for the circulation of the medium and 16mm insulating cavities on either side" (Wurm, 2012). At the bottom of the photobioreactor are all the pipes and valves integrated to service the photobioreactor. The first test results of this prototype are promising (Wurm, 2012).


Figure x: SolarLeaf in service (Wurm, 2012)

Harvesting of the photobioreactor is done periodically and stockpiled in tanks within the building. For extraction and energy production, a local energy company will buy and transport the algae biomass to a nearby heat and power plant, where it will be fermented. In this process, methane gas will be used to generate electricity (Wallis, 2013). For architecture, this creates an interesting new façade that is constant in motion with the rising air bubbles and the colors of the microalgae.

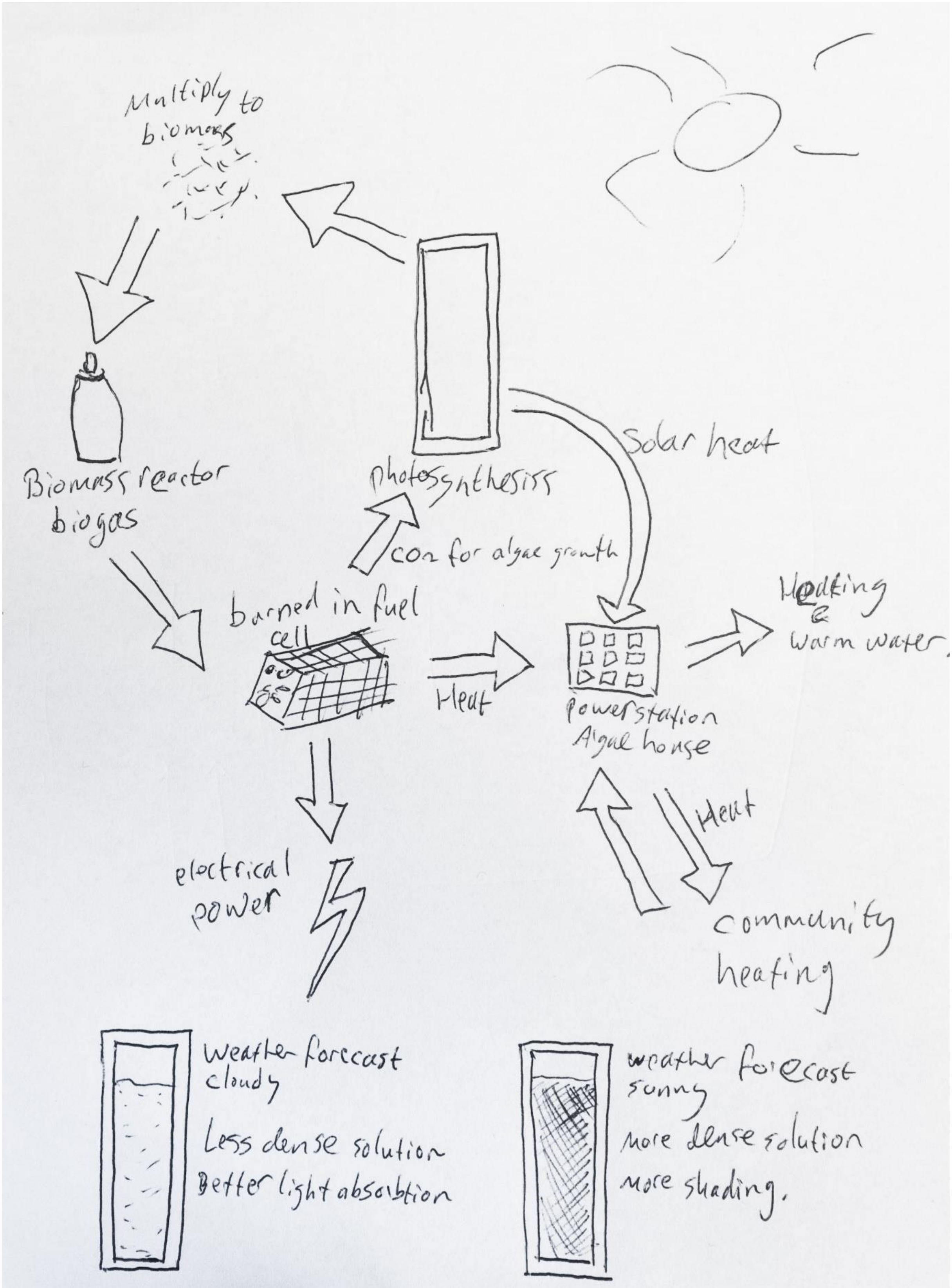


Figure 36: schematic B.I.Q. building (Qiu, 2013)

With the realization of this building, a lot of debate is going on about the feasibility of this approach. It could be a start of something big or it is just a one-time experiment. Jan Wurm acknowledges that this technique is more expensive than solar or conventional fuel systems. “In terms of investment cost you can't compare it to established, mass produced systems on the market" says Jan Wurm (Wallis, 2013).

The whole system can be recycled at the end of their life cycle and that makes this system Cradle to Cradle (Wurm, 2012)

David J. Bayless (professor of mechanical engineering at Ohio University) says that the B.I.Q. building is an important test case to get people in touch with this new technology. People are curious about the unknown technology and are skeptical until they see that it could work (Wallis, 2013).

This biotechnology can play an important role in setting a standard in surplus energy houses. It creates local and decentralized energy production directly on site if the whole process can be done at the building site.

Growenergy

Figure 37: Hydral system (Growenergy, 2013)

Growenergy is a San Diego, California based company that pioneers in developing structural bioreactors and self-sustaining, localized energy production systems (Growenergy, 2013). The company is developing two types of bioreactors called Verde and Hydral. Their Verde system is designed as components that can be used in existing homes and buildings. It will produce electricity and heat by a "minimally invasive combustion process" (Growenergy, 2013). The Hydral system is designed to culture algae for hydrogen as energy source and can eventually be used for homes and small buildings with new developments in this technique (Growenergy, 2013). Both systems have a positive influence on the environment by cleaning the air of pollutants.

Both of the systems are designed as a flat panel with the goal of achieving maximum biomass concentration on the one hand and reduce pump energy, limiting the viscosity and minimizing oxygen accumulation on the other hand. This all is done in a closed and fully automatic environment which allows for fully controllable conditions inside the photo bioreactor (Growenergy, 2013). With sensors in the panels, they control and monitor the pH values and temperature. The harvesting is done when the algae are fully grown and pumped out of the panel with a special harvesting pump and transferred and stored at a different vessel which in turn will be combusted to create electricity and heat (Growenergy, 2013) in the Verde system. When the biomass is combusted, the heat is used to keep the bioreactor on temperature as well as heating up de building. The combustion process uses all algae biomass and converted to heat and electricity (Growenergy, 2013).

Hydral uses hydrogen fuel cells to produce electrical energy and thermal heat (Growenergy, 2013). For optimal performance it is best to incorporate wastewater from the building and filter it with this system. The hydrogen fuel cells creates purified water and uses filtered water that is treated by living machines (Growenergy, 2013). In the process of using hydrogen fuel cell, not all the algae is used to produce electricity and the remainder of the biomass can be used for compost, human consumption or feedstock for animals due to the high protein and nutrients contents of algae (Growenergy, 2013).

The weight of both systems is designed to be less than 5 kg per m2 and different panels can be combined without problems and function as one without losing productivity (Growenergy, 2013). They claim that the glass panels are designed and developed to dilute incident sunlight and spread it over a lager surface area to increase the productivity and to protect the algae culture from over exposure of sunlight and cause photo oxidation (Growenergy, 2013).

The Verde system isn't actually reducing the CO_2 concentration, but also doesn't add extra CO_2 in the surrounding area. So we can say that creating electricity with combustion is carbon neutral (Growenergy, 2013). The released CO_2 can be used again to grow algae and it will create a constant CO2 supply to the algae culture. However if we use Hydrogen to create electricity, the byproducts will be purified water and little to no pollution. The CO_2 will not be released again and stay captured in the algae biomass which reduces the CO_2 concentration and becomes a carbon negative system (Growenergy, 2013).

A Verde system has the potential of producing 12.500 kWh/year with 185 m2 of surface area for algae cultivation (Growenergy, 2013), which is approximately 4 Dutch households. Solar panels

The main advantage of using algae biomass is the storage of energy when it is collected. While photovoltaic panels deliver directly electricity from the sun, the problem is the storage of this electricity in batteries made of lead or lithium (Growenergy, 2013). The process of manufacturing and recycling of the batteries is very polluting. The energy storage of the algae panels is stored in a natural way in energetic compounds (H2) and can be kept at ambient pressure and temperature (Growenergy, 2013).

Green loop Marina City Chicago

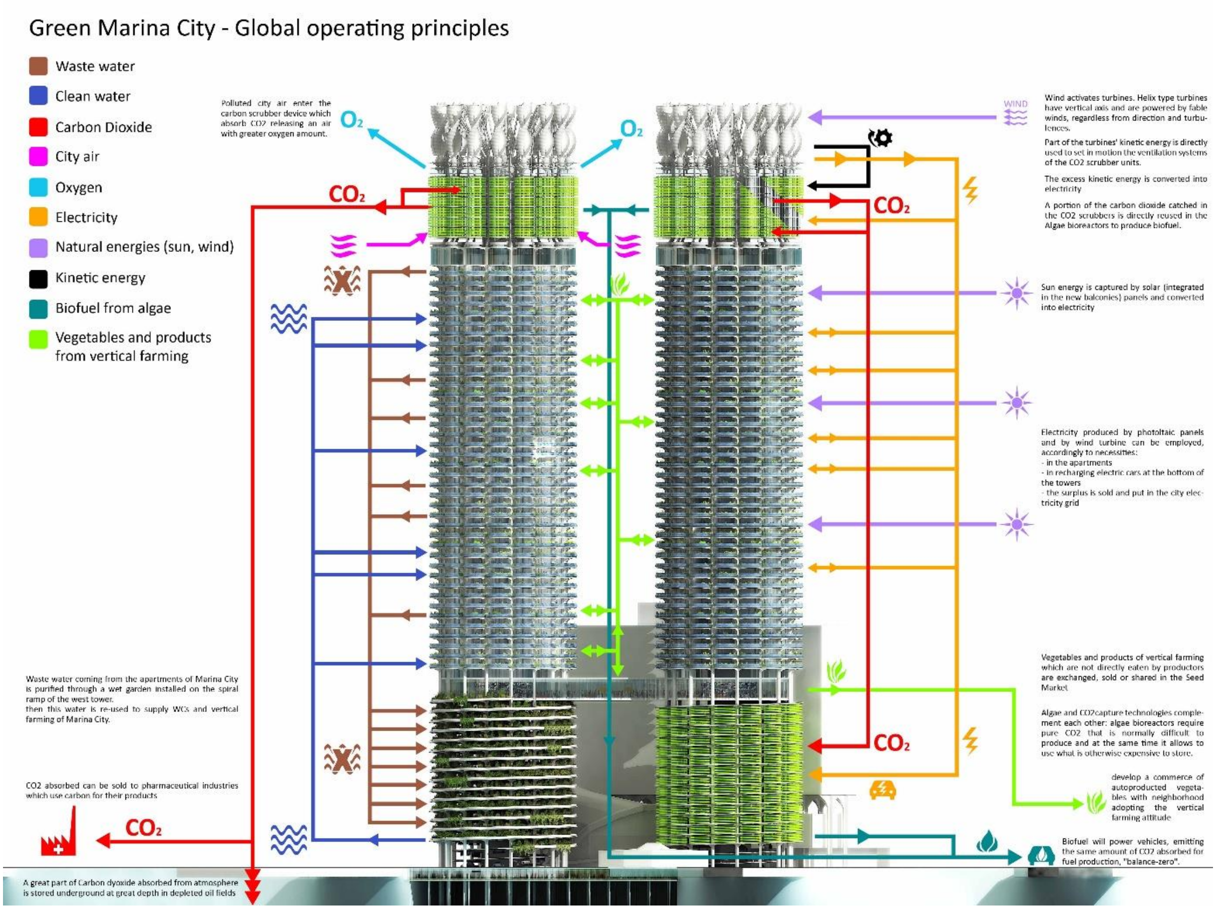


Figure 38: global operating principles (AETRANGERE, 2012a)

Influx studio submitted a plan is for the Marina City tower building in Chicago to retrofit the building with microalgae as one of the components to make the building more sustainable. The microalgae is used to clean polluted air, to create energy onsite, allow food production, and to process all wastewater to be reused (AETRANGERE, 2012b). The project is all about closing loops within the building. Carbon is captured by two carbon scrubbers at the top of the building and is then used for the microalgae cultivation. The oxygen is released from the carbon scrubber and microalgae cultivation which will clean the surrounding air. The carbon scrubbers are also used as wind turbines and will therefore generate electricity. The wastewater will be purified by a phytoremediation garden in the lower part of the tower which also functions a vertical farm.

Process zero

Figure 39: algae retrofitting (HOK & Vanderweil, 2012)

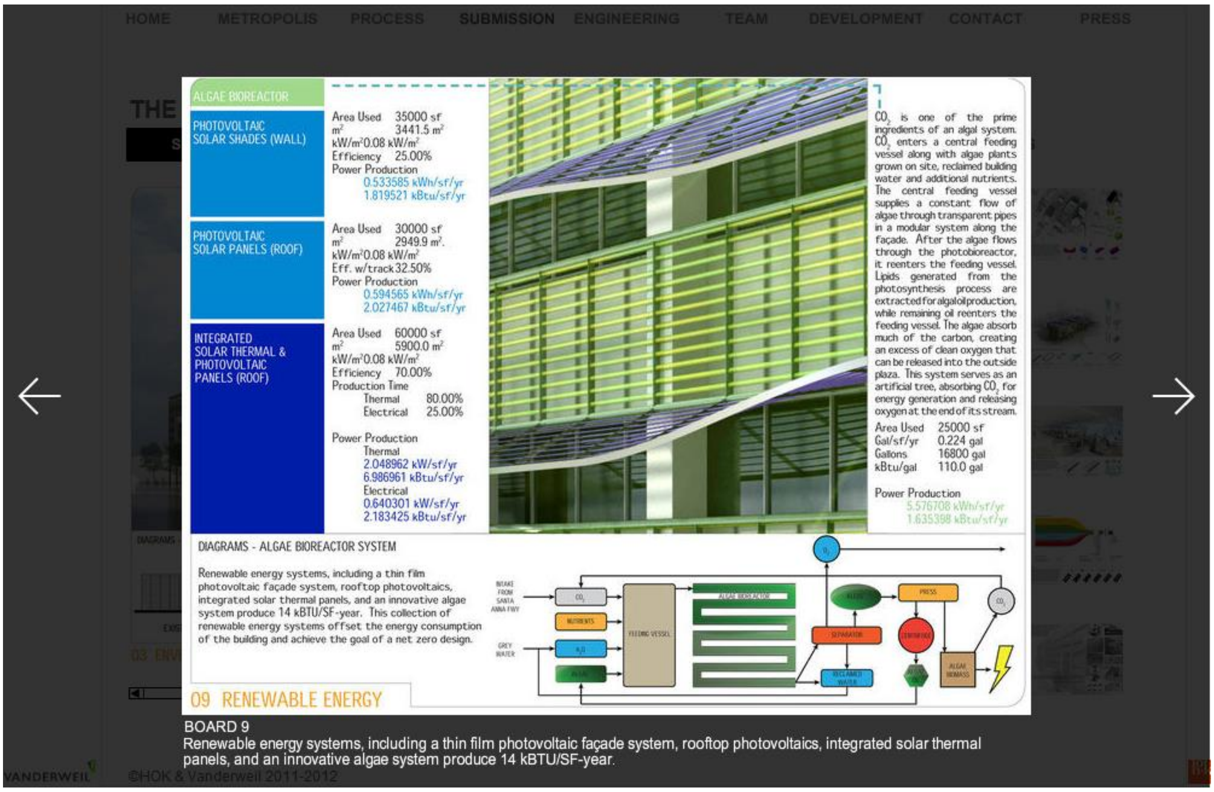


Figure 40: renewable energy (HOK & Vanderweil, 2012)

Appendix G: tubular PBR tests in Wageningen University

The system consists of a buffer vessel of 100 liter with a closed photobioreactor tube system with a tube diameter of 60mm and is 160 meters in length. The transparent tubes are 2/3 filled with water mixed with nutrients and is continuous pumped around with a liquid pump. Together with the liquid, also air with enriched CO_2 is pumped around and causes waves inside the tubes (Hemming et al., 2012). It started with a pure culture of 2 liter of C. sorokiniana and has a density of 0.5 g/l. These species of microalgae can multiply in 17-25 hours. These microalgae are cultivated until there was 6 liter with a density of 4 g/l before it is injected into the photo bioreactor (Hemming et al., 2012).

A conclusion from “algenteelt systeem Lans Maasdijk” is that tubes with smaller diameters have more production than those with bigger diameter. They have a test system with tube diameters of 63 mm, 110 mm and 160 mm (Hemming et al., 2012, p. 41).

By introducing an inclination in the cultivation tubes, a passive circulation can be established in the tubes and pumping is only needed to pump the water with microalgae back to the beginning (Hemming et al., 2012, p. 41).

Algen systeem	Onder het gewas			Op het pad		
PBR	0.06m	0.11m	0.16m	0.06m	0.11m	0.16m
Aantal buizen	390	260	130	130	130	65
Volume bioreactor [m^3]	106	237	251	35	119	126
Jaarrond gemiddelde buitenstraling [μmol/m^2/s]	527			527		
Jaarrond gemiddelde straling boven het tomatengewas [μmol/m^2/s]	359			359		
Jaarrond gemiddelde straling boven de algenreactoren [μmol/m^2/s]	30.6			82.4		
Jaarrond gemiddelde straling in de algenreactoren [μmol/m^2/s]	3.2	1.8	1.2	8.7	4.7	3.3
Totale DM productie [kg/jaar]	1485	1900	1507	1487	2854	2012
Volumetrische productiviteit [kg/m^3/jaar]	14.0	8.0	6.0	42.2	24.1	16.0
Productiviteit per teeltoppervlak [kg/m^2/jaar]	0.15	0.19	0.15	0.15	0.29	0.20
PBR volume per teeltoppervlak [m^3/m^2]	0.0106	0.0238	0.0251	0.0035	0.0119	0.0126

Tabel 1: algae production in a greenhouse in combination with crops and without crops (Hemming et al., 2012, p. 51)

The results are shown in table 1 for production without obstruction and with obstruction of light in a greenhouse situation. The tube diameters are different for testing purposes and we can see in the table that tubes with 60 mm in diameter have about the same DW production with different light situations. The lowest production per volume is in the tube with the biggest diameter (160 mm), this is due to the less efficient light penetration of the tubes. Nevertheless the DW production is higher than the smallest tube system. It seems that the tube with 110 mm is the highest producing system with the volumetric productivity in between the other two systems, but with the highest DW production.

Algen systeem	Kleinschalig systeem			Grootschalig systeem		
PBR	0.06m	0.11m	0.16m	0.06m	0.11m	0.16m
Aantal algenbuizen geïnstalleerd	37	22	11	520	390	195
Volume bioreactoren [m^3]	10	20	21	141	356	376
Breedte kascompartiment [m]	3.0	3.2	2.4	41	57	42
Jaarrond gemiddelde buitenstraling [μmol/m^2/s]	527			527		
Jaarrond gemiddelde straling boven algenreactoren [μmol/m^2/s]	361	361	361	361	361	361
Jaarrond gemiddelde straling in de algenreactoren [μmol/m^2/s]	39.2	21.0	14.3	39.2	21.0	14.3
Volumetrische productiviteit [kg/m^3/year]	146.7	95.1	68.5	146.7	95.1	68.5
Productiviteit per teeltoppervlak [kg/m^2/year]	5.18	6.16	6.46	5.18	6.16	6.46
PBR per teeltoppervlak [m^3/m^2]	0.04	0.06	0.09	0.04	0.06	0.09

Tabel 2: productivity small scale versus big scale tubular photo bioreactors (Hemming et al., 2012, p. 52)

In table 2 is shown that if you scale up this system, the results will remain the same and productivity will scale with it. (Hemming et al., 2012) says that with scale-up, the cost will drop drastically with the productivity remaining the same.

	PBR	PBR volume [m^3]	Kosten algen [€/m^2]	Opbrengst algen [€/m^2]	Winst algen [€/m^2]	Winst totaal [€/m^2]
Kleinschalig systeem	0.06m	10	118	259	141	-3.65
	0.11m	20	152	308	156	-2.60
	0.16m	21	198	323	125	-4.76
Grootschalig systeem	0.06m	106	59	259	200	54.58
	0.11m	237	77	308	231	79.66
	0.16m	250	97	323	226	54.61

Tabel 3: profit with small and big scale production systems (Hemming et al., 2012, p. 55)

A small scale system is almost always a negative investment table 3 if we assume that microalgae DW will sell for 50 €/kg. With scale-up the production will increase with it, but the cost of the system will increase less with the result that it will be profitable. It is calculated that the production of microalgae in a greenhouse cost about 11 €/kg.

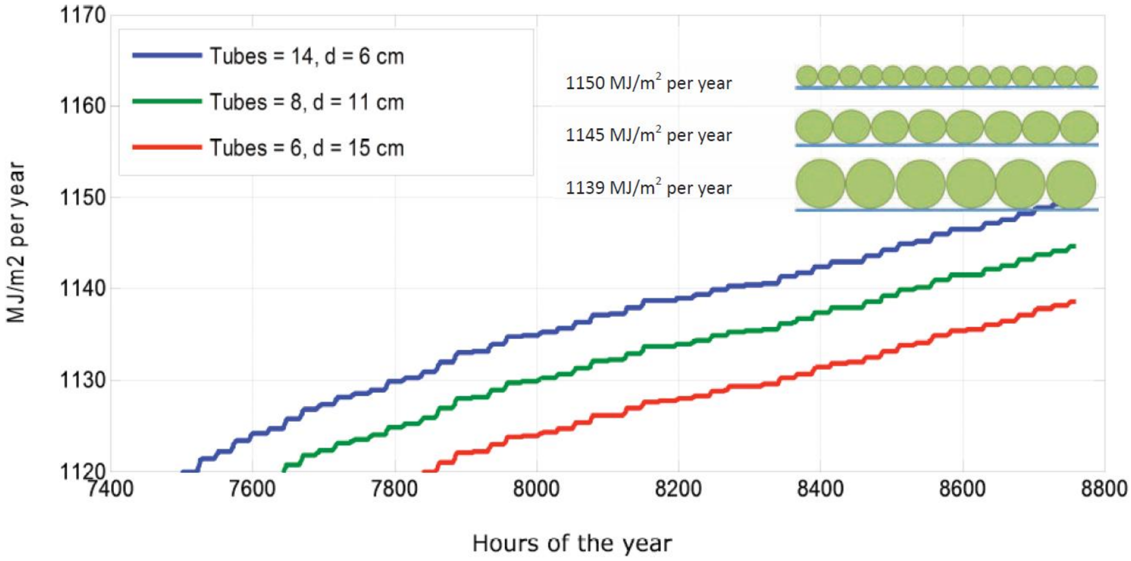


Figure 41: light capture of bioreactor tubes with different diameters and the same ground surface and different volumes (Hemming et al., 2012, p. 61)

In figure 41 is a graph about the light capture against the hours of sunlight in the year. As shown, the tube with the smallest diameter captures most of the light. This can be explained with the geometry of the tubes with small reflection losses. In this situation all the tubes are placed next to each other with no space between them. By doing this type of comparison, the gap in between is constant, but not the volume of the tubes.

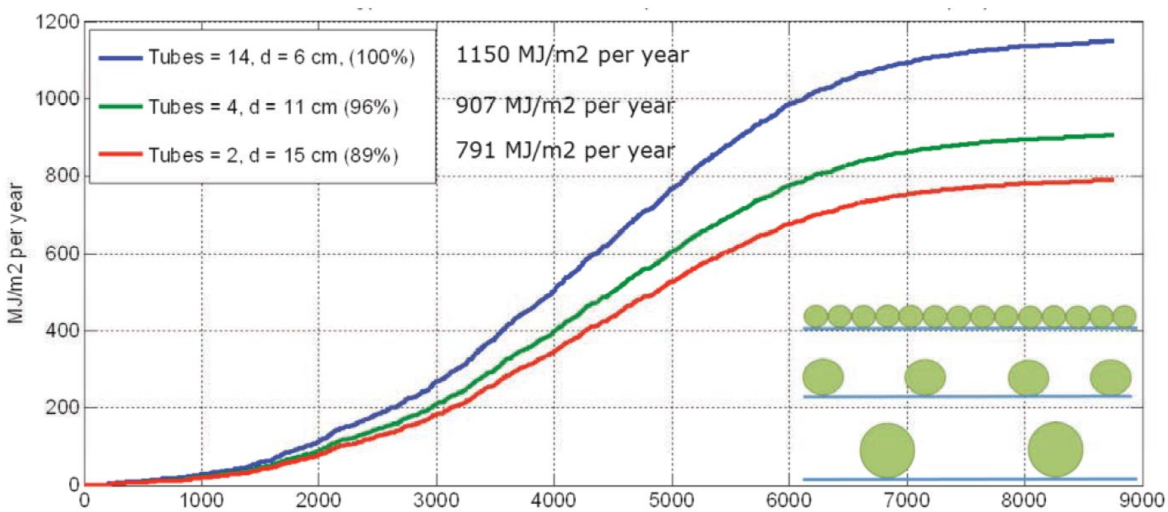


Figure 42: light capture of bioreactor tubes with different diameters and the same ground surface with the same volumes (Hemming et al., 2012, p. 62)

If the volume of the tubes is kept constant, then there will be cavities between the tubes with a diameter of 110 mm and 150 mm see figure 42. In this comparison it is clear that a continuous tube with no gap in between is more efficient than the bigger tube dimension with cavities in between for the same ground surface area. There will be light that falls in between the bioreactors that cannot be used and therefore loss of energy will occur.

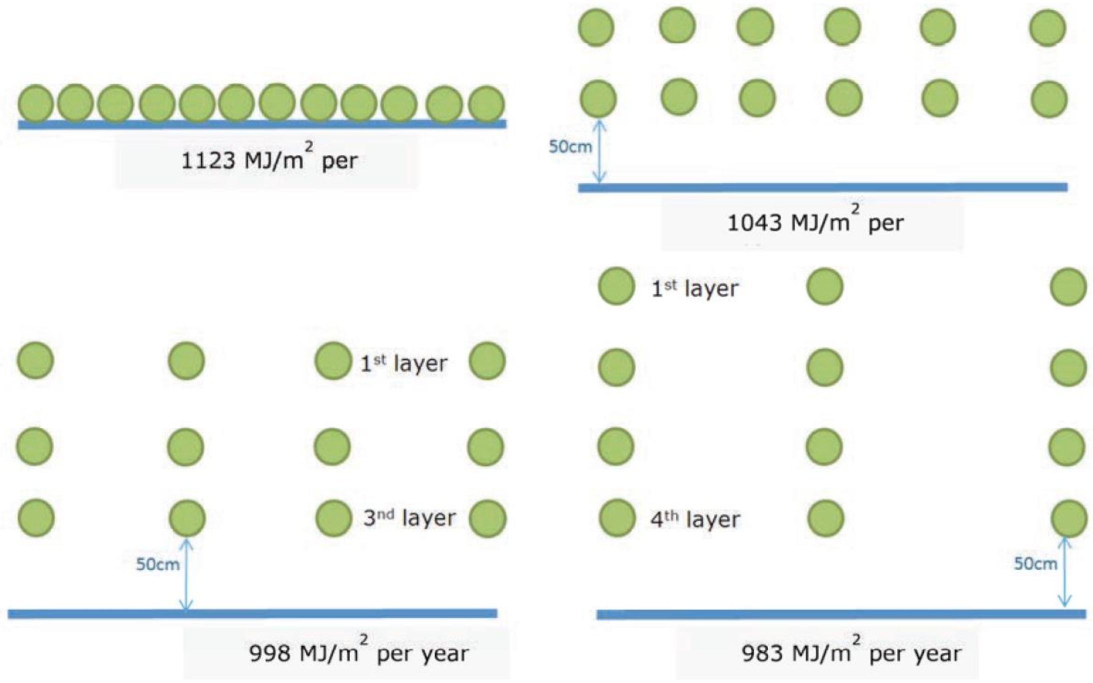


Figure 43: same amount of bioreactor tubes with different configurations and solar capture (Hemming et al., 2012, p. 63)

If we look at the most efficient light capture system with the tube diameter of 60 mm and change the configuration with the same ground surface area, the tubes will be stacked on top of each other. In figure 43 is illustrated how this would look like if there are 12 tubes. The tubes are raised 50 cm from the ground and the numbers below the diagrams are the measured values of light absorption. As expected, the one layer of bioreactor tubes that covers the whole ground surface area has the most light absorption and is the most efficient. The two layer system is a little less efficient because there will be light that direct hit the ground and that energy cannot be absorbed by the bioreactor. The same happens with the three and four layer system where even more light will hit the floor.

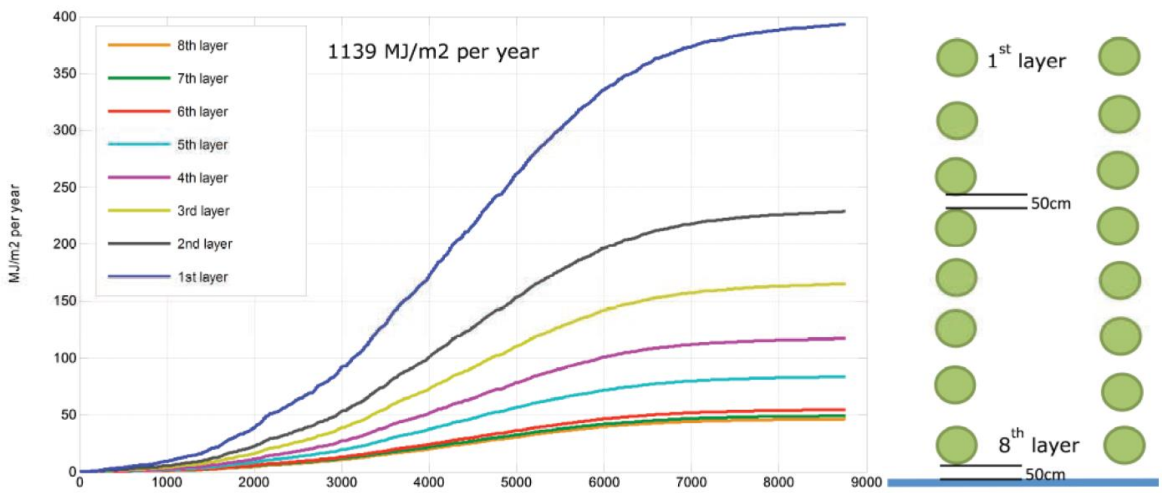


Figure 44: light absorption per layer with a vertical system with a vertical cavity of 50 cm and tube diameter of 110 mm (Hemming et al., 2012, p. 64)

The figure depicts the amount of light absorbed per layer. As expected, the top layer absorbs the most and the last layer the least sun light. The graph also shows that the light still reaches the last 8th layer in this setup. In this setup, more light can be absorbed on the same ground surface area and therefore the productivity will be higher. A well-functioning vertical system with 8 layers is when bioreactor tubes of 110 mm are used with vertical spaces between tubes of 250 mm and a horizontal space between bioreactor tubes of 400 mm. The maximum productivity was 6.25 kg/m2/year with a volumetric productivity of 84 kg/m3/year (Hemming et al., 2012).

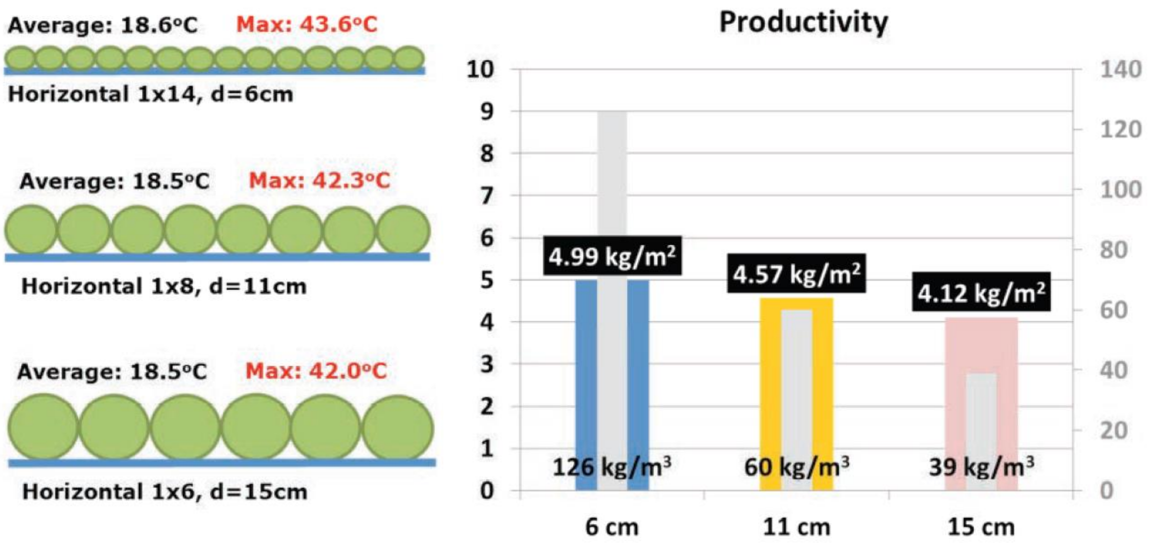


Figure 45: temperature difference with variable diameter (Hemming et al., 2012, p. 66)

The maximum temperature measured is higher for smaller tube diameters due to the mass of the water. Less water results in a quicker rise in temperature. Figure 45 shows that in tubes with 60 mm diameter the maximum temperature measured is 43.6 °C and in the 150 mm the maximum is 42.0 °C. The productivity is also higher in per volume and in dry mass per ground surface area in the small tube diameter.

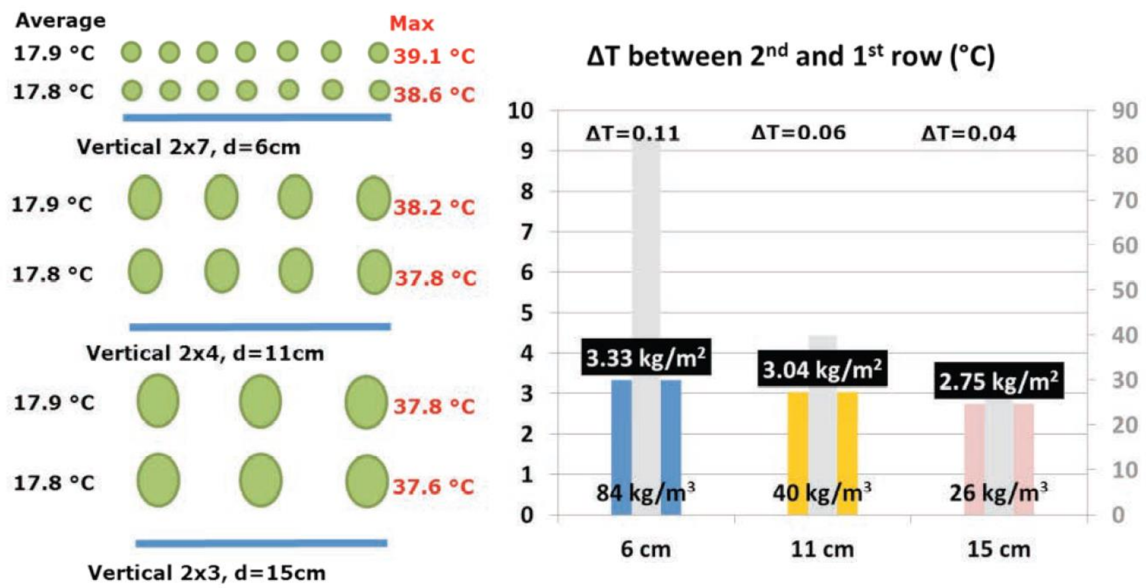


Figure 46: temperature difference with variable diameter (Hemming et al., 2012, p. 67)

If the tubes are stacked, the overall maximum temperature drops for all tubes with the same volume (figure 46). In vertical systems with two layers, the temperature measured was 67% of the time between 20-30 °C, which is considered the optimum temperature for microalgae to grow (Hemming et al., 2012, p. 65). Compared to a horizontal tube system, the productivity of the vertical tubes is lower, but temperatures are better controlled.

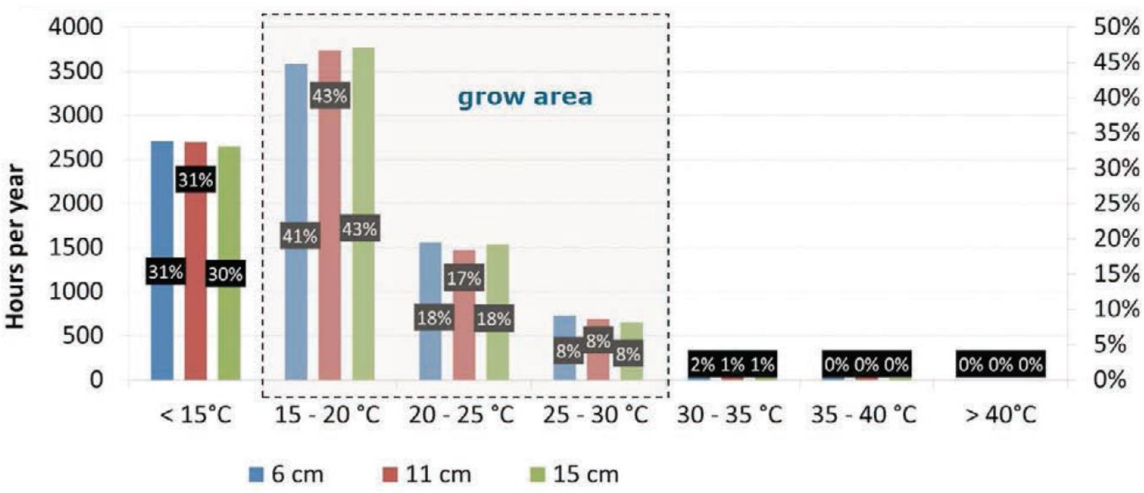


Figure 47: measured temperatures of one year in a two layered photobioreactor (Hemming et al., 2012, p. 68)

As depicted in figure 47, most of the time the temperatures are in the grow area (about 70%). 30% of the time, the temperatures are below 15 °C and heating is required to bring up the temperature to 20-30 °C for maximum productivity.

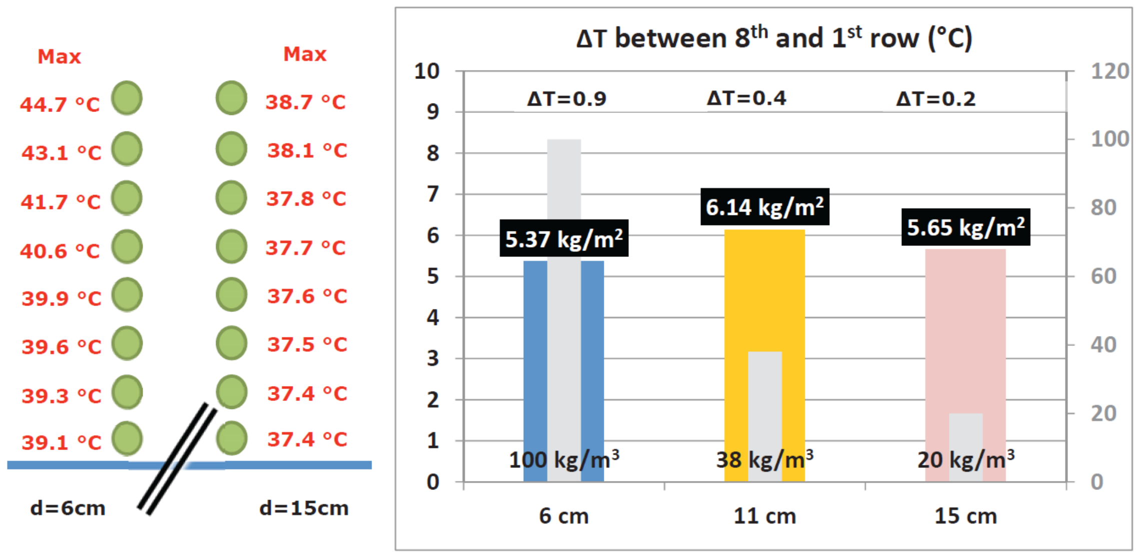


Figure 48: temperatures and productivity with 8 stacked photobioreactors (Hemming et al., 2012, p. 70)

There is a difference of 6 °C between 60 mm and 150 mm at the top row. The productivity however is the highest in the one with a diameter of 110 mm. The maximum measured temperature should be somewhere in between the 60 mm and 150 mm.

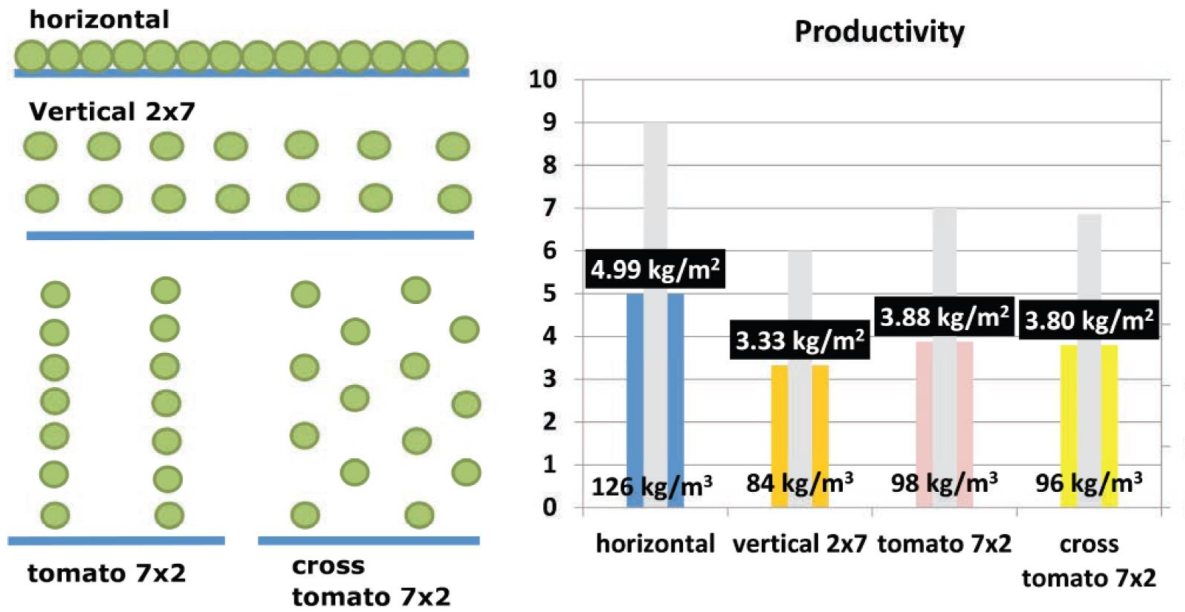


Figure 49: different setups for photobioreactor tubes (Hemming et al., 2012, p. 76)

Still the most productivity is obtained with a horizontal bioreactor (figure 49). A vertical bioreactor with two layers is the least efficient of the setups depicted in figure 49. Furthermore, it does not matter much if the tubes are stacked on each other or make a cross layout for the production.

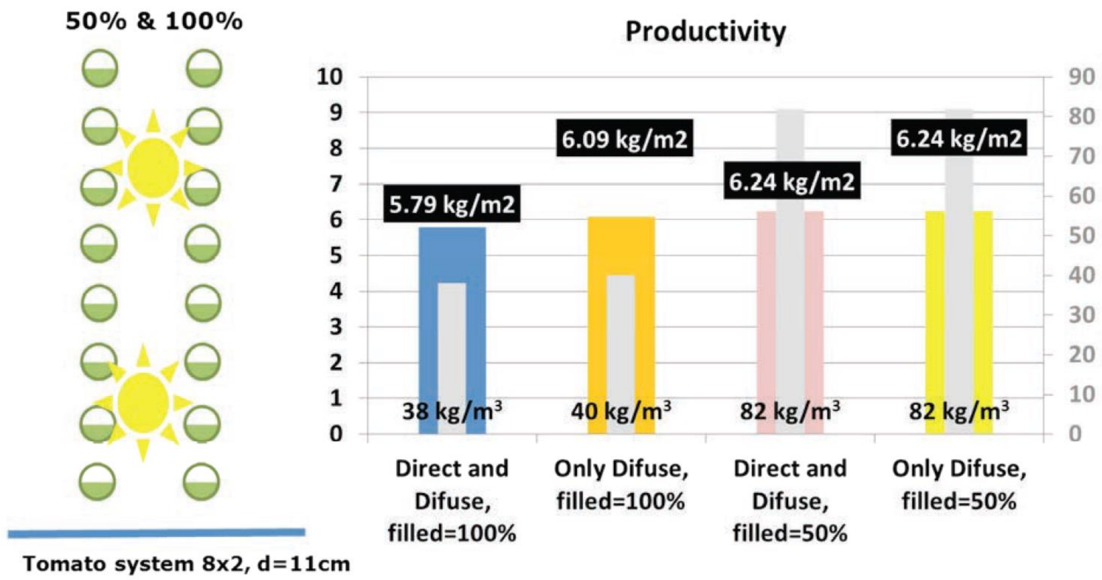
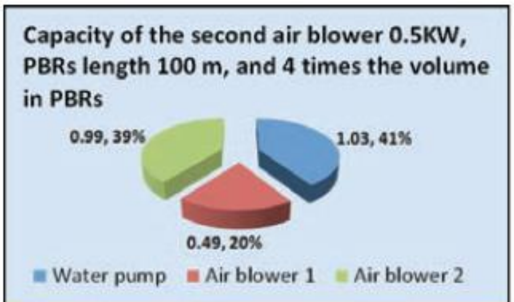


Figure 50: productivity with direct and diffuse light (Hemming et al., 2012, p. 78)

Microalgae are more productive with diffuse light than direct light (figure 50). The test is done with tubes of 110 mm diameter with 50% filled and 100% filled. Only at 100% filled bioreactors there is an increase in productivity.

LGem, producer of photobioreactors, claims that their horizontal photo bioreactors system use only 217 w/m^3 of energy for the pumps (Hemming et al., 2012, p. 81). In a vertical photobioreactor an energy usage of 105 W/m3 without an air pump and 229 W/m3 with an air pump is claimed by LGem (Hemming et al., 2012).

This is after optimization of the system. (Hemming et al., 2012) tested their own system and found out that energy can be saved by reducing the air pump capacity (50%), extend the tube length four times and increase the volume four times results in an energy saving up to 70% figure 51. The system uses 402 W/m3 and can be further optimized for even more energy saving. However, the risk of losing a whole big scale combined photo bioreactor with a malfunctioning system is much higher than a smaller but more manageable system. Smaller scale systems have less productivity, but with problems, it can be solved more easily without disturbing the other systems.



Algae volume_1 (caclulated):	5,121	L
Algae volume in PBRs:	3,528	L
Algae tube length:	100.0	m
% of algae volume in the algae tubes:	**68.9%**	
Energy consumption:	2.1	KW
Specific energy consumption_1 (caclulated):	**402**	W/m³
Energy saving	**68%**	
Current system		
Energy consumption:	3.1	KW
Specific energy consumption_1 (caclulated):	**1,246**	W/m3

Figure 51: test system with basic optimization (Hemming et al., 2012)

Temperature fluctuations in the photo bioreactors are smaller than the air temperature fluctuations, because there are two capture tanks that works as a heat exchange buffer and water has a higher heat coefficient than air. By placing the tanks (partly) under the ground, the soil will help to keep the tanks in a certain range of temperatures (Hemming et al., 2012, p. 85). The temperatures at the beginning and end of the tubes are not so different in short tubes (25 m) with a high circulation rate (Hemming et al., 2012, p. 85).

Appendix H: Productivity with flat panel photo bioreactor

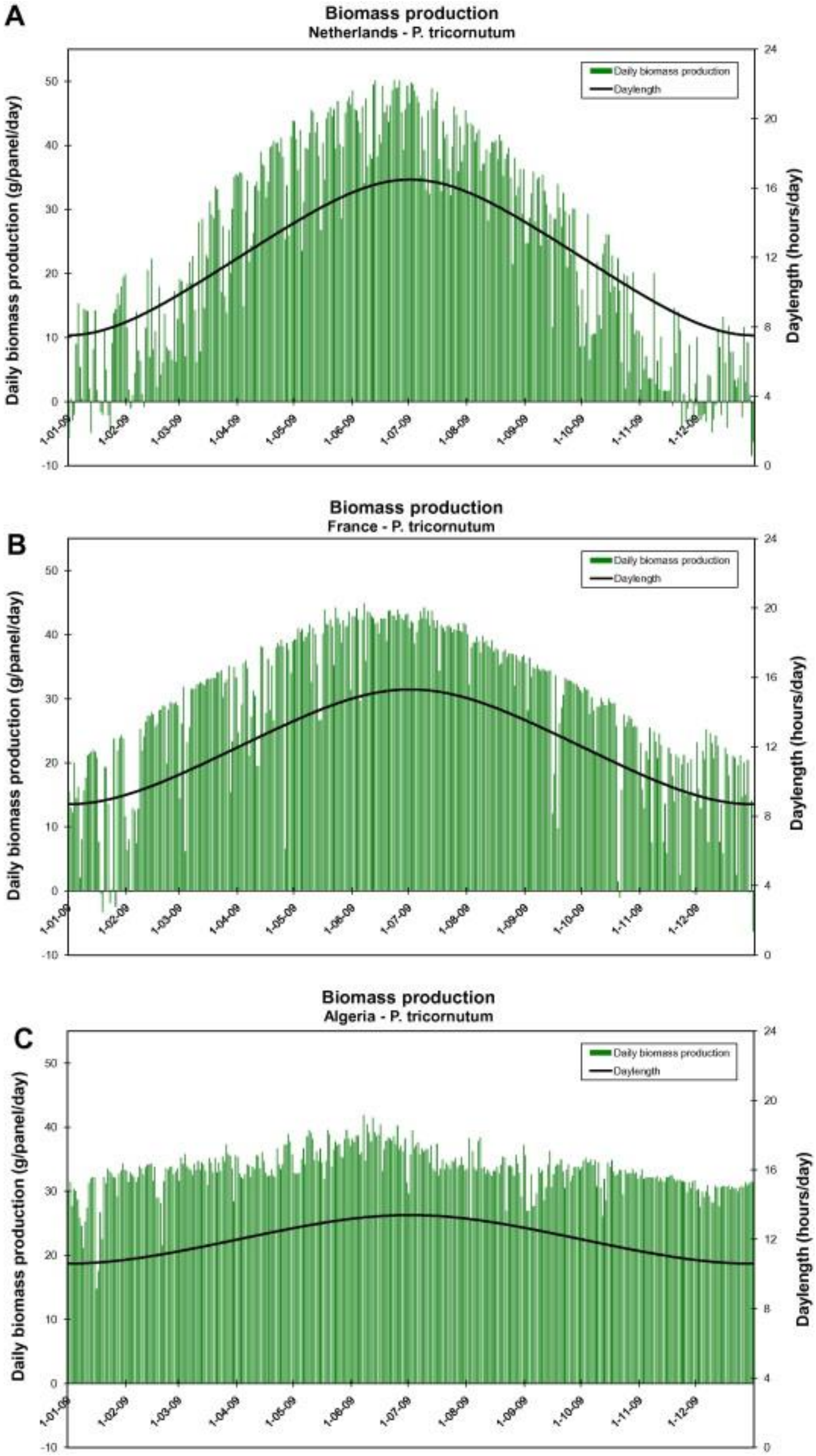


Figure 52: daily biomass production on three locations with flat panel photo bioreactors (Slegers et al., 2010, p. 3345)

In the Netherlands, large fluctuations in biomass production occurred on a daily cycle. In France the fluctuations is a little less compared to the Netherlands. In contrary to Algeria, where the biomass production is almost constant throughout the year. In the Netherlands and France, days occur with negative biomass production. This is the result of dark respiration in the night and overall low light intensities on that day. This phenomenon is more likely to happen in winter days in the Netherlands and France (Slegers et al., 2010). Also the way of regulating the temperature is different for the Netherlands and Algeria. The photo bioreactor in the Netherlands requires heating, in contrary to Algeria where cooling is needed (Slegers et al., 2010). In the summer, there will be light for more than 16 hours in the Netherlands compared to 13 hours in Algeria. This also means that the productivity in the Netherlands will be higher in the summer than in Algeria (Slegers et al., 2010).

	P. tricornutum	*T. pseudonana*
Netherlands	8.8 (kg panel^{-1} year^{-1})[a]	5.3 (kg panel^{-1} year^{-1})
France	10.6 (kg panel^{-1} year^{-1})	6.1 (kg panel^{-1} year^{-1})
Algeria	12.1 (kg panel^{-1} year^{-1})	6.7 (kg panel^{-1} year^{-1})

Tabel 4: productivity of P. tricornutum and T. pseudonana on three locations (Slegers et al., 2010)

Two species of microalgae are tested, namely P. tricornutum and T. pseudonana in the flat panel photobioreactor. The optimal growth temperature for P. tricornutum and T. pseudonana are 23 ^{o}C and 18 ^{o}C respectively. The biomass concentration of T. pseudonana was much lower and is partly caused by using a lower biomass concentration. However the microalgae can be grown throughout the year while that is not possible with P. tricornutum (Slegers et al., 2010).

High biomass concentrations does not necessarily also mean that it has the highest annual yield. The thickness of the cavity also influences the volumetric productivity. More volume decreases the volumetric productivity, but the overall production could be higher (Slegers et al., 2010). Different combinations of biomass concentration and cavity can lead to the same overall biomass production. The optimum result is when all light is absorbed and the loss of biomass due to dark respiration is kept to the minimum. It can be said that the most optimal system will be the one with a bigger cavity and lower volumetric productivity or the system with a high cell concentration with a small cavity (Slegers et al., 2010). Also by using artificial light in the dark hours will stop the decrease of biomass due to dark respiration and for a building with a public function and therefore always lighting for the microalgae to grow. This forms a perfect combination of microalgae growth and architecture.

The productivity cannot be exactly be predicted because it is dependent on the location, bioreactor setup, microalgae species and changing light conditions over the day and year. What can be influenced is the optimum bioreactor setup for a microalgae species and provide the right conditions for the microalgae to grow. The lack of direct sunlight can be supported by artificial lighting and keep the productivity on going in times of low productivity. Also by using multiple layers of flat panel bioreactors, the solar light will be shaded and diffused in parallel placed panels. The productivity decreases per panel with close a distance, but a higher areal productivity can be achieved when the panels are placed close to each other. The optimum space in between flat panels ranges from 0.2m to 0.4m (Slegers et al., 2010).

Appendix I: calculation

Energy with fuels
With fuels, the energy is often expressed in tonnes of oil equivalent (toe). Many fuel forms have been converted into toe with conversion factors seen in table 5-6.

1 t diesel =	1.01 toe
1 m^3 diesel =	0.98 toe
1 t petrol =	1.05 toe
1 m^3 petrol =	0.86 toe
1 t biodiesel =	0.86 toe
1 m^3 biodiesel =	0.78 toe
1 t bioethanol =	0.64 toe
1 m^3 bioethanol =	0.51 toe

Table 5: (European Commission, 2006, p. 13)

Biohydrogen =	120 – 142 MJ/kg
	33.3 – 39 kWh/kg

Table 6: (Fung, 2005)

Energy with biofuels.
Cultivating P. tricornutum in the Netherlands in a tubular PBR with a volumetric productivity of 0,62 g/L/day and 40% lipids in the biomass.

Daily production of lipids is 0.248 g/L/day.

Conversion to tonnes:	0.248 * 0.000001	= 0.000000248 t/L/day
Production per year:	365 * 0.000000248	= 0.0000905 t/L/year
1 t biodiesel is 0.86 toe ->	0.86 * 0.00009052	= 0,0000778 toe/L/year
1 toe is 11.36 mWh = 11626 kWh ->	11626 * 0.0000778	= 0.905 kWh/L/year

Tubular panel dimensions: with 14 tubes of diameter=0.05m, height=2.5 m

Total length:	14 * 2.5	= 35 m
Area:	$\pi * 0.03^2$	= 0.00196 m^2
Volume:	35 * 0.00196	= 0.0687 m^3 = 68.7 dm^3
Energy production per panel:	68.7 * 0.905	= 62.2 kWh/year
Surface area:	14 * 0.05 * 2.5	= 1.75 m^2
Energy production per m^2	62.2 / 1.75	= 35.54 kWh/m^2/year

Cultivating Chlorella sp. in a flat panel PBR with a volumetric productivity of 1,9 g/L/day and 40% lipids in the biomass.

Daily production of lipids is 0.76 g/L/day.

Conversion to tonnes:	0.76 * 0.000001	= 0.00000076 t/L/day
Production per year:	365 * 0.00000076	= 0.0002774 t/L/year
1 t biodiesel is 0.86 toe ->	0.86 * 0.0002774	= 0,00023856 toe/L/year
1 toe is 11.36 mWh = 11626 kWh ->	11626 * 0,00023856	= 2,774 kWh/L/year
The flat panel PBR have dimensions of:	width=0.7m, height=2.5m, depth=0.018 m	
The panel volume is:	0.7 * 2.5 * 0.018	= 0.0315 m^3 = 31.5 dm^3
Energy production per panel:	31.5 * 2.774	= 87.37 kWh/panel/year

Energy production per m^2:	(2.5 * 0.7)/ 87.37	= 49.92 $kWh/m^2/year$

This is a realistic value because it is comparable to the SolarLeaf bioreactor façade of B.I.Q. building with 50 $kWh/m^2/year$ (Colt International GmbH, 2013b)

Energy with hydrogen

Cultivating C. reinhardtii in flat panel PBR.

Daily theoretical maximum H_2 production of 20$g/m^2/day$

Production H_2 per year:	365 * 20	= 7300 $g/m^2/year$
		= 7.3 $kg/m^2/year$
1 kg H_2 is 33.3 – 39 kWh/kg ->	33.3 * 7.3	= 243.09 $kWh/m^2/year$
	39.0 * 7.3	= 284.7 $kWh/m^2/year$

The numbers are the theoretical highest achievable outcome from calculations with optimal conditions for microalgae to grow with no limitations. The highest yield in laboratory cultivation measured is 15-20% of the light is turned into H_2 (Melis & Happe, 2001). The Hydral system of Growenergy produces 12.500 kWh/year with 185 m2, which produces 67.6 $kWh/m^2/year$ (27.8 %). The technology is developing since 2001 and higher yields are now possible.

Wastewater nutrients calculations

The amount of nutrients is dependent on the productivity of the microalgae. The calculations are with microalgal of productivities of the 1.9 g/L/day and 0.62 g/L/day with 6-8 mg/L phosphorus and 40-60 mg/L nitrogen in the wastewater.

Productivity 1.9 g/L/day and concentration phosphorus 8 mg/L and concentration nitrogen 60 mg/L

1% phosphorus	= 0.019 g/L/day
Total wastewater needed	= 0.019/0.008 = 2.37 L
7% nitrogen	= 0.133 g/L/day
Total wastewater needed	= 0.133/0.06 = 2.22 L

So for the cultivation with microalgae with a production of 1.9 g/L/day, at least 2.37 L of wastewater is needed. To be sure that there is enough nutrients for growth, a higher amount of wastewater must be used.

Productivity 0.62 g/L/day and concentration phosphorus 8 mg/L and concentration nitrogen 60 mg/L

1% phosphorus	= 0.0062 g/L/day
Total wastewater needed	= 0.0062/0.008 = 0.775 L
7% nitrogen	= 0.0434 g/L/day
Total wastewater needed	= 0.133/0.06 = 0.72 L

So for the cultivation with microalgae with a production of 1.9 g/L/day, at least 0.775 L of wastewater is needed. To be sure that there is enough nutrients for growth, a higher amount of wastewater must be used.

Appendix J: microalgal matrix

Marine and freshwater microalgae species	Lipid content (% dry weight biomass)	Lipid productivity (mg/L/day)	Volumetric productivity of biomass (g/L/day)	Areal productivity of biomass (g/m2/day)
Ankistrodesmus sp.	24.0-31.0	-	-	11.5-17.4
Botryococcus braunii	25.0-75.0	-	0.02	3.0
Chaetoceros muelleri	33.6	21.8	0.07	-
Chaetoceros calcitrans	14.6-16.4/39.8	17.6	0.04	-
Chlorella emersonii	25.0-63.0	10.3-50.0	0.036-0.041	0.91-0.97
Chlorella platensis			1.09	15.3
Chlorella protothecoides	14.6-57.8	121.4	2.00-7.70	-
Chlorella sorokiniana	19.0-22.0	44.7	0.23-1.47	20.89
Chlorella vulgaris	50-58.0	11.2-40.0	0.02-0.20	0.57-0.95
Chlorella sp.	10.0-48.0	42.1	0.02-2.5	1.61-16.47/25
Chlorella pyrenoidosa	2.0	-	2.90-3.64	72.5/130
Chlorella	18.0-57.0	18.7	-	3.50-13.90
Chlorococcum sp.	19.3	53.7	0.28	-
Crypthecodinium cohnii	20.0-51.1	-	10	-
Dunaliella salina	6.0-25.0	116.0	0.22-0.34	1.6-3.5/20-38
Dunaliella primolecta	23.1	-	0.09	14
Dunaliella tertiolecta	16.7-71.0	-	0.12	-
Dunaliella sp.	17.5-67.0	33.5	-	-
Ellipsoidon sp.	27.4	47.3	0.17	-
Euglena gracilis	14.0-20.0	-	7.7	-
Haematococcus pluvialis	25.0	-	0.05-0.06	10.2-36.4
Isochrysis galbana	7.0-40.0	-	0.32-1.60	-
Isochrysis sp.	7.1-33	37.8	0.08-0.17	-
Monodus subterraneus	16.0	30.4	0.19	-
Monallanthus salina	20.0-22.0	-	0.08	12
Nannochloris sp	20.0-56.0	60.9-76.5	0.17-0.51	-
Nannochloropsis oculata	22.7-29.7	84.0-142.0	0.37-0.48	-
Nannochloropsis sp.	12.0-53.0	37.6-90.0	0.17-1.43	1.9-5.3
Neochloris oleoabundans	29.0-65.0	90.0-134.0	-	-
Nitzschia sp.	16.0-47.0	-	-	8.8-21.6
Oocystis pusilla	10.5	-	-	40.6-45.8
Pavlova salina	30.9	49.4	0.16	-
Pavlova lutheri	35.5	40.2	0.14	-
Phaeodactylum tricornutum	18.0-57.0	44.8	0.003-1.9	2.4-21
Porphyridium cruentum	9.0-18.8/60.7	34.8	0.36-1.50	25
Scenedesmus obliquus	11.0-55.0	-	0.004-0.74	-
Scenedesmus quadricauda	1.9-18.4	35.1	0.19	-
Scenedesmus sp.	19.6-21.1	40.8-53.9	0.03-0.26	2.43-13.52
Skeletonema sp.	13.3-31.8	27.3	0.09	-
Skeletonema costatum	13.5-51.3	17.4	0.08	-
Spirulina platensis	4.0-16.6	-	0.06-4.3	1.5-14.5/24-51
Spirulina maxima	4.0-9.0	-	0.21-0.28	25
Thalassiosira pseudonana	20.6	17.4	0.08	-
Tetraselmis suecica	8.5-23.0	27.0-36.4	0.12-0.32	19
Tetraselmis sp.	12.6-14.7	43.4	0.30	-

Tabel 7: algae matrix (Mata, Martins, & Caetano, 2010)

Appendix K:

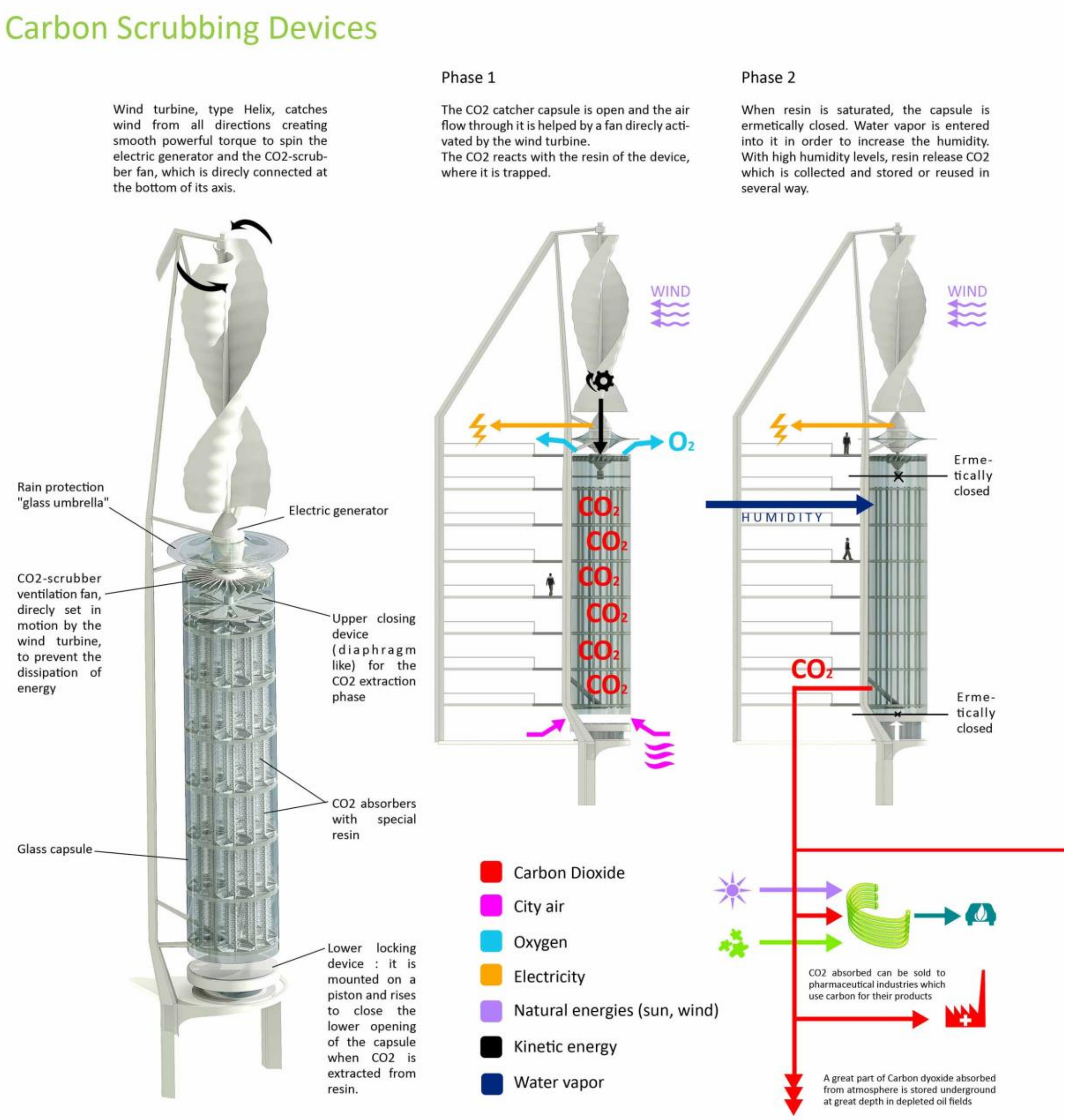


Figure 53: carbon scrubbing devices green loop marina city (AETRANGERE, 2012c)

Appendix: L: harvesting of the microalgae

Microalgae have a harvesting cycle of 1-10 days (Chinnasamy et al., 2012)

Microalgae will be grown to a certain density and then starved from nutrients. In this way the microalgae stop growing and produce more oil (Wolkers et al., 2011).

We can utilize a natural process called flocculation that make algae clump together. There are organism's that causes algae to flocculate or use chemicals to achieve this. The organism they use at the University of Kentucky naturally flocculates itself once a certain culture density, the cells will join together (settle out) (University of Kentucky, 2011).The concentration of biomass after flocculation will be around 1-5% from a dilute culture of algae depending on the culture broth (Tampier et al., 2009, p. 14). This is the first step in a two-step process to separate the biomass from the water. The second step is to further concentrate the biomass by centrifugation, filtration or micro straining and up the concentration to about 15-25% (Tampier et al., 2009, p. 14).

Originoil have developed a technique that brings back the extraction process from a two steps to one. They call it Single Step Extraction and claims that it is chemical-fee, low-energy, high flow and low-cost (Originoil, 2012). The technique involves precisely tuned electromagnetic waves to separate the algae from the water (flocculate) and to rupture the algae cell (lyse) (Originoil, 2012).

Figure 54: Single Step Extraction machine (Originoil, 2012)

The machine that Originoil has developed (figure 54) uses long specially-designed tubes through where the algae travels and gradually separated from the solution and if needed ruptured (Originoil, 2012).

Flocculation
In general the surface of the one celled algae have a negative charge that repels other algae. To make the algae clump together means that the charge have to be neutralized (Tampier et al., 2009, p. 14). There are different methods to flocculate the algae and each method has its own advantages and disadvantages. The most natural way to flocculate is by bio-flocculation. In this process occurs naturally for some algae species if they are transferred to containers and left alone to settle. It is identified that the efficiency is dependent on the stimulation of the algae by limiting nitrogen, dissolved oxygen and pH levels (Tampier et al., 2009, p. 14). However this process is very unreliable with fluctuating results in removal efficiencies (Tampier et al., 2009, p. 14).

A more stable form of flocculation is the use of chemicals to negate the negative charge on algae cell surfaces. We can distinct two kinds of chemicals substances which is inorganic chemicals and polyelectrolytes (natural polymeric electrolyte). Inorganic chemicals such as aluminum, ferric sulfate, ferric chloride or lime is used to neutralize or reduce the negative charge (Tampier et al., 2009, p. 14). The downside of this method is the cost of the chemicals. The use of metal salts creates disposal problems and limits the use for human and livestock feeds (Tampier et al., 2009, p. 14). Also some of the synthetic polymers are carcinogenic and thus poisonous. They are made of monomers that is obtained as byproduct of oil refineries. The reaction with algae and in the flocculation process, it doesn't react all of the substance so some parts of the monomer will remain soluble in the water (Laurent, 2010). It can affect the next culture of algae if the water is recycled. The usage of the biomass is limited only to biofuel which isn't sustainable at all (Laurent, 2010).

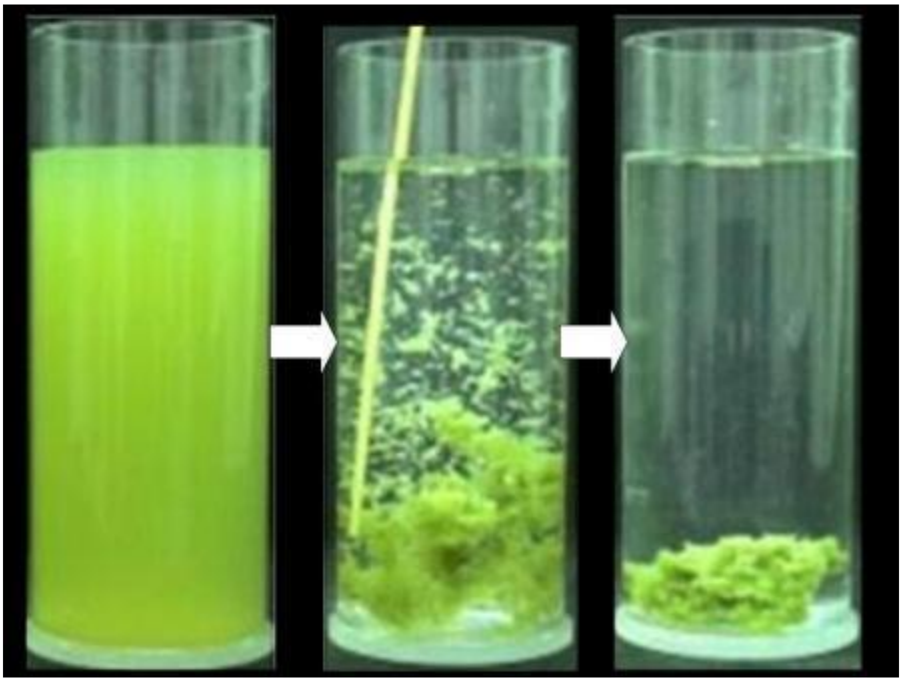
A safer way to flocculate algae is the use of polyelectrolytes which are charged organic molecules that not only neutralize the negative charge of algae, but it also forms a chemical bond between the algae (Tampier et al., 2009, p. 14). Also natural polymeric flocculants doesn't contain poisonous monomers and can capture all the algae and at the same time creating nitrates and phosphates. These are nutrients to algae and can be recycled back to the growing algae culture and feed the algae and saving supplemental nutrients and water (Laurent, 2010).

The characteristics of natural and synthetic flocculation is shown in table 8.

	Natural	Synthetic
Toxic to humans	No, biodegradable	Yes
pH sensitive to use	No	Yes
Can feed on intake pump	Yes	No
Contain carcinogenic monomers	No	Yes
Price affected by hydrocarbons	No	Yes
Easy to use	Yes	Yes
Cost effective when used treat algae	Yes	Sometimes

Tabel 8: comparison natural and synthetic flocculants (Laurent, 2010)

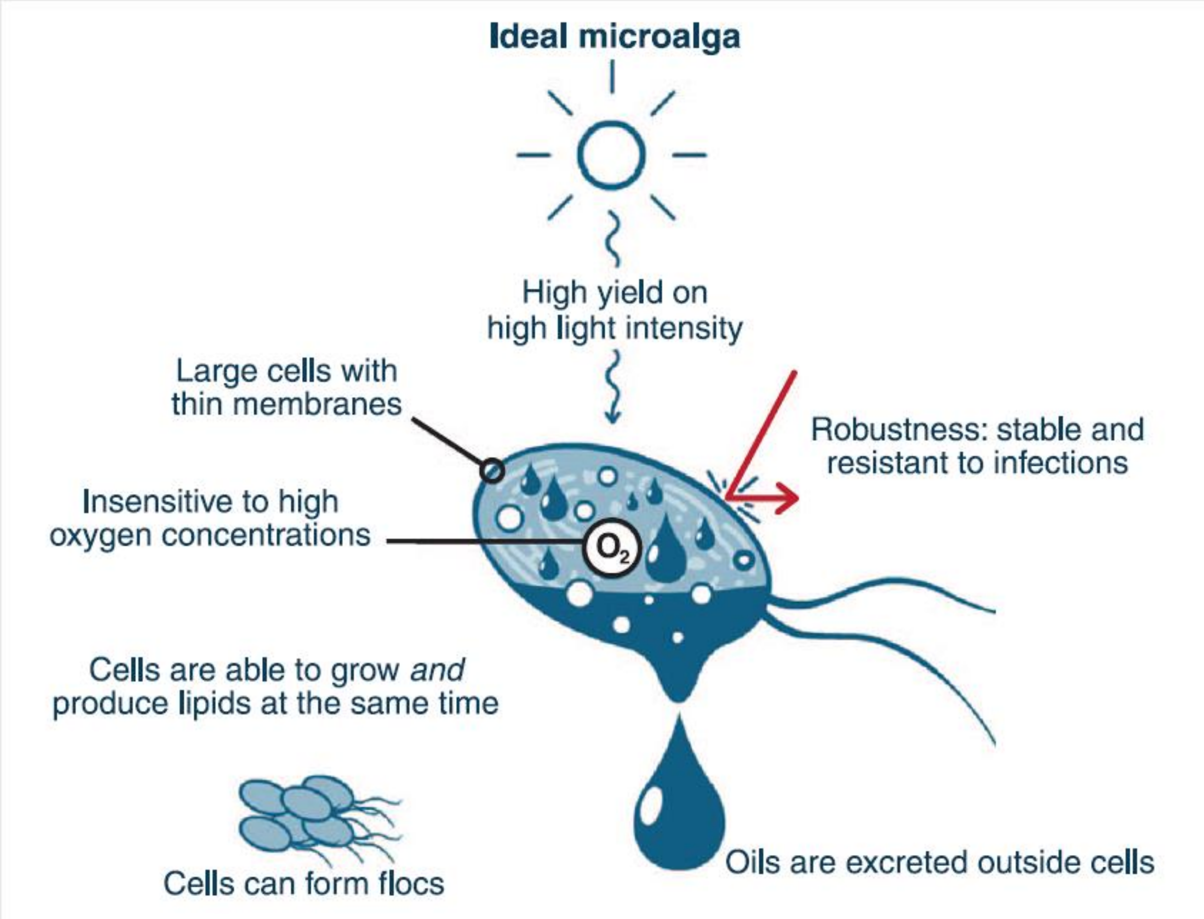
After the flocculation process is completed and the algae are clumped together, the biomass must be separated from the water. There are different ways to achieve the separation. One way is to let the algae settle in the reactor and it will form a layer of biomass at the bottom. The top layer of water can be pumped off and concentrated biomass will remain in the bioreactor (Tampier et al., 2009, p. 15).
Also the liquid can be pressurized which dissolves additional air and mixed with the algae at atmospheric pressure to release the air in the water as bubbles that attach to the flocks and make them float (Tampier et al., 2009, p. 15).


Figuur 55: flocculation process (Zhiting, 2011)

Centrifugation
Centrifugation requires energy to further concentrate the biomass by removing more water. Centrifuges are energy intensive and estimated to range from 0.3 to 8 kWh.m^3 (Tampier et al., 2009, p. 15). A less energy consuming method is filtration of the water and biomass with a screen that lets water through and capture the biomass. This process can be performed under pressure of vacuum for higher concentration of biomass. The energy consumption is ranging from 0.2 to 0.88 kWh/m^3 and 0.1 to 5.9 kWh/m^3 respectively (Tampier et al., 2009, p. 15). This method is only applicable to larger species of algae due to the limitations of the openings in the membrane and clogging of the screen.

Appendix M: microalgal development

Most algal strains are relatively small and have thick cell walls. The cell walls is the reason that very harsh conditions are needed to break these walls and extract the oil (Wijffels & Barbosa, 2010, p. 798).



Figuur 56: the ideal microalga (Wijffels & Barbosa, 2010, p. 798)

The characteristics of the ideal micro alga is depicted in figure 56. Some specific characteristics can be found in different strings, but never in one string (Wijffels & Barbosa, 2010, p. 799). If the microalgae can grow efficiently in high light intensities, light dilution is not needed anymore. Also if the microalgae can survive high concentrations of O_2, longer photobioreactors can be made and degassing is no longer required (Wijffels & Barbosa, 2010, p. 799).

The microalgal strains we use and research the most today is only a small part of the known species and there is still many undiscovered strains. Spirulina, Chlorella, Dunaliella, Haematococcsu and Nannochloropsis are among the most popular microalgal strains and it is likely that these strains aren't the best strains for biofuel production (Wijffels et al., 2010). Therefore we have to research new microalgal strains and modify it to produce have more lipid contents. If it is possible, we have to find and modify the microalgae strain with the following characteristics:

- High productivity

If the microalgae can produce biomass at a high rate, it will produce more energy and applications as faster reaction times for an adaptive sun shading reacting stronger on sunlight. The faster growing microalgae and more concentrated biomass will block more sunlight from entering the building and at the same time more energy can be harvested per surface area (Wijffels et al., 2010). It is also important that the metabolites contents such as lipids is also high, because the process of extraction of lipid from microalgal biomass is often a two-step process. First the biomass is grown and then stressed to accumulate the lipid contents of the biomass. With this method the lipid concentrations is high, but the volumetric productivity in the bioreactor is low in general (Wijffels et al., 2010).

- Genetic modification

Lipid contents of microalgae can be increases by genetic modification of the microalgae. Genetically engineered microalgae created by the National Renewable Energy laboratory in the USA have a lipid content in the cells of over 60% in laboratory conditions and above 40% in outdoor cultivation (Huang et al., 2010, p. 43). This will increase the energy output of microalgae, saving agricultural resources like land and water, higher yield of biomass and more lipid content than higher plants (Huang et al., 2010, p. 43).

- High yield on light

With an (theoretical) maximum yield of 9% of solar light, in practice this number is much lower due to the damage high solar intensities inflict on the microalgal cells. Strains are developed with smaller solar collector antenna sizes which allows a higher photosynthetic yield at higher solar intensities (Wijffels et al., 2010).

- Robust

The microalgae must withstand a more robust process to make it easier to extract the lipids and other contents in high volumes. A highly controlled and advanced process is almost not possible for large amounts of biomass (Wijffels et al., 2010). In the most ideal situation, the microalgae can be grown at large scale under extreme conditions.

- Efficient CO_2 supply

Microalgae needs CO_2 for growth for high productivity. In the ideal situation, it can be extracted from the atmosphere, but the concentration is too low for high productivities (Wijffels et al., 2010). In the ideal situation, atmosphere air can be captured and CO_2 can be filtered and concentrated for use in the photobioreactor on the building itself.

- Insensitive for oxygen

All microalgae produce oxygen and it can be seen as an important byproduct. However if the oxygen concentrations are too high, the productivity of microalgae decreases significantly. In open raceway pond systems it is not a problem, but in close photobioreactors it will accumulate in the photobioreactor. These systems needs to be degassed which requires energy, so if the microalgae can survive in high oxygen concentration, then it can be more productive (Wijffels et al., 2010).

- Flocculate

Most microalgae strains don't flocculate of its own and the most common harvesting method is centrifugation. This is an expensive and energy intensive process because the biomass concentration is low. Therefore large capacity centrifuges are needed.
Some microalgae strains flocculate which clumps the biomass in a more concentrated form. This can then be harvested by using filtration, sedimentation or flotation (Wijffels et al., 2010). Ideally all the cultivated microalgae strains flocculate spontaneously when a certain state in the process is reached.

- Large cells with a thin cell wand

Microalgae are in general small cells with thick cell walls. When we want to extract the products of the microalga, we have to break these cells. This can be achieved under harsh conditions by applying stress conditions like physical, chemical or mechanical stress. (Wijffels et al., 2010). The ideal microalgal strain is big cells with thin cell walls that takes no shear damage during production (Wijffels et al., 2010).

Appendix N: future developments

Nanocellulose

The molecular structure of cellulose is like an organic polymer (similar to plastics) and contains of molecules linked together in long chains (Sciencedaily, 2013b). The scientist R. Malcolm Brown, Jr., Ph.D. presented at the American Chemical Society on the 7th of April 2013 about nanocellulose. It is the first time presented that nanocellulose can be grown naturally with the use of algae as raw material for biofuels and many other products (Sciencedaily, 2013b). Cellulose is the base material of paper and cardboard and is the same material as tree trunks and branches (Sciencedaily, 2013b). There are “very few living organisms that can synthesize and secrete cellulose in its native nanostructure form of microfibrilis” (Sciencedaily, 2013b). Materials made from nanocellulose can be stronger than steel and stiffer than Kevlar (Sciencedaily, 2013b). The material is also lightweight and many applications can be thought of in the relation to buildings. It can be an construction element or we can create ballistic glass panels (Sciencedaily, 2013b).

Blue-green algae (cyanobacteria) are used in the process of creating nanocellulose. The natural process of photosynthesis and the absorption of CO_2 are the only needed ingredients to create the nanocellulose. These cyanobacteria aren’t making nanocellulose at great amounts in nature and the challenge is the scale up of this process (Sciencedaily, 2013b). Blue-green algae are easier to cultivate than the A. Xylinum bacteria discovered in the 1980s and 1990s. the Blue-green algae can make their own nutrients from sunlight and water and consumes CO_2 from the atmosphere while the bacteria need high-purity broth of food and other nutrients to grow in huge industrial fermentation tanks (Sciencedaily, 2013b). The research is now in a stadium that it moves from laboratory size to outdoor facilities (Sciencedaily, 2013b).

Rainbow colored algae

Biologist at UC San Diego have succeeded in creating colored algae with the use of fluorescent proteins in the algae cells. The colors of that they can make at the moment is blue, cyan, green, yellow and orange all with fluorescent protein. The algae will glow light and it can be implemented in façade design with different colors and as a small light source (Sciencedaily, 2013a).

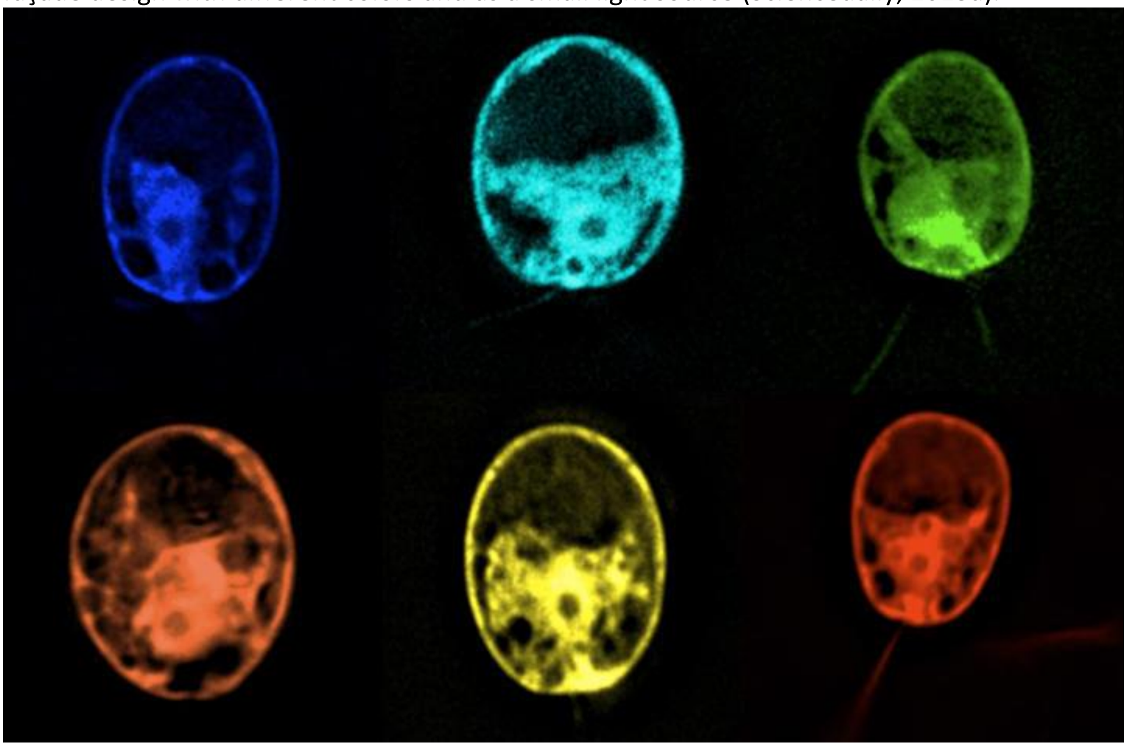


Figure 57: colored microalgae (Sciencedaily, 2013a)