DEFINING THE PROBLEMS IN INTEGRATION OF MICROALGAE PHOTOBIOREACTOR SYSTEMS TO ARCHITECTURE

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Abstract- With CO_2 absorption ability, waste water treatment quality, O_2 production potential and lots of other organismal features, as results of the extensive researches on microalgae it was understood that these organisms are the solution of clean energy problems for the world in the next century. The limited experience about using of microalgae photobioreactors in architecture requires shedding light on some issues. So, this paper mainly aims to explore the problems of photobioreactor systems which are integrated in architectonics. For this purpose, this study will examine totally 10 algae architecture projects. Microalgae photobioreactor systems commonly used in architecture in 3 different ways as building integrated photobioreactors as a secondary facade, holistic urban approaches in macro scale and individual installations. In the scope of study, 4 projects in building scale, 3 projects in urban scale and 3 projects a a singular installation are selected. The paper has concluded that the integration of algae to the architecture encounters some challenges, including the high initilal and operating cost, additional load to the structural system, accordanceand solidity to the weather conditions, compatibility to the local climate, limitation of view for the residents need for high space requirements for storage and operating systems and supplying limitations to the common infrastructure of the zone. With identifying this lookouts, this study provides an evaluation method to appreciate and take attention when the photobioreactor systems are applied in architecture. Besides that, using algae in architecture has brought many benefits like energy saving, CO_2 emission reductions, O_2 release, biofuel production, wastewater treatment from micro scale by using building facades and macro scale by integrating to the cities. The unrivalled benefits of the algae photobioreactor systems through the combination of the technical and biological and chemical cycles within architecture commence an innovative approach to renewable energy architecture by integrating environmentalist architectural design values and will shed light on future studies.

Keywords microalgae, photobioreactor, algae architecture, bioenergy, sustainability

1. Introduction

Energy brings comfort, mobility and efficiency to human life. Today, it seems impossible to live without energy in the world. The energy we use has become an indispensable part of our social life. Lifelong problems of human being is constantly increasing and that causes continuous energy hunger in the word [1]. Most of the energy we use is provided from fossil fuel sources and as a result of energy consumption, CO_2 release causes greenhouse gas emission [2]. Fossil fuel burnings used for energy consumption causes pollution and climate changes [3]. The combustion of fossil fuels releases a large amount of carbon into the atmosphere as carbon dioxide. Fossil fuel-based power generation is estimated to contribute approximately 1/3 of the total carbon dioxide released from today's fuel combustion [4]. Fossil fuels, especially oil, coal and natural gas, effectuate about 85% of our energy needs worldwide. Effective and efficient use of these energy resources in the context of providing basic energy needs, still remains a major problem. The biggest problem with fossil fuels is that they are finite sources and they will face danger of extinction in the near future [5]. Today, traditional energy sources such as oil and coal etc. are already being used more than renewable energy sources [6]. The Kyoto Protocol (1997) aims to significantly reduce CO_2 emissions. In order to achieve these target, the use of renewable energy sources such as nuclear energy, solar energy, geothermal energy, wind energy and biomass energy is inevitable [7]. Unlike fossil and nuclear fuels, alternative energy is provided by eternal natural sources (wind, sunlight, geothermal energy and biomass). Utilizing these resources to ensure our energy needs supports sustainable development by reducing greenhouse gas emissions. The development and use of renewable energies will provide significant benefits to all countries around the world, including energy production, environmental protection, pollution reduction and creation of business areas. Solar energy, wind, hydroelectricity, biomass and geothermal energy are considered as the most common sustainable energy sources [8].

According to academic researches, biomass energy is estimated to be the main source of renewable energy (up to 75% of renewable energy sources) [9]. Producing bioenergy is an important strategy for relieving greenhouse gas emissions and replacing fossil fuels as an energy source [1]. Biomass has significant advantages compared to other renewable energy sources. For example, it is available all over the world, it is relatively simple to process without requiring expensive equipment, it can be stored for long periods and can be reused. The biofuel generation by using biomass as a renewable energy source which is an inexhaustible source to solve the energy problem, is becoming increasingly important [6]. To obtain first generation biomass energy, which is thought to be an alternative fuel to traditional fossil fuels by producing biodiesel from oils extracted from various terrestrial plants such as soybeans, sunflower, palm, corn, coconut needs large agricultural areas. Plant-based biodiesel production affects global food resources and sustainability of agricultural production in the long term [10]. The use of agricultural land with limited capacity and the limited capacity of the oil obtained from the agricultural products, which form the basis of the fuel product, makes algae more important among the biomass types [6]. Although, photovoltaic solar panels and wind turbines as renewable energy sources integrated applications are common, algae biomass as a renewable energy source has limited utilization in architecture. With CO_2 absorption ability, waste water treatment quality, O_2 production potential and lots of other organismal features, as results of the extensive researches on microalgae, it was understood that these organisms are the solution of clean energy problems for the world in the next century. The limited experience about algae integrated architecture requires shedding light on some issues.

2. Method

The integration of algae to the architecture encounters some challenges, including the high initilal and operating cost, additional load to the structural system, accordance and solidity to the weather conditions, compatibility to the local climate, limitation of view for the residents, need for high space requirements for storage and operating systems and supplying limitations to the common infrastructure of the zone. With identifying this lookouts, this study provides an evaluation method to appreciate and take attention when the photobioreactor systems are applied in architecture. Thus, this paper mainly aims to explore the problems of photobioreactor systems which are integrated in architectonics.

In order to determine these problems, firstly, the following questions will be inquired;

- What are the differences between microalgaes and other common renewable energy sources?
- What are the types of photobioreactors as microalgae cultivation methods?
- What are the parameters that affect microalgae growing conditions in photobioreactors ?
- How to obtain energy from microalgae using photobioreactor systems?
- How can photobioreactors be integrated into architecture?
- What are the problems of integration of photobioreactors into architecture as an innovation?

The study which base on explaining the working principles and defining the problems that may occur in integration of the photobioreactor systems into the architecture discipline, continues with three main parts with generated new methodology by commenting the algae architecture studies.

Firstly, after explaining the energy potential of microalgae as a renewable energy source under the title of 'Algae Biomass As An Energy Resource' , the study will continue with the promulgated literature concerning with the proper types of photobioreactors for algae architecture and discourse the energy bioprocess which includes algae cultivation and harvesting methods regarding photobioreactors and their technical requirements by analyzing and classifying the domestic and foreign literature and at the end of this part, aims to create comparative review table which shows advantages and disadvantages of algae photobioreactor types.

In the second part titled 'Algae Architecture Evaluation Criterias' , algae architecture will be analyzed in terms of three criterias below;

- Photobioreactor applications integrated to building facades.
- Holistic urban algae photobioreactor approaches
- Individual expression photobioreactor installations

with selected 10 algae architecture projects in total which are applied on site and also the concept projects which are unapplied on side.

This look outs will be classified according to the following evaluation criterias and considerations which would be considered when designing a photobioreactor system integrated into the architecture will be determined.

- Submitted photobioreactor type
- Location of the project site

- Planned operation model

Finally, the results will be evaluated in terms of the innovations and challenges of architecture integrated algae photobioreactor systems.

3. Algae Biomass as an Energy Resource

3.1. Comparison of Algae with Other Renewable Energy Sources

Biomass is one of the best energy sources that can be converted into bioenergy by supplying CO_2 from the atmosphere through photosynthesis [11]. The importance of energy produced by using fossil fuels is undeniable. Biofuels are the sustainable equivalent of fossil fuels [12]. Biofuels are extracted from plants with lipid content in their cells and can be used as bioethanol, biodiesel, biogas, bio hydrogen [13]. Although biofuels are more expensive than fossil fuels, their production is increasing worldwide [14]. Biomass sources that are expected to be alternative fuel to conventional fossil fuels by producing biodiesel from oils extracted plants such as soybean, sunflower, plan, corn and coconut, needs large agricultural areas to grow. Plant-based biomass production affects global food sources and sustainability of agricultural production in the long term [10]. The use of agricultural lands with limited capacity and the low oil capacity obtained from the agricultural products which form the basis of the fuel product make algae more important among the biomass types [6,16]. The oil production potential which makes algae more prominent than other biomass recourses is expressed in Table 1.

Biomass Rawmaterials	Yearly Oil Production Per Acre (Liter)
Corn	68
Soybean	174
Sunflower	371
Cocoa	397
Colza Seed	462
Coconut	1045
Palmoil	2309
Algae	20000

Table 1. Oil Production Potentials of Common Biomass Raw Materials [15].

Renewable and carbon neutral biofuels are required for environmental and economic sustainability. Microalgal oil efficiency is better than the efficiency of best petroleum products. [17]. The calculations made by Chisti clearly show the strong scenario for microalgal biofuels. Algae have great energy potentials due to their use as energy crops, their easy adaptation to growth conditions, their ability to grow in fresh or marine waters and avoid huge land use. Moreover, 2/3 of the world is covered with water, so algae can be a potentially significant renewable option for global energy needs [18]. According to CO_2 use potential, microalgaes are more photosynthetic than other inland plants [19]. Algaes are divided into two parts as microalgae and macroalgae. Macroalgaes are known as seaweed and are left out of this study. Microalgae are more suitable for energy production because of their high lipid content and rapid growth rate. [11,15,20]. Algaes are different colors and varieties, commonly green, blue, brown and orange. In terms of energy production, the most valuable microalgaes are green ones. Algaes are oxygenic phototrophs. They use light as an energy source to grow. They produce oxygen [21]. In fact, algae produce more than 330 billion tonnes oxygen every year [22], in other words, algae are single-celled organisms which are well- known by producing 80% of all oxygen on earth with highly efficient photosynthetic cycle. This ability alone makes it one of the most important organisms in the biosphere [22], because, unlike algae, soil plants always spend some of their energy (90%) to support their physical external structures, such as roots, leaves, and stalks. Therefore, the organism that does not have any physical structure can nominate 100% of its energy to produce oxygen [23]. The microalgae use carbon dioxide in the atmosphere and through photosynthesis convert it into carbohydrates, proteins and lipids. Microalgae are used in the production of many products such as biodiesel, biogas, biohydrogen, bioethanol, as well as high-protein animal feed, food additives, agricultural protein-rich fertilizers, biopolymers, bioplastics, drugs and cosmetics [16]. According to academic researches, algae can produce 60,000 liters biofuels per acre. It presents surprising statistics that can redefine human daily life and its relationship with the environment [24].

3.2. Comparative Analysis of Photobioreactor Types Using for Growing Microalgae and Symbiosis with Architecture

In this part, common photobioreactor types that obtain energy from microalgae will be examined in order to understand what the photobioreactor is and the importance of photobioreactors for algae cultivation.

The system that allows microalgae to perform their biological reactions to produce energy is called photobioreactor (PBR) [25]. In terms of technical characteristics and environmental interactions; there are two common uses called open ponds bioreactors and closed system photobioreactors [26-29].

With the sub-headings in this section, photobioreactor types which are commonly used in algal cultivation , their technical characteristics and their working principles will be examined and the advantages and disadvantages of each other will be discussed with comparative analysis by using references from algae literatures.

3.2.1. Open Pond Bioreactors

Open pond bioreactors are the oldest, easiest and simplest way to generate a bioreactor [30,31]. Despite the fact that the installation and operating costs of open systems are economical and suitable for algae cultivation [32], they have many disadvantages. Open pond systems are need too much field usage for micro algae cultivation. They have contamination risk. Temperature control of the bıo reactor is difficult. Loss of water through evaporation may occur. The use of light is uncontrolled. CO_2 losses are uncontrolled as they are in contact with air. Not all micro algae varieties, but only the types which can live in very high salinity, pH and pressure cultures can be grown efficiently in open ponds. Therefore, they are limited in terms of micro algae types that can be grown compared to closed systems. For this reasons, biomass productivity in open systems is less efficient than closed photobioreactors [32-37]. Open pond bioreactor systems are generally used for commercial and industrial algae cultivation. The most common uses of open pond bioreactors are large raceway pons (RWP) ands circular ponds [38]. Typical designs for open pond bioreactors are such as a one-way loop or a curved loop [39]. In Fig.1, open pond photobioreactors are expressed with schematic explanations.

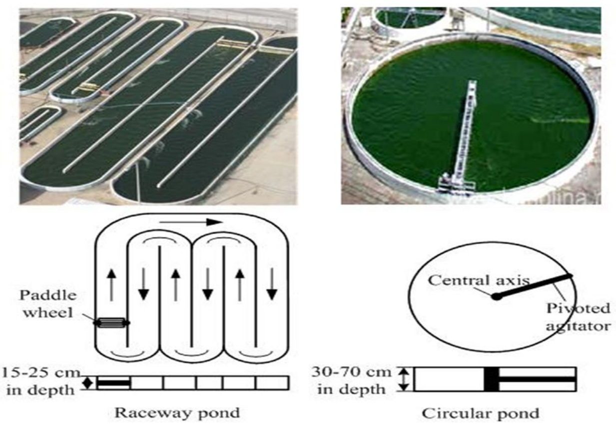


Fig. 1. Open Pond Bioreactors [39].

These ponds usually have a large mixing propeller that gently circulates the water to avoid it from recession. This circulation and continuous mixing is very crucial for consistent nutrient and termal diffusion It keeps algae cells in suspension and improve the efficiency of light use. [29]. Feeding is done from the front of the wheel [29] and the harvesting is done from the back of the Wheel [16]. The wheel operates continuously to prevent microalgae from subsiding [16,26]. Water circulate through the pond using paddle wheels or pumps. When it needs, air is supplied to the pond to assist the mixing [40-42]. The depth of a open pond varies from 20 to 50 cm due to light limitations. [16,42]. The materials used for open bioreactors must be water impermeable to prevent water loss to the soil. Based on these considerations, plastics such as PVC and concrete are often preferred materials [27]. Although the open pond systems, which are still more important for large scale algae cultivation and they have many technical disadvantages, Their ability to clean the air as a result of the effective reduction of CO_2 concentration in the air is an undeniable fact. The research by Caleb Stuart and Mir-Akbar Hessami from Monash University on open pond bioreactors has proven that under a natural daily light exposure cycle, a 4000 m3 open pond system can clean CO_2 up to 2.2 kilometers per year [43]. According to the researchers, it is seen that open pond bioreactors have reached the technological limits. For this reason, today, many innovative studies are being carried out to increase the efficiency of photobioreactors [35]. As a result of these studies, closed photobioreactor designs, which are easier to control and interfere with, were born [44].

3.2.2. Closed Photobiorectos

In order to overcome the problems related to open ponds for microalgae cultivation, various approaches have been applied to develop closed bioreactor systems [44]. Studies on the bioreactor types for algae cultivation have shown that, less operating costs, less water usage, less land usage and less energy usage are important issues. Closed systems have begun to replace open systems in the context of these requirements [33]. Closed photobioreactors are generally characterized by their geometry. Common geometries; horizontal and vertical tubular, vertical columns and flat panels [32,45,46]. Photoreactors can be illuminated by sunlight or artificial light or both [32]. Closed systems are the most expensive systems among bioreactor applications, but they are 5-10 times more efficient than other systems. Although microalgae can grow at various temperatures and their production is possible throughout the year [38,47], optimal growth varies according to algae types. Seasonal and even daily temperature changes can affect algae production. Therefore, cooling equipment and shading techniques are important to prevent temperature increases that are dangerous for algal growth in closed photobioreactors [38]. It is a common misconception that algae should be exposed to direct sunlight for a long time. This high intensity exposure to sunlight can result in lower productivity, stopping growth and decay of the algae. As a result of the investigations, the most efficient method for algae cultivation for the bioreactor types where the surface / volume ratio is the highest. Because, in this way, the preferred growth conditions can be provided in a highly controlled manner. Therefore, the bioreactor type which provides these conditions become an important factor in the creation of effective algae growth systems [33]. In closed photobioreactors, it is the primary objective to capture the sunlight and to achieve an optimum and equal light intensity on each algae [48]. This shows the cause of the growth rate of algae and it shows why closed photobioreactors are the most productive reactor types [49].

3.2.2.1. Flat Panel Photobioreactors

Flat panel photobioreactors are considered the most efficient design in closed photobioreactors [32]. It has been reported that these photobioreactors can achieve very high photosynthetic efficiency compared to other designs (Fig. 2) [50,51]. The flat panel photobioreactor system may consist of a flat, transparent glass, plexiglass, polycarbonate or polyethylene film [20,52,53].

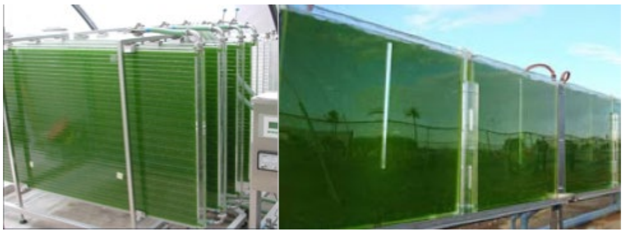


Fig. 2. Flat Panel Photobioreactor Examples [45].

Compared to tubular bioreactors, flat panel PBRs have higher efficency due to higher surface / volume ratio [28,54]. Self-shading of microalgae cells between flat plates may prevent the process of photosynthesis and microalgae efficiency. For this reason, optical fibers or LED lights can be used for additional indoor lighting to ensure efficient use of light in culture and to increase the penetration of light. [28,54]. Microalgae growth and efficiency vary depending on all inputs in the panel [55,56]. For example, gas velocity and ventilation rate determine mass transfer, which also affects gas distribution and bubble sizes [34]. Mixing is provided by risingthis bubbles. Bubbles can also prevent O_2 accumulation [57]. In order to reduce the risks of inputs that could affect the operation of the mechanical system, it must be effectively mixed and circulated in the culture within the photobioreactor [58]. In general, mixing in flat panel photobioreactors is done by ventilation. The ventilation unit is placed under the reactor. Increased movement of gas bubbles helps mixture, gas transfer, nutrient transfer, heat transfer and also helps homogenous distribution of cells and light [59]. In cases where any problems are encountered in the mixing conditions, the photobioreactor can be equipped with mechanical wheels. The wheels can work as in open systems, helping to effectively mix the culture and also prevent the sedimentation of cells [34]. Operating mechanism of the flat panel system is showed in Fig.3 below.

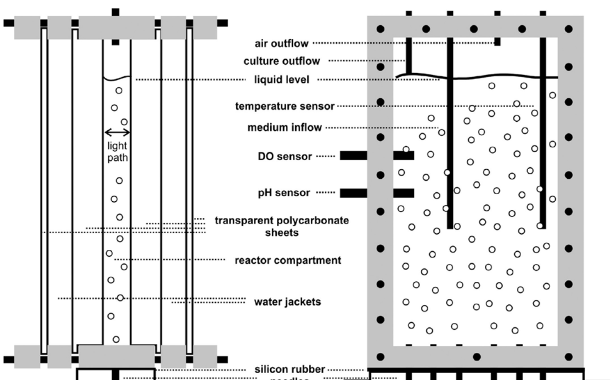


Fig. 3. Side View And Front View Of A Flat Panel [60].

Orientation is an important factor affecting the design of a flat panel PBR by directly affecting the utilization of the sun. For microalgae cultivation, Sierra et al. [61] indicated that the orientation of the vertical and flat PBR's was the orientation of the east / west orientation for latitudes above 35 ° N and that the north / south direction should be preferred in latitudes below 35 ° N. lnokaly and Keeling [62], with experimental studies conducted at the University of Lincoln Campus, UK, showed that the southern orientation was the preferred orientation of PBRs to achieve higher daylight factors. In B.I.Q House algae facades are located on the southeast and southwest direction [63]. Provost and Legendre says that, the architecture firm X-TU recommended the south orientation according to the research and development of the SymBio2 project in Nantes Saint-Nazaire (47°N) supported by AlgoSource Technologies for the flat-panel PBR facades. [15]. According to Marsullo et al., Flat panel PBRs should not be thicker than 5-6 cm to allow light to enter the panel [64]. Compared to vertical flat panel PBRs, inclined flat panel PBRs can provide a substantial control of light and temperature using the light optimally [54]. It is possible that the microalgae culture that is exposed to excessive light may be damaged. Therefore, use of light should be controlled It is possible that the microalgae culture that is exposed to excessive light will be damaged. Therefore, use of light should be controlled. Otherwise, due to the light saturation limits of algal culture, at higher irradiation levels, cell death, called photo inhibition, can be triggered [65-67]. This is one of the operational challenges in outdoor cultures where the lighting rate is dependent on the sun. The position of the photobioreactors operating in the outside environment can be changed by the inclination of the panels with simple guidance systems depending on the daily movement of the sun. This angle of inclination is an important design parameter in natural illuminated cultures, where seasonal changes and climatic conditions also have an effect. It also helps provide the most favorable conditions for the use of light and no longer prevents lighting and extreme temperature [34]. Slegers [68] stated that the panel orientation had a great impact on productivity at high latitudes and that the difference in productivity between north / south and east / west orientation could be as high as 50%. Microalgae growth is affected by increased pressure. The structure of the flat panel PBRs cannot resist too high pressure. Therefore, scale-up ability is potentially limited [53]. When the flat panel photobioreactor designs are needed to be enlarged, the returns of the surface area and the volume of the culture should be taken into account and the use of light in the design should be considered as the primary. Therefore, in order to increase amount of harvest in industrial scale, instead of increasing the size of the single photobioreactor, rising up the number of PBRs is more suitable. [48]. However, it is important to use materials such as laminated safety glass [15].

3.2.2.2. Tubular Photobioreactors

Tubular PBRs are special designs developed from the combination of piping systems [69]. In this system, the tubes are transparent [26]. In tubular systems, tubes can be designed as horizontal or vertical alignments in a single row and multiple consecutive rows. Algae cultivation in single row tubular photobioreactors may be unprotected when there is too much sunlight. Due to high light intensity, their growth may be delayed in the reactor. Therefore, multilayer vertical or horizontal tubes are preferred when designing tubular photobioreactors (Fig. 4). Thus, the tubes that shade each other reduce the light intensity and provide controlled light. Tube materials can be glass, soft polyethylene, acrylic, plastic or very transparent silicone rubber [20,70].

Fig. 4. Vertical and Horizontal Tubular PBRs [20].

The basic design principle of the tubular photobioreactors consists of two parts. The first of these is the part of the tube that gives the name of the reactor which contains the culture medium in which microalgae are grown. The second one is the degasser unit that removes the gas collected in the system and the pump system that provides circulation in the culture [71]. As a result of the investigation of the prototypes of tubular photobioreactors designed so far; it can be concluded that photobioreactors may be in any desired shape such as pyramid, cone or diamond. [15]. Tube diameter is a limiting factor in design and construction. Due to difficulties in capturing light, tube diameters cannot exceed 10 cm. Therefore, the diameter of tubes in a closed system is limited [57]. Tubular photobioreactors can be designed in different sizes. However, one of the disadvantages of systems where the size is increased is low mass transmission. This can lead to high levels of dissolved oxygen accumulation in some horizontal tubular photobioreactor systems, which prevents algae cultivation in the long run [72]. An increase in diameter reduces the surface / volume ratio. In tubular photobioreactors, the microalgae is circulated and mixed in tubes using air pump technology or air lifting system (Fig. 5). Thus, ventilation of the culture is executed. [27,28,32,47,54,70,73]. Increasing tube length may cause problems over degassing, culture circulation, condition of mixture, ventilation, photosynthetic activity, PBR performance and efficiency [74]. Tubular PBRs have a smaller surface/volume ratio due to the geometry of individual tubes. However, the surface/volume ratio (efficiency) of the entire tube system can be increased by increasing the length and number of tubes [16,34,75]. The mixing of tubular PBRs is achieved by pumps or air lift systems or a combination of both. As in all closed photobioreactor systems, mixing determines mass transfer rates, gas diffusion, O_2 removal, light use and it prevents cells from collapsing into the bottom of the tube [76]. The basic design mentality for tubular PBRs is the management of appropriate pumping systems for the mixing and circulation of culture [77].

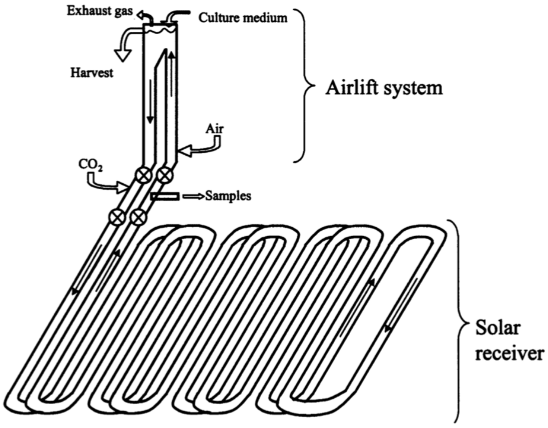


Fig. 5. Air-lifting Tubular Photobioreactor [76].

Grima et al. suggested that tubular reactors should be designed as the pipe diameter is not more than 0.1 m, continuous tube length must be 80 m and also flow rate must be 0.3-0.5 m/s [75]. Due to the geometric form of the photobioreactor, algae cells can shade each other. Algae at the bottom of the tube may not receive enough light to grow. Microalgae may stick to the photobioreactor surfaces and that may prevents light use. In such cases, a good mixing system is required. In any case, efficient light distribution for algae can only be achieved by developing a good mixing system in the tubes. [32]. According to Sierra, tubular photobioreactors are the most economical method for algae cultivation [61].

3.2.2.3. Vertical Column Photobioreactors

In vertical column photobioreactors, microalgae culture is grown on a large volume of cylindrical containers (Fig. 6). They are photobioreactors with low cost and easy to operate. They are suitable for use on a large scale, but not on a mass scale [32].

Fig. 6. Vertical Column Photobioreactors [45].

Vertical column photobioreactors are called bubble columns or airlifts according to their working principles. Rising gas bubbles cause mixing in the reactor by generating flow. Wheels increase the mixture, and gas diffusion [32]. Airlift reactors have the additional advantage over bubble columns due to their ability to control algae growth by simulating the culture. Chui et al. [78] showed that algae grown in concentrated airlift reactors had a higher specific growth rate (0.226 days^{-1}) than concentrated bubble columns (0.180 days^{-1}). In the bubble-column photobioreactors, the air inlet is provided from the bottom and circulated in the culture as a flow cycle. (Fig. 7(a)). This situation can damage microalgae cultures, it is used with traction tubes in the photobioreactor system in order to prevent damage, or it is designed by dividing the cylinder geometry. Vertical column photobioreactors called air lifts can be defined by dividing into two parts according to the working principle. The first of these is Draft Tube Air Lift Photobioreactor. In this system, a tube is inserted into the center of the system to draft. The air supply in the system allows mixing. Draft tube separate the system two pieces and mixing is formed in the opposite directions. (Fig. 7(b)). The other one is Split-Cylinder Airlift Photobioreactor. In this system, the culture flow in the cylinder is carried out with the rising region and the refluent region. (Fig.7(c)). When the bubble-column photobioreactors are designed with a diameter of up to 0.19 m, they can work as a tubular photobioreactor [47]. Air lift photobioreactors are the systems where mixing, gas transfer and air supply processes are performed simultaneously. Sufficient and effective mixing is carried out by the controlled liquid flow. CO_2 feeding and O_2 removal in air lift photobioreactors do not limit reactor efficiency. In addition, the formation of dark areas within the reactors according to biomass density serves as a specific blocking shield against intense light [79].

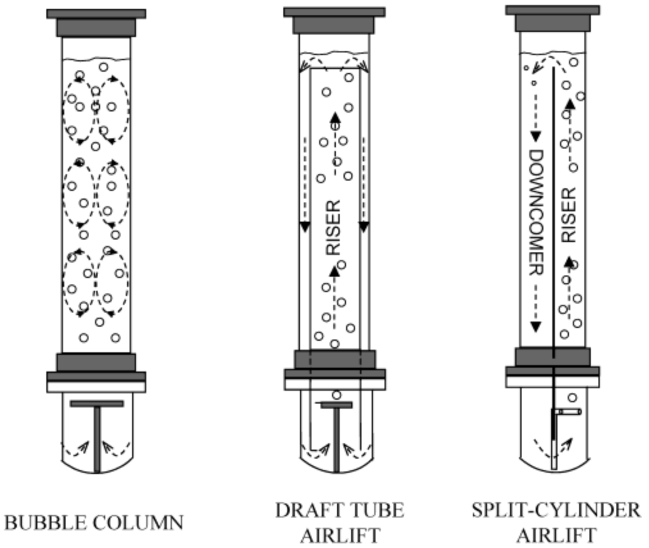


Fig. 7. Vertical Column Photobioreactor Types [80].

This type of photobioreactor may have deficiencies in temperature control and hydrodynamic load management [81]. The air pump is less flexible than normal pumps and requires air supply for operation. Periodically, photobioreactors must be cleaned and sterilized. This can be easily achieved by using automatic cleaning systems. [82-84]. Vertical-column photobioreactors have high mixing and mass transfer property.

They have low energy consumption. They can be designed on a large and small scale. Their cleaning is easy. They reduce the oxidation due to light by preventing geometric structures and working principles and the exposure of the algal culture to excessive light. With their geometry and working principles, they reduce oxidation which may be occur due to light by preventing algal culture to be affected from excessive light. With increasing sizes, the use of light in vertical - column photobioreactors decrease inversely in size [32]. The highest efficiency in this type of PBR is measured in summer [84].

Although open pond photobioreactor systems are low-cost, closed photobioreactor systems have been found better than open ponds in order to have less contamination risk , to provide more system control, to achieve better mass transfer and to obtain much higher density biomass with low water requirement.

In the next section, parameters that are affecting microalgae cultivation will be expressed.

3.3. Microalgae Growing Conditions in Closed Photobioreactors

Biomass production from microalgae is based on a simple scheme describing all the requirements of this biological process [85].

$$CO_2 + H_2O + \text{Nutrient} + \text{Light} \rightarrow \text{Biomass} + O_2 \quad (1)$$

Numerous parameters affect algae cultivation and lipid content of the algae, thus affect the harvested biomass. Photosynthesis is the reaction that provides the first transformation of sunlight into energy. Therefore, all components involved in photosynthesis contribute to algae growth. These are; CO_2, water consumption, nutrient (nitrogen, phosphorus) supply and concentration, light, O_2 removal, temperature, pH and salinity [16,38,86-90]. In addition to the environmental parameters that can make micro-algae photosynthesis for efficient harvesting of microalgae, operational parameters are also very important. These operational parameters refer to microalgae growing conditions in the photobioreactor system Lighting, mass transfer, mixing [91], dilution ratio, harvest frequency [92,93], scaling and process management and cleaning [47] parameters are important operational parameters in order to create optimal conditions for microalgae cultivation. [25]. The general expression of microalgae growing conditions which vary depending on many parameters was tabulated by Coutteau [94] and it was seen that these values were used as reference in the literature studies that were examined later. (Table 2). Couteau emphasizes that the variables at the optimum level in a study condition may have a different value for another study.

Parameters	Value	Optimal
Temperature	16-27	18-24
Salinity	12-40	20-24
Light Intensity (%)	1-10	2,5-5
Fotoperiod (hour)	-	16:8 min-24:0 max
pH	7-9	8.2-8.7

Table 2. General value table of the most important parameters for microalgae development [94].

When these variables are examined, it is seen that some of them affect microalgae development and efficiency at environmental level, some at operational level and some at both environmental and operational level. The parameters required for microalgae cultivation by using photobioreactors were analyzed in Table 3 with the graphical explanation of environmental and operational parameters. The most important point to note here is that these parameters cannot be considered independent from each other. Because, as a result of researches, in the absence of one or more of these parameters can either slow or stop microalgae growth. Therefore, it is very important to control and optimize all parameters together to ensure microalgae production and efficiency in the best possible way.

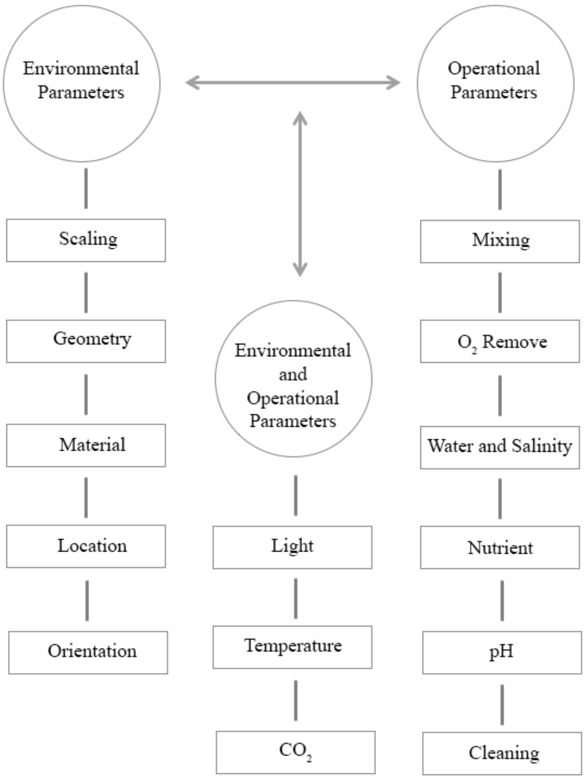


Table 3. Parameters expressing microalgae growing conditions.

3.4. Energy Producing Processes from Microalgae

In this section, it is the main objective to understand how energy is produced from microalgae. In this subsection, how to produce energy from microalgae, how photobioreactor systems work and how the holistic bioprocess system works. The use of microalgae to produce fuel as biomass energy is the most discussed and investigated area in terms of biological processing of algae [16,25]. The biofuels used in energy obtain using microalgae can be divided into four categories according to conversion technologies (thermo-chemical conversion, biochemical conversion, transesterification and photosynthetic microbial fuel cell) as shown in Table 4 [95]. Biodiesel produced from microalgae is an important option for energy. Because it is a clean renewable energy source with physical and chemical properties similar to petroleum [96]. Microalgae can be used as a source of raw materials for many types of biofuels. It is possible to produce methane by anaerobic degradation of microalgal biomass, biodiesel from microalgal oils and biohydrogen by photobiological reactions. If microalgae used for biodiesel production, the algae species with high oil content; if it used for the production of biohydrogen, hydrogen-producing species; if it used for bioethanol production, species with high carbohydrate content should be selected. In addition, the selection of suitable nutrients for culture, environmental conditions and the appropriate bioreactor are important parameters affecting the biofuel efficiency [97].

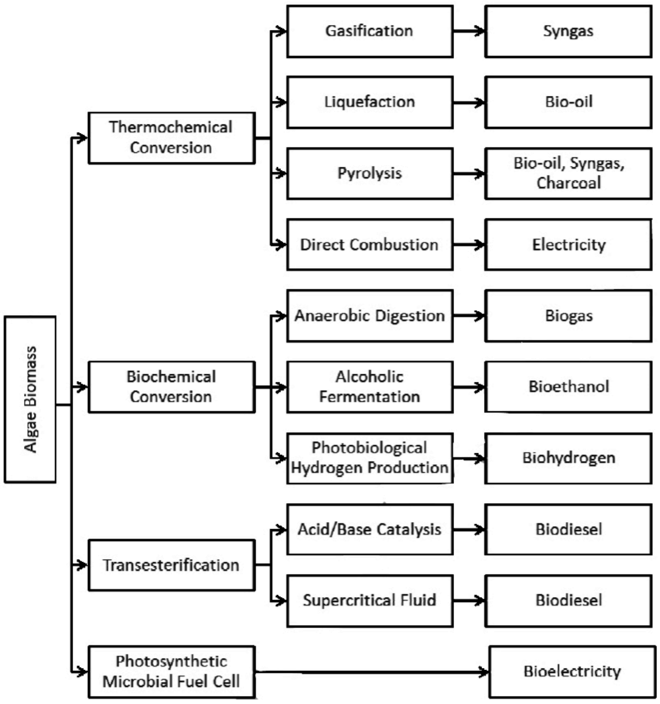


Table 4. Conversion of Microalgae Biomass to Biofuels [95].

Microalgae harvesting can be performed daily by centrifugation, filtration, flotation, precipitation or ultrasound techniques. [15,28]. The composition of the extracted biomass may vary, but is generally in the form of a composition comprising about 15% carbohydrate and 10% ash or waste, with a protein / fat ratio of 2/1. The fat component is converted to biodiesel and the untransformed biomass is separated. Non-oil biomass can be used for fertilizer, animal feed and other auxiliary products. The waste nutrients in the system are removed from the water and recycled to produce biomass. Part of the used up biomass is used to produce electricity which is spend during biomass production or to produce biogas by anaerobic digestionExcessive electricity can be stored in batteries or sold to the city grid. Photovoltaic cells can also be used to protect the electricity generated by the microalgae system. Waste from anaerobic digestion can be used as a nutrient rich fertilizer. Hydrogen gas is also released from microalgae biomass. But as a source of hydrogen, micro algae are still under investigation and development. So far, microalgae hydrogen production methods have been able to produce only small amounts of hydrogen from algae [15].

Erayies [15] has schematically expressed all inputs and outputs of the process from microalgae to energy production and conversion to other products (Fig.8).

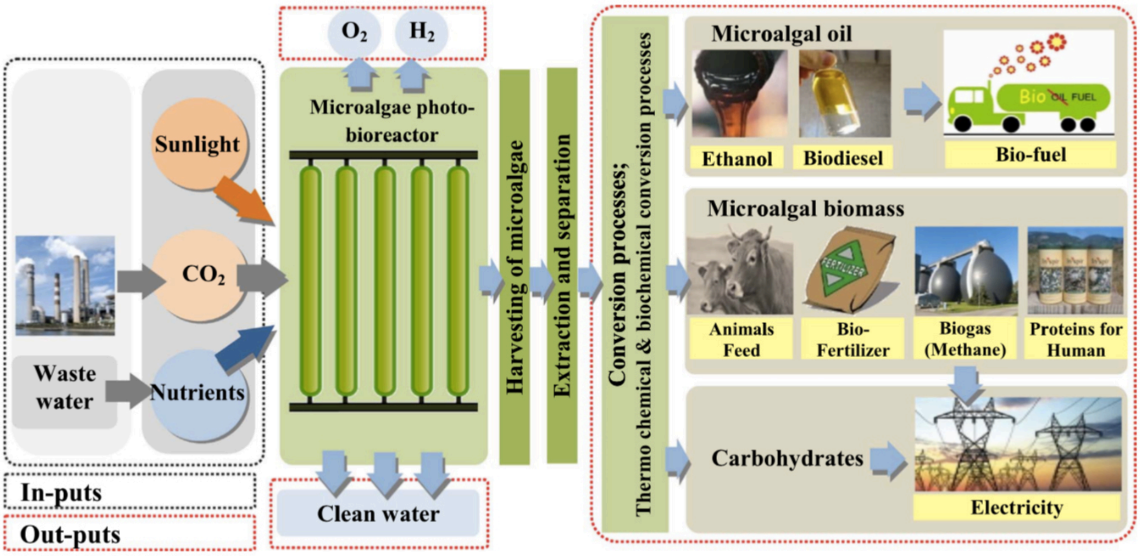


Fig. 8. The Obtaining Of Bioenergy From Microalgae And The Transformation Of Other Products [15].

Oil is extracted by drying microalgae. After oil extraction, anaerobic fermentation of the high organic content algae sediment is carried out. Thus, biogas energy is obtained from the high organic matter content of the microalgae used for biodiesel production [16]. Biogas conversion to biogas produces electricity that can be reused for microalgae cultivation. Thus, biodiesel, biogas, animal feed and electricity are produced from the microlites at the same time (Fig. 9).

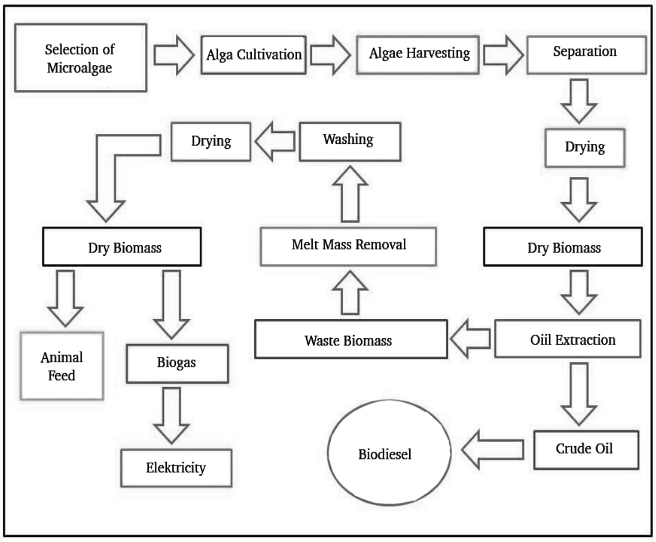


Fig. 9. Schematic representation of the harvesting process following the cultivation of microalgae in photobioreactors [16].

4. Algae Architecture and Evaluation Criteria

With the examples of integration of microalgae into architecture are examined, it has been determined that they are used in architecture in three different ways as building facade integrated photobioreactors, singular illustration photobioreactors and holistic urban photobioreactors. Under this title, the following 4 projects which are integrated to the building facades, 3 urban scale photobioreactor implementations and 3 projects from individual installations; so, totally 10 algae architecture projects, were examined.

- Photobioreactor applications integrated to building facades.

1) B.I.Q House, Hamburg, Germany
2) Algae Textile: A Lightweight Photobioreactor for Urban Buildings
3) Photo.Synth.Etica, Dublin, Ireland
4) Process Zero Concept Building, Los Angeles, California, USA

- Holistic urban algae photobioreactor approaches

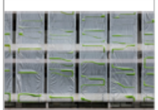
1) Carbon T.A.P. (Tunnel Algae Park), Philadelphia, USA
2) Culture Urbaine, Geneva, Switzerland
3) AlgaEnergetic City İstanbul

- Individual expression photobioreactor installations

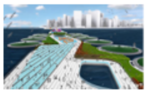
1) Urban Algae Canopy, EcoLogicStudio
2) Street Lamp, Pierre Calleja
3) Living Things, Jacob Douenias +Ethan Frier

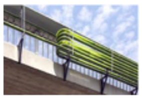
Building Facade Integrated Photobioreactor Designs		B.I.Q House - Hamburg, Germany	
Explanation	**Evaluation Criteria**	**Positive**	**Negative**
 Flat Panel Photobioreactor	**Photobioreactor Type**	The photobioreactor panels used as secondary facade provide controlled sunlight with shading.	The flat panel photobioreactors, which are placed from the floor to the ceiling as secondary facade, prevent the user's view when they are completely filled with algae.
		Double-skinned facade panels provide heat and sound insulation for the building.	The photobioreactor panels, which are used as secondary facade elements, have added extra load to the existing structure system due to their weight.
		Tubular and flat panel photobioreactor types have been tried in the project design. Flat panel photobioreactors have more efficiency than tubular photobioreactors.	Excessive amount of algae accumulation in the corners of the panels is a problem for cleaning. Although it is an irrigation system for cleaning, the cleaning of the mass accumulation in the panel corners can be done by hand, not by the mechanical system
		Flat panel photobioreactors require less maintenance than tubular photobioreactors.	There are technological concerns about contamination and leaks during the working period of photobioreactor systems. Possible leaks and technical failures can cause problems for human and environmental health. Any damage or leakage may cause bad smells.
53.5° North Hamburg Germany	**Location**	Due to the fact that the area is not too hot, The temperature inside the photobioreactor could be prevented from falling below 5 ° C in winter and above 40 °C in the summer.	In very hot days, when the effect of sunlight could not be controlled, degradation in microalgae culture was detected due to overheating.
		The building reduces CO2 emissions by 6 tons every year and absorbs 2.5 tons of CO2. The photosynthetic building clears the air by releasing O2 to the atmosphere.	Sunlight is converted to bioenergy in 10% and to heat in 38% efficiency. This situation is not sufficient for a fully sustainable structure design criteria.
Heating Energy by Biogas Production & Hot Water Supply From Photobioreactor System And Geothermal Boreholes	**Proposed Operational Model**	Due to the heating feature provided by the photobioreactor system, excess heat is directly used for hot water supply. Hot water can be supplied to all flats in the building.	Although the original plan predicted the use of photovoltaic panels on the roof surface, this could not be implemented. All necessary electricity for the building is withdrawn from the city grid. Only one of the 15 available apartments can be supplied with electricity generated in the system.
		In order to be used in cases where necessary, stored excess heat is stored on the ground with geothermal boreholes.	The biogas production process, in which energy production takes place, cannot be implemented inside the building and can be done outside. Arising transport costs are not economical.
		Holistic operation system works automatically. Thus, when there is a significant problem intervention can be done quickly.	It is seen that, 4-floor building needs a 1/4 scale of normal plan size technical room. This extra space requirement is important problem in terms of functionality.
		The waste water of the toilet is used for algae cultivation and recycled.	The building scale application cannot be integrated into the infrastructure of the existing region and therefore it has to work individually. This situation brought with additional economic difficulties and lack of technical equipment. The photobioreactor system costs more than other renewable energy sources in terms of initial installation and operation.

Building Facade Integrated Photobioreactor Designs		Algae Textile: A Lightweight Photobioreactor for Urban Buildings	
Explanation	**Evaluation Criteria**	**Positive**	**Negative**
Membrane PBR 	**Photobioreactor Type**	Due to the fact that the photobyoreactor can be designed in the desired geometry, the problem of limiting the user view can be eliminated. The structure of the photobyoreactor provides sunlight control	The mobility required for microalgae growth is limited. Therefore, degradation of culture and death of microalgae cells can be observed.
		The lightweight and flexible structure of the membrane material does not cause extra load to existing structural system.	Produces lower efficiency biomass compared to industrial photobioreactor types
		Algae Textile has a system, small parts, small scale support systems which can be assembled in factories and then can be constructed in the field with less work load.	In areas where the photobioreactor system is constricted during mass transfer because of the photobioreactor geometry, algae accumulation may cause difficulties in cleaning.
Unspecified	**Location**	No location has been expressed for the proposed design and the applicability to all buildings on urban scale has been stated.	Due to the polyethylene structure, the photobioreactor can tear in climatic zones where the weather is heavy. This has been neglected in the design.
Waste Water Treatment & Biomass Production	**Proposed Operational Model**	It is stated that it can be integrated not only in new buildings but also in existing urban building systems.	In the proposed design, after microalgae cultivation, harvesting processes and biomass production will be solved in technical rooms inside the buildings. In this case, the extra technical volumes that should be added to the existing buildings in the integration may not occur in terms of structure functionality.
		No operational model has been proposed in the design context. It is stated that the data and needs will change according to the project scale. Potential algae benefits are stated to be obtained such as waste water recycling, oxygen production as a result of carbon emission and biomass production from microalgae.	Considering the integration of the system into the architecture, it was emphasized that attention should be paid to the integration to the existing urban infrastructure and mechanical infrastructure, but no solution proposal could be developed.

Building Facade Integrated Photobioreactor Designs		Photo. Synth. Etica , Dublin, Ireland	
Explanation	**Evaluation Criteria**	**Positive**	**Negative**
 Plastic Bag PBR	**Photobioreactor Type**	Due to the fact that the photobyoreactor can be designed in the desired geometry, the problem of limiting the user view can be eliminated. The structure of the photobyoreactor provides sunlight control.	The wide range of motion observed in the panel and tubular industrial photobioreactor types is not captured here. The mobility required for microalgae growth is limited. Therefore, degradation of culture and death of microalgae cells can be observed.
		The lightweight and flexible structure of the membrane material does not cause extra load to existing structural system.	In areas where the photobioreactor system is constricted during mass transfer because of the photobioreactor geometry, algae accumulation may cause difficulties in cleaning.
53° North Dublin İreland	**Location**	Due to the fact that the area is not too hot, The temperature inside the photobioreactor could be prevented from falling below 5 ° C in winter and above 40 °C in the summer. Due to the shape of the sunlight can use efficiently.	Due to the polyethylene structure, the photobioreactor can tear in climatic zones where the weather is heavy. This has been neglected in the design.
Photosynthesis & Small Scale Biomass Production	**Proposed Operational Model**	The system absorbes 2.2 kilograms of carbon dioxide from the air per day and this corresponds to the carbon behavior that 20 trees can make. The plant, which consists of 16 photobiopractor modules, uses daylight to grow the microorganisms that capture the carbon dioxide molecules and supplied oxygen and cleaned the air.	Although it has a more aesthetic structure in terms of design compared to industrial photobioreactor types, the complex working principle of photobioreactors has not been evaluated in this project. The concepts such as biomass energy, heating and electrical energy of the building which can be obtained from the photobioreactor system have been neglected. Only a living plant has the mission of cleaning the air in the property. Microalgae growing in panels are collected by simple methods and biomass is obtained.

Building Facade Integrated Photobioreactor Designs		Process Zero Concept Building, Los Angeles, California, USA	
Explanation	**Evaluation Criteria**	**Positive**	**Negative**
	**Photobioreactor Type**	Tubular photobioreactors with 25%, 60% and 80% openings were used on the facade of the building. In this way, photobioreactors were evaluated as sun shading and they did not restrict the user's view as flat panel photobioreactors.	The photobioreactor panels, which are used as a secondary facade element covering an area of 2,322,5 m2 on building, have brought additional load to the existing structure system due to their weight.
		Double-skinned facade panels provide heat and sound insulation for the building.	There are technological concerns about contamination and leaks during the working period of photobioreactor systems. Possible leaks and technical failures can cause problems for human and environmental health. Any damage or leakage may cause bad smells. The possibility of leakage in tubular photobioreactors is higher than flat panels.
Tubuler Photobioreactors		The photobioreactor system provides 9% of the energy needs of the renewed office building. The microalgae photobioreactor system combined with photovoltaic panels reduced the overall energy demand of the building by 84% rate.	The tubular photobioreactors are handicaped for cleaning compared to flat panel photobioreactors due to their curved structure. Excessive amount of algae accumulation in the corners of the tubes is a problem for cleaning. Although it is an irrigation system for cleaning, the cleaning of the mass accumulation in the panel corners can be done by hand, not by the mechanical system
34° North Los Angales, California USA	**Location**	The project proposal is considered as a renewal of an existing structure. In the present situation, solar tubes were placed in the structure which could not use sunlight and all units were provided with sunlight. The coordination of the project area is between 37 ° North and South latitudes, which are determined as the study area suitable for microalgae photobioreactor systems. It is planned to make the best use of climate conditions.	In very hot days, when the effect of sunlight could not be controlled, degradation in microalgae culture was detected due to overheating. It is thought that the system which has less efficiency than flat panel photobioreactors will have more maintenance and repair problems.
Heating Energy With Photovoltaic Panels & Hot Water Supply From Photobioreactor System And Geothermal Boreholes & Biomass Production	**Proposed Operational Model**	The waste water of the toilet is used for algae cultivation and recycled.	The photobioreactor system is designed as an integrated system. However, in the project presentations, there are diagrams independent from the existing grid such as geothermal boreholes, obtaining electricity from microalgae and using the waste water of the toilet. An integrated design is offered to the existing structure, integration into the existing infrastructure has been neglected.
		In order to be used in cases where necessary, stored excess heat is stored on the ground with geothermal boreholes.	The biogas production process, in which energy production takes place, cannot be implemented inside the building and can be done outside. Arising transport costs are not economical.
		The photovoltaic panels placed on the roof of the building are directly used for hot water supply. It is stated that hot water can be supplied to all flats in the building. While there is no detailed information about the warming principle of the building, the diagrams shows that electricity is obtained from the photobioreactor system. However, it is not stated how the operational system is will be.	The building scale application cannot be integrated into the infrastructure of the existing region and therefore it has to work individually. This situation brought with additional economic difficulties and lack of technical equipment. The photobioreactor system costs more than other renewable energy sources in terms of initial installation and operation.

Holistic Urban Photobioreactor Designs		Carbon T.A.P. (Tunnel Algae Park), Philadelphia, USA	
Explanation	**Evaluation Criteria**	**Positive**	**Negative**
 Tubuler PBR	**Photobioreactor Type**	In the project, the artificial use of tubular photobioreactors on a wide area of agricultural and industrial size has been proposed. The artificial algae farms placed on the ocean can achieve high efficiency with large surface volumes.	Although the aesthetic damage of the large area on an ocean within the urban area of the proposed system is attempted to be reduced by walking paths, parks and public spaces, it is a negative situation in terms of large area occupation and the establishment of large systems used in agricultural lands in crowded areas of the city.
39° North Philadelphia USA	**Location**	The idea of creating a urban focal point and social space connected to the Brooklyn-Battery tunnel ventilation system has been proposed. A holistic mechanical system providing energy efficiency has been proposed, and this holistic system has been shown to benefit not only the infrastructure and technical aspects but also social benefits.	Ocean waves may damage the system. The whole mechanical system is outside so it brings difficulties according to weather conditions. These are neglected in the project.
Photosynthesis & Large Scale Biomass & A New Infrastructure Proposal & Energy production	**Proposed Operational Model**	This new infrastructure aims to produce oxygen, biofuels, bioplastics, nutraceuticals and agricultural feed, while using a proprietary industrial-scale algal farming system to limit and consume greenhouse gas emissions. The system connected to the Brooklyn-Battery tunnel ventilation system uses the carbon released by the vehicles in the tunnel. Provides oxygen to air. It also produces biomass with artificial algae farms on the ocean.	Major investments are required to renew and replace urban infrastructures on the basis of federal, state and local governments. This brings high costs. Nowadays, while the aim is to conceal and mitigate the urban infrastructure, the design here is external, need wide spaces.

Holistic Urban Photobioreactor Designs		Culture Urbaine, Geneva,Switzerland	
Explanation	**Evaluation Criteria**	**Positive**	**Negative**
 Tubuler PBR	**Photobioreactor Type**	The wide glass surfaces of flat panel and vertical column photobioreactors could easily be damaged by stone spills which is scattered from the cars on the bridge. Tubular photobioreactors have narrower surface area and due to horizontal positioning that have a protective effect on each other.	Inability to use the sun sufficiently situation may cause corruption of the microalgae in the culture. Some problems may occur such as inability of the sun may cause death cells.
46° North Geneva Switzerland	**Location**	Energy and food production in the city, on the motorways, on the streets, not outside the city provides preventing the wasted occupation of agricultural lands. So that carbon dioxide is a contaminant produced by automobile engines, the Geneva Motorway Overpass is the right choice.	Any intervention and microalgae bioproses can be difficult to control because of the project location. The status of a continuous traffic and the distance of the operating systems to the current area brings some problems as workload problems.
Photosynthesis & Small Scale Biomass & Food Supply & Energy Production	**Proposed Operational Model**	It absorbs the carbon from the vehicles passing by the highway and produces oxygen and cleans the air. Uses renewable energy. Offers a new infrastructure system. It can be used to create raw materials from motorway biodiesel, electricity, medicine, cosmetic products and even food. .	In the project, there is no solution for integration into existing infrastructure. The things which are needed for photobioreactor system like pumping, filtering, water and nutrient supply, and the extra space for the mechanical and chemical processes required for the harvesting of microalgae mass are important problems in terms of cost and aesthetics.

Holistic Urban Photobioreactor Designs		AlgaEnergetiCity Istanbul, Turkey	
Explanation	**Evaluation Criteria**	**Positive**	**Negative**
 Tubuler and Flat Panel PBRs	**Photobioreactor Type**	According to the project scenario, two different types of photobioreactor systems have been proposed as secondary façade elements according to the orientation of the high-rise buildings where the system will be applied and the situation of exposure to the sun. The proposed tubular photobioreactor system is intended to be modular or desirable, so that controlled sunlight is provided and photobioreactor systems are also intended to be used as sun shading. Flat panel photobioreactors have been recommended in areas where fully sun protection is required. Double-skinned facade panels provide heat and sound insulation for the building	The flat panel photobioreactors, which are placed from the floor to the ceiling as secondary facade, prevent the user's view when they are completely filled with algae. The photobioreactor panels, which are used as secondary facade elements, have added extra load to the existing structure system due to their weight. Excessive amount of algae accumulation in the corners of the panels is a problem for cleaning. Although it is an irrigation system for cleaning, the cleaning of the mass accumulation in the panel corners can be done by hand, not by the mechanical system. There are technological concerns about contamination and leaks during the working period of photobioreactor systems. Possible leaks and technical failures can cause problems for human and environmental health. Any damage or leakage may cause bad smells.
36° North Istanbul Turkey	**Location**	Due to the fact that the area is not too hot, The temperature inside the photobioreactor could be prevented from falling below 5 ° C in winter and above 40 °C in the summer. The coordination of the project area is between 37 ° North and South latitudes, which are determined as the study area suitable for microalgae photobioreactor systems. It is planned to make the best use of climate conditions.	Although the accumulation of calcium in the photobioreactor system is considered to be mostly manageable problems due to the hardness of the region's water, it may be necessary to reduce production in case of accumulation in pipes and to intervene in this process by monitoring. In very hot days, when the effect of sunlight could not be controlled, degradation in microalgae culture was detected due to overheating.
Photosynthesis & Heating Of Electricity And Biogas Production & Hot Water Supply From Photobioreactor System And Geothermal Boreholes & Holistic Microalgae System Proposal For The Whole City	**Proposed Operational Model**	Due to the heating feature provided by the photobioreactor system, excess heat is directly used for hot water supply. Hot water can be supplied to all flats in the building. In order to be used in cases where necessary, stored excess heat is stored on the ground with geothermal boreholes. The waste water of the toilet is used for algae cultivation and recycled. The project is considered to be a holistic approach rather than the evaluation of the microalgae system in a building scale. Capture of carbon from vehicles exhausts in bridges is offered. According to the morphological type of the city, the buildings where the facade system cannot be applied, it is suggested to use fertilizers that are produced from photobioreactors on the roof terraces.	The building scale application cannot be integrated into the infrastructure of the existing region and therefore it has to work individually. This situation brought with additional economic difficulties and lack of technical equipment. The photobioreactor system costs more than other renewable energy sources in terms of initial installation and operation. Microalgae photobioreactor systems needs piping and mechanical systems for pumping, mixing and cell transfer. In the project, the suggestion that these should be solved in the floor of the building or in the installations in the auxiliary walls contradicts the discourse of integration with existing buildings. However, it is possible to apply this to new buildings. In addition to the overhead, the piping and mechanical system, which will be hidden in the floor beside the load system, will increase the floor dimensions and application costs.

Singel Installation Photobioreactors		Urban Algae Canopy, EcoLogicStudio	
Explanation	**Evaluation Criteria**	**Positive**	**Negative**
Membrane PBR 	**Photobioreactor Type**	The flexible plastic membrane material of the photobyoreactor offers geometrical flexibility. The structure of the photobioreactor provides shading. The aim is to build a system that integrates with the green system of cities, helps to absorb carbon dioxide and produces oxygen, acts as a second facade of buildings, supports passive cooling, and enhances the shadowing of the facade.	The wide range of motion observed in the panel and tubular industrial photobioreactor types is not captured here. The mobility required for microalgae growth is limited. Therefore, degradation of culture and death of microalgae cells can be observed. In areas where the photobioreactor system is constricted during mass transfer because of the photobioreactor geometry, algae accumulation may cause difficulties in cleaning. Produces lower efficiency biomass compared to industrial photobioreactor types. It is thought that the system which has less efficiency than flat panel photobioreactors will have more maintenance and repair problems.
45° North Milano Italy	**Location**	It has been developed to showcase the central passageway of the Expo area in Milano, Italy. The designed installation provides shadow to the visitor. Cleans the air. Produces biomass.	In very hot days, when the effect of sunlight could not be controlled, degradation in microalgae culture was detected due to overheating. Due to the polyethylene structure, the photobioreactor can tear in climatic zones where the weather is heavy. This has been neglected in the design.
Lighting & Photosynthesis & Air Cleaning & Biomass & Renewable energ	**Proposed Operational Model**	Photobioreactor system recycles waste water. Absorbes carbon and produces oxygen. Provides biomass from microalgaes. It is stated that the storage and mechanical system of the photobioreactor system will be solved in the basement of the building. The recommended operation system for the algae tent is to clean the air and to benefit from the protein of the biomass it produces. The algae canopy removes 4 kg of carbon dioxide from the atmosphere every day and releases 2 kg of oxygen with the photosynthesis. The produced oxygen is enough for 3 adults to daily breathe. The protein produced by the microalgae is equivalent to the daily need of 12 people, the protein produced is equal to the amount of protein taken from 2 kg of meat per day. Algae canopy produces equivalent oxygen produced by 4 hectares of forested area. Every day, produces more than 150 kg of biomass which consists 60% of the natural protein.	The building scale application cannot be integrated into the infrastructure of the existing region and therefore it has to work individually. This situation brought with additional economic difficulties and lack of technical equipment. The photobioreactor system costs more than other renewable energy sources in terms of initial installation and operation. The biogas production process, in which energy production takes place, cannot be implemented inside the building and can be done outside. Arising transport costs are not economical. Although the canopy of algae is seen as inspiring in terms of sustainability and use of renewable energy, it is not yet possible to achieve the desired values and expected data, which are limited in practice in these small individual scales.

Singel Installation Photobioreactors		Street Lamp, Pierre Calleja	
Explanation	**Evaluation Criteria**	**Positive**	**Negative**
 Vertical Column PBR	**Photobioreactor Type**	The lamp is designed to store and use the energy generated by photosynthesis. Vertical column photobioreactors which have more volume than flat panel photobioreactors and tubular photobioreactors have been proposed. It has the ability to absorb at least one tonne of carbon from the air in one year.	It can be experienced as a result of the widespread use of whether the lamps designed with the singular approach can absorb much of the carbon dioxide at the individual level. What does not increase in the study is how much maintenance a photobioreactor needs. In the event of any damage or working disorder, the intervention will be hand-held.
Streets and Carparks	**Location**	It is designed modularly for using as car park lighting and urban area lightning. It is stated that by using lamps in the streets, Each lamp would make one ton of carbon emissions annually and help solve two social problems such as lightning and carbon increase at the same time.	Although the designer states that the lamp can be charged with the energy obtained by the photosynthesis and can work without any power supply, it is contradictory to use in the car parks with a non-sunshine closed area and use as artificial lighting. An extra power supply will be needed for artificial lighting. Although the mentioned feature is applicable in open spaces, this is a problem in closed areas.
Photosynthesis & Lighting & Air Cleaning & Small Scale Biomas	**Proposed Operational Model**	The designer proposes to use this photobioreactor prototype as a lighting element, not for energy production. The lamp can be used as a biofuel when it is separated from the water in algae culture	In order to use the produced biomass, the water of the culture in the lamp will have to be replaced at certain intervals. Manual control is laborious and impractical. When the studies are examined, the amount of electrical energy obtained from microalgae is very small and it is thought that the trillions of photosensitized cells will be needed for one hour to capture the amount of energy stored in a simple AA battery.

Singel Installation Photobioreactors		**Living Things, Jacob Douenias +Ethan Frier**	
Explanation	**Evaluation Criteria**	**Positive**	**Negative**
 Vertical Column Photobioreactor	**Photobioreactor Type**	It is intended to be used as interior lighting armature and furniture. Instead of non-aesthetic industrial geometries such as tubular, flat panel, more valuable shapes have been tried in the context of architectural decoration and aesthetics. Vertical column photobioreactor geometries have been differentiated in order to be used as illumination element. A design is obtained near the globe in geometry. Thus, the large volume advantage of vertical column photobioreactor types was evaluated. The aim is to illuminate more space and to obtain more biomass on a small scale.	The amount of carbon dioxide released by the user may not be sufficient for the use of photobioreactors. In cases where it is not enough, the additional carbon supply will bring extra cost and workload. Here, it can be experienced whether the lamps designed with a singular approach can absorb much of the carbon dioxide individually at the said level can be experienced as a result of their widespread use. What does not increase in the study is how much maintenance a photobioreactor needs. In the event of any damage or working disorder, the intervention will be hand-held.
Interior	**Location**	Photobioreactor designs, is designed for offices, apartments etc. in all kinds of interior spaces as lighting armatures	Photobioreactors which designed as lighting elements are not practical because of their large volume in interior space.
Lighting & Photosynthesis & Air Cleaning & Small Scale Biomass	**Proposed Operational Model**	It is aimed to increase the indoor air quality by absorbing the carbon which is emitted by the user and releasing oxygen. It has a working principle similar to the working mechanism of other photobioreactors. The designer proposes to use this photobioreactor prototype as a lighting element, not for energy production.	As a result of the microalgae growth, the volume of the culture medium in the lamp will have to be changed at certain intervals in order to ensure the re-use of the filled volume and to use the resulting biomass. Since the principle of working with any mechanical monitoring system will affect the transportability and applicability to each area in terms of design, manual control is a laborious and impractical situation. This contradicts the aesthetic perception of the interior design.

4.1. Evaluation Criteria for Algae Architecture Difficulties

As a result of the evaluation of academic studies, the architectural applications and design ideas in architecture and sustainability, the use of microalgae in architecture has many contributes like reducing carbon emission, supplying oxygen to the atmosphere, biomass producing and bioenergy supply by using renewable energy, waste water recycling, sun protection and controlled sunlight usage. Besides them, it is seen that the problems which need to be taken into consideration. In this section; in order to overcome the difficulties arising from the integration of microalgae into architecture, evoluation criterias are determined to design photobioreactor systems which are based on the holistic working principles and selected algae architecture projects are classified and compared according to these evaluation criterias and signified with table. According to the usage in architecture, algae architecture examples; It is observed that changes according to the photobioreactor type used in the design, the location where the project is applied and holistic operating system of the project in the form of design scenario. These differences have positive and negative returns to projects and designs. Considering the negative conditions within the scope of the study, problems to be taken into consideration for future studies related to integration of photobioreactor systems into architecture are determined.

4.1.1. Submitted Photobioreactor Type

Due to the technical characteristics of the selected photobioreactor type such as additional load to the structural system, limitation of view for the residents, cleaning, maintenance and repair problems have been identified.

4.1.1.1. Additional Load to The Structural System

Considering the integration of the system into an architectural structure, the additional load to the existing structural system is a problem for the building. Microalgae photobioreactor systems were found to be integrated in the existing buildings as a secondary facade proposal in building scale or additional secondary material to the bridges in urban scale. In the stations photobioreactor systems used as a secondary facade, occurred extra weight to the load system of a structure which continues its current activity should be calculated again. Because, the weight of the microalgae panels will increase with the cultivation of the moving culture over time and the environmental loads such as wind, rain and snow will be added to this additional weight in variable periods. The additional weight added to the façade will require additional strength on the walls of the existing structure and may incur additional costs. An approach to minimize this would be the use of lightweight building materials in photobioreactor designs. Bogias Petra [98], in her proposal, proposed a lighter and more cavity photobioreactor façade design that could solve both situations by considering the extra weight load and limitations of the user's view.

4.1.1.2. Limitation of View for The Resident

As a result of the comparative studies between samples, the most important issue affecting the user view is the type and geometry of the photobioreactor used in the design. The photobioreactor installations used as double-facade elements provide ease of shading by integrating into the building facades as well as the permeability of the panels decreases with the time that the microalgae grows in the system and fills the transparent panels as a result of the first algae cultivation. This is due to the structural and operational conditions of photobioreactor system and it is a negative condition for user comfort. It is an important design problem according to architects. For this reason, The photobioreactor geometry, which does not limit user view, should be selected when installing photobioreactor applications on building facades or it should be noted that the structure should be evaluated in parts which will not obstruct the user's view. In designs where flat panel photobioreactor systems are preferred, this is much more inconvenient. Here, the flat panel photobioreactors placed in front of the façade from the floor to the ceiling completely obscure the user view when the panels are filled with microalgae. As a result of algae architecture examples, the use of tubular photobioreactors as secondary facade restricts the view of the user, but it can be increased by decreasing the diameter of the tubes and increasing their distance between each other. Thus, controlled sunlight is provided, such as a solar panel. Therefore, it is thought to be more useful in terms of architectural aesthetics.

4.1.1.3. Cleaning and Maintenance Problems

It has been mentioned by designers that photobioreactor systems have technological concerns about contamination and leaks throughout the working period. The point is that some algae (such as cyanobacteria) contain hepatotoxins and neurotoxins, which are all harmful for human health [99]. For this reason, possible leaks and technical failures can cause problems for human and environmental health. When the samples are compared, the possibility of leakage according to the type of photobioreactor varies. There is a possibility that there may be more leakage of tubular photobioreactors than tflat panel photobioreactors. In addition, any damage or leakage may cause bad smells [100]. Therefore, although there are many environmental benefits arising from the technology brought by the system, there are also problems in the design of the fully mechanical system due to possible technical failures.

Cleaning of glass panels or pipes is another technical matter. Wilkinson et al. [100]; stated that the techniques used to clean the inside of photobioreactors can be solved with the references taken in the aquarium design and the measures taken against cleaning. Control of cleaning of photobioreactor panels is done by computer systems. Excessive amounts of algae may accumulate in the corners or areas where the water flow used for cleaning is insufficient.But the necessary intervention is best done by hand.This can cause problems with cleaning. B.I.Q. Wilkinson et al. [100]; they stated that such a cleaning in the upper floors of a multi-storey building would increase the maintenance costs. As a proposal to reduce the responsibility for cleaning, they stated that special glasses with low friction coefficients should be used to reduce algae death due to algae accumulation. In addition, they stated that optimum working conditions can be achieved by watching computer monitoring systems regularly. As a result, they have proposed innovation opportunities in glazing technology

4.1.2. Compatibility to The Location

The location chosen for the integration of photobioreactors into architecture is as important as the type of photobioreactor. Sierra [61] stated that one of the most important factors determining the efficiency of a photobioreactor system is the location and orientation of the reactor. According to the preferred location, the amount of sunlight usage and durability to the weather conditions of the photobioreactors which are used in exterior can be varied. This causes significant changes in the photobioreactor efficiency.

4.1.2.1. Accordance and Solidity to The Weather Conditions, Climate and Sunlight Utilization

As seen in the algae architecture examples, photobioreactor systems are in contact with the outdoor weather conditions by requiring sunlight and using CO_2. For this reason, ability and durability of photobioreactor systems according the weather conditions are also an important problem. Considering this context, affecting from the weather conditions should be considered together with the utilizing the sunlight and battling with the climate change. The problems that may be occurred based on photobioreactor geometry and more or less sunlight exposure according to the location should be considered such as darkening, fouling, adhesion and damage. According to the latitudes where the building is located, the rainy and sunny days should be considered as a return of the climatic conditions and all materials considered for the system should be evaluated separately for each project in For example; if the B.I.Q House built in a location where is warmer and have more sun utilization than Hamburg, Germany, It could be expected to achieve in higher biomass production rates. In this case, more biomass product recovery would result in increased storage space requirements, more frequent cleaning requirements, more maintenance and repair needs, more costal requirements and faster operating condition needs. For the building in Hamburg [101] is not a problem due to the lack of sufficient sunlight and maintenance in the winter, but it may be possible to degrade the culture medium due to overheating of photobioreactors in another climate zone. If there are several cloudy days consecutively according to the weather conditions of the region, handicaps that may be experienced should be considered if the changing routine cannot be controlled. Therefore, there will be a need for computerized monitor systems that control the system and enable it to operate. The water used will have different properties in different regions . Because some areas have hard or soft water. Where hard water areas, calcium may be stored in photobioreactors. This is generally accepted as a manageable problem. If the water accumulates in the pipes, the production rate may decrease. In such cases, it is necessary to intervene with the monitoring process.

4.3. Selected Operational Model

When the examples of usage in architecture are examined; The operation of the photobioreactor system begins with the supply of nutrients, water, light and CO_2, and microalgae grow and multiply in the culture. The working mechanism continues with microalgae production and collection and extraction processes. After that microalgae harvesting proscess begins. Biogas, biodiesel, electricity and heating energy from microalgae biomass are obtained according to the design scenario of the project. This refers to holistic microalgae bioprocess.When the algae architecture examples are compared, it is seen that the working scenarios vary according to the architectura design where the photobioreactor systems are integrated. This holistic working principle can only take place on a building scale, in a single installation or on an urban scale. The microalgae bioprocess, combined with the design scenario of the project, constitutes the operating model of the algal architecture system.

4.3.1. Initial and Operating Costs

When the examples of usage in architecture are examined; The operation of the photobioreactor system begins with the The use of microalgae as a photobioreactor façade element as a renewable energy source is more costly than other renewable energy sources compared to building systems such as solar panels and wind turbines. In order to provide the same amount of energy, microalgae photobioreactor façade elements to be integrated into the system were found to be disadvantageous in terms of installation and operating costs compared to other integrated systems. Other renewable energy sources have been used for many years and more research and development studies have been carried out on the developing technology. Microalgae systems are still very new and have not been sufficiently studied, and also a living organism is used and because of these reasons, it is much more expensive and less efficient as a result of difficulties such as maintenance, repair and cleaning after installation. The hollistic operation system which is needed after the installation of microalgae photobioreactor systems can be processed; the need for harvesting and bioprocessing after microalgae growth requires extra cost. Photobioreactor systems integrated to the building facades, urban scale photobioreactor installations and singular photobioreactor applications are compared with each other; as the application scale increases, the required infrastructure and the necessity of the holistic application, which is the return of the operating system, increases the cost. Thus, single installations can be solved at the most cost-effective, while building-scale approaches are more costly than single installations. The integrated systems in the city will need the highest economic expense in this comparison. The first applied microalgae photobioreactor facade building, B.I.Q. House building cost about 5 million Euros according to the figures announced by Arup. This is a very high amount in Germany for the construction of a 4-storey building. According to Wilkinson et al. [100], the microalgae photobioreactor system now has an initial cost of US $ 2,300-3,300 / m^2 and this rate may increase according to the size of the project.

4.3.2. High Space Requirements of Storage and Operating Systems

In the case of technical details and operation of the system; the need for storage and operating systems can be a problem in terms of functionality. As seen in the algae architecture examples, microalgae harvesting where all mechanical processes where the system cycle is performed, as the pipe ducts of the system and all operations such as computerized tracking units that provide automatic control cannot yet be solved in the building floor in practice. Thus extra space requirements are required. This situation restricts the architects in order to realize the most suitable design in terms of functionality and usability in the arrangement of the space. With the examination of B.I.Q House, it is seen that, 4-floor building needs a 1/4 scale of normal plan size technical room with machines and piping systems for storage and mechanical systems. Compared to other renewable energy sources, this situation constitutes an important problem in architecture.

4.3.3. Supplying limitations to the common infrastructure of The Zone According to Recommended Holistic Algal Bioprocess

If the applicability of this system in architecture considered with how the operational model would be, some problems may occur. As seen from the alga architecture examples examined, although the emergence discourses of design and applications are expressed as a holistic contribution to the built environment, all samples are expressed with their own operating models. The designs is evaluated only in theirselves and the designs are not considered together with the urban infrastructure of the project locations. Problems such as geothermal boreholes where hot water is stored, biogas production facilities where energy production occurs, transportation costs arising from the location of the biodiesel production refineries according to the location of the building, economic difficulty of rebuilding in case of lack of infrastructure and lack of technical equipment can be an obstacle to the full capacity of the system. For this reason, different operational model proposals have emerged according to the application scenarios for each project. This makes it necessary to review the existing infrastructure and energy operating systems, and to work them compatible with microalgae photobioreactor systems. Nowadays, all of the other renewable energies such as solar and wind energy, which are more preferred, produce more energy than microalgae and are compatible with the existing infrastructure. Wilkinson et al. [100], reported using solar panels to produce approximately 1400 kwh / m^2 / year of energy in Australia. These energy values are about 40 times more than of B.I.Q. House in Hamburg, Germany.

5. Conclusions and Suggestions

With the use of photobioreactor systems as a secondary facade element in buildings, supported by environmentally conscious approaches on a single scale and the integration of them to cities with innovative approaches on micro and macro scale; It has been seen that it provides many benefits such as energy conservation, air supply to the atmosphere with oxygen supply as a result of emission of harmful carbon in the air, production of biofuels with the use of renewable energy and recycling of wastewater. But in the integration of photobioreactor systems into architecture; some problems such as high cost of implementation compared to other current renewable energy sources, additional load brought to the carrier system, potential to be affected by climatic conditions, limitation of user view brought by the physical property of the system, the need for large storage and operation demands of the photobioreactor system, lack of urban infrastructure to respond to design proposals of the region where the project is implemented have been identified.

Over the years, the use of photobioreactors on the facades is expected to continue to increase with the technological developments. Among these developments, the structural progress of the facade technologies and the studies on renewable energy and the problems described in this study can be overcome. The integration of the photobioreactors into the structure can not only be used as a double-facade, but can also be devised and designed with the structure to develop innovative system details. Photobioreactors can be used in different building types by using more practical and different materials, developing with different joining shapes and increasing energy efficiency, thus increasing their preferability. It has been seen that photobioreactors are integrated to the facades of the building, as a symbol of urban installation and by being supported with interior design. This situation demonstrates a holistic sustainability approach that can incorporate the whole city with the integration of photobioreactors designed using microalgae. With detected evaluation criterias this dissertation can be considered as an informative addition to the idea for algae architecture. The unrivaled benefits of algal photobioreactor systems through the combination of biological and chemical cycles in architecture will bring an innovative approach to renewable energy architecture by integrating environmental design values into the architecture and will shed light on future studies.

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