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Microalgae: Prospects for greener future buildings

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ABSTRACT

As a result of the growing global demand for energy, together with the depletion of resources and the growing emphasis on mitigating climate change and greenhouse gas emissions, an urgent need for an evolution of the renewable energy resources has emerged. On the architectural scene, we have become accustomed to seeing buildings incorporated with photovoltaics and wind turbines. Despite the great contribution of biomass as a clean energy producer, the integration of biomass into architecture is quite modest and still in its initial phases. Microalgae, as a plant-based biomass, can outperform other renewable resources with their potential to absorb CO_2, recycle wastewater, and release O_2. The limited experience regarding building-integrated microalgae photobioreactors (PBRs) requires shedding light on some issues. So, this paper aims to explore the following: 1) the proper types of PBRs for integration with buildings, 2) the overall bioprocess and the design considerations regarding PBRs and their technical requirements, 3) the environmental and energetic performance of PBRs, 4) their challenges, and 5) their prospects. Thus, the paper's methodology consists of 1) reviewing the promulgated literature concerning microalgae and PBRs, 2) reviewing and analyzing three building-integrated PBRs and three urban-integrated PBRs, and 3) reviewing the environmental and energetic performance of building-integrated PBRs. The paper has concluded that the symbiosis between PBRs and façades encounters some challenges, including 1) the biorefinery infrastructure, 2) the provision of a source of CO_2, and 3) the high initial cost. On the other hand, the multifaceted environmental prospects of building-integrated PBRs are represented in 1) energy savings; 2) GHG emissions reduction; 3) oxygen and hydrogen release; 4) biofuel production; and 5) wastewater treatment. The unique benefits of the bio-façades through the combination of the technical and biological cycles within buildings inaugurate an innovative approach to sustainability by integrating environmental, energetic, and iconic values.

1. Introduction

Energy accounts for two-thirds of total greenhouse gas emissions, and 80% of CO_2 alone. Any effort to reduce emissions and mitigate climate change must include the energy sector [1]. According to 2013 estimates, the fossil fuel energy share is about 78.3% of global final energy consumption [2]. Furthermore, fossil fuel is a big contributor to CO_2 emissions, which has been directly linked to global warming [3]. Energy crises beginning in the 1970s and the growing emphasis on mitigating climate change have contributed to the growth of renewable technology production and its related supporting policies [4,5].

Despite the world shift towards the production of energy from renewable resources, the estimated share of global electricity production from renewable energies accounts for only 22.8%. Among this percentage, the share of solar and wind energy accounts for 0.9%, and 3.1%, respectively, while bio-energy (energy from biomass) accounts for 1.8% [2]. Although biomass demand continue to grow steadily in the heat, power, and transport sectors [4] and despite the large role of biomass resources in developing and emerging economies, the contribution of biomass is relatively small [6].

The building sector consumes up to 40% of the total energy consumption and contributes to up to 30% of the global annual GHGs emissions. Furthermore, GHG emissions from buildings are expected to double over the next 20 years. Therefore the mitigation of GHG emissions from buildings must be a cornerstone of every national climate change strategy [7]. Holistic approaches must be adopted to improve building energy performance. That comes by addressing all the aspects of efficient building design in a way that optimizes the overall performance [2].

Biomass is a promising eco-friendly alternative source of renewable energy [8]. It has great potential for the production of bioenergy and bioproducts [9]. Accessing energy-based biomass promises to reduce the depletion of resources, especially fossil fuels [10]. Nevertheless, the sustainability concerns associated with the use of biomass are still under discussion, especially where related to deforestation, and with land and water competing with food [4]. When we talk about biomass,

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we talk about traditional biomass (fuelwood, crop residues, food crops and animal dung), and modern biomass (organic waste, energy crops, and algae). Approximately 60% of the total biomass used for energy purposes is traditional biomass, which is currently used primarily for cooking, heating, and lighting in remote and rural areas of developing countries by combustion in open fires or inefficient stoves. Hence, sustainability concerns associated with the use of traditional biomass continue to be debated and there is doubt about the use of biomass being truly carbon neutral [3,4]. Modern biomass is used for modern bioenergy [4]. However, the technology to produce energy from modern biomass is still being developed [3].

Algae, the earth's oldest organisms, can help address all these major issues. Feeding from light, mineral salts, and carbon dioxide, algae grow into a biomass that can then be treated to create biofuel and other bioproducts. Moreover, they absorb carbon dioxide from the atmosphere, produce oxygen, and filter air and water [11].

Many scholars and designers have integrated solar energy and wind power into their research, designs, and projects, while other renewable resources applications in architecture, such as biomass, are still limited. The integration of algae, as a modern energy-based biomass, into architecture is still in its initial stage. So, the paper provides an overview of integrating microalgae into architecture, along with the techniques and requirements, efficiency, prosperities and challenges, as a promising source of bioenergy.

Vertical façades can become smart photosynthetic surfaces that respond to the current state of climate warming [12]. According to Carlo Ratti, microalgae are 10 times more efficient photosynthetic machines compared to large trees and grasses [13]. Integrating microalgae into buildings' façades can increase their passive performance. microalgae can act as a building-integrated part of creating healthy and livable buildings [12]. It promises to transform the envelopes of buildings into factories of energy [14].

2. Materials and methods

The first main point of this study is to investigate and explore the use of biomass as a renewable source of energy in architecture apart from common renewable resources such as wind power and solar energy. This has led to the revelation of microalgae as modern energy-based biomass resources and their unique potential as sustainable bioenergy resources. That is alongside the potential of the symbiosis between buildings' façades and microalgae that is represented in photobioreactors (PBRs). These findings, consequently, have led to the advent of some questions;

- What are the different types of photobioreactors? How can PBRs be integrated into buildings?
- What are the criteria that control the design of PBRs?
- What are the technical requirements for the inclusion of PBRs in buildings?
- What are the anticipated prospects from this technology?
- What are the challenges that confront the inclusion of this technology into buildings?

The constructed methodology to answer these questions consists of three parts.

First, this paper introduces a theoretical background of biomass as a renewable source of energy and its related terms, feedstock, bioenergy, biofuel, and microalgae. This part sheds light on the types of bioreactors, and the most appropriate designs to be integrated into buildings on the basis of the literature.

Second, this paper reviews and analyzes six microalgae-powered projects in terms of PBR façade design, *building services system,* and PBR efficiency. Three of them are on the building scale, and the other three are on the urban scale.

The **third** part is to investigate the overall viability of PBR façades through reviewing the literature regarding daylighting performance, potential visibility, thermal performance, *acoustical* performance, capital costs, environmental viability, and the aesthetics of PBRs façades. **Finally**, the results are organized in terms of the technical requirements of building-integrated PBR façades and their prospects and challenges.

3. Biomass and biofuel generations

Biomass is a renewable energy source that can be converted to other forms of energy, such as electricity, heat and biofuel, while feedstock is the term used for biomass that is used to produce biofuels [15]. Biomass feedstock can be found wherever plants and animals live. Feedstock refers to crops, residues, and other biological materials that can be used in the production of biofuels, including the two main types, biodiesel and ethanol. Sugarcane, grains, and corn, feedstocks for ethanol, must be fermented with fossil-fuel heat. In contrast, biodiesel is a clean-burning fuel obtained from the vegetable oils of plants such as soybeans, oil palms, jatropha and algae. These oils can be burned directly in diesel engines to produce biofuel [11].

Biofuels are renewable energy resources that ultimately don't contribute to global warming [16]. The development of biofuels is classified into three generations according to their feedstock [17], which will be summarized below.

Like wind energy, solar energy, and the other renewable energies, biomass can contribute positively to decreasing climate change impacts by lowering dependence on fossil fuel as a source of energy. However, biomass has the potential to induce a wide range of environmental and social impacts, both positive and negative, according to the type of feedstock used and how it is produced. That's why biomass needs to be produced and harvested as sustainably as possible [18].

Growing the new biomass relies on the photosynthesis process which uses solar energy to extract CO_2 from the atmosphere and convert it into combustible organic compounds, thus skipping the GHG generated by burning [16]. But the traditional and the predominant uses of biomass that have existed in households in developing countries, particularly burning wood, are associated with one of the issues that call for the sustainable use of biomass. The inefficient means of combustion for domestic cooking, heating, and lighting causes air pollution related to harmful emissions, especially when not offset by plant re-growth [19,20]. In addition, burning biomass fuel in conventional electricity power plants generates greenhouse gases [16]. According to the IEA, large-scale biomass burning, post-burn decay, peat decay, waste, and solvent use account for 14% of the global anthropogenic GHG in 2010 [1].

However, food crops, the most commonly used energy feedstocks related to **first-generation biofuel**, raise the issue of "food versus fuel". The crisis has arisen from shifting lands from producing food to producing food crops such as sugar cane, sugar beets, rapeseed, soybeans, oil palms, and corn as alternative energy resources. First-generation feedstocks compete with food, contribute to increasing the prices of many of these crops and severely threaten the world food market [3,18,21]. The inflation of the dollar and the rapid rise in the prices of fossil fuels also contribute to that increase in food crops prices [18]. Moreover, first-generation biofuels such as corn ethanol and soybean biodiesel are inefficient in terms of energy yield per acre [11].

Second-generation biofuels address some of the above problems. They are produced from biomass in a more sustainable way, which is actually carbon neutral or even carbon negative in terms of its impact on CO_2 concentrations. They are derived from lignocellulosic agriculture, forest residues, and non-food crop feedstock that have been termed energy crops (such as Jatropha and Pongamia) [3,21]. Although the second-generation biofuel reduces the problems of the first-generation biofuel, there are concerns related to the competition for land use [21]. Vast areas of land are needed for cultivating energy crop-based biofuel, and much of the energy is needed to harvest and transport crops to power stations, in addition to the need to restore the ash containing mineral nutrients to the land in order to achieve long-term sustainability. Although some of the second-generation biofuels such as grasses and agricultural waste are ideal sources of biofuels, the energy content of these biofuels is only about half as much as coal [16].

Third-generation biofuel derived from algae is considered a viable alternative energy resource that is freed from the major drawbacks associated with the first- and second-generation biofuels [21]. Competing with other oil crops, microalgae are characterized by having a high photosynthetic efficiency [22] and more oil yield productivity [3] with their high ability to store large amounts of lipids (60% lipids produce over 50% net oils) [11]. That qualifies algae to be one of the most promising sustainable sources of biofuel [23]. Algae store solar energy in the forms of oils and carbohydrates, which, combined with their high productivity, means that they can produce from 2000 to as much as 5,000 gallons of biofuels per acre per year [23]. Table (1) compares the oil production potential of the three generations based on their relative feedstocks.

Table 1
Oil production potential of biomass feedstocks [11].

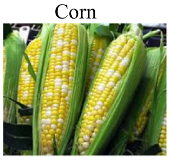
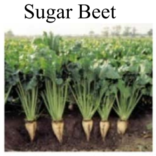
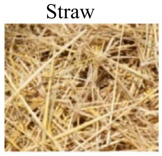
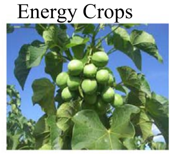
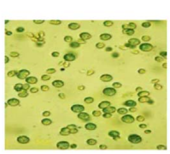
Feedstock	Gallons per acre per year
Corn	18
Soybeans	46
Sunflowers	98
Cocoa	105
Rapeseed	122
Jatropha	194
Coconut	276
Oil palm	610
Algae	5000

4. Algae overview

Algae, or seaweed, use sunlight through the photosynthesis process to capture CO_2 either from water or from air and release O_2. Every pound of algae biomass cuts off 1.8 pounds of CO_2. Although algae represent only 0.5% of total plant biomass, they produce about 60% to more than 75% of the oxygen needed for humans and animals [11,24] (more than all the forests and fields created). In the process of absorbing carbon and releasing oxygen, algae produce green bioenergy and nutritious protein [11]. Furthermore, algae don't need fresh water to grow; they thrive in any kind of water, fresh water, salt water, or wastewater. Microalgae derive their required nutrients from wastewater (sewage), thus they play a great role in wastewater treatment [22]. The types of nutrient sources that can be used for microalgae are municipal wastewater, animal wastewater, industrial wastewater, and anaerobic digestion effluent. Nevertheless, the use of wastewater as nutrients in buildings requires careful monitoring of the harmful chemicals potentially found in the wastewater, such as solvents, paints, and pharmaceuticals, in addition to dirt and mold [25].

In addition, algal biomass can be converted into highly valuable compounds for food, fertilizers, and animal feeding [11,22]. These reasons collectively make algae ideal sources for biodiesel production. Table 2 illustrates a comparison between the three generations of biofuel based on their feedstocks and addresses the large potential of algae to produce biofuel.

Table 2
A comparison between the three generations of biofuel based on their feedstocks.
Source: the author after [11,22,26].

Generations of Biomass Feedstock			Prosperities
1st Generation (food crops)			
Starchy Materials	Sucrose-Containing Feedstocks		
Corn	Sugar Beet	Sugar Cane	1. Produced mainly from agricultural crops traditionally grown for food and animal purposes 2. Causes food crisis and contributes to higher food prices, carbon stores, and land use
			
2nd Generation (waste and energy crops)			
Lignocellulosic biomass			
Wood residues	Straw	Energy Crops	1. Produced from non-edible crops grown on non-arable land 2. Produced from wood waste, agricultural waste, energy crops, organic waste, waste water, and landfill wastes 3. Harder to extract the required fuel
			
3rd Generation			
Algae			1. Most microalgae grow through photosynthesis by converting sunlight, CO2, and a few nutrients, including nitrogen and phosphorous, into biomass 2. Algae can be grown using non-arable land and water unsuitable for food production (brackish, sea and wastewater), therefore reducing the strain on already depleted water sources 3. High yield per acre 4. Minimal impact on fresh water resources 5. Using CO_2 emissions from power plants 6. The oil productivity of microalgae is greater than that of other energy crops
			

4.1. Microalgae cultivation regime

Algae grow all over the earth [11] in two forms, microalgae and macroalgae. Regarding energy production, microalgae are better suited because of their high lipid content and growth rate [27]. There are various colors of algae, ranging between green, cyan, brown, orange, and blue. The energy-producing microalgae are green. Microalgae have been harvested for decades in Africa, Asia, and Central and North America on small scales for food [11,24]. Mass cultivation of microalgae requires an appropriate culture system. The system in which microalgae need to carry out their biological reactions is called a Photobioreactor (PBR) [28]. The available different technical reactors are represented in 1) fermentation tanks, 2) open PBRs (known as open ponds), 3) closed PBRs [24,29], and 4) algal film (bio-film) photobioreactors [30]. Fermentation is the simplest and common algae cultivation method on laboratory scale. Due to its limited vessel size, it has never been established on bigger scales [29]. Open ponds are the most common cultivation system worldwide [24]. They are shallow pools with a depth of about 15–30 cm [28,31,32]. Water is often circulated by gravity or paddle wheels. Despite their lower construction and operation costs [31], they aren't the most effective method [24]. They need large areas of land and are subjected to contamination, weather, evaporation, and poor light penetration [28,31]. They are hard to monitor, and their design limit effective photosynthesis and the conversion of sunlight to energy [24]. Comparable to open ponds, algal film PBRs produce more concentrated algal biomass. Regarding productivity, biofilms are the same as open ponds. The temperature control of biofilm PBR is poor, and the species control is very poor [30]. Despite the biofilm PBR prototype (algae textile) developed by Bogias [33], Genin claimed that the existing designs of algal film PBRs aren't currently convenient for integration into buildings [30]. Those systems have proven their effectiveness in wastewater treatment applications, whereas the other designs of biofilm PBRs are still under development and haven't been widely demonstrated [30]. According to Yoo et al., biofilm PBRs could take various shapes: flat, horizontal, or vertical tubular. Among the three designed film PBRs made of polypropylene film developed by Yoo et al., the vertical tubular biofilm PBR showed the optimum performance [34].

Closed PBRs will require a more detailed review.

4.1.1. Closed PBRs

Several approaches have been conducted to develop closed bioreactor systems to overcome problems associated with open ponds. Many different systems have been tested, but only a few approaches are able to be performed on an industrial scale [35]. In closed PBRs, maximizing the surface area-to- volume ratio is the key principle of PBR design to achieve higher growth rates. This is due to obtaining the distribution of solar radiation on a greater photosynthetic surface area. So, the unique geometry of a bioreactor influences the light distribution [36].

The design of closed PBRs is also affected by the particular characteristics of different microalgae species. That's why a variety of closed PBRs have been designed to fit different microalgal strains. Sunlight and temperature also have an important impact on the PBR design [37]. Although microalgae grow at a variety of temperatures and their production is obtainable throughout the year [36,38], optimal growth is limited according to algae species. Even seasonal and daily variations in temperature can influence algae production. So, cooling equipment and shading techniques may be integrated into closed bioreactors to inhibit temperatures above that needed for algae growth [36]. Closed PBRs are formed either in tubes or in flat panels as will be disclosed below.

4.1.1.1. Tubular PBRs. In tubular systems, tubes are arranged either horizontally in one layer or vertically in multiple arrayed layers. One layer tubes lead to greater exposure to sunlight and subsequently, high light intensities causing retardation of microalgae growth. So, multi-layered vertical tubes cast shadows, hence lowering light intensities and achieving higher productivity. Tube materials can either be glass, soft polyethylene, acrylic, plastic, or highly transparent silicone rubber [27,39]. The diameter of the tube in a closed system is limited (generally 0.1 m) [40,41] because the increase in diameter decreases the surface-to-volume ratio. The tube length is also limited because an increase in the length leads to O_2 accumulation, which is toxic to microalgae, and in turn inhibits photosynthesis. The algae should be circulated and mixed through the tubes by airlift technology [38,41], a centrifugal pump [42], or quantum fracturing [39].

There are various designs of tubular PBRs that have been developed to make accommodations for a thin layer of culture suspension, optimum light exposure, low pumping energy consumption, and contamination purity [35]. Tubes in developed helical PBRs can be coiled to form cylindrical, conical, and diamond shapes as in Helical PBR, Diamond PBR, Originoil Helix PBR, and the Christmas Tree Reactor.

From studying the previously developed prototypes of tubular PBRs, it can be concluded that 1) tubes can be coiled around a frame with any required shape either pyramid, cylinder, cone, or diamond; 2) the whole bioreactor can be illuminated from the inside by any artificial light source and from the outside by solar light; 3) the system can work in shade and also in complete darkness if it is internally illuminated; and 4) OriginOil developed an innovative technology, termed Quantum Fracturing, that stimulates algae to grow by creating micronized bubbles of carbon dioxide and nutrients that are easier for algae to absorb. Furthermore, Quantum Fracturing provides algae with only the wavelengths of light needed to stimulate growth through tuned microwaves. It can also be concluded that 5) the double-walled highly transparent ELASTOSIL silicone rubber tubular PBR system that has been already developed by GICON and their partners with its novel pulsed gas flow process secure good exposure to light during the entire day, low energy input, and a high dedicated radial mixing rate [27,39,43–45]; and 6) the spiral shaped tubular PBR does not need a specific orientation as its shape allows for good exposure to solar light during the entire day at any geographic direction. A specific angle of inclination is just needed to adjust the reactor according to the course of the sun at various latitudes [42]. Such designs, like the tree-like shaped Gicon's PBR, can be incorporated into buildings' roofs or on layouts (see Fig. 1).

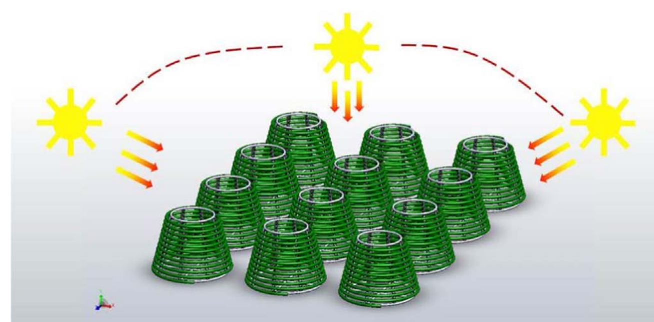


Fig. 1. The tree-like shaped PBRs allow for good exposure to solar light all day long. *Source* [42]: (© Gicon).

4.1.1.2. Flat-panel PBRs. The flat-panel PBR system is a flat, transparent vessel of glass, plexiglass, polycarbonate, or polyethylene film [27,46,47]. According to Marsullo et al., flat-panel PBRs shouldn't be thicker than 5–6 cm to guarantee light penetration in the medium [48]. Compared to tubular bioreactors, flat-panel PBRs have a high surface-to-volume ratio [40,41]. For outdoor cultivation, panels could be arranged in parallel or adjacent plates [27]. Self-shading of microalgae cells among flat plates may inhibit the photosynthesis process and microalgae productivity. So, to reach an efficient use of light in the culture, and to improve the light penetration, optical fibers or LED lights could be used for additional internal-illumination [40,41]. Moreover, Fresnel lenses could be used to track the sun's movement and direct the sunlight into the shaded areas [49].

As microalgae growth and productivity depend critically on mixing cells, a flat-panel design, along with the tubular PBRs, allows that feature through air-lifts. Mixing is caused by rising bubbles which also provide mixing nutrients and prevent O_2 accumulation [32].

The structure of flat panel PBRs can't resist very high pressure (as pressure increases with the increase in volume). Moreover, microalgae growth is affected by the increasing pressure. So, scaling-up is potentially restrained [47]. Nevertheless, this may necessitate a conscious selection of certain types of materials from which the reactor is manufactured, such as laminated safety glass.

Orientation is an important factor that influences flat panel PBR design as the productivity of any microalgal system is a direct function of the total solar radiation intercepted. For outdoor microalgae cultivation, Sierra et al. stated that the east/west orientation of vertical flat PBRs is the favorable orientation for latitudes above 35°N, and the north/south orientation is the preferred in latitudes under 35°N [37]. Similarly, Slegers stated that panel orientation has a large effect on productivity at higher latitudes, and the difference between north/south and east/west orientation may go up to 50% [50].

For flat-panel PBR façades, Provost and Legendre found that a southern orientation is recommended according to the research and development of the SymBio$_2$ project in Nantes Saint-Nazaire (47°N) that was supported by the architecture firm X-TU, AlgoSource Technologies, the GEPEA laboratory, and various design companies [51,52]. Elnokaly and Keeling, through their empirical study conducted at the University of Lincoln Campus UK, have indicated that the southern orientation is the preferred orientation for their vertical tubular PBR to accomplish higher daylight factors [53]. In the BIQ house in Hamburg (53.5∘N), the bio-façades are housed in its southeast and southwest façades [54].

Compared to vertical flat-panel PBRs, inclined flat-panel PBRs may provide the optimum exposure to light and a substantial control over the temperature. Nevertheless, the operating costs will be higher, as the inclination angle needs to be adjusted throughout the year. So, vertical flat-plate PBRs, compared to inclined flat-plate PBRs, are more commonly used for the cultivation of microalgae for their cost-effectiveness [41]. Table (3) summarizes the principle design parameters of flat-panel PBRs for microalgae cultivation on façades.

Table 3
Principle design parameters of flat-panel PBRs for microalgae cultivation on façades.

Principle design parameters of PBRs		Source
Orientation	It depends on solar light intensity relevant to latitudes. However, it is noted that the southern orientation is common in previous studies	[25,37,41,50–54].
Thickness	It shouldn't be thicker than 5–6 cm.	[48]
Materials	Many types of glass and plastic (laminated safety glass, plexiglass, polyethylene film, transparent acrylic, transparent polycarbonate, and ETFE).	[27,46,47,55,56]
Temperature	It is advisable for zones with temperatures above 15 °C, which are located between 37° north and south latitudes. The optimal temperature is between 20–30 °C. Microalgae stop growing below 5 °C and above 35 °C.	[22,27]
Light intensity	The level of light intensity is critical because algae reach light saturation at a certain level and dissipate the excess heat. Light intensity can be enhanced by optical fibers and/or LED lights.	[36,41]
CO_2	Approx. 1.8 t of CO_2 are needed to grow 1 t of microalgae biomass. Factories oil refineries, flue gasses from power plants, and micro-combined heating and power (MCHP) can be used as sources for CO_2.	[11,22,25,28]
Nutrients	Nitrogen and phosphorus required for the cultivation system can be obtained from agricultural fertilizers, fish aquaculture, or wastewater (municipal wastewater, animal wastewater, industrial wastewater, and anaerobic digestion effluent)	[22,25,28].
Water	Any kind of water can be used, such as sea water and waste water. Approx. 0.75 l of water is needed per kg of algae biomass to produce one liter of biofuel.	[22,27,57]

4.2. Microalgae harvesting regime

Microalgae harvesting may occur daily either by centrifugation, filtration, flotation, sedimentation or ultrasound techniques [11,40]. The composition of the extracted biomass varies, but it may be 50:25, oil to protein, with about 15% carbohydrates and 10% ash or waste. The oil component is converted into biodiesel, and the recovered biomass is extracted. The non-oil biomass may be used as fertilizer, animal feed, and for other co-products. The residual nutrients are extracted from the water and recycled for biomass production. Part of the spent biomass is used to produce biogas by anaerobic digestion to generate electricity, most of which is consumed during biomass production. The excess electricity may be stored in batteries or sold to the grid. Photovoltaic cells may also be used to save the electricity generated by the microalgae system. Liquid waste from anaerobic digestion may be used as a nutrient-rich fertilizer. Microalgae as hydrogen producers are still under research and development. To date, methods of hydrogen production from microalgae have produced only small amounts of hydrogen from algae, but research and development have been conducted by NREL and other labs on algae as a biological hydrogen source [11]. Fig. 2 explains the inputs and outputs of the entire process of converting microalgae into bioenergy and other products.

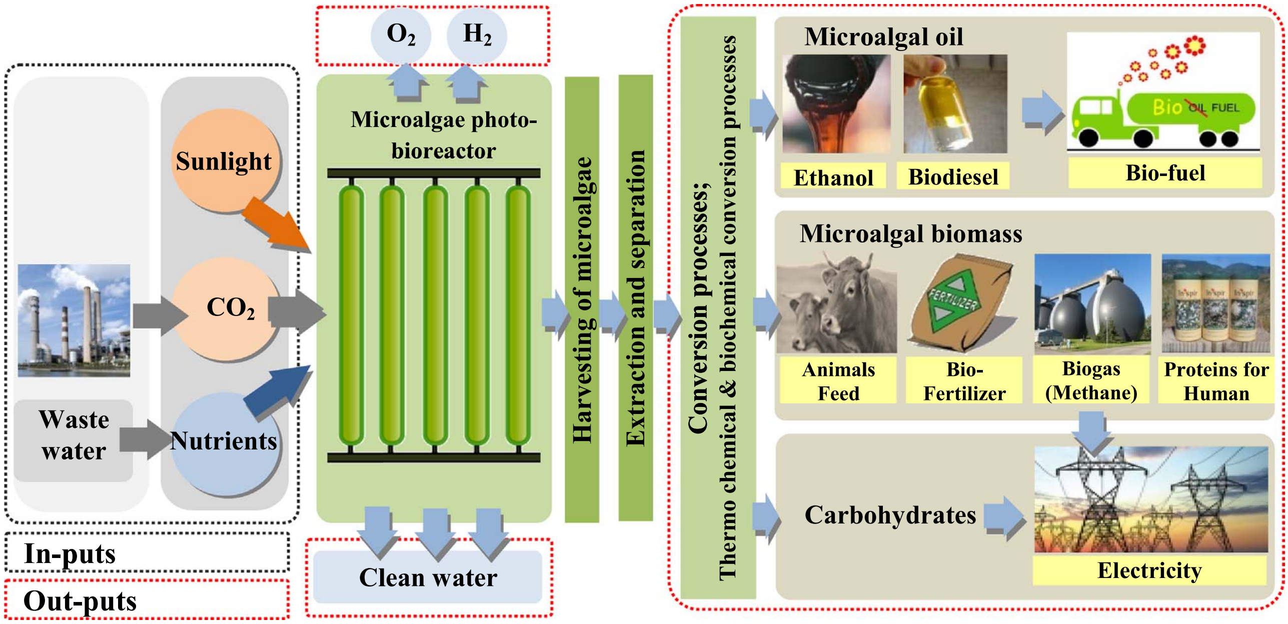


Fig. 2. A schematic concept showing the process of converting microalgae into bioenergy and other products.
Source: drawn by the author from [11,21,58].

5. Building-integrated PBRs

Regarding the major issues related to climate change, the production of green biofuels and sustainable development often refer to plants. The role and the great sustainable potential of microalgae are only known to the experts in that field. Nevertheless, since the beginning of the 21st century, the amount of academic research linking algae with biofuel has increased [59]. Incorporating algae into buildings and architectural design is considered to still be in the early phases and has not yet been included in an adequate share of studies in that regard.

Architects' trends and thoughts in the context of algae-powered buildings can help in configuring an idea about the requirements needed and the possibilities in the architectural design of such buildings. The next part will review and analyze three illustrations of three microalgae-powered buildings. The first is a real-world building, while the other two projects are competition prize winners. Indeed, those three projects aren't the only designs that have been introduced to the architectural scene in recent years, but those three have reasonable data that cover the review methodology. Those buildings are 1) the BIQ *building,* 2) the Algae Green Loop Tower, and 3) the Process Zero Concept Building. The aspects of analysis include PBR façade design, *building services system (energy center),* and the efficiency of PBRs. A comparative analysis of the three cases is represented in Table (4). The afterward section addresses three urban-integrated PBRs. Those urban illustrations are 1) the Flower Street Bioreactor, 2) the Energy Flowers/Helix BR, and 3) the Urban Algae Canopy. This section will be illustrated in Table (5). The aspects of analysis are bioreactor design, outputs by the bioreactor*, and* technology and materials used.

5.1. Bio-Intelligent Quotient (BIQ)

The BIQ building is the first algae-powered building in the world. The project was led by Arup in cooperation with the German consultancy SSC (Strategic Science Consult) [60] for the International Building Exhibition (IBA) 2013 in Hamburg, Germany [61]. The building was a prize winner in the 2013/14 Land of Ideas competition [62]. The design uses the concept of flat-plate PBRs installed for the first time in the BIQ house to produce heat and biofuel (biogas), with the aim of making a self-sustainable building as the energy demand of the building will be covered by the algae cultivation [63]. The PBR façade, branded as the "SolarLeaf" bioreactor façade by Arup and Colt, is the first façade system in the world to cultivate microalgae to generate heat and biomass as renewable energy resources. The SolarLeaf façade is based on the idea of using the biochemical process of photosynthesis for the design of energy-efficient buildings [61]. Glass flat panels are filled with a microalgae mixture, capturing thermal heat and light from the sun and fed by CO_2 and nutrients to produce biomass in order to generate electricity and biofuel [63] (see Fig. 3).

The BIQ is a cubic five-story residential building. The microalgae PBR façades are housed in its southeast and southwest façades [54]. A holistic building concept supports the PBRs of the building [64]. That infrastructure concept includes 1) the CO_2 supply; 2) the nutrients supply; 3) biomass filtering and harvesting; 4) monitoring and controlling the temperature and circulation of the culture liquid; 5) heat harvesting, storing, and distribution; and 6) algae biomass transportation to the biogas plant to be converted to methane to be subsequently processed into electricity [61,64]. The system can be run automatically (including the nutrient supply), thus preserving maintenance costs [64].

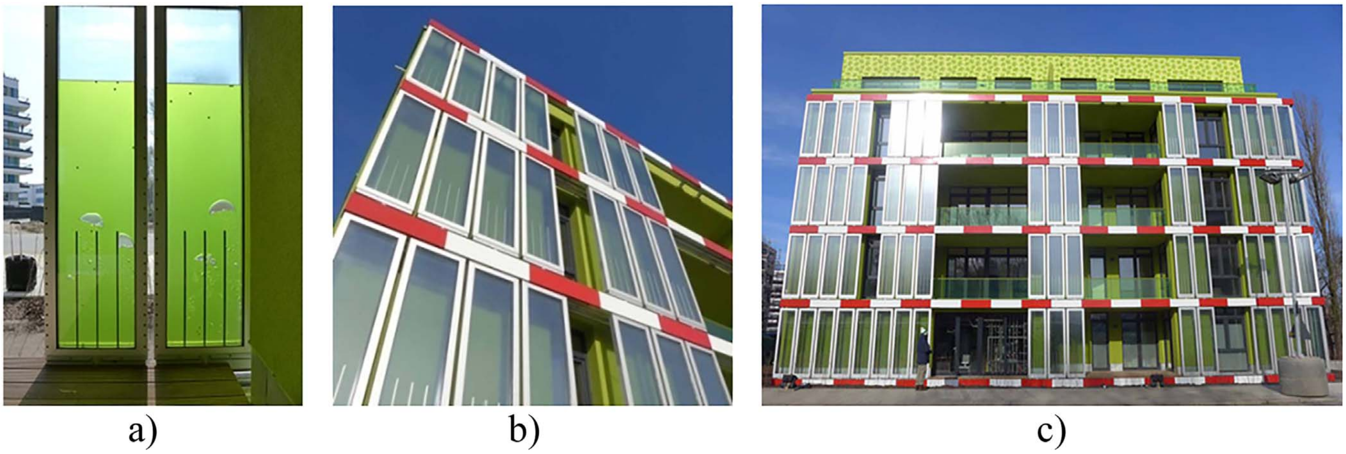


Fig. 3. *The BIQ building*, the first *algae-powered building by Arup* (© Colt International, Arup Deutschland, SSC GmbH).
Source: a) [65]; b), c) [60].

5.1.1. PBR façade design

In total, 129 PBR panels are installed on the southeast and southwest façades of the building as a secondary layer. Each PBR panel measures 2.5 m × 0.7 m with a thickness of 0.8 m. It has a capacity of 24 l of liquid for microalgae culture. The PBR is clad on both sides with laminated safety glass for safety and thermal insulation [54,61,66]. The bio-adaptive façade is fully integrated with the building services system to harvest, distribute, store and use the solar thermal heat on the site, and algal biomass [61]. Two processes are undertaken in the PBR: the first is the conversion of light into heat as a solar thermal process, and the second is the conversion of light into biomass in a biochemical process (photosynthetic process) [67]. Two separate pipe systems supply the PBR, a compressed air system and a water system [54]. The injection of compressed air from the bottom of the panel creates rising air bubbles that guarantees the circulation of the medium to keep the microalgae in suspension, washing the inner surfaces to inhibit the deposition of algae, and stimulate the absorption of carbon and light [54,64]. The water system includes water, as a culture medium, enriched with nitrogen, phosphorus, and trace elements as nutrients [54]. These two pipe systems of the PBR are integrated into the perimeter framing, which is linked by a closed loop to the plantroom (building services system) [64] (see Fig. 4). CO_2 is derived from the flue gas of an onsite biogas-fueled microCHP (combined heat and power unit). Membrane technology and a saturation device are used to provide the water circuit with an enriched CO_2 stream [54,66]. Then, the concentrated CO_2 is dissolved and circulated to the microalgae inside the culture, together with the nutrients and water [66].

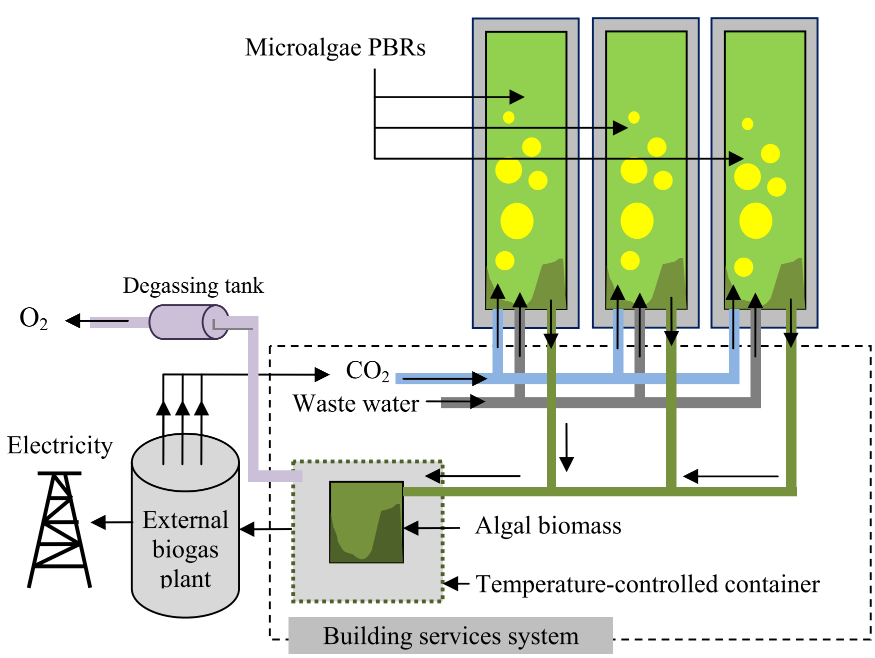


Fig. 4. A schematic diagram of PBR.
Source: drawn by the author.

5.1.2. Building services system, room plant, or energy center

The central building energy management system (BMS), called Rockwell SPS, monitors the inputs and outputs of the loop system automatically. It controls the supply of nutrition, the algae cell density, and the harvesting of the algal biomass [54,64,67]. *When the microalgae are ready to be harvested,* algal biomass is filtered out by a flotation system, collected in a temperature-controlled container *in the building services system,* transferred and converted into biogas (methane) in an external biogas plant, and then used to supply energy to the city (see Fig. 5). This process occurs about once a week. The conversion into methane is not done on site because this technology is not yet ready for use in residential buildings [54]. The building's energy management system also controls the level of the temperature to be below 40 °C [64] in summer and above 5 °C in winter to suit microalgae cultivation [54]. As the microalgae PBR panels are solar thermal collectors and act as shading devices, they produce heat that is used for warming the building [54,64]. Heat is extracted by a heat exchanger at the energy center of the building service system [54]. The produced heat energy is utilized in heating the building and preheating hot water. Excess heat is drawn with heat pumps and stored in geothermal borehole wells [54] located under the building subsoil [67].

hours per year). So, the entire system can fully operate one apartment with the electricity produced, while the heat generation from the bioreactor façades (6000 kW-hours per year) can supply four apartments with heat [54]. According to Build Up, and Wurm, the generation of energy from biomass is 30 KWh/m^2 per year and from heat is around 30 KWh/m^2 per year [67,68].

5.2. Algae Green Loop

The Green Loop project, by Influx Studio architects, was the winner of the Abundance Prize of the 2011 International Algae Competition. The Green Loop vision, which is committed to the Chicago Climate Action Plan [69], introduces a new sustainable model that allows closed loops in terms of achieving zero environmental footprints in the core of the city of Chicago. The Green Loop project is an installation in the existing building of Marina City Towers, Chicago, Illinois. This project represents the first architectural proposal that integrates an on-site algae bioreactor with this new CO_2 sequestration technology into an existing building. This project represents a toolbox to reduce CO_2 emissions, harvesting energy, filtering water, producing food, and allowing sustainable economic growth by utilizing algae green technology. Furthermore, it includes heating, cooling, hot water, and lighting systems integrations in the building envelope. The closed loop bioprocesses integrate three different levels of carbon reduction: 1) direct carbon extraction from the air to feed the microalgae bioreactor, 2) absorption by vegetal photosynthesis (algae, vertical farming and phytoremediation), and 3) reduction by energy saving (introduction of solar and wind-harvesting energy) [70].

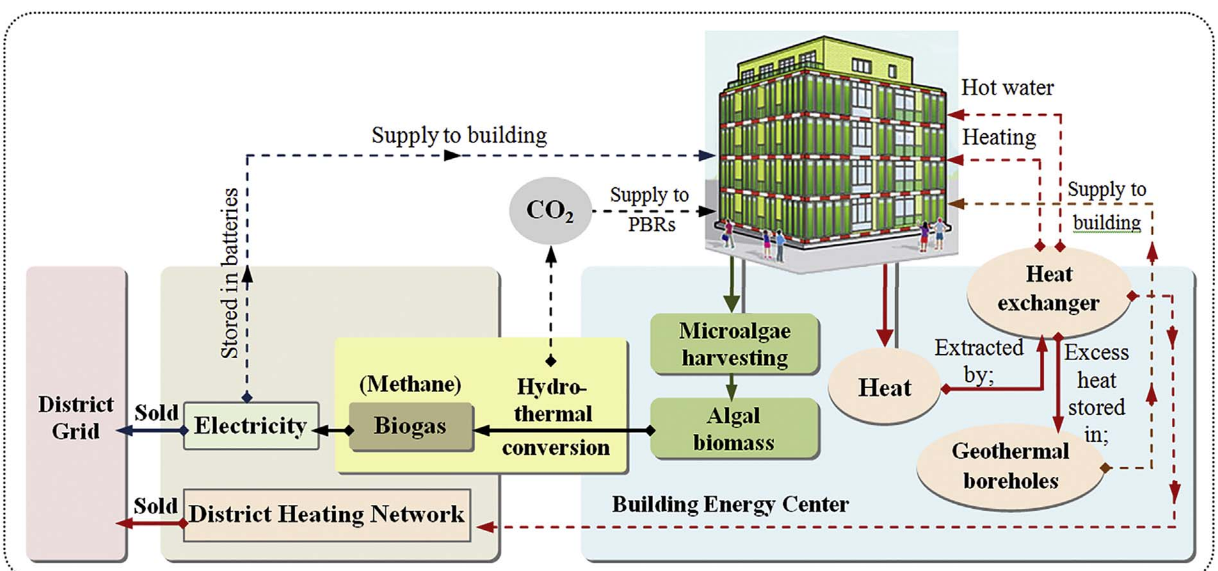


Fig. 5. The systematic energy path of the BIQ building.
Source: drawn by the author.

5.1.3. PBR efficiency and the initial results

The PBRs façade system of the BIQ building has been subjected to intensive monitoring [65] of energy and technical capacity throughout the year in order to evaluate and develop a reliable evidence base for the BIQ model project. The efficiency of the operation still remains to be proven [54]. Yet, after operating for almost a year after running, the system has reached a conversion efficiency of 58% in total, 10% for biogas and 48% for heat. Conversion efficiency refers to the amount of light hitting the façade that is converted to energy [66].

According to IBA Hamburg GmbH [54], about 4500 kW-hours of electricity is generated by the 200 m^2 algae façade, which is a little more than the average household consumption in a year (3500 kW-

5.2.1. Bio-façade design

The CO_2 scrubbing integrated system developed by Influx Studio is comprised of the algae production system with other green technologies such as wind and solar harvesting for energy production. The integrated system cleanses the air of CO_2, produces energy, produces food, processes waste water, and produces biodiesel from algae [63]. The two carbon scrubbing plants, positioned on the tops of the two towers, are comprised from two main parts, the CO_2 scrubbing modules and PBRs.

The CO_2 scrubbing modules are based on an advanced technique, the humidity swing, developed by Dr. Klaus Lackner (Lenfest Center for Sustainable Energy, Columbia University). The humidity swing permits the capture of CO_2 from the surrounding air and the release of oxygen with the aid of wind turbine power that provides the system with electricity in a sustainable and economic way [70]. The carbon scrubbing technology supplies the algae bioreactor with the needed CO_2, solving the problem of transporting and storing the captured CO_2 [71]. The bioreactors are installed around the carbon scrubbers at the towers' tops and in the 18 floors in the parking ramp of the east tower [63,71]. Helix-type wind turbines catch the wind flow from all directions, creating a smooth, powerful torque to spin the electric generator and the CO_2 scrubber fan [71]. The CO_2-catching capsule is opened, and the air flows through it. The CO_2 then reacts with the resin of the device, where it is trapped. When the resin is saturated, the CO_2 is released and harvested to feed the algae in the bioreactors to produce fuel and food [71].

Photovoltaic and solar thermal panels are used on the semicircular balconies exposed to sunlight as a supplementary source of electricity, which promise to, according to Furuto, improve the system autonomy [70]. On the parking ramp of the west tower, a phytoremediation garden has been integrated, taking advantage of the gentle slope of the ramp that allows water to flow by natural gravity through special soil and plants' roots. The filtered water can be reused in the WCs of the Marina or to irrigate vertical farming [71]. That constant cycle involves towers occupants and makes them a part of the system [63]. It links the people with the eco-market bridge and the algae showroom (the bridge between the towers), where they can exchange, share, sell, or buy food harvested from vertical farming on their own balconies [71] (see Fig. 6).

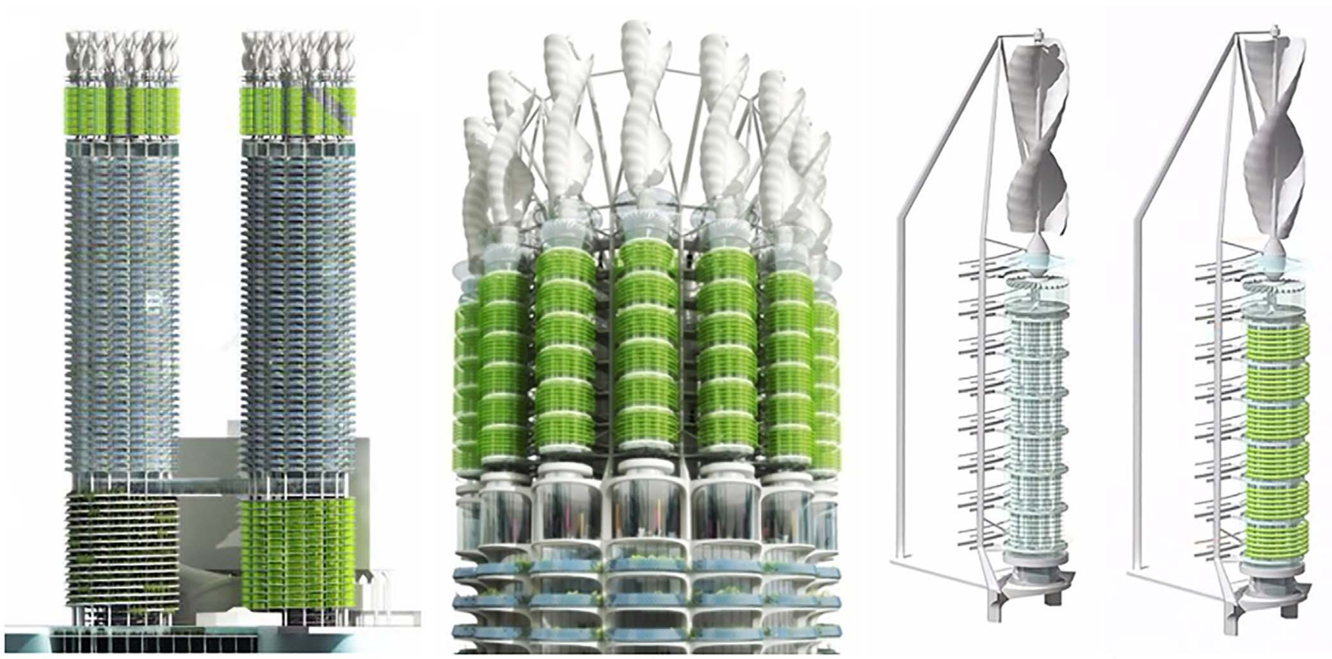


Fig. 6. a) The Marina City towers; b) carbon scrubbing plant; and c) The "humidity swing" captures CO_2 from air. Images permission from the designer, Mario Caceres
Source: [70].

5.2.2. *Efficiency*

There is no documented information about the energy efficiency of the Green Loop project. Nevertheless, the algae bioreactor was designed to cover the building's energy requirements [70].

5.3. *Process Zero Concept*

HOK and Vanderweil utilized microalgal PBRs to power the Net Zero building as a retrofit solution for the 46-year-old federal office building in downtown Los Angeles, the GSA office building. The Net Zero retrofit solution, the winner of the International Algae Competition and the Metropolis Magazine's Next Generation Design Competition 2011, was introduced in order to reduce building emissions by 30% by 2020 [31,72]. The microalgal PBRs cover 25,000 ft^2 of the GSA building's envelope with a modular network of tubular PBRs. The PBRs capture sunlight, absorb CO_2, release O_2, and produce lipids for fuel production on site. Simultaneously, the PBRs provide the interior spaces with sun shading [72]. Fig. 7 illustrates the retrofit solution and the tubular PBRs.

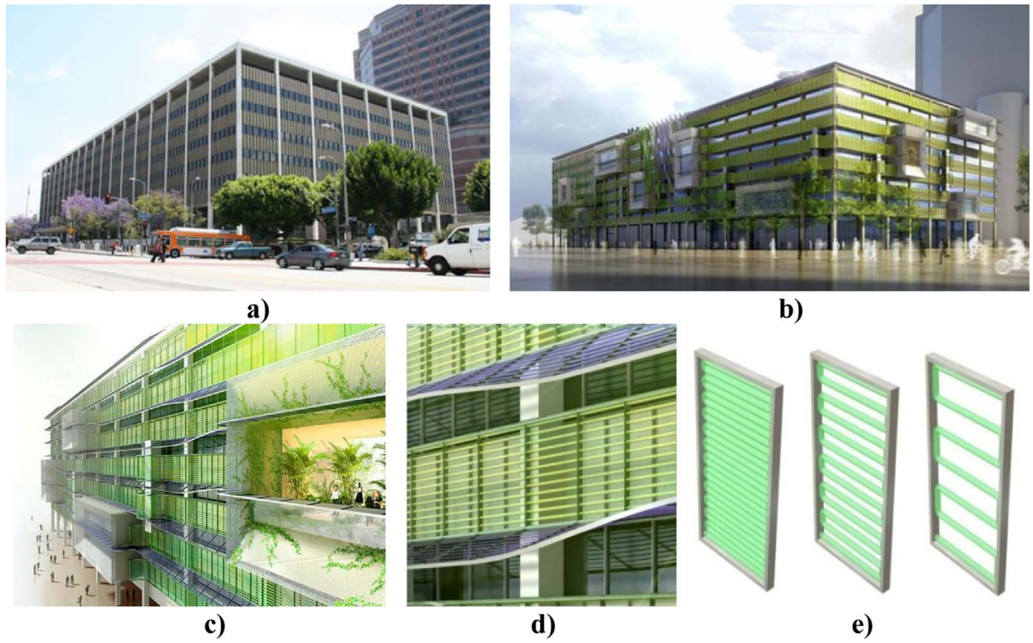


Fig. 7. a) GSA office building before retrofitting, b),c) the Process Zero retrofit of GSA; d), e) the tubular setup of the retrofit solution panelized grid (microalgae membrane).
Source [73]: (© HOK /Vanderweil).

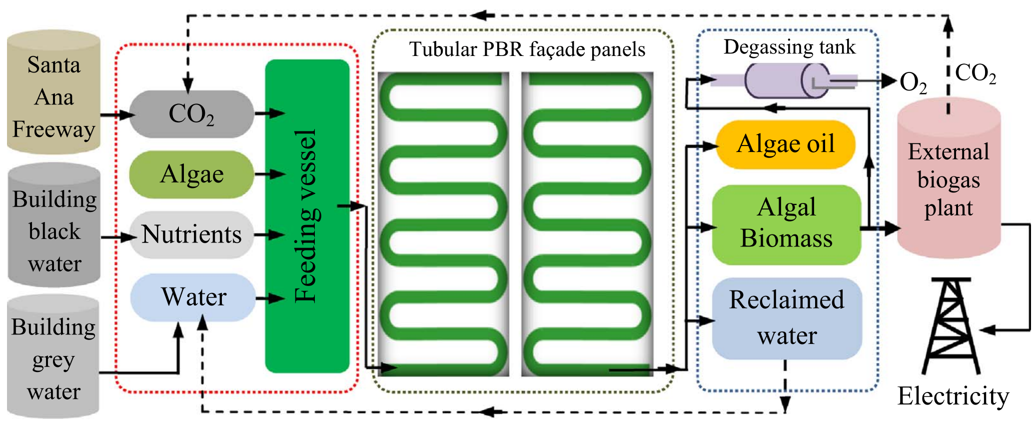


Fig. 8. Schematic concept of the microalgae photobioreactor system of the Process Zero Retrofit building.
Source: drawn by the author from [72].

5.3.1. Bioreactor façade design

A thin-film photovoltaic shading system is used to protect the glass bioreactor tubes and avoid overexposure. Microalgal PBRs are part of a full-scale closed system of holding tanks and filtration ponds to complete the bio-energy network [31]. The system derives its CO_2 from the nearby Santa Ana Freeway [74]. CO_2 enters a central feeding vessel along with the building's waste water and additional nutrients that are derived from processing the building's black water. The central feeding vessel, containing microalgae cells that are grown on site, supplies the modular tubular bioreactors on the façades with a constant flow of microalgae, CO_2, waste water, and nutrients. The produced reclaimed water is reintroduced to the system; the lipids produced are extracted for algal oil production [72] or can be burned in co-generators for heat and electricity [75], and O_2 is released into the plaza [72]. Fig. 8 articulates the path of the process.

5.3.2. Efficiency

According to HOK and Vanderweil, the microalgal PBR system generates only 9% of the renovated federal building's power supply. So, a collection of renewable energy systems, including a thin film photovoltaic façade system, rooftop photovoltaics, integrated solar thermal panels [72], phase-changing materials that provide ceiling insulation, and a cloud computing system that replaces the heat-generating computer equipment [74], are used to comprise the innovative microalgae system. This collection reduces building energy intensity by nearly 85% (from 86 to 14 KBTU/SF/Year), while generating the remaining 16% on-site, offsetting the energy consumption and achieving the goal of a net zero design [72].

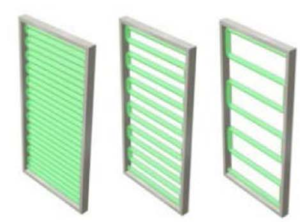
6. Energetic, environmental, and cost viability of PBR façades

The energetic and environmental potentials of PBR façades will be reviewed and discussed in this section in terms of daylighting, potential visibility, thermal insulation, noise insulation, environmental viability, capital costs, and aesthetics.

6.1. Daylighting performance

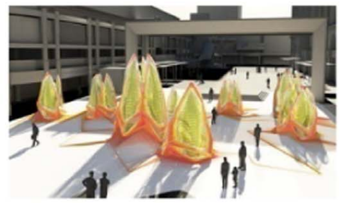
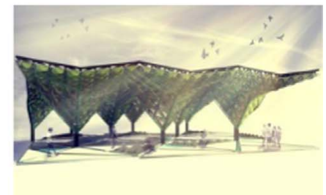
Since the green microalgae have the ability to absorb the red

Table 4
A comparative analysis of the three selected building-integrated PBRs.
Source: adapted from [31,54,61,63,66,70–72].

Case study	Green Loop Tower, Chicago (41.8° N), Illinois	BIQ building, Hamburg (53.5°N), Germany	Process Zero, Los Angeles (34°N), California, USA
PBR Integration into Facade			
PBR Installation According to Building Type	Both new and retrofitted buildings.	Both new and retrofitted buildings.	Both new and retrofitted buildings.
PBR Orientation	The helical PBRs are wrapped around the entire perimeter of the cylinder-shaped building.	The flat-plate PBRs are installed on the southeast and southwest façades.	The tubular PBR panels cover the four building façades.
PBR Specification	A modular system of algal tubes is coiled around the CO_2 scrubbing units in a helical manner on the tops of both towers. In addition to the semicircular algal tubes those are installed in the first 18 floors (around the parking ramp of the east tower).	In total, 129 PBRs are installed on the southeast and southwest facades. Each PBR panel measures 2.5 m x 0.7 m with a thickness of 0.8 m. It has a capacity of 24 liters of liquid for algae growth. PBR is clad on both sides with laminated safety glass for safety and thermal insulation.	The PBRs cover 25,000 ft^2 of the GSA building's envelope with a modular network of transparent glass tubing PBRs. PBRs are part of a full-scale closed system of holding tanks and filtration ponds to complete the bio-energy network.
Microalgae PBR Design	 **Helical tubes PBR**	 **Flat vertical panel PBR**	 **Tube-panel PBR**
Source of CO_2	From CO_2 scrubbing plant based on the humidity swing technique positioned on the tops of the two towers. Air is captured by a wind turbine and then harvested and released by the CO_2 scrubbing unit to feed the algae PBR.	From flue gas of a biogas-fueled microCHP on site. A membrane technology and a saturation device are used to provide the water circuit with a CO_2 stream. Then the CO_2 is dissolved and circulated to the PBRs together with the nutrients and water.	The system derives its CO_2 from the nearby Santa Ana Freeway on site.
Source of Water and Nutrients	Waste water of Marina City inhabitants. All waste water is processed to be reused either in the WCs of Marina city or to irrigate vertical farming.	The culture medium enriched with nitrogen, phosphorus, and trace elements as nutrients.[a]	Waste water of the building is the source of water. The black water of the building is processed to be a source of nutrients.
Building Services System Location	NA[b]	Under the building subsoil.	NA[b]

[a] No documented information about the source of nutrients
[b] No documented information about the building services system location

Table 5
A comparative analysis of the three selected urban-integrated PBRs.
Source: the author from [43,44,76–83].

	Flower Street Bioreactor Los Angeles, 2009	Energy Flowers/Helix BR: Perth, Australia, 2009	Urban Algae Canopy, Expo Milano 2015
Architect	Emergent architects	Emergent architects	Ecologic studio
Project illustration			
Type of the project	A shop window installation on a Los Angeles street	A public art installation	Urban algae canopy installation
Bioreactor design	It is an aquarium-like bioreactor measuring 9 x 19 ft that is inserted into the façade of a building. It is designed to raise awareness of alternative fuels by creating a sense of beauty around new technologies in addition to generating biofuel to emit lights at night**.**	Seven BRs are tied together through a path of biofuel lines leading to the Perth train station. The outer construction of the PBR is from pleated fiber. It supports large transparent apertures to allow in sunlight. Algae housed inside in coils of transparent acrylic coils contain a helix of lights and obtain its electricity from charging the thin-film solar transistor system embedded in the transparent polycarbonate apertures.	The cushions of the canopy are made from three layers of ETFE cladding where microalgae are cultivated. It utilized special CNC technology to design the form of the cushions and to control the fluid dynamic behavior of the water medium as algae travels through it.
Outputs	Provide light at night by biofuel production.	Feed Perth train station with biofuel produced,while admitting light at night.	Provide shading by algae growth, release O_2, and produce biomass.
Technology used and materials	The aquarium is made of thick transparent acrylic molded to create the complex BR shape. BR is a self-adjusting growth bio-feedback system, invented by OriginOil, and uses tuned LED controller lights that vary in color and intensity to support algae growth maximizing output.	Quantum fracturing is used to stimulate algae to grow. It creates micronized bubbles of CO_2, nutrients that are easier for algae to absorb, and wavelengths of light needed to stimulate growth through tuned microwaves. The system works in shade and in complete darkness, as it is internally illuminated.	Growth of algae admittedly increases shading potential. The presence of visitors also triggers electro-valves to alter the speed of algal flow through the canopy, changing transparency, color and shading potential. The larger installation of the urban algae canopy will produce oxygen, up to 150 kg of biomass per day.

radiation, PBRs act as sun-shading devices [56]. Consequently, they affect the penetration of daylight. According to Öncel et al. and Elnokaly and Keeling, the microalgae's dense culture will reduce light penetration [38,53]. In a study conducted by Kim [55], she proposed a façade system with algae bioreactors in contemporary high-rise building as a sustainable alternative to conventional glass façades. A prototyping of algae façades was carried out at the fabrication lab in the School of Architecture at UNC Charlotte. The prototype consists of two zones, the algae zone and the vision zone. HDR (high dynamic range) photogrammetric techniques were used to evaluate daylighting potential and space color created by the algae zone. The study showed that the vision zone of the algae façade can light the perimeter zone of an interior space without artificial lighting. To regulate color transmission through the algae zone (green color), she suggested using films to block color penetration [55]. Decker et al. [84] indicated that the light penetration and indoor daylighting levels depend on the various stages of algae growth alongside the PBR frame configuration and the panels' rotation angle. They stated that there is a slight lack in the inside lighting levels, which is mainly due to the reactor geometry framework. They monitored an increase in the inside daylight levels once the rotation angle was increased by more than 40 degrees. In essence, they arranged the factors affecting the daylighting as follows: the density of algae culture in the reactors, then the rotation angle of the flat panels, and finally the frame geometry [84].

Elnokaly and Keeling [53], through their empirical study conducted at Lincoln UK, specify the relationship between light transmittance and microalgal culture density. They have found a decrease in the daylight factor with the increase in microalgal culture density. However, they have referred to a weak relationship between the increase of the culture density and the increase of the shading efficiency.

Those two results support the fact that an increase in daylight levels correlates with a decrease in microalgal culture density. Generally, they have indicated that PBR façades regulate daylight levels through shading. That fact conforms to the fact that southern-oriented façades achieve both optimum shading efficiency and microalgal growth [53].

Pagliolico et al. [56] studied the levels of daylight produced by a building's PBR façade in two different daylight availability locations (Palermo and Turin) and in three different directions, north, south, and west. The kind of PBRs used in this feasible study were various shapes of modular, transparent, disposable plastic bags that were affixed to a glass window. The results have shown that light transmission (taken as an annual constant value) for the designed system (glazing and microalgae) is equal to 0.55 under clear sky conditions (where LT $_{glazing}$ = 0.72, and LT $_{microalgae}$ = 0.76). However, Pagliolico et al. have pointed out the biconvex shape of the PBRs and its potential impact on light transmission. Compared with a venetian blind case, the results showed an increase in the amounts of daylight and a decrease in the energy required for lighting [56]. Even though the aforementioned studies strongly support the role of PBR façades in optimizing daylight levels, further studies are required to measure daylight levels and distribution all over task levels.

6.2. Potential visibility

The integration of PBRs in the buildings' façades affects their transparency and consequently, the potential visibility via it [56,84]. Despite the need for films to block the varying colored effect of microalgae*, a visually interesting* dynamic *look is created according to the* seasonally varying activity of microalgae and the rising movement of bubbles through PBRs. *Herein, it could be said that the bioenergy production forms a part of the architectural configuration of PBR façades* [54,60]. Nevertheless, to enable clear vision through PBRs, swiveling the panels would make outside vision accessible. Simultaneously, this rotation enables the adjustment of the exposure to solar radiation [84]. Pagliolico et al. pointed out through their feasible study the glare caused by their designed PBR façade, which leads to a kind of visual discomfort. They have recommended applying PBRs in the clerestory area as a shading system while applying double-pane glazing for the view window [56].

6.3. Thermal performance

The PBR façade creates sun shading [67,84,85] *for the building's interiors keeping it cooler on sunny days* [67]. The density of microalgae cells is the factor behind this capability [86]. As PBRs act as sun shadings, they replace mechanical shading devices [67]. Sardá and Vicente urged that the photosynthesis process absorbs solar radiation and consequently contributes to temperature reduction, in addition to the shading effect of the medium, which increases the thermal insulation and increases the potential for saving energy [87]. Pruvost et al. stated that in the summer, PBRs filter the thermal loads and protect the building, while in the winter, excess heat can be used to warm the building. This process, according to them, is a symbiotic relationship between the bio-reactor and the building [88]. In the study conducted by Kim [55], the thermography-based thermal testing indicated that the U-factor of the algae façade is comparable to a low-e coated IGU (insulated glass unit). Kim expected that the algae façades perform better in IGU in the real application. Her claim was based on the thermal mass potential of algae and the addition of CO_2 circulation in the water cavity of the PBR façade. According to her prototype design, the vision zone requires two layers of acrylic paneling to provide good insulation value and thermal comfort [55]. Öncel [38] stated that thermal comfort can be accomplished through PBRs. He attributed that to the role of PBRs as bio-heat exchangers between indoor and outdoor temperatures. Moreover, the continuous transferring of the algae culture ensures the avoidance of problems related to light intensities and high temperatures. The control of the transfer of the culture acts as a security valve to take control of the variation of temperatures and light intensities, in tandem with the advantage of adjusting the PBR tilting angles. Öncel stated that, as thermal façades, PBRs can save 33% in regard to fuel consumption and 10% in regard to electricity [38]. According to Sardá and Vicente, if PBR façades act only as thermal insulators, they will amortize the investment in a period of 6–10 years [87].

Those above facts can confront, to some extent, the argument that the energy productivity from microalgae is uneconomic so far.

6.4. Acoustical performance

According to Build Up and Sardá and Vicente, the inclusion of the microalgae culture of the façades increases the sound insulation [67,87]. But, there have been no attempts to measure the performance of sound insulation of PBR façades thus far.

6.5. Environmental viability

Microalgae beat the other renewable resources with their multiple potentials to absorb CO_2, recycle wastewater, and release O_2 [89]. Nevertheless, the sequestration rate of CO_2 and the release of O_2 through PBR façades cannot be exactly determined, as the rate of photosynthesis varies from one case to another depending on the reactor specifications [55]. The reduction of CO_2 estimated from the 200 m^2 PBR façade of BIQ is up to six tons per year [54,67].

6.6. Capital cost

Although closed bioreactors allow for greater control over the design parameters for microalgae growth, capital costs stand as a major obstacle for closed systems [36]. The cost of PBRs is the basic criterion influencing customers and private sector attention [38]. The capital costs of PBR façades include the cost of construction, operating costs, and the cost of the high amount of energy needed for nutrients mixing and keeping algae in suspension [24,87]. The cost of the real-world building-integrated PBR, BIQ, was approximately € 5 million (funded by the Hamburg Climate Protection Concept) [54]. According to Sardá and Vicente, the cost of the construction is still really high [87], and the cost of PBRs is more than solar or conventional fuel systems. Nevertheless, Entwistle urged that prices are coming down currently [65], and Schiller stated that the ongoing energy costs that microalgae will reduce and the long-term benefits are considerable [90]. Provost and Legendre and Pruvost et al. stated that the symbiosis between PBRs and the buildings promises to reduce the capital and operating costs of PBR technologies [51,88].

Although the cost of a PBR façade is more than a conventional wall system [88], it is lower than some types of façades such as high-tech, stainless steel and aluminum curtain walls and stone or ceramic tiling façades. Sardá and Vicente [87] estimated that the costs of the operation and maintenance of some PBRs may be covered in a repayment period of about 9 to 13 years according to the PBR type and the final product. They argued that the improvement and dissemination of the industry will improve the time factor [87].

6.7. Aesthetics

Many scholars state that the inclusion of living organisms in the building envelopes enriches its aesthetic values. The algal tissue, with their dynamic chemical and physical processes, can artificially plant life in the inert surfaces of buildings' envelopes. According to Genin et al. (2016), the aesthetics of the PBR façades are very pivotal, as the attractive façades may make customers readier to facing the high costs of the building-integrated PBRs. Therefore, it is important to integrate engineering and design well to produce a vibrant PBR façade

[30,33,85,87]. According to Öncel, architecture plays an important role as a catalyst to widen PBR façades' popularity [38].

7. Conclusion and discussion

The main objective of this review is to clarify the potential applications of bioenergy in architecture, namely the building-integrated PBRs. The main contribution of this paper within its field has been clearly demonstrated in this section. This paper has addressed the important aspects of microalgae as a biomass-based bioenergy source, PBR façades and their possible types, the composition and mechanisms of PBR façades, and the implications of such façades in terms of energy and environmental performance and their architectural configurations. Moreover, this review has shed light on the challenges that encounter such technology. The conclusion of the beforehand review will be organized in terms of the technical requirements of the PBR system, its challenges, and its prospects.

7.1. Staple demands and technical requirements for microalgae bio-façades

Table 6 summarizes the inputs and outputs of the building's bio-façade, together with the technical requirements of the system based on both the theoretical and the review section.

7.2. Challenges

One of the most profound challenges of establishing the bio-façades system is the provision of a biorefinery infrastructure (see Fig. 9). The system includes the efficient supply of nutrients, water, light, and CO_2 along with microalgae harvesting and extraction system that should be done on site to prevent energy loss during transportation. Furthermore, microalgae-powered buildings should be equipped with their own biogas plants to produce methane from their produced algal biomass, which could be subsequently processed by anaerobic digestion to generate its own electricity. The provision of a biogas plant may be difficult to achieve, or it may still be too new to be executed, particularly on a residential-scale. Along with the vital role of the biogas plant in generating electricity, the biogas plant is an ideal source of the CO_2 needed by the bio-system. The inability to provide a biogas plant on the building site will be faced with the need of providing a source of CO_2. Integrating CO_2 capturing, sequestering and storing systems are well known in the industry. But, the integration of these systems into buildings represents a big challenge so far. However, the unique CO_2 scrubbing plant with the humidity swing technique will surpass this issue if its cost-effectiveness and applicability are proven. It is worthwhile to indicate to other unique CO_2 capturing systems such as CE's Air Contactor designed by Carbon Engineering [92].

Alongside the aforementioned challenge, Öncel [38] pointed out to the factors driving the expansion of the design of PBRs on a building scale as follows: lightweight materials with reasonable cost, durability, balancing between cost and payoff, and easy maintenance [38].

From the experience of the real-world bio-façade of BIQ, taking into account the variations in environmental conditions, we find that a holistic bio-building system with 200 m^2 PBR can supply the electricity needs of one household unit according to the estimation of 2014. (The world average electricity consumption per household is about 3353 kWh/hh/year [93].) And, from the estimation of the energy viability of the Process Zero building, we find that the bio-façade system generates only 9% of the renovated building's power supply. So, we can deduce that the inclusion of PBR façades alone may not cover all of the energy needs of the building and extra power may be needed to run the building. So the design should be complemented and supported by other renewable resources such as photovoltaic cells and wind turbines to operate the process and cover the energetic needs of the building.

Integrating the biorefinery system, including the bio-digester, as a main requirement of constructing building-integrated PBRs, necessitates agreement with buildings' legal regulations. Although these may be stringent with residential buildings, there are promising global

Table 6
The basic inputs and outputs of the building's bio-façade and the technical requirements.

No.		Inputs	Technical requirements
1)	Carbon dioxide	**Flue gases from power plants, factories, high ways, etc.** If there is no adjacent source of CO_2, the capture of CO_2 for algae cultivation will be limited. So it is imperative to consider a reasonable geographic proximity of stationary sources or to provide a CO_2 source as an integral part of the building [91]. Systems attached to the buildings, such as the CO_2 scrubbing system solve the problem of transporting and storing CO_2. In the CO_2 scrubbing system, a source of electricity is required for the operation. So, an integrated wind turbine can operate the system in a sustainable way.	1. Geographic proximity to CO_2 sources and/or 2. CO_2 scrubbing system.
2)	Water	**Any kind of water** Microalgae can bloom in any type of water (sources of water not suitable for consumption). The resulting water can be reused again as reclaimed water, making a closed-loop of the water path within the PBR.	1. Sea water; 2. Rainwater; 3. Saltwater; 4. Brackish; 5. Polluted or wastewater
3)	Nutrients	**Building's gray and black water** Nutrients can be obtained from the building's liquid wastes, from gray and/or black water.	1. Nutrient separation system
4)	Microalgae	After harvesting microalgae, it is important to store it in temperature-controlled containers until the conversion process. The conversion process can be operated on the building's service system, or the microalgae can be transported outside the site to be converted into oil, electricity, or other products.	1. Temperature-controlled container
		Outputs	
5)	Heat	As the PBR façade acts as a thermal insulator, it converts solar light into heat. The resulting heat participates with a considerable percent of the produced energy. Heat needs to be extracted by a heat exchanger to be used in the building's heating purposes. The excess heat can be stored in geothermal boreholes for future use, or it can be sold to the district heating network.	1. Heat exchangers 2. Geothermal boreholes
6)	Algal biomass	A filtration system, as centrifuge equipment, is required for extracting the green products. Oil from algae is used for biofuel production, algal biomass is used to generate electricity when converted to methane by an external biogas plant, and reclaimed water is reused for the culture.	1. Centrifuge 2. External biogas plant
7)	Oxygen	In flat-plate PBRs , a gas-liquid interface is needed for the removal of oxygen gas [49]. A degassing column is required for O_2 removal [40].	1. Gas-liquid interface 2. Degassing column

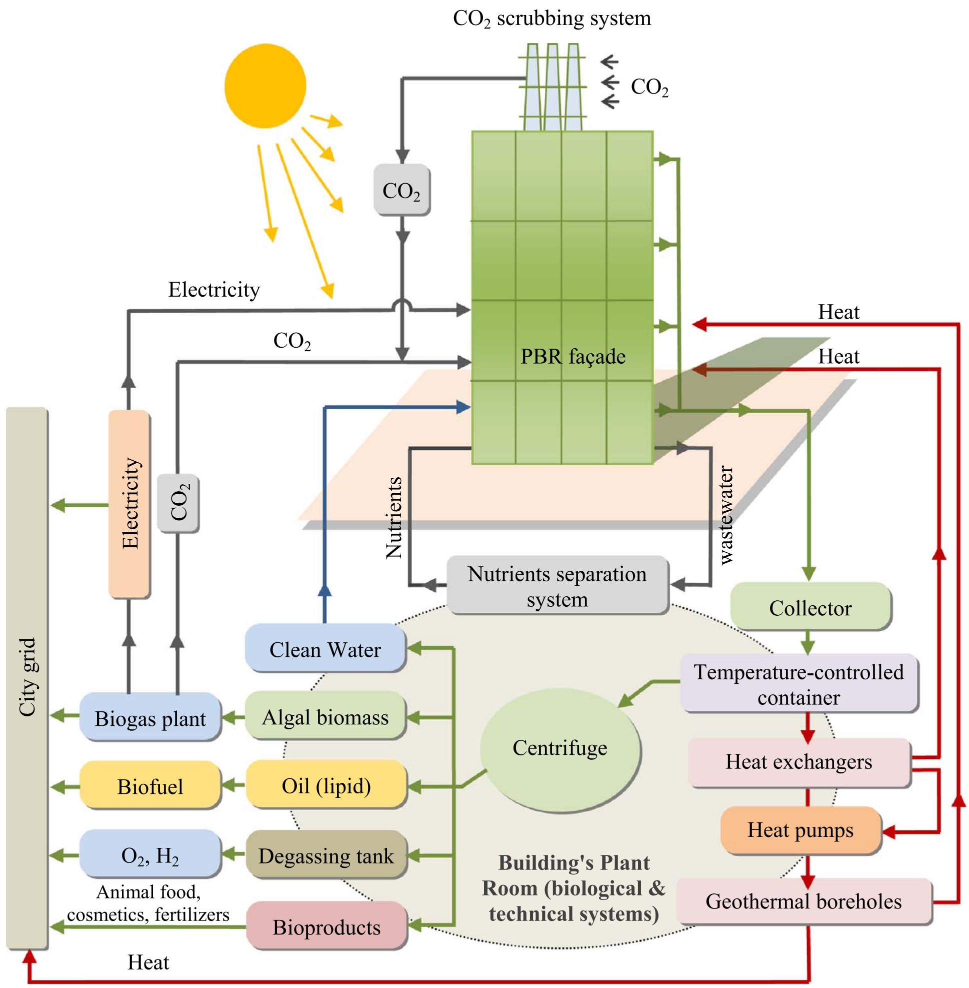


Fig. 9. Schematic concept of the holistic building's biorefinery infrastructure in building-integrated PBRs.

potentials for new regulations for building-integrated PBRs [30].

A significance challenge from the architectural point of view is that the live microalgal façades disturb clear vision. Therefore, in order to provide clear vision to the outside, it is important to incorporate clear vision zones among the PBR façade or divide the window wall into a clerestory PBR window and a clear glazing window (at the level of the occupants' line of view). This integration unleashes different PBR façade configurations.

The segmentation of PBR façades alongside the conscious decision to use durable types of PBR materials is considered a necessity to face the problem of the incapability of the PBR façades to tolerate the increase in pressure with the scaling-up.

7.3. Prospects

1. Bio-façades promise to purify the atmosphere in our crowded cities from harmful carbon emissions as microalgae biomass is the only renewable energy resource that sequesters CO_2 from the atmosphere and generates O_2. As a result, microalgae are regarded as a climate-neutral energy source.
2. Despite the debates about the high capital costs of the construction and the operation of the bio-façade system, the long-term benefits are considered and clearly expressed.

   The symbiosis and the collocation between the building and PBRs promise to reduce the cost via the multiple outputs generated by the centralized biorefinery processing system [30].
3. The inclusion of bioreactors into architecture is not limited to the buildings' façades, but they can also be employed at the urban level as street art installations and urban canopies. These urban installations can perform many functions. They produce biofuel, admit light, provide shade, and raise the public's awareness of alternative fuels.
4. A PBRs façade system is suitable for various types of buildings, including commercial constructions sites, buildings for public infrastructure, trade, and residential buildings, in addition to having great potential for being applied to large industrial buildings. Industrial buildings can be operated economically with PBR façades with the expanded façades and roofs in such low-rise buildings. Furthermore, the integration of PBRs into industrial buildings promises the dissipation of the CO_2 that arises from the process [54].
5. Despite the fact that bio-façades alone don't cover the buildings' entire energy demands, we can deduce indirect aspects of their economic and energetic viability. These indirect aspects can be represented in their function as thermal insulators and sun-shading devices.
6. The integration of bio-façades into buildings encourages a shift towards decentralization in infrastructure systems. Decentralization is intended to make the building like a power plant, generating the energy it requires for itself and for its urban context and providing energy storage. The integration of bio-façades into buildings qualifies the buildings to perform additional functions, such as generating power, taking advantage of the waste heat, and wastewater treatment.
7. The symbiosis between the buildings and PBRs requires a blend of experiences that open up a field of interdependence between several disciplines in the field of engineering, including architectural, chemical, electrical, mechanical, software and civil engineering.

8. In essence, the incorporation of microalgal PBRs into architecture and the built environment can address national energy security, economic security, and climate change and enrich the iconic values.

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