Algae-Powered Buildings

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Environmental pollution, global warming, energy consumption, and limited natural resources are some key factors from which the built environment faces interrelated problems and their management plays a vital role in sustainability. Application of bioactive elements on buildings' façades is a novel approach for solving the problems. Algae building technology (ABT) is an innovative approach to energy efficiency in the built environment.

Keywords: bioactive-façade ; algae-powered buildings ; energy efficiency ; green walls ; carbon neutral

1. Introduction

Approximately, more than 35% of global final energy use and nearly 40% of energy-related CO_2 emissions are attributed to the construction sector. It is expected that GHG emissions from buildings will be doubled over the next 20 years; thus, designing more energy efficient buildings is important to achieving a low carbon future [1][2][3][4]. Energy efficient buildings are "buildings that need less energy with the precautions taken during the design phase, meet the energy they need from renewable sources and make minimum emission by using the energy in the most efficient way" [5][6]. Of the required stock for 2050, 87% is expected to have already been built; therefore, concentrating on retrofitting can have a more significant effect than new construction [7][8].

Green building standards and rating systems for buildings, such as the American LEED [9][10] and the British BREEAM [11], provide practical tools for designers with the aim of achieving high quality architectural solutions on one hand, and making it easy for consumers to identify product quality and encouraging the demand for green buildings on the other hand [12]. Elements such as solar panels and small wind turbines are incorporated in the next generation of buildings to generate local clean energy; however, they are not able to supply 100% of the energy demand, and additional renewable technologies are required to back up and supplement these systems [2][13]. The conversion of algal biomass produced on buildings' façades into bioenergy is a new approach to supplying the energy required for a building's need. Different forms of energy such as electricity, heat, and biofuels are produced by conversion of biomass as a promising eco-friendly alternative source of renewable energy. In 2014, it was claimed that bioenergy is no longer in transition due to 88 GW worldwide energy production using biomass [14][15][16]. The "symbiosis" between a building and a microalgae photobioreactor (PBR) has the potential to reduce the consumption of fossil fuels by the building and consequently to reduce the carbon footprint. This symbiosis is mutually beneficial for algae growth and building performance: on the one hand, the high capital and operating costs of PBRs are reduced by integrating buildings with PBRs; on the other hand, the thermal function of the building will also be improved, reducing thermal loads and the energy and heating requirements of the building through the conversion of algal biomass to biogas for use in the infrastructure, supplying hot water and partially gaining electricity [5][17][18]. Aggravated urban warming and the constant increase of energy use lead us to the intelligent utilization of energy and improvements to its efficiency. Investigating data on temperature effect shows that the energy consumption due to air-conditioning can be reduced up to 30–60% as a result of insulation related to the stagnant air layer created by green walls [19][20][21]. Alongside the energy saving resulting from increased thermal efficiency, it is claimed that PBR-integrated buildings purify polluted air and wastewater, and consequently provide improved air quality [5][22][23]. The PBR's function includes dynamic shading, thermal insulation, solar thermal collector, and biomass production. A balance between climates, building space, window-to-wall ratio (WWR), aesthetics of microalgae growth, energy savings, and occupants' satisfaction should be considered in the design and placement of microalgae enclosures. According to the expansion of renewable energy use, these buildings are both more energy efficient and sustainable and can offer environmental, economic, and commercial opportunities [17][18].

2. Algae-Powered Buildings: Energy Efficiency and Environmental Performance

One of the building energy efficiency indicators is energy use intensity (EUI), which explains the level of building energy performance and is determined by dividing total annual energy use by building. Comparing different buildings across energy efficiency is conducted according to this index. A lower EUI indicates lower usage of energy or higher building efficiency. An average primary EUI is around 120 kBtu/ft^2/year and 200 kBtu/ft^2/year for residential and commercial stocks, respectively [24]. Space heating and cooling, lighting, water heating, and ventilation consume more than half of the building's energy usage. Major energy loss has been related to poor building envelope construction and inefficient HVAC systems. Other factors affecting energy consumption include the geometry of the building, energy characteristics of opaque walls and windows, WWR, and microclimate control such as shading, trees, and landscape. Indoor air quality is also affected by building enclosure and some other factors such as off-gassing interior materials, molds/bacteria due to leaks, or lack of ventilation. Energy management in general requires more efficient use of energy, water, and air quality protection, and wastes and pollution control. Energy interventions play an important role in reducing pollutant emissions and energy bills. The energy cost savings due to energy efficiency and on-site energy production can improve living affordability. Integrating climate-responsive design strategies with energy-efficient active systems and renewable energy generation typically increases upfront cost. However, it can lead to faster economic payoff with operational energy savings [24].

The Paris Agreement aims for GHG reduction in the world. Public acceptance to improve building energy efficiency is intensified by greater awareness of climate emergency and economic returns. However, to deal with the climate crisis, both mandatory and voluntary implementations are required. New York City obligates carbon neutrality by 2050 and demands improvement of buildings energy efficiency up to 23% above 2012 levels by 2030. It is targeted to reach 40% GHG reduction by 2025 and 50% by 2030 [24]. At the voluntary level, over 65,000 Passive House (PH) (a voluntary standard for energy efficiency in a building which reduces the building's ecological footprint) buildings are certified around the world, starting in Germany in 1990s. The performance requirements are 15 kWh/m^2 of each heating and cooling demand focus with maximum 60 kWh/m^2/year of renewable primary energy demand (heating, hot water, and domestic electricity use) [24][25][26]. To meet the energy requirements, there are strategies such as high insulative building enclosures, energy-efficient windows, thermal breaks, and air tightness, which are related to high-performance building enclosures, and ventilation heat recovery, which is related to energy-efficient HVAC systems.

Buildings supplying their required energy (heat and electricity) from microalgae (**Figure 1**) can serve as an alternative building system. The mechanism of the process is as follows: first, water containing nutrients is being filled in the façade PBRs, where daylight and CO_2 are converted to algal biomass through photosynthesis; secondly, the biomass and heat generated by the façade element are transferred through a closed loop system to the plant room, where both forms of energy are exchanged by a separator and a heat exchanger, respectively. For the supply of hot water and heating the building, a hot water pump is used to adjust the temperature levels of the generated heat [27][28].

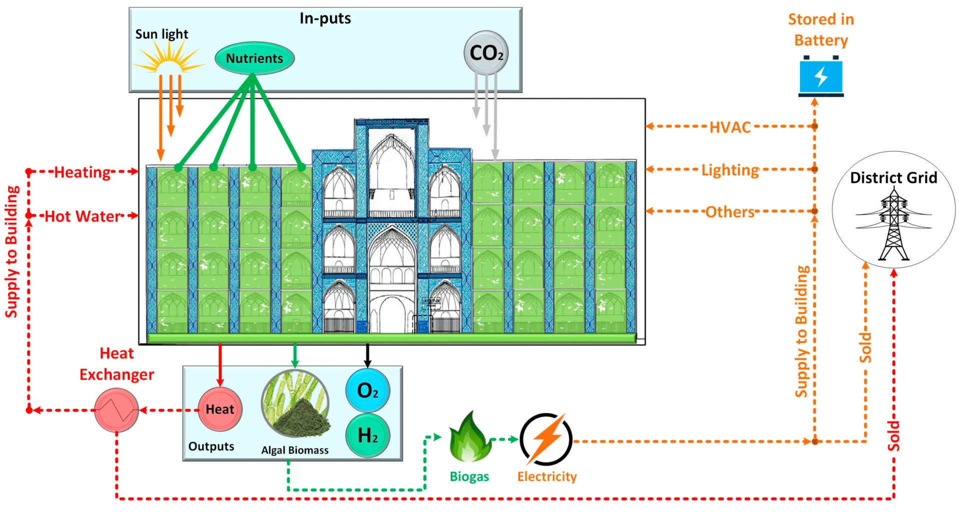

Figure 1. Schematic of algae-powered buildings.

Microalgae enclosures buildings not only generate clean energy but also play a role in GHG mitigation and can be considered as a carbon-neutral power source of energy. Alongside the positive environmental effects, they also have financial profitability due to the reduction of energy and operating costs and taxes which consequently cause lower life cycle costs and increased rental costs without decreasing occupancy [29][30]. These systems are also of interest in the field of net zero energy because of their effectiveness in improving building energy efficiency, renewable power generation, and good air quality. Resulting in better temperature control, PBR façade-integrated buildings can reduce energy consumption by more than 33% in terms of fuel consumption and 10% in terms of electricity consumption [19][23][31]. There is a micro-community integrated with microalgae systems which restores wastes from buildings and converts them into operational valuable resources; they can achieve off-grid power and water independency along with polluted air decarbonation and wastewater treatment [24][32][33]. In 2013, an algae-powered building was implemented in Hamburg, Germany. Since then, there have not been any implemented real-world applications other than small-scale experiments for testing feasibility [24].

Energy savings and occupant satisfaction in algae-powered buildings is enhanced by geometric configuration along with the cell concentration and color changes of microalgae due to environmental effects. Efficient photosynthetic performance of microalgae enclosures lead to building energy savings by reducing heating, cooling, and artificial light demand, along with CO_2 reduction and indoor air quality improvement. The One World Trade Center in New York City, a 94-story skyscraper enclosed with microalgae windows, was investigated as a study building for estimating the energy savings. The computer simulation indicated that the building would reduce energy usage (heating, cooling, lighting, and ventilation load) by an average 20% annually and save over USD 1 million a year in electricity costs with a seven-year return on investment (ROI) [24][34]. The simulation results for estimating annual EUI of commercial and microalgae buildings in different climate zones shows an average 20% energy saving that can be achieved from microalgae window buildings by reducing heating, cooling, ventilation, and lighting loads. This energy savings also results in an average reduction of 6000 tons CO_2. Alongside the carbon reduction due to energy savings, the study buildings can sequester over 7000 tons of CO_2 annually using a CO_2 sequestration rate of 5 g/ft^2 [24].

There are different parameters including panel size, orientation, and type of microalgae which affect the thermal performance of the PBR façades. Some studies concentrated on the *U*-value of the flat PBRs show that the air layer thickness has the greatest effect on providing effective insulation. The thickness of PBR material and PBR depth are also effective, respectively [5][35][36]. Other studies show that the *U*-value is affected by the growing algal medium inside the PBR due to the lower heat transmittance of the algae zone compared with the vision zone. Thus, algae culture density is another important parameter on thermal insulation [37]. The density of algae is also effective in shading, and the more concentrated culture within the PBR has more prevention against solar and light penetration into the building. In addition, there are other factors such as climatic conditions, orientation, and geography which affects the shading. Comparing three different façade systems as shading elements, Martukusumo et al. showed that PBRs on the west façade had an effective role in protection from excessive solar radiation [38]. As façade, PBRs act as solar collectors, and the heat generated in PBRs is also affected by the above-mentioned factors. The evaluations conducted by Negev et al. showed that as well as the thickness of the unit and the algal concentration, type of algae is also a significant factor [2]. They observed that *Chlorella vulgaris* has less light and heat transmission compared to *Chlamydomonas reinnhardtii*. The produced algal biomass should be stored and then used for heat and energy generation. The biomass productivity is affected by different factors including climatic conditions of the building location, PBR material, PBR size and orientation, the intensity of solar radiation, and the algae type. Studies show that the biomass productivity in PBRs with 45° inclination changes through the year, while it is constant in vertical PBRs [18]. A 28.7% increase in productivity was also observed by using *C. vulgaris* at an inclination of 75° compared to *Dunaliella tertiolecta* at 90°. Optimization of the mentioned factors would increase the energy efficiency of PBR-integrated buildings. **Table 1** summarizes the parameters affecting the energy efficiency of the façade integrated PBRs from different aspects and **Table 2** summarizes the value of influential parameters affecting the performance of PBR façades according to different studies.

Table 1. Effective parameters for increasing energy efficiency in PBR-integrated buildings.

Influencing Factor	Influential Factors
Thermal insulation	**PBR material** **PBR size** **Building WWR** **Algae type** **Culture medium density**
Shading	**PBR size** **Orientation** **Surface to volume ratio** **Culture medium density**

Influencing Factor	Influential Factors
Biomass production	**Regional climatic conditions** **Algae type** **Surface to volume ratio** **Inclination degree** **Orientation** **Material thickness** **Building aspect ratio**

For adopting algae façades by building sector, environmental, technical, political, economic, and the social performance of practically implemented algae-integrated buildings should be evaluated in decision-making process. In a common set of buildings, the performance assessment seems difficult before the systems are operated [33][39]. Therefore, for implementing algae façades in buildings, the requirements should be defined and investigated. In a construction project, sustainable design considerations should be conducted as early as possible to make the process time- and cost-efficient [40]. System dynamics (SD) support integrated decision-making and its models are applied for considering repetition and feedback processes. Therefore, SD models can support the decision of applying algae façade systems in the building design and also the multiple subsystems and food–energy–water (FEW) feedback processes [41]. In a study conducted by Chang et al., a framework based on building information modeling (BIM) is presented which helps define the critical factors when applying algae façades in buildings, analyzes energy and waste streams through an SD model, and evaluates the performance considering different building contexts [33]. This framework can be applied to determine feasibility when the algae façade is integrated in a building by running the BIM-integrated SD model simulation.

Table 2. Influential factors affecting the performance of PBR façades.

Recommended PBR Design Parameters						
PBRs Type		**Vertical Bubble Column**	**Vertical Airlift PBR**	**Flat Panels**	**Tubular PBR**	**Ref.**
Material		**Glass, Low Density Polyethylene (LDPE), PVC, PMMA (poly methyl methacrylate)**	**Glass, LDPE, PVC, PMMA**	**Glass, Plexiglas, Polycarbonate, PVC, PMMA, Polyethylene, Plastic bags**	**Polypropylene acrylic, Polyvinylchloride, PVC, PMMA, LDPE**	[42] [43] [44] [45]
PBR dimensions	**Thickness/Diameter(D)**	**D < 20 cm**	**D < 20 cm**	**D < 7 cm**	**5–9 cm**	[24] [44] [46]
	Height/length (H)	**H < 4 m**	**H < 4 m**	**1.5 m**	**100–150 m**	[24] [44] [46] [47]
	Width	**-**	**-**	**10 cm**	**-**	[46]
Surface to volume ratio (S/V)		**2–8 m^{-1}**	**2–8 m^{-1}**	**20–80 m^{-1}**	**up to 100 m^{-1}**	[45] [47] [48] [49]
Type of Mixing		**Via gassing (Bubbling of CO_2-enriched air)**	**Via gassing**	**Circulation flow, Peristaltic pumps and Via gassing**	**Circulation flow, Peristaltic pumps**	[42] [45] [46] [48]
Oxygen mass transfer coefficient		**High**	**High**	**Low**	**Low**	[48]
Risk of photo-inhibition		**Low**	**Low**	**Medium**	**High**	[48]
Risk of self-shading of cells		**Medium–High**	**Medium–High**	**Low (at thin panel thickness)**	**Low (at thin tube diameter)**	[48]
Risk of bio-fouling		**Low**	**Low**	**High**	**High**	[48]
Investment costs		**Low**	**Medium**	**Medium–High**	**Medium–High**	[48]
Space occupation		**Low**	**Low**	**Medium**	**Medium**	[48]

Recommended PBR Design Parameters						
PBRs Type		**Vertical Bubble Column**	**Vertical Airlift PBR**	**Flat Panels**	**Tubular PBR**	**Ref.**
O_2 -release		Easy	Easy	Difficult	Very difficult	[48]
Scalability		Difficult	Difficult	Very easy	Very easy	[48]
Advantages		Compact, good mixing with low shear stress, low energy consumption, easy to sterilize, good for immobilization of algae, reduced photo-inhibition and photo-oxidation		Suitable for outdoor cultures, good light path, high biomass productivities, easy to clean up, low power consumption and shear stress, easy temperature control, low operating cost	Suitable for outdoor cultures, good biomass productivities, improvement of air residence time	[42] [50]
Limitations		Construction requires sophisticated materials, stress to algal cultures, decrease of illumination surface area upon scale-up, high cleaning cost		Scale-up requires many compartments, difficulty in controlling culture temperature, some degree of wall growth, possibility of hydrodynamic stress to some algal strains	Gradients of pH, dissolved CO_2 and O_2 gradients, fouling, some degree of wall growth, photo limitation, high capital, and operating costs	[42] [50]
Recommended Operational and Environmental Parameters						
pH	*Chlorella*	7.5–8				[24] [51] [52]
	Spirulina	9				[24] [53]
	Chlorococcum	8.0–8.5				[24] [50] [53]
	Haematococcus	7				[24]
Nutrients	Macro nutrients:	Phosphorus and Nitrogen				[51]
	Trace metals:	Fe, Mg, B, Mo, K, Co, Zn, Mb				
Temperature		20–30 °C				[24] [50] [51]
Light intensity		5000–10,000 Lux (100–200 μmol/(m^2 × s))				[24] [51]
Liquid velocity		20–50 cm×s^{-1}				[24] [50]
Partial pressure of CO_2 in gas phase		0.2 kPa (0.076 mol × m^{-3})				[49] [50]
Aeration (bubble size)		1–7 mm				[24]

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