A HYBRID FACADE THAT COMBINES AN ALGAL BIOREACTOR WITH PHOTOVOLTAICS

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ABSTRACT

For an algal facade that is operated as a flat plate bioreactor, the biomass in the facade is capable of producing energy as oil, or through methane digestion of the cells, while absorbing radiation that would heat the building. However, an algal facade could also produce electricity if coupled to a photovoltaic (PV) module.

Experiments were conducted with a PV module situated behind a flat plate, algal bioreactor to determine the relative power output for such a hybrid facade compared to a PV module without the algal layer. Two container materials were tested (polypropylene and acrylic), for two algal species (a green algae and a coccolithophore), at 4 biomass concentrations. The containers were two rectangular boxes with a volume of 0.4 liters and 1 liter, corresponding to path lengths (i.e. thicknesses) of 0.9 cm and 2.8 cm, respectively. Experimental results were presented as attenuation coefficients versus algal biomass, photovoltaic power output versus scalar irradiance, and modeled power output based on biomass concentration and container thicknesses.

The acrylic container transmitted more light than the polypropylene and had statistically lower attenuation coefficients. Water in both container types had a minor contribution to attenuation while algal concentrations gave high attenuation. The highest attenuation occurred for the green algae and was a result of increased pigments. The highest coccolithophore concentration, in combination with the shorter path length, produced 95% of the maximum PV power output. Generally, power output increased with decreasing algal concentration since more light was transmitted to the PV module.

The amount of light transmitted through the container to the PV module was modeled based on light attenuation by algal biomass and container thickness. Using the model for full sunlight, we determined that with high algal concentrations and realistic facade thicknesses, high power output can be achieved from PV modules in parallel with algal growth. The next step is to build a prototype facade to assess the effect of full sunlight under these design criteria, as well as the effect of heat dissipation by the facade.

Keywords: hybrid algal facade, integrated photovoltaics, light attenuation

INTRODUCTION

Since visible light can pass through transparent facades, it is feasible to use them as algal bioreactors to create living buildings that can produce energy from biomass. Spectral light transmission through transparent facades is strongly dependent on the angle of light and the color of the facade material, with clear glass transmitting >80% of the visible spectra (400-700 nm) at angles $\leq 20^{o}$ [1]. Additionally, the thickness of the facade will attenuate light. In 2013, the first commercial algal facade, covering the surface a building, was unveiled in Hamburg, Germany [2]. Recently other designs for algal facades have been proposed [3, 4].

Commercial algal bioreactors come in various sizes (1 to 10^6 L) and shapes (e.g. cylinders, flat plates, coils, trapezoidal channels) and are used to produce oil (i.e. lipids) for biofuels, and other compounds for pharmaceuticals and food supplements [5]. Smaller algal bioreactors, between 200 L and 1000 L, with high illuminated surface to volume ratios, are the most productive and can achieve high oil yields [6]. One of the most efficient bioreactors for algal facades is a flat plate reactor, which has a large, rectangular surface area and thicknesses from 0.1 to 10 cm [7, 8]. A flat plate bioreactor maximizes the illuminated surface area and minimizes the light path length, such that even with high light attenuation by algae, sufficient light is transmitted through the bioreactor to promote high algal growth rates.

In this paper we present data that demonstrate that light passing through an algal bioreactor is utilized by a photovoltaic module to generate electricity. We use these data in a model to examine parameters for a full scale, hybrid algal facade capable of producing biofuel from algal oil, electricity from a PV module, and which may have implications for heat dissipation from the building envelope.

METHODS

The experiment consisted of placing transparent containers (i.e. bench scale facades) with medium and algae, on top of a 20 cm x 20 cm mono-crystalline, single-cell PV module (rated at 4 W for STP and 1000 W m^{-2} radiance) on a level bench and measuring both spectral and scalar light transmission through the containers, as well as the power generated from the PV module. Two container materials were tested (polypropylene and acrylic), for two algal species (a green algae and a coccolithophore) each at 4 biomass concentrations. The control was a container without algae, only the salts and algal nutrients (i.e. medium). The containers were two rectangular boxes with a volume of 0.4 L (polypropylene) and 1 L (acrylic), corresponding to path lengths (i.e. thicknesses) of 0.9 cm and 2.8 cm, respectively. The containers were laid flat on the PV module such that they extended beyond the edges of the PV module, ensuring that only light passing through the container impinged on the PV module and thereby avoiding edge effects. Measurements were done from high to low algal concentrations by successively diluting each sample with sterile media to attain the desired concentration.

Containers were oriented perpendicular to a light source, which simulated solar radiation using an array four of small halogen flood lamps (2000 W, 3000 K) surrounding one large lamp (1000 W, 6000 K) all hung from the ceiling. Spectral light was measured every 10 nm for visible wavelengths (400-700 nm) using a spectrometer. Scalar measurements of photosynthetically active radiation for plants, PAR, were taken with a quantum meter set to detect light from an electronic source. The total scalar irradiance on the container surface was 490 μE m^{-2} s^{-1} and varied only 4% during the experiment.

Attenuation of light in the containers was calculated from the Beer-Lambert Law as,

$$k = -\frac{ln\frac{I_z}{I_0}}{z} \tag{1}$$

where I_z was the light measured leaving the container, I_0 was the light measured impinging on top of container, and z was the container thickness. Total attenuation was given by the sum of individual attenuation coefficients based on water, container material, and algal type and biomass concentration,

$$k = k_{water} + k_{container} + k_{algae} \tag{2}$$

Graphics and ANOVA statistics were done using Kaleidagraph (v4.5) software.

RESULTS

The acrylic control container transmitted more light than the polypropylene control for thickness of 0.9 cm (95% vs. 84%) and 2.8 cm (90% vs. 73%) and had statistically lower attenuation coefficients (*df*=7, *F*=19.6, *P*=0.007, Table 1). There were no statistical differences in attenuation coefficients based on container thickness for either the polypropylene (*P*=0.101) or the acrylic (*P*=0.43) controls, indicating that the path length through water (medium) in the containers had a minor contribution to attenuation.

Table 1. Attenuation coefficients for algal biomass and controls (no algae).

	% Biomass Concentration	Biomass (10^6 Cells L^{-1})	K (polypropylene) (cm^{-1})	K(acrylic) (cm^{-1})
Control container*				
z=0.9 cm		0.0	0.150	0.067
z=2.8 cm		0.0	0.102	0.042
Algae container				
Coccolithophore	100	5.00	0.185	0.091
	50	2.50	0.127	0.047
	18	0.90	0.095	0.023
	7	0.36	0.082	0.012
Green	100	2.00	0.225	0.084
	40	0.80	0.185	0.081
	16	0.32	0.120	0.047
	6	0.13	0.082	0.011

* Containers with medium were used as controls.

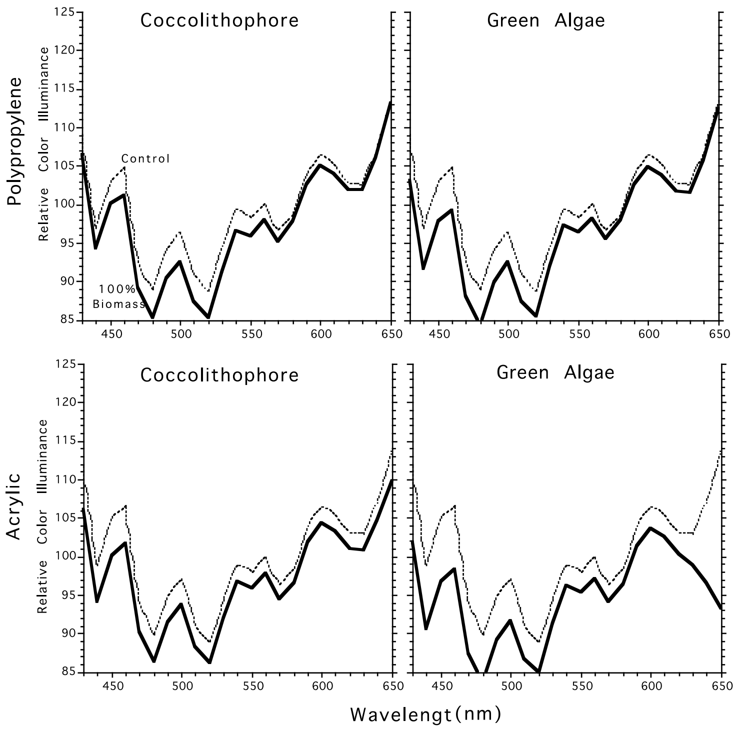

Figure 1. Spectral light transmission for cococlithophore (left) and green algae (right) in the polypropylene (top) and acrylic (bottom) container for the control with water (dashed line) and the 100% biomass concentration (solid line).

The polypropylene control had lower light transmission in the blue wavelengths (400-450 nm) than the acrylic control container, however, both controls had higher transmission than algae at all wavelengths (Figure 1). Both algal types had strong attenuation in the blue spectral band (430-480 nm), although the green algae also attenuated in the other bands (i.e. green, yellow, and red).

The highest algal biomass concentrations produced the highest attenuation coefficients and as algal concentrations decreased, light attenuation also decreased (Table 1, Figure 2). The polypropylene container consistently had higher attenuation than the acrylic one, for all but the most dilute coccolithophore and green algae biomass concentrations (Figure 2). Green algae attenuated more light than the coccolithophore at all biomass concentrations (Figure 2).

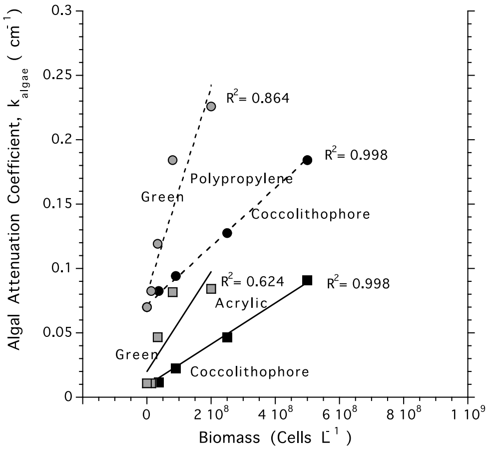

Figure 2. Attenuation coefficients versus algal biomass for coccolithophore (black) and the green algae (grey) and polypropylene (circles, dashed lines) and acrylic (squares, solid lines) containers*, where regression lines indicate the best fit.*

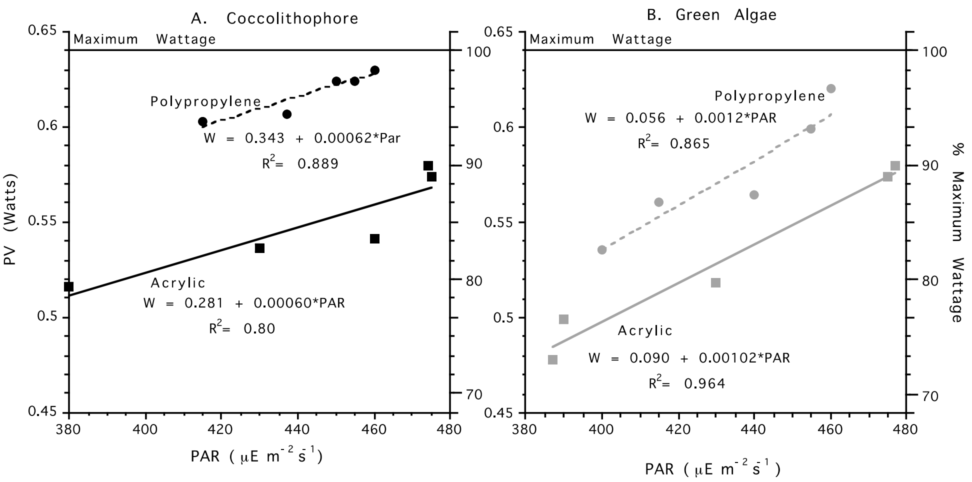

Figure 3. Photovoltaic power output as Watts (left y-axis) and percent maximum wattage (right y-axis) versus scalar irradiance (PAR) for: A. coccolithophore (black) and B. green algae (grey) in polypropylene (circles, dashed lines) and acrylic (squares, solid lines) containers. Regression lines and equations indicate the best fit. The solid horizontal line is the maximum wattage produced by the PV module with no containers.

Reducing the algal concentration resulted in reduced attenuation of light with concomitantly higher power outputs for the PV module for both container types (Figure 3). The 0.9 cm container transmitted more light and therefore produced more power than the 2.8 cm container for both the coccolithophore (Figure 3A) and green algae (Figure 3B). However, the coccolithophore had a higher power output than the green algae for the same container thickness.

The highest coccolithophore concentration, in combination with the shorter path length (0.9 cm), produced 95% of the full PV power output, while the highest green algae concentration at the shorter path length produced 84% of the maximum power. Even with the thicker container (2.8 cm), the highest algal concentrations produced 80% and 73% of the maximum power for the coccolithophore and green algae, respectively.

DISCUSSION

As discussed by Caram et al. [1], different facade materials attenuate light differently. In our work, the polypropylene container transmitted less light than the acrylic container. When algae biomass was added to the container, light transmission decreased further and attenuation increased for all but the most dilute algal biomass concentrations. The high attenuation by algae can be attributed to light absorption by photosynthetic pigments. The fact that the green algae had more pigments and was larger (7 μm) than the 3 μm coccolithophore, explains why it also had higher attenuation coefficients at similar biomass concentrations. Additionally, the spectral signatures of visible light attenuation coincided with known absorption spectra of the green algae and coccolithophore. However, algal attenuation is a result of both absorption of light by pigments and scattering of light off the cell surface [9]. Since only bulk attenuation was measured, we were not able to separate these two variables.

Even though the 2.8 cm acrylic container had lower attenuation, it let less light through than the 0.9 cm polypropylene container because it was thicker. The result of this thicker container was a longer light path, and so higher numbers of algal cells intercepting and absorbing light over the path length. Therefore, the power output from the PV module was a function of the container thickness, the algal concentration, and to some extent the container material.

A model of light attenuation in an algal facade can be parameterized as:

$$I_z(\lambda) = I_0(\lambda) e^{-k(\lambda) z} \tag{3}$$

where $I_0(\lambda)$ is the spectral irradiance at wavelengths, λ, impinging on the facade surface, $I_z(\lambda)$ is the spectral irradiance passing through the facade of thickness z (i.e. front to back) and $k(\lambda)$ is the spectral attenuation coefficient that accounts for the reduction of irradiance as the light passes through an algal. The scalar (PAR) form of equation 3 would be the same except irradiance would be integrated over the visible spectrum as,

$$I_{PAR} = \int_{400\,nm}^{700\,nm} I(\lambda)\, d\lambda \tag{4}$$

Using attenuation coefficients from Table 1, modeled PAR irradiances were calculated from equations 3 and 4 and used in the regression equation for power as a function of PAR for coccolithophore biomass, $PAR(B)$, $Watts = 0.343 + 6.2x10^{-4}\ PAR(B)$ (Figure 3A), in order to determine the power generated from a prototype facade with a PV module.

The model shows that at a biomass concentration as high as 10^{11} cells L^{-1}, 78% of the maximum PV power is generated for a 0.1 cm thick facade (Figure 4). For thicknesses < 0.25 cm, enough light is transmitted to generate > 50% of the maximum PV power. The advantage of maintaining high algal concentrations is that higher yields of algal oil can be produced per unit volume of facade. Therefore, it should be possible to optimize oil production by the algae and power production by the PV panel, as well as heat dissipation by the facade. This model, however, assumes that the regression equation and k values are the same for a full-scale facade as for the laboratory containers. This assumption, however, must be validated for a full scale (1 m^2) facade exposed to solar irradiance and under controlled conditions. Still, these results indicate the necessity of further research to determine if a hybrid algal facade can be deployed on buildings to provide electricity and heating oil.

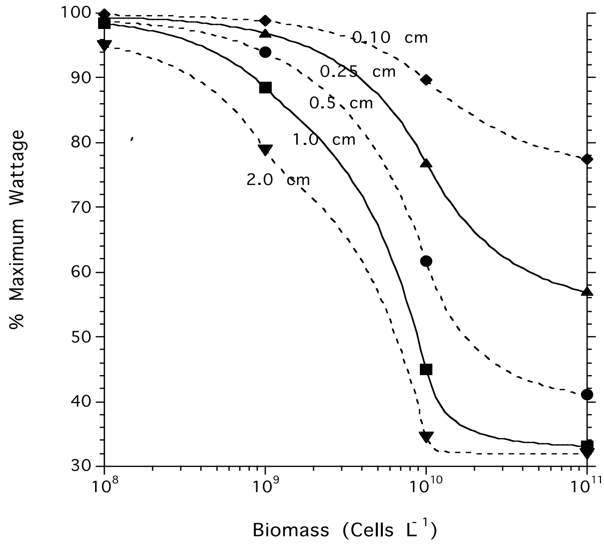

Figure 4. Modeled PV power output versus coccolithophore biomass concentration for facade thicknesses from 0.1 cm to 2.0 cm.

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