Chapter 15
Potential of Converting Solar Energy to Electricity and Chemical Energy

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Abstract Chemical energy can be produced from solar energy via photosynthesis. Solar energy can also be converted into electricity via photovoltaic devices. These two mechanisms would seem to compete for the same resources. However, due to differences in the spectral requirements, there is an opportunity to coproduce both electricity and chemical energy from a single facility. We propose to introduce an active filter or solar panel above a microalgae pond to generate both electricity and chemical energy. There are several advantages to such technology including reduced heating (saving freshwater) and an independent electricity supply. Additionally, by channeling targeted illumination back into the microalgae ponds, we can double the amount of light absorbed by the microalgae. This can result in increased biomass productivity.

15.1 Introduction

There is no doubt that available fossil fuel resources are depleting. Despite new reserves of some fossil fuels, the current reserves of oil, coal, and gas will last 40, 200, and 70 years, respectively (Shafiee and Topal 2009). There is also the issue of human-induced climate change. These situations have resulted in increasing worldwide interest in the renewable energy sector. Apart from fuel, there is also an urgent need for sustainable food production for the ever growing human population.

One of these alternative and renewable energy supplies is that of photovoltaic modules (solar panels). These are solid-state devices that directly convert solar

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energy into electricity. Photovoltaics have been used widely for many decades to convert sunlight to electricity (Wenham et al. 1994) and are a well-established technology despite faults that appear in some modules (Djordjevic et al. 2014). Photovoltaic devices take incident illumination and through the use of a charge separating junction can supply electrons to an external circuit. Although in their initial uses they were for specialized projects such as the space program and for remote area power supplies, there is an increasing demand for terrestrial and domestic systems. Solar panels are becoming a common sight on rooftops in suburban areas.

Biofuel (biodiesel and bioethanol) has been used widely as an alternative source of chemical energy (de Boer et al. 2012). It is projected that the global annual production of bioethanol and biodiesel will increase from 113×10^9 and 28×10^9 L in 2012 to 167×10^9 and 40×10^9 L in 2022, respectively (OECD/FAO 2012). There is no doubt that renewable transport fuel production using crops such as oilseeds or sugarcane has economic as well as ethical problems. This is mainly due to the competition for limited resources (freshwater and nutrients) with food crops. Therefore, there is a need for an alternative source of raw material for biofuel production.

These two energy production methods, one for chemical and the other for electrical, seem to compete for the same resource. They both require illumination from the sun to drive their different processes. However, photosynthesis and the production of biomass are largely reliant on the blue and red end of the solar spectrum, whereas photovoltaics are highly efficient in the green part of the spectrum. These differences in spectral requirements are discussed later in this chapter and can be seen in Figs. 15.2 and 15.3. This suggests that if there was a mechanism for splitting the solar spectrum between these applications, it would be possible to convert the entire solar spectrum to electricity and chemical energy.

We have previously described the scenario of placing an active filter or solar panel above an microalgae pond (Moheimani and Parlevliet 2013; Parlevliet and Moheimani 2014). We produced a conceptual framework and model that described the total amount of power provided to a microalgae culture and the subsequent electrical generation from the solar cells. In this work, we have further developed the model to examine the amount of power absorbed by the microalgae, this taking into account the varying absorption spectra of different microalgae. This work provides a more detailed description of the model and the expected increases in illumination that can be provided to the microalgae.

15.2 The Solar Spectrum

The surface of the Earth receives significant amounts of electromagnetic radiation from the Sun in the form of light. This irradiance has been well characterized (Neckel and Labs 1984) and varies in intensity with different wavelengths. For example, the peak irradiance from the Sun is in the visible part of the spectrum and this tails off into the infrared. The intensity and spectrum of the light that are measured on the Earth's surface (the terrestrial spectrum) are significantly different from the spectrum of light that would be measured outside of the atmosphere (the extraterrestrial spectrum). This is due to absorbance within the Earth's atmosphere. With its importance to many industries and sciences, the solar spectrum has been well characterized and two standard terrestrial solar spectral irradiance distributions (ASTM 2008) have been defined. These standard distributions are used in the photovoltaics industry for testing of PV modules under standard test conditions. This allows the comparison of the efficiency and performance of different solar modules.

Two different spectral distributions are described in these standards (Gueymard et al. 2002). The first of these spectral distributions is the direct normal spectrum. This is "*the direct component contributed to the total hemispherical (or 'global') radiation on a 37°-tilted surface*" (Gueymard et al. 2002). The second applies specifically for photovoltaic modules and is a good approximation for modules that are tilted toward the equator at 37° (Gueymard et al. 2002). Average values for the atmospheric composition, aerosols, water vapor, and ozone content are taken into account in the standards defined in ASTM G-173-03 (ASTM 2008). Due to the absorbance of light in the atmosphere, the irradiance is dependent on the optical path length through the atmosphere. This is known as the air mass. The spectra in ASTM G-173-03 use an air mass of 1.5. For the midlatitudes, this is a reasonable average. This is a good approximation for modules in the United States of America and southern regions of Australia. As this spectrum is well defined, it is suitable for use in modeling the power absorbed by microalgae as well as the power produced by photovoltaic modules.

The extraterrestrial irradiance and the Global Tilted AM1.5 spectra described in the ASTM G-173-03 standard are shown in Fig. 15.1. This plot shows the irradiance in terms of W m^{-2} nm^{-1} which is an expression of the power in each part of the spectrum incident on a particular area. This can also be described in terms of μ mole photons s^{-1} m^{-2} which is often used when discussing photosynthesis. Converting from one to the other is wavelength specific and can be done using:

$$I_{\mu} = \frac{I_w \lambda}{hcN_A \cdot 10^{-6}}$$

where I_{μ} is the irradiance in μ mole photons s^{-1} m^{-2}, I_w is the irradiance in W m^{-2}. nm^{-1}, λ is the wavelength, h is Planck's constant, and N_A is Avogadro's number.

The daily global solar radiation exposure is defined as the total amount of solar energy falling on a horizontal surface per day. The daily solar radiation exposure typically ranges from 1 to 35 MJ m^{-2} and will depend on the time of year, clarity of the air, and the level of cloud cover. For example, the daily solar radiation exposure would usually be highest in clear, sunny, conditions during the summer and lowest during winter or very cloudy days. Some regions of the world have very high radiation exposures due to their location and number of cloud free days. The northern and central regions of Australia experience high levels of incident illumination.

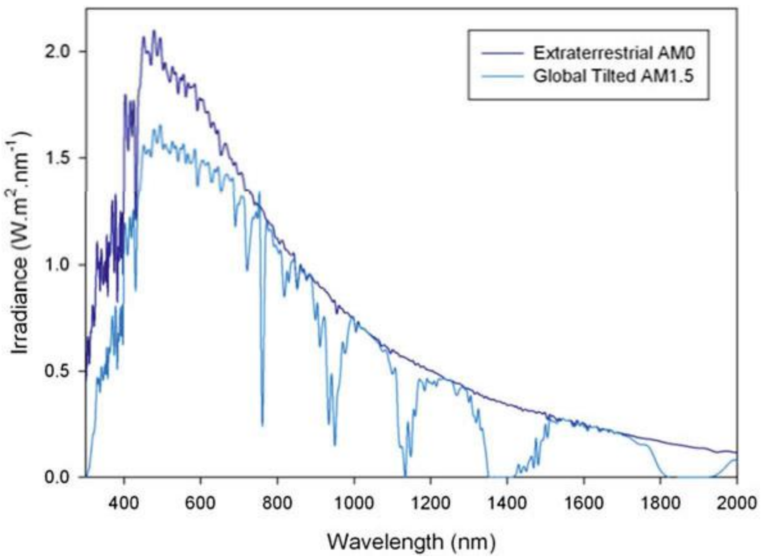

Fig. 15.1 Standard solar spectra as defined in ASTM G-173-03 (ASTM 2008)

This makes them particularly good for photovoltaic electricity production and biomass production (Clifton and Boruff 2010; Borowitzka et al. 2012). Successful conversion of solar energy into chemical energy in the way of biofuel also relies on the availability of abundant water supplies (i.e. seawater or large aquifer resource). Prime locations for algae farms and biofuel production exist where these are available and there is abundant solar radiation (Borowitzka et al. 2012).

15.3 Spectral Requirements of Microalgae

Photosynthesis makes use of solar energy to convert CO_2 into glucose. This process is vital for life on Earth. Photosynthesis can only use parts of the solar spectrum that are in the photosynthetic active radiation range (PAR) (irradiance between 400 and 700 nm). Based on the measured average solar spectrum at the Earth's surface, the proportion of total solar energy within PAR is about 48.7 % of the incident solar energy (Zhu et al. 2008). Pigments are responsible for capturing this light. Photosynthetic organisms contain several pigments. As a matter of fact, pigments are responsible for the names of different divisions and classes of algae. For instance, Cyanophyceae and Rhodophycea contain Chl *a* and phycobillins, while Haptophyceae and Bacilariophycea contain Chl *a* and *c*. It is to be noted that all photosynthetic organisms contain Chl *a* which has the strongest absorption at 430 and 662 nm.

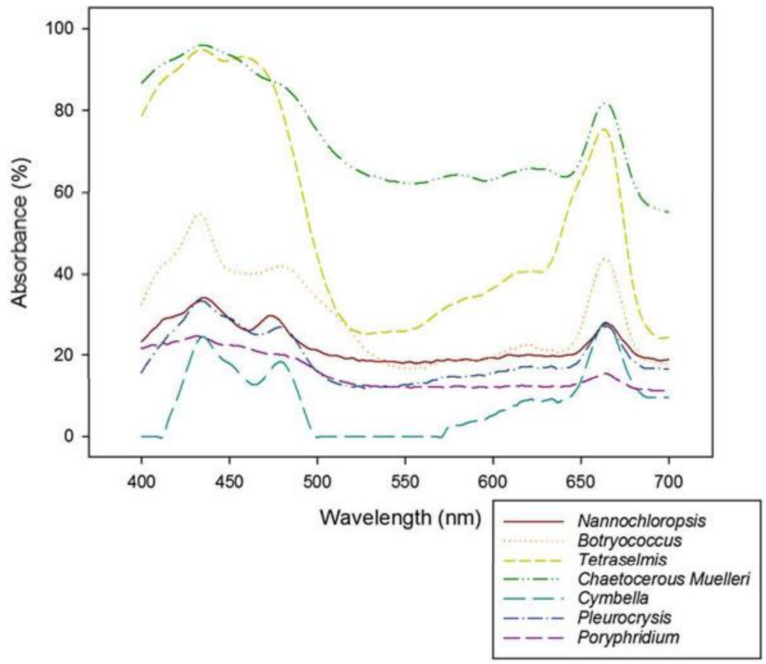

Fig. 15.2 Absorbance spectra of different microalgae species

Other accessory pigments have different absorption spectra allowing the organism to more effectively collect different spectra of light (Frigaard et al. 1996). The absorption spectra of some microalgae species are summarized in Fig. 15.2.

15.4 Spectral Requirement of Solar Cells

Solar cells are devices for producing electricity which use incident illumination to supplying electrons to an external circuit. The use of these has even been described as the "art of converting sunlight directly into electricity" (Wenham et al. 1994). There are a range of technologies and materials used to produce solar cells, each with their own benefits and drawbacks. By far, the most common and familiar example of a solar cell is that of crystalline silicon. Crystalline silicon solar cells currently dominate the world market and held over 93.5 % market share in 2005 (Singh and Jennings 2007), decreasing to 83 % in 2010 (Tyagi et al. 2013) and 86 % in 2011 (Fraunhofer 2012). Crystalline silicon solar cells have a long history and have undergone major improvements in efficiency over the years. The first crystalline silicon solar cell had a limited efficiency of 6 % (Chapin et al. 1954); however, new solar cells have been developed with efficiencies greater than 25 % in the laboratory and 22 % in full modules (Green et al. 2012; Beardall et al. 2009). Although solar cells are generally optimized to absorb strongly across the whole solar spectrum, each individual technology will have variations in performance. These variations are due to a number of factors including the properties of the semiconductor, such as the bandgap.

15.5 The Semiconductor Bandgap

The semiconductor bandgap determines the optoelectronic properties of the semiconductor material. A semiconductor's bandgap has a significant influence on the properties (including absorption in the case of a solar cell) of devices produced from them. The bandgap defines the minimum amount of energy needed for an electron to jump from the valence band to the conduction band.

The value of the bandgap (E_g) is characteristic of each semiconductor. This value affects the properties of the solar cells produced from each semiconductor (McEvoy et al. 2003). For example, semiconductors are effectively transparent to photons of energy less than the bandgap energy as these photons have insufficient energy to excite an electron from the valence to the conduction band and hence are not absorbed.

The minimum room temperature bandgap energy values for some common semiconductors range from 0.67 eV for germanium (Lide 2005) to 1.35 eV for gallium arsenide (Lide 2005). The semiconductors used for solar cells should ideally have a bandgap energy close to the peak of the energy range of light in the AM1.5 spectrum (1–3 eV). Not all semiconductors are appropriate for the use in solar cells. The most suitable semiconductors will have a bandgap of about 1–1.6 eV(Wenham et al. 1994). Silicon, with a bandgap of 1.12 eV (Lide 2005), is a good candidate material use in solar cells. Ideally, a solar cell should have a flat response to irradiance of different wavelengths. However, this is not usually the case as each will respond differently to different parts of the spectrum. A measurement known as the spectral response can characterize the quantum efficiency of the solar cell to different wavelengths of light.

The spectral response of a solar cell is defined as the short-circuit current (output current under short-circuit conditions) per unit power of incident monochromatic light, as a function of the wavelength of the incident light (Cuevas et al. 2002). The spectral response measurement shows how the solar cell will perform under different spectral conditions and can have implications on which technology is deployed in the field. For example, Ruther et al. (2002) have shown that crystalline cells are more suitable for "red" spectra and that amorphous silicon solar cells are more suitable for "blue" spectra (Ruther et al. 2002). This can contribute to the better performance of a-Si:H cells during summer months and the better performance of c-Si cells during winter months, due to the seasonal variations in the spectra of light received by the solar cell (Ruther et al. 2002). Comparison and analysis of the spectral response measurements for different solar cell technologies enables the most appropriate solar cell to be deployed given the spectra of light they are likely to encounter.

15.5.1 Crystalline Solar Cells

Solar cells manufactured from doped crystalline silicon solar cells are among the most widely recognized varieties of solar cells. Crystalline silicon solar cells made up about 86 % of the market in 2011 (Fraunhofer 2012). Currently, state-of-the-art single crystal silicon solar cells are reaching a conversion efficiency of up to 24.7 % (Beardall et al. 2009). A similar 24 % efficient (when measured under AM1.5 at 25 °C) passivated emitter, rear locally diffused (PERL) solar cell has been reported with a conversion efficiency of up to 46.3 % (Zhao et al. 1996). This was under monochromatic light of 1040 nm (Zhao et al. 1996). The broad spectral response of this solar cell can be seen in Fig. 15.3.

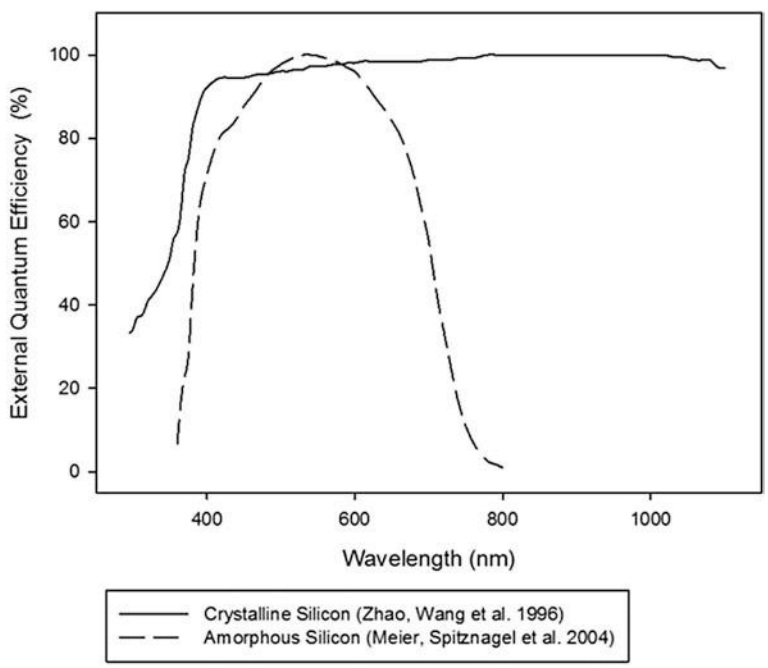

Fig. 15.3 The spectral response of two different solar cell technologies

15.5.2 Thin-Film Solar Cells

In comparison to crystalline solar cells, thin-film solar cells use significantly less material. The development of thin-film solar cells was in part driven by high material costs of crystalline silicon. Thin-film solar cells were much more efficient in terms of material usage and had potentially lower fabrication costs. Thin-film solar cells are fabricated from layers of doped semiconducting materials. These layers produce a charge separating junction often in the form of a p-i-n junction (McEvoy et al. 2003). As they use significantly less material and are inherently thin, thin-film solar cells can be semitransparent to visible light. When a transparent substrate (such as glass) is used, this can allow some irradiance to pass through the device (Shah et al. 2004). Although a single-junction thin-film solar cells can be relatively inefficient in comparison with their crystalline counterparts, several junctions can be stacked so as to produce a more efficient device (Shah et al. 2004). These multi-junction devices can be made from identical junctions or the junctions can be tuned to different wavelengths and parts of the solar spectrum so as to absorb as much of the spectrum as possible. There are a range of examples of thin-film solar cells, and one of the most well-known examples is amorphous silicon.

Hydrogenated amorphous silicon solar cells have been in development since the late 1970s (Wilson 1980). Although thought to be a good alternative to crystalline silicon, amorphous silicon solar cells had one significant drawback in the form of a light-induced degradation, photodegradation, known as the Staebler–Wronski Effect. This is the process whereby the performance and efficiency of the amorphous silicon solar cell degrade upon extended exposure to light (Staebler and Wronski 1977). The degradation occurs over a period of time as the solar cell is exposed to light. The efficiency and performance of the cell degrade asymptotically to a stabilized minimum, upon which point the stabilized cell does not degrade any further. Any additional exposure to light after this point has minimal effect on the solar cell's performance. This light-induced degradation can be revered by annealing the cell above 150 °C for a period of time (Staebler and Wronski 1977). Despite these drawbacks to amorphous silicon, a thin-film amorphous silicon solar cell has been produced on a antireflection-coated glass substrate with a reported stabilized efficiency of 9.47 % (Meier et al. 2004). The spectral response from this solar cell is shown in Fig. 15.3. As can be seen, the device had lower quantum efficiency in the blue and the infrared portions of the spectrum compared to the crystalline silicon PERL solar cell. However, it does have a comparable peak in efficiency in other parts of the solar spectrum.

15.5.3 Luminescent Solar Concentrators

While both the crystalline silicon solar cells and amorphous silicon solar cell examples shown in Fig. 15.3 are optimized to have a broad spectral response, it is known that photovoltaic devices would work with a higher efficiency if they only had to absorb monochromatic light (Sark et al. 2008) or light from a very narrow spectral range. One way to provide a limited portion of the spectrum to a solar cell, to make the most of its peak efficiencies, is to use a luminescent solar concentrator (LSC). A LSC is a flat-plate solar concentrator made from a thin transparent polymer (such as acrylic) containing a luminescent material (Sark et al. 2008). They work by accepting light from the AM1.5 solar spectrum and directing a portion of the light toward the edges of the flat polymer sheet. Solar cells are located at the edge of this flat sheet for converting the light into electricity. Photons incident upon the polymer sheet with enough energy will excite the luminescent materials. These materials will then re-emit a photon with a longer wavelength. As the photons are emitted in random directions, a portion of these will be captured by total internal reflection in the flat sheet and transmitted to the edge where it can be collected by a solar cell (Sark et al. 2008). With the photons being re-emitted in random directions, there will be some that are transmitted out of the concentrator, and however, a portion is captured and directed toward the edge for collection. Photons without insufficient energy to excite the luminescent material will be transmitted through the concentrator with very low loss. The beauty of these flat-panel concentrators is that increasing the size of the polymer sheet will directly increase the number of photons captured via total internal reflection and able to be converted to electricity. That is, the concentration factor increases with the area of the concentrator. This increase in output from the concentrator can be achieved without increasing the size of the solar cell itself.

Although the efficiency of LSC has historically been fairly low (Sark et al. 2008), there have been devices reported with efficiencies of up to 7.1 % (Sark et al. 2008) which bodes well for the technology. This style of concentrator relies on the use of only a small portion of the solar spectrum. For example, if a luminescent material that emitted green photons was used, all incident light with longer wavelengths would be transmitted through the concentrator. The re-emitted green photons would be directed to a solar cell with a high efficiency in this part of the spectrum. This would potentially be a good match for a system that would convert solar energy into electricity and grow microalgae.

15.6 Electrical and Chemical Energy Co-production

Using the AM1.5 direct solar spectrum as a baseline, we can model the amount of energy that can be converted into electricity by a solar cell if a portion of the solar spectrum is diverted to algae production and only the remainder is provided to the solar cells. This allows us to determine the viability of a cultivation system based on this concept in terms of generating electivity or increasing the portion of specifically targeted PAR available for cultivation. The proposed lossless system places a filter or device above the algae pond to split the spectrum into the appropriate components. We do not consider the mechanism used to redirect the light or the specifics of how the system will function. However, one candidate technology would be the luminescent solar concentrator or a variation thereof. Although the exact mechanism is not described, the model assumes all the light not provided to the algae is directed to a solar cell. The model assumes there are no losses associated with transmission of light through the filter or reflections from the surfaces of the filter or solar cell. The model also disregards electrical resistance in the transmission of the generated electricity.

The first aspect of this model is to determine the component of the spectra absorbed by the microalgae. As can be seen from Fig. 15.2, on average the main chlorophyll absorption peaks are centered at 434 and 662 nm. The portion of the spectrum transmitted to the algae was varied by changing the threshold around these peaks. For example, full-width half-maximum (50 % threshold) meant the spectra from 400 to 492 nm and 644 to 678 nm was transmitted to the algae, while for a threshold of 80 %, only the spectra from 417 to 458 nm and 656 to 670 nm were transmitted to the algae. Additionally, the light given to the algae is limited to between 400 and 700 nm as this is the region typically considered PAR (photosynthetically active radiation). All energy not transmitted to the algae is provided to the photovoltaic device for producing electricity. To calculate the power absorbed by the different microalgae species, the AM1.5 solar spectrum is multiplied by the absorbance spectrum (Fig. 15.2). The allocation of the solar spectrum as the bandwidth changes and the power absorbed by the microalgae (nannochloropsis) can be seen in Fig. 15.4.

With this allocation of the solar spectrum, we can calculate the power generated by a solar cell in hypothetical system using the reported spectral response graphs and parameters for crystalline silicon (Beardall et al. 2009) and amorphous silicon (Meier et al. 2004).

The short-circuit current density (J_{SC}) generated by a solar cell is calculated from:

$$J_{SC} = \int EQE(\lambda)\left(\frac{\qquad}{\qquad}\right).d\lambda$$

where $EQE(\lambda)$ is the external quantum efficiency as a function of wavelength, $\Phi(\lambda)_{AM1.5}$ is the photon flux density calculated from the AM1.5 (Global Tilted) solar spectrum, $PV(\lambda)$ is function defining the portion of spectrum not transmitted to the microalgae, and q is the charge of an electron.

The open-circuit voltage (V_{OC}) of the solar cell is dependent on the short-circuit current density and will vary with the irradiance that is incident upon the cell. This can be calculated from (Messenger and Ventre 2010):

$$V_{OC} = \frac{kT}{q}\ln\left(\frac{\qquad}{\qquad}\right)$$

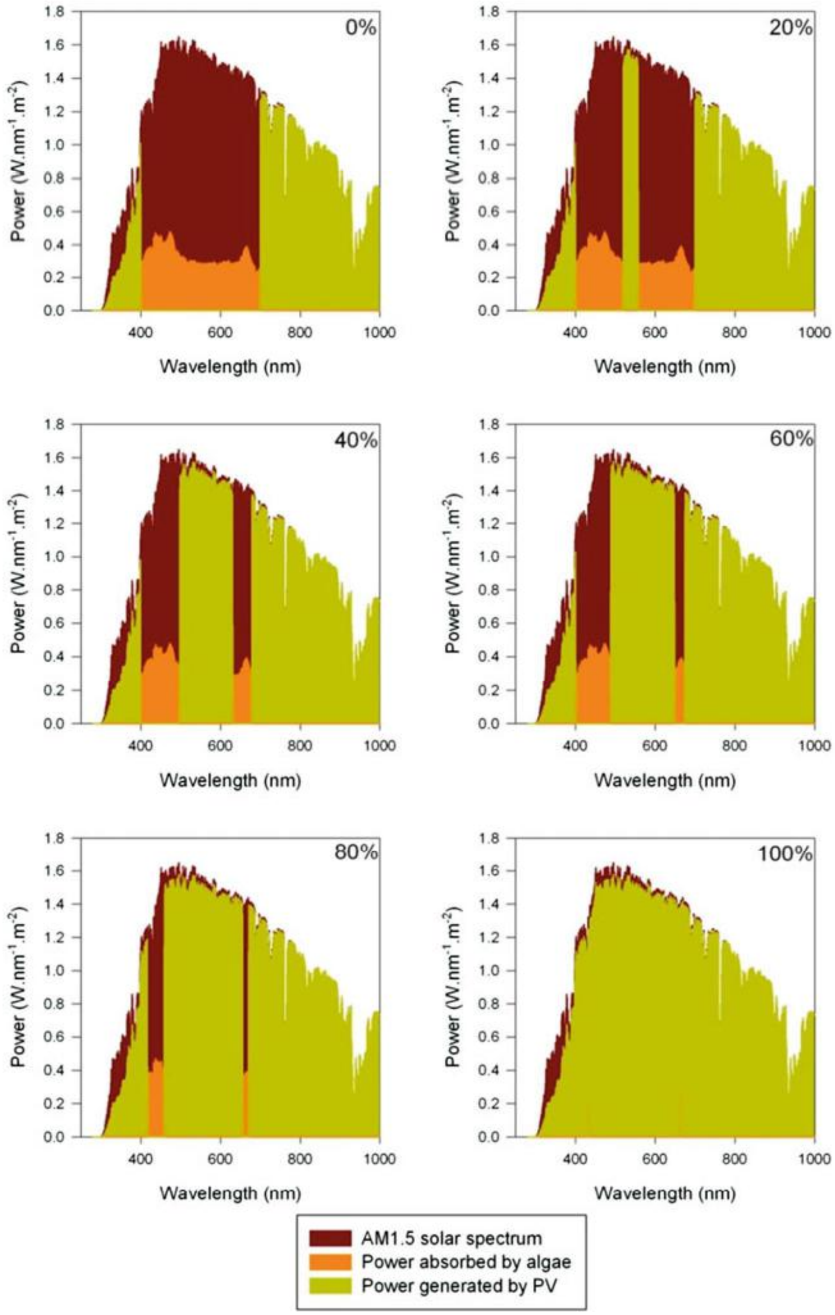

Fig. 15.4 Power absorbed by nannochloropsis and power generated by a crystalline solar cell for different bandwidths

where E_g is the bandgap of the semiconductor material, k is Boltzmann's constant, T is the cell temperature in K, and J_0 is derived from the published parameters of each device.

The power generated (P) in W.m^{-2} from the cell is then:

$$P = FF.I_{SC}.V_{OC}$$

where the fill factor (FF) is the value published in the literature for each cell type.

The power generated by the photovoltaic modules from this limited spectrum and as the bandwidth changed can be seen in Fig. 15.4. The power produced from the solar cells can be directed to the powering facilities associated with the growth of microalgae (pumps and monitoring systems) or to provide additional illumination to the microalgae. The former would reduce the costs of running the plant whereas the latter can boost growth productivity. Light emitting diode (LED) arrays can be used to most efficiently provide additional lighting to the microalgae at a specific wavelength. LEDs are highly efficient solid-state devices for converting electricity into light. They can be designed to emit light in a range of wavelengths to match the spectral. The internal quantum efficiency of high quality LEDs can exceed 99 %. This sounds extremely efficient, and however, there are difficulties in extracting the light from the LED which leads to low external quantum efficiencies (EQE) in the order of only a few percent (Schnitzer et al. 1993).

There is a significant amount of research effort into increasing the external quantum efficiencies of LEDs. As a result, LEDs are produced from a range of materials and use a variety of technologies. Some of the resulting LEDs include blue emitting InGaN-GaN LED's with a EQE of 40 % (Gardner et al. 2007), thin-film GaAs LEDs with a 30 % EQE, (Schnitzer et al. 1993), and organic LEDs with an EQE of 30 % (Kim et al. 2013). In some cases, careful texturing can improve the light extraction efficiency which yields LEDs with an EQE greater than 50 % and in some cases up to 60.9 % (Krames et al. 1999a).

The most useful LED for adding targeted illumination to a microalgae pond would be those LEDs with high external quantum efficiencies at particular wavelengths, such as those discussed by Krames et al. with efficiencies of 60.9 % (Krames et al. 1999a).

The additional power (P) in Wm^{-2} that can be produced using the power generated (P_{in}) using the system modeled above can be calculated from:

$$P = EQE_{LED}.P_{in}$$

where EQE_{LED} is the external quantum efficiency of the LED.

The additional irradiance from these LEDs is assumed to be tailored to the peak absorbance of the respective microalgae species. The total power absorbed by the algae is thus the irradiance absorbed directly by the microalgae and the peak absorbance multiplied by P.

15.7 Results of the Model Under Ideal Circumstances

The power output under constrained lighting situations from both a crystalline and amorphous silicon solar module has been calculated using the model outlined earlier. This is independent of the species of algae used as the power produced by the photovoltaics relies only on the portion of the spectrum they would receive. The threshold determines the portions of the spectrum provided to the photovoltaics as shown in Fig. 15.5. The power produced is not zero when the entire PAR is provided to the microalgae as there is an extensive part of the spectrum beyond PAR which photovoltaic devices can convert to electricity. It is clear that crystalline silicon solar cells are much more efficient in the regions outside of PAR than amorphous silicon is. This is due to the extended spectral response of crystalline silicon into the infrared part of the spectrum and the higher efficiencies of the crystalline solar cells (Fig. 15.3). The energy generated by these crystalline silicon solar cells can be used to power additional lighting to add more irradiance to the microalgae. If a LED system with external quantum efficiencies in the order of 55 % (Krames et al. 1999b) is used, a substantial amount of additional illumination can be provided to the microalgae.

The model we have created for this scenario is highly dependent on the absorption spectra of the microalgae. The power generated by the PV cells can be directed to a series of LEDs which will provide additional illumination to the microalgae. As can be seen in Fig. 15.6, the augmented power absorbed by the

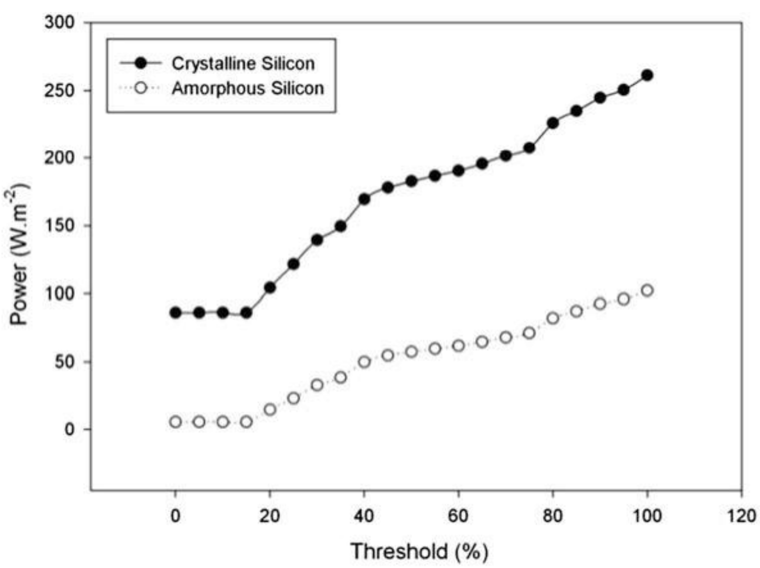

Fig. 15.5 Power produced from two different solar cell technologies as the spectrum threshold is changed

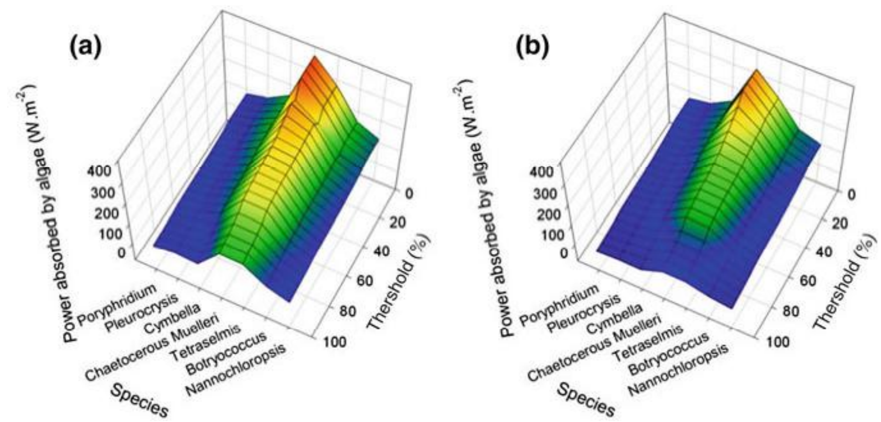

Fig. 15.6 Power absorbed by microalgae of different species when augmented by additional illumination from electricity coproduced by **a** crystalline and **b** amorphous silicon solar cells

microalgae is distinctly higher from some species when compared to others. Notably, this is chaetoceros and tetraselmis. The reason for this is apparent in Fig. 15.2. These two species of microalgae have a much greater absorbance than the other species in the measured absorbance data. This does not necessarily mean they are the most productive and only that they absorb the greatest portion of irradiance. The second trend which appears in the graphs in Fig. 15.6 is that a system augmented with electricity generated by crystalline silicon solar cells will generate more power and have a larger portion able to be provided back to the microalgae via LEDs. This highlights the importance of a highly efficient collecting device. For the remainder of this work, we will focus on results from the crystalline silicon parts of the model which are a best-case scenario.

A more useful visualization of this data is to examine the change in the amount of power absorbed by the microalgae as the threshold is changed. Figure 15.7 shows the change in power absorbed by various microalgae species when compared to the minimum situation. That is, the situation where all irradiance between 400 and 700 nm is transmitted through to the microalgae. Additional illumination is still provided by LEDs using the IR and UV parts of the spectrum. When compared to this baseline, it can be seen that even if all the irradiance in PAR is transmitted to the algae, there is a boost of 20 % in the total amount of power absorbed by the microalgae. This is from the additional irradiance provided by the LEDs which are powered by infrared radiation (>700 nm) captured by the crystalline silicon photovoltaics. As the threshold is increased, the total amount of power provided to the microalgae decreases and beyond 50 %, there would be no net benefit for this system. At first glance, this would seem to indicate there is not a great deal of advantage in filtering the light as described in this model and combining electricity and biofuel production. However, it needs to be recognized that much of the power being absorbed by the microalgae may not be assisting in photosynthesis. There is

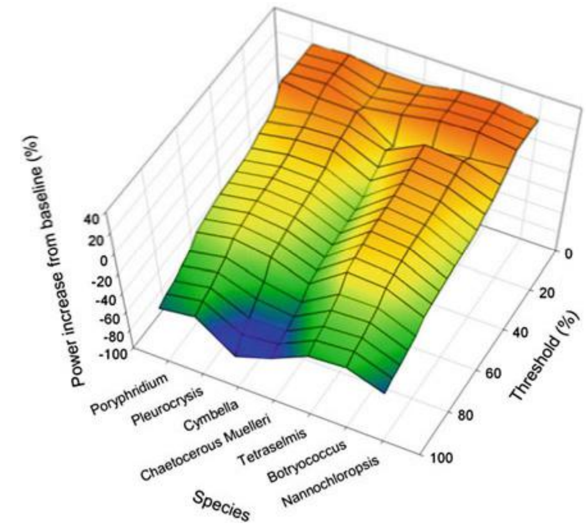

Fig. 15.7 Change in power absorbed by microalgae compared to the 0 % threshold situation

still significant absorption in other portions of the spectrum. If, for example, the green portion of the spectrum is not required for photosynthesis, it can be entirely removed from the spectrum provided to the microalgae and instead converted to blue or red light which will be absorbed efficiently by the microalgae.

A better comparison would be to the 50 % threshold. This equates to a full-width half-maximum band-pass around the main absorption peaks of the microalgae as seen in Fig. 15.2. This situation is shown in Fig. 15.8. From this figure, it can be seen that there are gains in the amount of irradiance absorbed by the microalgae by

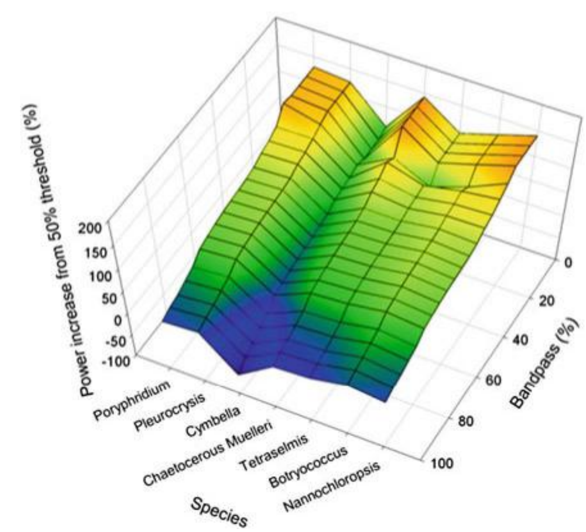

Fig. 15.8 Change in power absorbed by microalgae compared to the 50 % threshold situation

in excess of 100 % in some situations and for some species. This is a significant increase in irradiance absorbed by the microalgae and should lead to more productive growth.

A combination of these two energy production methods (solar energy and chemical energy) can efficiently use the whole solar spectrum. We recognize that an area covered by PV panels of the same scale as a microalgae farm would produce more electrical energy than the algae can store as chemical energy. However, the advantage of our proposed method is the production of chemical energy for transportation or other high value crops and can increase the productivity of microalgae systems.

This suggests that a combination of the two energy production systems would allow for a full utilization of the solar spectrum allowing both biofuel and electricity production from the one facility. This makes efficient use of available land, or it can enhance biofuel production by management of the spectrum and the addition of targeted illumination. Therefore, we propose a co-production system that uses an active filter or photovoltaic system above a microalgae pond to capture and efficiently convert the whole solar spectrum into usable energy or products. While the mechanism for splitting the spectrum is not fully determined as yet, there are several candidate options, including a specifically tailored semitransparent thin-film PV, luminescent solar concentrators, or other advanced energy harvesting flat glass panel that match the spectrum not used by the microalgae. One excellent candidate technology system that can transmit arbitrary visible light wavebands, capture the infrared part of the spectrum, concentrate it on the edge of a glass panel, and convert it to electricity has been recently developed and patented (Rosenberg et al. 2013).

15.8 Benefits of Coproduction of Electricity and Biofuel

There are several key benefits to a system that can coproduce electricity and chemical energy from the solar spectrum. Our proposed system would filter the light before it is provided to the microalgae ponds. This will reduce the total amount of energy provided to the algae in the parts of the spectrum where it is not required for photosynthesis. This in turn will reduce the heating of the ponds and subsequent evaporation of the water. It is to be noted that most places with high light irradiance, that are suitable for microalgae cultivation, also have a high evaporation rates and limited supplies of freshwater. By reducing evaporation, the use of freshwater in the production facility can be reduced. This also reduces the salinity of the microalgae ponds, allowing alga with a lower salt tolerance to be grown for a longer period of time.

Our proposed system would also generate electrical energy. This can be used to aid the production by powering motors and other electrical items at the production facility. This is advantageous in remote areas where grid connection and stable electricity supplies can be an issue. Introducing a method of cogeneration of electrical energy has benefits in the remote areas that microalgae cultivation takes place, such as northern and central Australia. In these areas, the cogeneration of electricity would reduce the reliance on grid-supplied electricity and diesel generators. By generating some of its own electricity, rather than purchasing electricity (or diesel fuel), the costs associated with production, dewatering, and extraction of oil from microalgae can be reduced which leads to more cost-effective production of biomass.

Alternatively, the electricity can also be used augment the light received by the algae to aid their growth. As shown in the model, we have described that this additional illumination could more than double the amount of energy absorbed by the microalgae. This would result in an increase in productivity and growth.

15.9 Conclusion

While there are a number of factors that influence biomass productivity, photosynthesis places upper limits on how effectively solar energy can be transformed into chemical energy (in the form of carbohydrate, lipid, and proteins). As ultimately light via photosynthesis is the main limit to the growth and a key component of the productivity of microalgae, it is understandable that an increase in the amount light provided for photosynthesis will result in more photosynthesis and thus more productivity. Solar panels are another established mechanism for utilizing the solar spectrum. In this case, they convert sunlight into electricity. While these two methods of energy production would normally be competing for the same resource, we have shown in the model described here that they can complement each other. By allowing the portions of the solar spectrum not required by the microalgae to be diverted to highly efficient solar panels, we can generate both electrical and chemical energy from a single facility.

There are several advantages to using a filter system to divert portions of the solar spectrum to different tasks. These include a reduction in heating and evaporation, co-production of electricity, and a subsequent boost in the productivity of the microalgae. This allows for the cheaper and more efficient/sustainable production of biofuel or value-added crops in remote locations which are located away from sources of electrical power.

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