Renewable and Sustainable Energy Reviews 27 (2013) 494–504

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Sustainable solar energy conversion to chemical and electrical energy

Navid Reza Moheimani [a,c,*], David Parlevliet [b,c]

[a] Algae R&D Centre, School of Veterinary and Life Sciences, Murdoch 6150, Western Australia
[b] School of Engineering and Information Technology, Physics and Energy, Murdoch 6150, Western Australia
[c] Murdcoh University, Murdoch 6150, Western Australia

ARTICLE INFO

Article history:
Received 22 February 2013
Received in revised form
4 July 2013
Accepted 5 July 2013
Available online 3 August 2013

Keywords:
Microalgae
Sustainable energy
Renewable energy
Solar panel
Open ponds
Closed photobioreactors

ABSTRACT

The Earth receives around 1.9×10^6 EJ of energy in visible light each year and only a fraction of this light energy is being converted to biomass (chemical energy) via the process of photosynthesis. Out of all photosynthetic organisms, microalgae, due to their fast growth rates, have been identified as potential source of raw material for chemical energy production. Solar panels have also been used worldwide for electrical energy production. Here we explore and introduce a novel methodology on combining solar panels with microalgae cultivation systems. These two methods of energy production would appear to compete for use of the same energy resource (sunlight) to produce either chemical or electrical energy. However, some groups of microalgae (i.e. Chlorophyta) only require the blue and red portions of the spectrum whereas certain types of solar cells absorb strongly in the green part of the solar spectrum but not as much in the red or blue portion of the spectrum. This suggests that a combination of the two energy production systems would allow for a full utilisation of the solar spectrum allowing both the production of chemical and electrical energy from one facility making efficient use of available land and solar energy. In this review we propose to introduce a solar panel as a filter above the algae culture to modify the spectrum of light received by the algae and utilise the unused parts of the spectrum to generate electricity.

Contents

1. Introduction

The global final annual primary consumption in 2010 was estimate to be 3.44×10^{17} Btu [1]. A very small amount of this primary energy was derived from non-fossil fuel resources. Furthermore, the

* Corresponding author at: Murdcoh University, Murdoch 6150, Western Australia. Tel.: +61 893 602682.
E-mail address: n.moheimani@murdoch.edu.au (N.R. Moheimani).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.07.006

estimated world fossil fuel reserve depletion times for oil, coal and gas is 2044, 2116 and 2046 respectively [2]. This means that in the post year 2046 there will be almost no liquid fuel available for transport. In relation to liquid fuels, between January 1990 and 2012 a barrel of North sea crude oil fluctuated between US$20 and US$90, which at present seems to have stabilised at around US$90 (all in 2012 dollar terms) [1]. Furthermore, the energy information administration (EIA) has projected that world energy consumption will increase at an average rate of 1.1% y^{-1} from 5.05×10^{17} Btu to 7.70×10^{17} Btu between 2008 and 2035 [3]. Therefore, the decline of finite fossil fuel resources, as well as recognition of global warming together with an ever increasing global demand for energy has led to substantial interest and activity in developing alternative renewable fuels.

One of these alternative renewable energy supplies can be generated directly from sunlight by using photovoltaic modules (solar panels). This has been described as the 'art of converting sunlight directly into electricity' [4]. Photovoltaic devices, or solar cells, are capable of using incident illumination to supply electrons to an external circuit. Although the first few solar cells were used primarily in the space programme, there has been an increasing demand for terrestrial applications and we are now seeing widespread adoption of photovoltaic roof top arrays.

Biomass has been used widely for millennia as a source of chemical energy. Modern commercial liquid biofuels are bioethanol and biodiesel. Bioethanol is mostly produced from fermenting sugarcane and, biodiesel is made through the process of transesterification of vegetable oil [5]. It is projected that the global annual production of bioethanol and biodiesel will increase from 75×10^9 and 15×10^9 L in 2007 to 159×10^9 and 41×10^9 L in 2019, respectively [6]. The production of renewable transport fuels from crops such as oilseeds or sugarcane has economic as well as ethical problems, and it is mainly due to the potential competition for limited resources with food crops. Therefore, there is a need for an alternative source of raw material for chemical energy (i.e. biomass) production.

Microalgae are microscopic plant-like largely photosynthetic organisms belonging to a number of Phyla (major taxonomic groups) [7]. They are extremely diverse and can be found in most habitats of the world including fresh and sea water, salt lakes, soil, snow and on surfaces such as rocks and the bark of trees [7]. The size of algae ranges from about 1 μm (nanoplanktons) to more than 40 m (kelp). Microalgae have been suggested as a raw material for bioethanol and biodiesel production [8,9] and since a United Nations committee recommended that conventional agriculture be supplemented with high-protein foods of unconventional origin, microalgae have become natural candidates for this [10]. Without any doubt, the primary source of all food and organic raw materials is solar energy [11–13]. Exponential increases in the world's population and its demands for finding possible resources of food and energy will depend on how efficiently we can learn to use solar energy. Conventional agricultural systems are very inefficient in this respect as (1) most plants can only utilise less than 0.5% of the sun light that falls on them, (2) most farms cover only a small land area, (3) only a small proportion of each crop plant is edible, and (4) maximal production is highly limited by the availability of CO_2 [11].

2. Microalgae

Microalgae promise important advantages to improve the solar efficiency utilisation that (1) they can be grown reliably long term in semi-continuous and continuous culture providing maximal annual productivity, (2) microalgal cells contain relatively low structural material with the possibility of using the whole biomass for nutrition or other economic uses, and (3) addition of CO_2 to a microalgal culture systems is relatively simple compared to field crops [14–18]. Despite all of these advantages of microalgae over conventional agriculture, the feasibility of microalgae as a food or fuel source is yet to be proven and it is mainly limited by the high cost of production [9]. Production of microalgae is, on the other hand, already an economical method of aquaculture feed and high value products [17,19,20]. Decreasing the cost of microalgae production for different purposes such as a source of oils, polysaccharides, fine chemicals, etc. has been the subject of many studies since 1940s [21]. During the 1950s a world-wide interest in novel sources of protein to feed the growing human population led researchers to investigate the possibilities of large-scale algal cultivation systems [21]. The use of microalgae as a source of biofuel offers an attractive sustainable alternative to other raw materials as algae production does not necessarily compete for fresh water (e.g. marine algae) or arable land [9]. Furthermore, algae photosynthetic rates are higher on an areal basis than terrestrial plants and this offers an accordingly smaller footprint of the operation, provided a suitable climate and sunshine hours are available (e.g. Western Australia). For instance, the Pacific Northwest National Laboratory, part of the U.S. Department of Energy, reported that renewable fuel from algae alone could eventually replace 17% of U.S. oil imports [22]. While microalgae seems to be a very important contender for biofuel production, to date and despite a large investments in this field, no large scale economical microalgae fuel has been made. One of the main reasons for the lack of success in this field is factors limiting growth of microalgae.

Microorganisms, especially bacteria, have been successfully cultured in large-scale systems such as fermenters for more than half a century. The basic principles of microalgal cultures are the same as other microbial cultures with the exception of the light requirement in autotrophic or mixotrophic cultures. For successful microalgal culture, a suitable species must be selected mainly based on general physical chemical and biological characteristics together with the growth optimisation of selected species on a suitable medium [14].

The question of what limits algal growth and product yield in microalgal cultures is of fundamental importance in the development of a commercial large-scale algal process. High cell density mass production cultures are unattainable due to a number of physical, chemical and biological factors [23,24]. These factors are: (a) light (quality and quantity), (b) temperature, (c) nutrient concentrations (i.e. N, P, Si, Fe), (d) CO_2, pH, bicarbonate and alkalinity, (e) growth inhibitors, (f) mixing (too much or too little), (g) dilution rate, harvest frequency and pond depth and (h) contaminations by pathogens or other algae.

2.1. Light

The Earth receives around 3.9×10^6 EJ of total solar energy [25], with 48% in visible light, each year and only a fraction of this light energy is being converted to biomass (chemical energy) via process of photosynthesis. Photosynthesis can only use solar spectrum in the range of 400 and 700 nm which is called photosynthetic active radiation (PAR). 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 [26]. The most important limiting factor for the mass cultivation of microalgae, irrespective of the cultivation system, concerns the effective use of light [27]. This is especially important in mass cultivation of microalgae outdoors as growth and performance of all photosynthetic organisms are strongly linked to the quality and quantity of available light [28,29]. The amount of light absorbed by an algal cell suspended in an algal cultivation system depends on many factors, including the specific position of the cell at a given instance, the density of the culture, and the pigmentation of the cells [30] (for more details see section *Light*