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Short communication

Modeling of smart mixing regimes to improve marine biorefinery productivity and energy efficiency

Alexander Golberg [a,*], Alexander Liberzon [b]

[a] Porter School of Environmental Studies, Tel Aviv University, Israel
[b] School of Mechanical Engineering, Faculty of Engineering, Tel Aviv University, Israel

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ABSTRACT

Biorefineries aim to provide sustainable production of food and generation of low carbon energy in the next decades. Current strategies for biorefinery reply mostly on the classic terrestrial agriculture for biomass production. However, land availability, competition with food crops and total energy balance are challenging limiting factors for terrestrial bioenergy crop production. Off-shore macroalgae production could provide alternative, sustainable feedstocks for biorefineries without competition with food crops. Increasing the yields of off-shore macroalgae cultivation systems could further improve the total energy balance of the marine biorefineries. In this work, based on the fundamental principle of timing differences between light harvesting and carbon fixation in algae, we developed a theoretical framework for increasing the yields of off-shore macroalgae biomass using external mechanical mixing. We show that for a given physiological parameter of macroalgae light harvesting and carbon fixation, mixing could allow for increase of the total energy gain by two orders of magnitude. The overall biorefinery to biofuel efficiency, however, is constrained by drag and macroalgae thallus size.

1. Introduction

Sustainable production of food and generation energy is the major challenge of the world for the next decades. The integrated production of food, fuels and platform chemical from biomass is coined biorefining. Design of a sustainable biorefinery, which will generate sustainable food, fuels and chemicals is a complex task and is largely influenced by local raw material supplies, advances in multiple technologies and socio-economic conditions. Current strategies for biorefinery reply mostly on the classic terrestrial agriculture for biomass production. However, as indicated by the European Biorefinery Joint Strategic Research Roadmap for 2020: *A key issue for biomass production in Europe is land availability* [25]. This statement is also true for multiple countries outside the EU. Besides the shortage of land, concerns over net energy balance, potable water use, environmental hazards, and processing technologies question the cereal crops and lignocellulose biomass to provide sustainable answer to the coming food and energy challenges [11]. The on-shore cultivation of microalgae for energy, though promising, is currently impossible due to the costs of required land preparation, infrastructure and negative net energy balance on the entire systems [7]. However, an expanding body of evidence has demonstrated that marine macroalgae can provide a sustainable alternative source of biomass for sustainable food, fuel and chemical generation [1,5,16,30,31]. Macroalgae, which contain very little lignin and do not compete with food crops for arable land or potable water, are additional candidates for future sustainable food and transportation fuel feedstocks. One of the limiting factors in the macroalgae to biofuel value chain is the biomass yields. Increased yields of macroalgae were achieved in on-shore ponds using intensive cultivation methods which include extensive mixing [5]. These on-shore systems, however, have the same limitations previously discussed for the microalgae systems. The alternative solution for the sustainable biomass to biofuel production is the off-shore cultivation. The development of the off-shore cultivation systems is slow and by most is limited to the near shore systems. The current concepts of off-shore marine biomass cultivation include Near Farm Concepts for kelp growth, Tidal Flat Farms, Floating Seaweed Cultivation [2], ring cultivation systems [6] and most recently wind-farm integrated systems [21].

One of the limitations of the biomass yield is the ability of photosynthetic receptors to capture photons and regenerate a process known as light/dark reactions [15]. Plants have evolved the ability to harvest almost 100% of the arriving protons; however, the total photosynthetic efficiency is only around 8% due to the low utilization of photons. In the normal illumination, at the out-door environment, the rate of photosynthesis is not limited by a number of photons. Multiple studies have shown that the rate of photosynthesis is limited by multiple physiological processes such as diffusion, plant metabolism, carbon fixating reaction metabolism, for example slow rate of catalysis by Rubisco in some plants and algae, and slow metabolism of 3-phosphoglycerate in cyanobacterium [9,18,22,26,27]. In addition, electron transport through the cytochrome b6-f complex in the thylakoid membrane also limits the photosynthesis rate [13]. The reengineering of photosynthesis system

* Corresponding author.
E-mail address: agolberg@tauex.tau.ac.il (A. Golberg).

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to improve its efficiency is an extremely complex task [20] and the suitability of the engineered plants and algae in the open field environment is an open question. Therefore, alternative approaches are needed to increase the biomass yields in the near future. Multiple previous studies have shown that equal photosynthetic rates can be achieved by continuous and pulsed light (with specific frequencies) [28]. This property has been widely used in the design of the on-shore photobioreactors, when mixing was used to intensify the total microalgae and macroalgae yields [5,24]. In this process, however, mixing is usually used to improve the nutrient diffusion and provide optimum aeration to the plants. In such mixing regimes, most of the energy is wasted on the friction with walls.

The goal of this paper is to introduce a concept of an off-shore macroalgae cultivation system in which an increase of yields per area can be achieved by external mixing, adapted to the natural photon capture:carbon fixing rate ratio. In this new mode, mixing will enable utilization of the volume of the floating off-shore macroalgae reactor, by exposing the macroalgae cells to the solar energy for a short time to capture photons and then to take the algae to the depth for a period of time required for carbon fixation, when a new layer of algae is exposed to the sun. The ultimate goal of this system is to increase the total energy efficiency of the biorefinery to capturing increasing the photon utilization yields per area of installed macroalgae off-shore farm. To the best of our knowledge, this approach has never been proposed for the off-shore macroalgae cultivation systems. The intensification of macroalgae cultivation off-shore is of importance particularly for the bioenergy sector, as it should decrease the total areas required for the biomass production, which is a major obstacle in the field due to the large installation and maintenance efforts required.

2. Energy flows in marine biorefineries

Energy flows and losses in the marine biorefinery, which produce only biofuel, are shown in Fig. 1. Macroalgae, cultivated on the area nD (D is the diameter of the total serviced area and n is the proportion of sea allocation for macroalgae cultivation) collect solar energy flux Q_{solar}. W_0 is the photosynthesis solar energy loss. The resulting biomass is harvested and transported to the biorefinery by a boat, which consumes a certain amount of fuel per km of transport (W_1). Once delivered to the biorefinery, the fuel crops are converted to liquid fuels. The conversion efficiency depends on multiple factors such as crop type and processing technology. Previous analyses of biorefinery efficiency suggest that conversion efficiency increases with biorefinery size [10]. W_2 is the energy lost during the crop to fuel conversion process. Finally, the produced biofuel is distributed to consumers. W_3 is the biofuel distribution energy loss. In order to maximize the total useful energy received in the form of a biofuel (W_u), it is necessary to minimize the energy losses. Previously, we derived the equations for the optimum size, capacity and efficiency of a local biorefinery without taking into account possible improvements in the energy losses during photosynthesis [12]. The maximum efficiency of a local biorefinery is:

$$\eta_{\max} = 1 - \frac{W_{\min}}{Q_{solar}\left(nD_{opt}\right)^2} \quad (1)$$

where $W_{\min}$ is the minimum wasted energy ($W_0 + W_1 + W_2 + W_3$) and D_{opt} is calculated as in [12].

In the previous work we have shown how to reduce the energy losses associated with conversion of the macroalgae biomass into transportation fuels using two-step fermentation process (W_2) [12]. We have shown that two-step fermentation first by a yeast (*Saccharomyces cerevisiae*) and second by a bacterium (*Escherichia coli*) might be possible to reduce the energy losses on bioconversion by 34% [12]. Here we show that optimal mechanical mixing could further reduce the energy losses during biomass growth (W_0) and thus improve the total energy efficiency of the marine biorefinery.

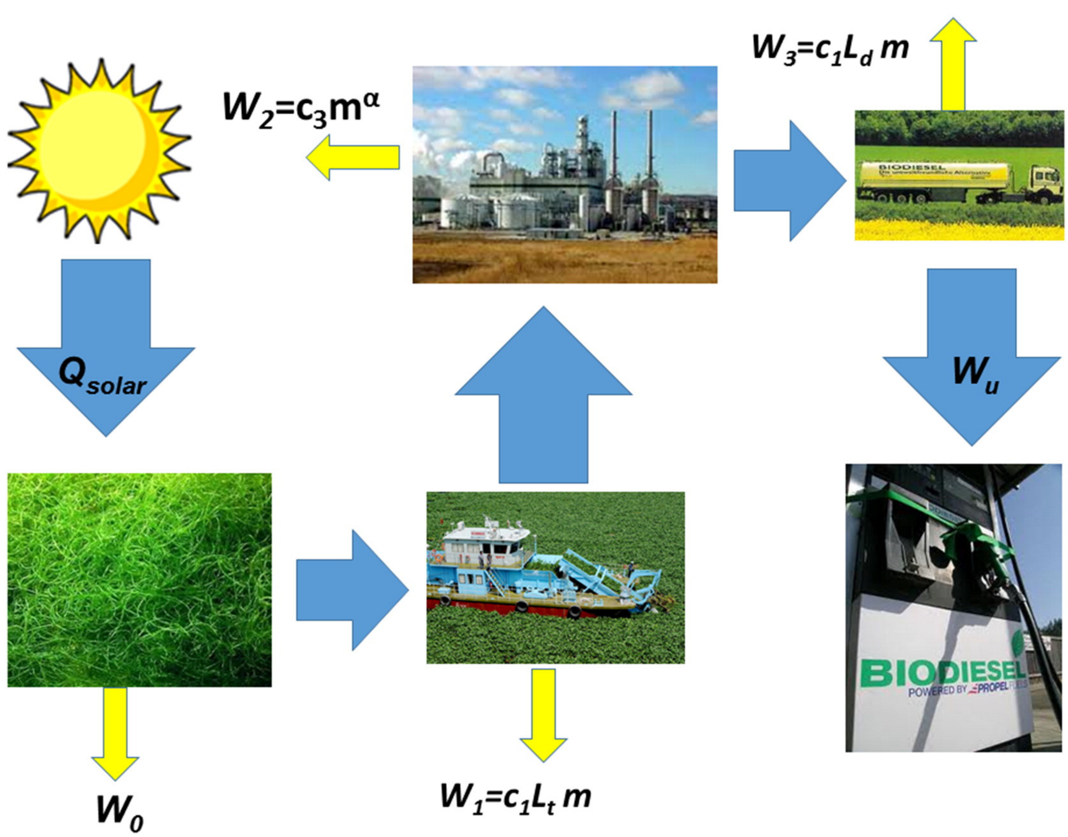

Fig. 1. Energy flows in the marine biorefinery producing biofuels. Q_{solar} is the solar energy flux, W_0 is the photosynthesis energy loss, W_1 is the biomass collection energy loss, W_2 is the fuel conversion energy loss, W_3 is the fuel distribution energy loss, and W_u is the total useable transportation fuel energy supplied to the population.