“The Emerald Forest”—An Integrated Approach for Sustainable Community Development and Bio-derived Energy Generation

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The welfare of humankind seems to be on a crash course with two fast approaching major potential crises: Namely, the possibility of depletion of fossil fuel reserves, which so far have single-handedly supported the complete needs of the post-industrialization economy, and the alarming increase of carbon dioxide in the atmosphere to unprecedented levels, which is predicted to lead to a catastrophic global warming phenomenon. These problems are compounded by the explosive rate of population increase in some parts of the globe and the fast depletion of worldwide usable land resources. The recent sudden decrease in oil and gas prices might lead the policy planners to relegate the plans for renewable energy research to the back burner, but we must not forget the skyrocketing rate of increase in energy costs of only a year ago. There is ample evidence that the future of the human race depends on immediate and expedient plans for sustainable development. Where energy needs are concerned, the arguments proposed here indicate the urgent need for the development of alternative fuel forms that, if not carbon-free, are at least carbon-neutral. This makes a strong case for biomass-derived fuels, which some proffer as a stop-gap measure to help us transition to the promised hydrogen economy, but which will arguably always be an essential element of the global energy economy, as detailed herein. This article is a concept paper that proposes an integrated approach, in which the
large-scale massive production of biomass for bio-derived fuel production is coupled with the development of sustainable communities through the reclamation of arid and/or uninhabitable regions. Many challenges exist to the successful implementation of efficient integrated developments of this type; we focus briefly on one of these challenges, namely the design of optimal assemblies for optimal sunlight utilization.

The utilization of biomass as a source of fuels is a carbon-neutral process that consumes about as much carbon dioxide in growing the biomass as is eventually released during the combustion and/or gasification steps. Photosynthetic biological entities are efficient agents that primarily capture solar energy and combine it with a carbon source and some essential nutrients to increase the amount of, highly usable, biomass. To date, there have been major successes in producing bioethanol, via fermentation, from carbohydrate rich agricultural crops. Ethanol is being produced in the US and China from corn. Brazil has also developed a comprehensive ethanol fuel infrastructure based on its abundant production of sugarcane. Europe has had successes in producing biodiesel from oil-rich crops. These approaches however are heavily criticized, and arguably deserve such criticism, by their opponents for many factors: The dearth of arable land, the competition for human and cattle food supply, the need for immense land masses that represent a sizeable proportion of the earth’s total, and the often necessary utilization of precious freshwater resources. Energy crops, such as switchgrass, have been proposed as alternatives that do not compete with essential food supply, still require arable land but not necessarily the premium soil quality that corn requires, and that grow more efficiently than traditional agricultural crops. These are currently being investigated and might offer a sustainable solution, but fall short of the potential detailed here of land-based aquatic biomass.

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**Integrated Sustainable Communities**

The concept presented here integrates the production of biomass and biofuels with selected solar and wind energy technologies to develop combined sustainable living communities and green energy production facilities. An example implementation is presented in Figure 1, which shows the detailed interactions among the various renewable energy technologies used and the sustainable components. The two major elements of the system presented in Figure 1, are the “Emerald Forest” biomass production facility and the living sustainable community. Such developments involving these massive artificial forests are best located on desert lands that are in proximity of ocean waters. Many such areas are available in the United States, for example along the southeast coast, the Gulf of Mexico, the western states and parts of Nevada,
Arizona and New Mexico. The worldwide potential is orders of magnitude larger, for example the African Sahara desert can be alone sufficient for the production of a considerable portion of the world’s liquid fuels need.

The forest consists of tree-like bioreactors filled with seawater and algae and continuously fed with carbon dioxide and nutrients. The tree-like design is selected for its natural efficiency in capturing sunlight. A potential design for the tree photobioreactors is presented in Figure 2 and discussed later.

The integrated development (Figure 1) is centered around a housing community with artificial lakes and ponds. These serve an important ecological function in regulating the arid desert microclimate by providing moisture through evaporation and the accompanying evaporative cooling effect. However, since excessive evaporation can lead to a non-sustainable increase in salt concentration, these ponds have to be supplemented with salinity-control technologies. A solar desalination plant is included to produce sufficient amounts of fresh water for make-up of the evaporation losses both from the communal lakes and ponds, as well as from the biomass artificial forest. Some of the energy needs of the compound derive from solar photovoltaic technology, and, if suitable to the specific location, for a windmill farm generating electrical power. However, the majority of the power is generated in a power plant that uses a portion of the fuel gas generated through gasification of the biomass produced in the artificial forest. The gasification plant receives the cellulosic portion of the produced algal biomass after the oil and carbohydrate portions are

**FIGURE 1**
An example of sustainable community development integrated with biofuel production.
separated. These are sent for off-site processing in biodiesel and bio-ethanol/butanol facilities to produce liquid fuels for automotive applications. The gasification step can be optimized to produce hydrogen, or syngas. As mentioned, a small portion of this fuel gas will be used onsite to generate the majority of the energy needed, while the larger portion is used for energy production to support the needs of nearby cities and communities.

The cornerstone of sustainability in this approach is the use of the carbon dioxide generated in the gasifier (after separation from the fuel gas) to provide a carbon-rich source for the algae nutrition and growth. The micronutrients that are also needed for algae are recycled after separation from the ash remaining after gasification.

**FIGURE 2**
Artist rendering of one possible design for the photobioreactors.
In order for this approach to sustainability to work, the scale of production of biomass should be optimized in relation to the size and energy requirements of the living community and the available natural resources in the area. The economics have to be balanced such that the external energy production revenue exceeds the cost of internal energy generation. Calculations for typical scenarios will be presented at the conference.

Many challenges and obstacles need to be resolved for the efficient design and implementation of such integrated communities, and especially of the central tree-like bioreactors. These issues include the development of algal strains optimized for the area and for the energy need distribution, development of weather-resistant and bio-compatible polymeric materials, the development of technology for carbon dioxide separation and absorption, as well as the development of an optimized optical capture and distribution assembly. The latter is discussed in further detail below.

Design of Photobioreactors for Optimal Light Distribution

The main bottleneck in rendering closed algae production systems feasible is the limitations on the availability of light at high concentrations of biomass. Consequently, devising methods for minimizing light limitations is crucial for the future production of algae on large scales, specifically the scale required for use as a sustainable energy source and efficient medium for sequestration of carbon dioxide. Different designs have been suggested, most commonly tubular and flat-plate bioreactors. Both suffer from a main serious limitation: low ground productivity (defined as unit algae produced per unit of land). In this work, we present a tree-like photobioreactor design fitted with an optical capture assembly to maximize the collection of solar radiation, and optimize the distribution of light to dark regions inside the reactor. This design allows the use of reactors with larger diameters, and much larger capacities than the traditional algae pond production systems, hence improving the algae ground productivity.

Using optical assemblies for light collection and distribution has been proposed in the literature on multiple instances. Pulz et al. (1) experimentally studied the use of optical fibers in illuminating a plate-type photobioreactor. They concluded that optical fibers do, as expected, improve the productivity. Jin-Lan et al. (2) studied algae growth in a 40-Liter five-compartment rectangular reactor with a triangular optical guide collector system and perpendicular optical guides for light distribution. The distribution guides are plates fitted with grooves to diffuse light in the lateral direction. The compartments are connected together to allow circulation of biomass for harvesting. They used geometric optics to determine the dimensions of the optical guide that would reduce losses. The experimental data provided is however
very limited and not enough to judge the efficiency of the reactor or that of
the optical assembly. Cuello et al. (3) provide a short review of algae pho-
tobioreactors with optical fibers for concentration and distribution of light,
focusing on the work funded by NASA and the DOE for solar-concentration
and transmission using mirrors, lenses and optical fibers. They also review
their own work on light distribution in flat-plate algae bioreactors. From
their review, they conclude that optical-fiber based distribution systems are
very promising but have not yet been sufficiently developed. They report
that solar-concentrating systems have reached efficiencies higher than 45%.

The photobioreactor design exemplified in Figure 2 consists of a large ver-
tical cylindrical reactor of up to 15 meters high, and an internal capacity of
2-3 m³ filled with the algal suspension. The top portion of the tree sports an
optical capture assembly consisting of branches and leaves built from optical
waveguides and complemented with holographic concentrators and photo-
voltaic elements. The assembly is designed to capture sunlight and redirect
it towards an internal illumination optical shaft. The light is thus dispersed
into the inside of the reactor both form the internal shaft, as well as from
the external transparent walls. In order to design the optical system in an
optimized method, we have to explore the different methodologies for the
modeling of light travel and distribution.

**Modeling Light Distribution**

In order to *a priori* predict the performance of new reactor designs, it is nec-
essary to develop a reliable tool for modeling of light distribution inside the
algal medium. Several models have been used in the literature, the main
approaches are discussed.

*Geometric Ray tracing*: The simplest approach for modeling the propaga-
tion of light is ray tracing, which finds its foundation in geometric optics.
Fermat’s principle, the cornerstone of geometric optics, states that “Light rays
follow a path that is an extremum compared to other nearby paths,” which in
other words means that light follows paths with the shortest optical length,
i.e. the path that takes the shortest amount of time. The laws of reflection and
refraction are both derived based on that same principle. The application of
ray tracing generally requires the assumption of a uniform and nonabsorb-
bent medium. Strong restrictions are thus imposed on the use of ray tracing
in modeling photobioreactors, limiting their use in early stages of operation
(where biomass concentration is still significantly low and the medium is for
the most part non-participating i.e. no absorption and no scattering), and also
for use in modeling optical assemblies that collect/distribute light. Zijffers
et al (4) used ray tracing without scattering in modeling light distribution for
a novel design of algae photoreactors, which includes a Fresnel lens for light collection and an optical guide for distribution. Their model was limited to the optical assembly and was used to determine the amount of radiation reaching the surface of the algal solution. Mohseni et al (5) used the Monte Carlo approach with the ray tracing method to determine light intensity distribution in a fluidized bed photoreactor for the removal of organic pollutants from water using TiO₂ catalyst. A stochastic method was first used to determine a homogeneous particle distribution in the reactor. The results were validated by comparing the measured values of effective transmittance with those predicted by the model. For the most part, the results were in good agreement with experimental data, although the transmittance was under-predicted for higher bed expansions, which the authors attribute to errors in prediction of particle distribution.

The Radiative Transport Equation (RTE) has been used since the 1960s in modeling radiative heat transfer (6), the general RTE can be derived by performing a photon balance on a fixed volume, in a manner similar to that used in deriving the general transport equation. A detailed derivation of the RTE is provided in (6). The final form of the equation for a frequency \( \nu \) and direction of propagation \( \Omega \) is:

\[
\frac{dl_s(s, \Omega)}{ds} + [k_\nu + \sigma_\nu] I_s(s, \Omega) = j_\nu^s(s, T) + \frac{\sigma_\nu}{4\pi} \int_{\Omega' = 4\pi} P(\Omega' \rightarrow \Omega) I_{\nu'}(s, \Omega') d\Omega'
\]

where \( I_{\Omega'}(s, \Omega) \) is the amount of radiation reaching point \( s \) in direction of propagation \( \Omega \); \( k_\nu \) and \( \sigma_\nu \) are the absorption and scattering coefficients respectively; \( j_\nu^s \) is the emission term, usually modeled using the Planck’s blackbody radiation model making it a strong function of temperature; and \( P(\Omega' \rightarrow \Omega) \) is the phase function, which determines the probability of in-scattering of radiation from all solid angles \( \Omega' \) into a volume defined by solid angle \( \Omega \).

The first term on the left hand side of the equation represents the amount of radiation per unit volume, whereas the second term represents the extinction by absorption and out-scattering. The first term on the right hand side represents the radiation emitted, and the last term represents the radiation entering the control volume (which is defined by a solid angle) by scattering from other control volumes. It is important to note that this equation is written for a certain waveband, \( \nu \), for which the absorption, scattering and emission are defined. The equation may therefore be solved for different frequencies of interest separately, or solved for an average frequency by averaging the different properties that are functions of frequency.

Several assumptions are made in the derivation of this equation (6), most notably:

1. Scattering is coherent, i.e. the frequency of radiation is not changed after scattering.
2. Single scattering: the energy scattered is not re-scattered again.

3. The incident radiation at any point, G, can then be found by integrating the radiation intensity on all solid angles:

\[
G_x (x, y, z) = \int_{\Omega} I_x (s, \Omega) d\Omega = \int_{\phi=0}^{\pi/2} \int_{\theta=0}^{2\pi} I_x (x, y, z, \theta, \phi) \sin \theta d\phi d\theta
\]

The integro-differential RTE equation has no analytical solution except for highly idealized cases. Thus the discrete ordinates (DO) method is used to solve it by discretizing the terms in the equation spatially and directionally (i.e. angularly). The main advantage of the DO model is that it solves the complete RTE, with no assumptions leading to inherent errors. The main source of error is thus associated with the discretization and can be minimized by using a fine spatial and angular grid.

The original DO model does not conserve radiant energy at the surfaces in complex geometries (7), and therefore a conservative variant of the DO model, the finite volume method, is usually used in commercial CFD packages. This allows relatively simple integration of fluid dynamics with radiation modeling in the same environment.

There has been a lot of work on modeling light in photoreactors using the DO model, especially reactors for removal of pollutants in the presence of a photocatalyst, usually TiO₂. Sgalari et al (8) used the DO method to model the distribution of light in an annular photoreactor, and used results from Monte Carlo simulations to validate their results. For photo removal of a pollutant, Adesina et al (9) used the DO model with the granular Eulerian-Eulerian model to determine light intensity distribution with scattering due to the presence of photocatalyst. Trujillo et al (10-11) used the DO model in conjunction with Eulerian-Eulerian approach to describe the liquid-gas mixture to model the light intensity distribution in photocatalytic reactor. In both cases, the flow problem was solved first to obtain local solid volume fractions/gas holdups (since catalyst particles and bubbles are the main scatterers in these problem). The data are then used to determine the absorption and scattering coefficients, and hence predict distribution of light in the reactor and the local amounts of pollutant removed. Pareek et al (12) used the DO to model the same annular photoreactor with TiO₂ catalyst, and included a distributed light source using the commercial CFD package FLUENT (Ansys, USA). They assessed the effects of wall reflectivity, catalyst loading and phase function parameter.

In our work, the DO implementation in FLUENT is used to solve the RTE for several candidate designs for the optical capture and distribution assembly, the internal light shaft, and the algal suspension. Results are discussed in the presentation.
References


