“The Emerald Forest”

An Integrated Approach for Sustainable Community Development and Bio-derived Energy Generation

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Outline

- The Emerald Forest Vision
- Research Challenges and Obstacles
- Optical System Design
- Conclusions
The Emerald Forest Concept

- Biofuel production from massive/vertical farms growing marine algae biomass coupled with Desert reclamation.
- Integrates biomass production with a Living Community whose energy and water needs are fully Sustainable.
- Suitable for arid environments within reasonable distance (50-100 miles) from coastal waters.
- Addresses three Global Crises: Energy, Climate Change, and Overcrowding.
Why Biomass?

- **Need for Elimination of Fossil Fuels**
- **Carbon Neutral/Reduced**
- **Dependence on liquid fuels**
- **Need for transition technology, but maybe long-term sustainable**
Why Algae?

- No need for Agricultural Landmass
- Minimal need for fresh water
- High Yield and productivity
- Biodiversity
- **Challenge:** Large scale production

**Historical Context:** NREL Aquatic Species Program, mid 70s to mid 90s
Why Massive / Vertical?

- Economy of scale
- Coupling with biofuel production technology
  - Demand/supply issues
  - Optimal plant size requires large amounts of biomass
- The need for process intensification
- Global needs are increasing
- Higher impact on fossil fuel displacement
Energy Crisis

- Continued dependence on fossil fuels is non-sustainable
  - Diminishing supplies, volatile prices, and political leveraging.
- Fossil fuel conversion to materials brings a lot more value-added than Fossil fuel to energy.
- Sustainable routes to renewable fuels is needed
Climate Change Crisis

- Burning fossil fuels for energy to elevated levels of **Carbon dioxide and GHG levels** in the atmosphere
- Unprecedented levels of GHG predicted to lead to a catastrophic **global warming** phenomenon.
- Annual net **loss of planetary green mass** resulting from deforestation, desertification, and non-sustainable agricultural practices.
- Desertification destroys **ecological biodiversity**
Overcrowding and Prosperity Crisis

- Overpopulation and the need for decent quality, affordable housing is not a problem reserved for the developing world only.

- In the Developing World:
  - Severe overcrowding.
  - Inadequate housing developments.
  - Insufficient resources.

- In the Developed World:
  - The urban sprawl phenomenon is systematically depleting arable rural land that otherwise would be contributing to the betterment of quality of life.
The Emerald Forest Concept

Wind Farm

Solar Farm

Solar Desalination & Salt Extraction

Power Plant & Electricity

Aquatic Biomass Production

Sustainable Living Community

Biomass Conversion Plant

Sea Salt

Liquid and Gaseous Fuels

Oil for biodiesel

CO₂

Fuel gas

nutrients

ash
Challenges and Issues of Importance (I)

- Optical assembly design and optimization
- Photovoltaic integration
- Reactor Design – Flow patterns and mixing
- CO$_2$ transient sequestration and nutrient delivery
- Organisms: pH compatibility, Fast growth, Robustness, Mixed cultures, diverse portfolio of products, Odor control
- Materials: Algae attachment - UV stability
Challenges and Issues of Importance (II)

- Sustainable Architecture
- Sustainable salt extraction methodology
- Biofuel / energy delivery technologies
- Scheduling and Control MADCABS (NSF ITR Grant, PI: Çinar, Teymour, Hood)
- Process Integration and Design problem of a new nature – coupling a societal system with a production system.
The Ecology of the Emerald Forest

- A Modern-day desert oasis
- Living community
- Salinity-controlled ponds
- Fish and shrimp hatcheries
- Sustainable Agriculture
- Palm trees
- Switchgrass underfoot
- Bird Sanctuary
- Microclimate control/rainfall (???)
Reactor Issues
Requirements for Algae Production

- Physical
- Chemical

Nutrients
- Nitrogen
- Phosphorus
- Micronutrients

Carbon Source
- Physical
- Chemical

Regulation of
- pH
- Temperature

Conditions

Light
- Avoid Photolimitation and Photoinhibition
- Dark/Light Cycles (1-100 millisecond periods)

Mixing
- High Mass Transfer (carbon delivery and oxygen removal)
- Prevent wall adhesion and settling
- No concentration gradients
- Low shear stresses

Bottlenecks

Algae Production
Algae Production in Open Systems

**CONs:** Low Productivity
- Lack of control on growth conditions
- Inefficient light utilization
- Low mass transfer due to stagnant nature
- Vulnerable to evaporative losses and contamination
- Reached their upper productivity limit

**PROs:** Simplicity
- Smaller capital
- Easier to build and operate

[Artificial vs. Natural images]

*Chicago, Illinois, April 2010*
Algae Production in Closed Systems

- No light limitation (Diameter around 8 cm)
- Lower mass transfer: fouling; nutrient, carbon gradients; high oxygen content
- Flow induced by power-intensive pumping
- Low productivity per unit area
Algae Production in Closed Systems

Examples of Gas-Mixed Reactors
• Growth concentrated in downer since light is not available in riser
• Dark/light cycle frequency controlled by gas flow rate
• Fluid circulation (controlled by gas bubbling and reactor geometry) to induce mixing
• Maximum thickness of downer around 5-10 cm due to light attenuation

• Dark/light cycle frequency controlled by gas flow rate and size of bubbles
• Rising bubbles induce mixing
• Maximum thickness of downer around 5-10 cm due to light attenuation
The Tree Design (one possibility)

- Optical Gathering Assembly
- Large Volume (3 m$^3$)
- Internal Structure
- Circulation
- CO$_2$ addition

12-15 m high
0.5 m diam
Design Concept

- **Outer Wall**
- **Internal light shaft**
- **Optical Waveguide**

3-4 times optical path

Tree diameter
Tree-like Photobioreactor Design
Reactor Flow Patterns and Mixing

- Gas lift over tall span could be challenging
  - Distributed $CO_2$ Injection along height
- Prevent Settling of Algae
- Provide the needed light/dark short cycle
- Recirculation patterns will depend on internal structure design. Will be simulated by CFD (FLUENT).
- Hydrostatic pressure difference could lead to unique bubbling characteristics for physical $CO_2$. 
## Design Target for Biomass Productivity

<table>
<thead>
<tr>
<th>Biomass Type</th>
<th>Productivity (tons/acre/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional Biomass</td>
<td>4-5</td>
</tr>
<tr>
<td>Energy Crops</td>
<td>10-15</td>
</tr>
<tr>
<td>Algae</td>
<td>100-200</td>
</tr>
</tbody>
</table>

### Analysis

- **400 Biotrees/acre**
  - **0.5 ton/tree/year** → **1.4 kg/tree/day**
  - **3 m³/tree @ 0.01 solid content**
  - At maturation contains 30 wet kg → 3 dry kg
  - **Harvest 50%** → means harvest once a day

**Critical assumption**
- Depends on light penetration

**200 tons/acre/year requires a doubling time on the order of 1 day**, which falls in the range of reported kinetics for various species; especially with CO₂ assistance.
Carbon Dioxide Issues
**CO₂ Sequestration**

**Underground in Geologic Formations**
- Energy intensive, requires compression.
- Capacity is unlimited.
- Could be used for secondary oil production, if injected strategically.
- Long-term fate is unknown.
- Effect on stability of the formations is unknown.

**Underwater**
- Much easier, but still requires energy for compression.
- Has a marked impact on ocean acidity, especially in a specific region.
- Interference with marine life can lead to even more environmentally disastrous results.
**CO₂ Sequestration**

*In Biomass Form*

- Plant Biomass has been fixating Carbon for millions of years.
- Requires Carbon source and solar energy.
- Process is Carbon Neutral.
- The challenge is in transportation.
- Two avenues for solution:
  - Locally integrated power production for a portion of the biomass with immediate recycling of CO₂
  - Development of technologies for transient sequestration of CO₂ in aqueous media.
Transient CO$_2$ Capture and Delivery

- Aqueous medium in the form of
  - *Physical carbonation*
  - *Chemical fixation (NaHCO$_3$, KHCO$_3$)*

- Many species capable of utilizing both forms (*Botryococcus braunii, Tetraedron minimum, Chlamydomonas noctigama, …*)

- Challenges:
  - *Offshoot CO$_2$ usually hot, sometimes pressurized*
  - *Liquid medium requires intermediate process steps*
  - *High temperature sorbents (2-step process)*
Other Issues
Biofuel Technology

Sustainability requires TOTAL biomass utilization.

Produced biomass can be used along multiple routes:

• Biodiesel
• Fermentation to bio-ethanol, bio-butanol
• Biomass gasification
• Catalytic Hydro-reforming
• Nutrient supply for fish and shrimp hatcheries.
Sustainable Architecture

Example Technology  BIPV

• **Building Integrated PhotoVoltaics**
• **Uses Windows, facades, building skin**
• **Can be enhanced with holographic elements**
BIPV with Holograms

- Redirects the light
- More light reaches PV element

Diagram showing sunlight being redirected by holograms to reach the solar cell more effectively.
Sustainable Architecture (Other)

- Wind-integrated buildings
- Geothermal heat pump for heating/cooling
- Green roofs
- Storm water collection and reuse
- Solar thermal collectors
- Thermal storage management with phase change materials
- Sustainable building materials
- Recycled polymers for paints and coatings
- Energy efficient windows
- Advanced control systems
Optical System Design
Objectives

1. Design a collection system that maximizes light capture and utilization at all times of day.

2. Design and optimize the light distribution system to achieve near-even distribution, avoid dark spots, and minimize shading effects.
Optical System Components

- Transmitting leaves + photovoltaic leaves
- Total internal reflection elements
- Holographic elements
- Mirrors
- Internal illumination shaft
- Illumination at varying depths
Optimization of Light Distribution

Internal shaft vs. external walls

Distribute at all levels, bypass shading effects
Modeling Light Propagation in Scattering/Absorbing media

Ray tracing (Monte Carlo)

- Fire a large ensemble of light rays
- Trace each ray through reflection, refraction, and scattering, until it is either absorbed or leaves the bounds of the system
- Calculate light intensity distribution for the ensemble
- Computationally intensive

Fermat’s Principle:
“Light rays follow a path that is an extremum compared to other nearby paths”
Solves the Radiative Transport Equation (RTE) derived by performing a photon balance on a fixed solid angle and volume

In finite-volume scheme, problem is discretized spatially and angularly

Scattering and absorption are directly modeled in each control solid angle and volume

Accuracy of the results depends on the spatial and angular grid used

Qualitative results can be obtained in relatively short computational times
The Radiative Transport Equation (RTE)

\[ \nabla \cdot I(\vec{r},\vec{s}) + (a + \sigma_s) I(\vec{r},\vec{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_{0}^{4\pi} I(\vec{r},\vec{s}) \Phi(\vec{s} \cdot \vec{s}') d\Omega' \]

Divergence of radiation
Intensity reaching solid angle \( \Omega \) in direction of propagation,

emission term, negligible for algae problems

extinction by absorption and out-scattering

radiation entering control volume (defined by a solid angle) by scattering from other control volumes

The phase function \( \Phi \) determines probability of in-scattering from all solid angles \( \Omega' \) into volume defined by solid angle \( \Omega \)
**FVDO Model solution in FLUENT**

**Grid Geometry and Discretization**
- Spatial Discretization: Tetrahedral elements
- Angular Discretization to represent directional dependence of radiation at each spatial node; each octant is divided into $N_\theta \times N_\psi$ solid angles

**Assumptions**
- Wavelength independence; isotropic scattering
- Integration over each solid angle in each CV
- Outward fluxes approximated by upwind differencing

**Solution Strategy**
- Equations coupled by inscattering term (dependent on incoming radiation from other directions), and by fluxes crossing CV surfaces (which are approximated in terms of the intensities in neighboring cells)
- Iterative solution is used

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**Advantage of this approach:** Light modeling and hydrodynamic CFD can be integrated in the same simulation environment, with the same grid discretization.
Wall Boundary Conditions in FVDO

Opaque Walls

**Specular reflection**

\[ \vec{s}_r = \vec{s} - 2(\vec{s} \cdot \vec{n})\vec{n} \]

\[ I(\vec{s}_r) = (1 - f_d)I(\vec{s}) \]

**Diffuse reflection**

\[ I_{out} = \frac{f_d}{\pi} \int_{\vec{s} \cdot \vec{n} < 0} I_{in}\vec{s} \cdot \vec{n} \ d\Omega \]

- Diffuse fraction is material dependent \((f_d)\)
- NO absorption, NO emission
Wall Boundary Conditions in FVDO

Semi-Transparent Walls

Wave guide

culture

$\sin \theta_a = \sin \theta_b \frac{n_b}{n_a}$

Snell’s law

$I(\vec{s}_r) = r_b(\vec{s})I(\vec{s}) + \tau_a(\vec{s}')I(\vec{s}')$

reflected portion

$I(\vec{s}_t) = r_a(\vec{s})I(\vec{s}) + \tau_b(\vec{s})I(\vec{s})$

transmitted portion

$r_b = \frac{1}{2} \left( \frac{n_b \cos \theta_a - n_a \cos \theta_b}{n_b \cos \theta_a - n_a \cos \theta_b} \right)^2 + \frac{1}{2} \left( \frac{n_b \cos \theta_b - n_a \cos \theta_a}{n_b \cos \theta_b - n_a \cos \theta_a} \right)^2$

$\tau_b = 1 - r_b$
Total Internal Reflection (TIR)

At the critical angle

Wave guide \( n_b > n_a \) Air

Above the critical angle

reflected portion

\[ r_b = 1 \]

transmitted portion

\[ \tau_b = 0 \]
Reflection in Semi-Transparent Media

- Incident
- Front reflected
- Back reflected
- Transmitted

Air → Polymer → Air
Simple Waveguides: Modeling & Testing

Straight cut

Bevel cut
Results: Simple Waveguide

Normal Incident Light rays, 200 W/m²

Notice scattering resulting from imperfections

96% Transmitted
Results: Simple Waveguide

45° Incident Light rays, 200 W/m²

127 W/m²

88% Transmitted

Losses 6% front reflection, 6% back reflection
**Results: Scalability**

**Normal Incident Light rays, 200 W/m²**

- *guide length has no considerable effect on the efficiency of light transfer*
- *It is possible to model shorter versions and expect results to be similar for a longer waveguide*
Results: Beveled (45°) waveguide

Normal Incident Light, 200 W/m²

Transmitted Light concentrates at tip
Axial and Radial Distributions

Normal Incident Light rays, 200 W/m²

92% Transmitted

Axial distribution

Radial distribution
Results: Beveled (45°) waveguide

45° Incident Light, 200 W/m²

More uniform radial distribution
Results: Bent Waveguides (redirection)

Normal Incident Light rays, 200 W/m²

- Large losses
- Most transmission is at junction
- Need for optical insulation

6% Transmitted

15% Transmitted

Chicago, Illinois, April 2010
Effect of Insulation with reflective coating

Reflective material in neck region

22% Transmitted
Effect of Insulation with reflective coating

Reflective material all over

Inlet

Too much (32%) back reflection

Outlet
Results: Compound Y-shaped Waveguide
Results: Compound Y-Shaped Guide

- 53%
- 16%
- 14%
- 6%
- 3%
- 5%
Results: Compound Y-Shaped Guide
Results: Compound Y-Shaped Guide

All walls Irradiated by incident 45° light

Light distribution on outer surface of guide
Results: Y-shaped guide, 45° incident light

Outer surface collects a lot of light, but delivers at junction below critical angle.
Results: Photobioreactor with Algae Suspension

PBR Optical Regimes

Reactor Segment Geometry

Algae Concentration

Scattering/Dominated

Absorption/Dominated

σ_s \approx a

σ_s \ll a

σ_s > a

Time
Results: PBR with Algae Suspension

\[ G(\mathbf{r}) = \int \frac{I(\mathbf{r}, s) d\Omega}{4\pi} \]

Scattering-dominated Medium

\[ \sigma_s = 10 \cdot m^{-1} \]

\[ a = 5 \cdot m^{-1} \]
**Light Collection System Schematic**

**17% Efficiency**

**Incident** = \(200 \cdot \frac{\pi (1.2)^2}{4} = 226.19 \cdot \text{Watts}\)

**Collected** = \(0.12 \cdot 6 + 0.96 \cdot \frac{\pi}{4} (0.5)^2 \cdot 200 = 38.42 \cdot \text{Watts}\)

200 W/m²

5 cm diameter

10 cm

35 cm

50 cm

120 cm

FRONT

TOP
15% Efficiency

Incident = 200 \cdot \sin 45 \cdot \frac{\pi (1.2^2)}{4} = 159.94 \cdot \text{Watts}

Collected = 0.11 \cdot 6 + 0.86 \cdot \frac{\pi}{4} (0.5)^2 \cdot 200 \cdot \sin 45 = 24.54 \cdot \text{Watts}
Light Collection System - Target

- **Modular design approach**

- **Need optimized Junctions and compound guides**

- **Genetic algorithm for optimization by addition and mutation of elements**
Tree in a Lab
Photo-Bioreactor
Reactor Setup
Tracking Growth of Chlorella Pyrenoidosa in PBR-1
Monitoring Transmitted Illumination intensity at the surface of the reactor is indicative of algal growth.
Growth of CP at a constant Low Salinity (400 mg/l) and various pH values

Medium pH increases and then leveled off.
An inflection point around DOD of 1.
Within an alkaline pH range 7.47 to 9.75
Summary and Conclusions

- The Emerald Forest Concept has a high potential for alleviating the energy and climate changes crises, and for desert reclamation into sustainable living communities.
- Many challenges exist that require broad-spanning parallel research efforts.
- FVDO modeling was demonstrated for light propagation.
- Can lead to efficient genetic optimization algorithms using a modular permutation approach.
Thank You!

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