Photobiocatalytic Conversion of CO$_2$ to Drop-in Fuels: A Primer
The **Helioculture® Platform:**

**Groundbreaking Technology for CO2-Neutral Fuels and Chemicals Production**

Disruptive technologies transform existing markets by pushing beyond apparent boundaries of cost and productivity to create new industries. The **Helioculture process**, in contrast to conventional biomass feedstock-based processes, is a transformative technology that promises to redefine the petroleum-based marketplace via efficient capture of solar energy and waste CO2 to catalyze the direct-to-product synthesis of renewable fuels and chemicals.

The energy-intensive steps of biomass growth, harvesting, deconstruction and batch fermentation have been at the foundation of first and second generation biofuel production. These processes require the conversion of biomass to inexpensive sugars or oils for subsequent conversion to fuels, e.g., cellulosic ethanol, or biodiesel from vegetable oils and algal biomass. In some processes, the material produced by the bioprocess must be chemically processed to a fuel.

In contrast to these technologies, the **Helioculture** approach is a biocatalytic process whose feedstock is CO2. Like a chemical catalyst that promotes a chemical reaction while remaining unchanged, the photobiocatalyst manages light energy and carbon from CO2 to continuously synthesize and secrete drop-in fuels while producing no new biomass.

In the **Helioculture** process a photosynthetic cyanobacterium has been engineered to divert 90-95% of its fixed CO2 to synthetic metabolic pathways to make fuels or chemicals, and to operate for extended periods in a closed photobioreactor (PBR), called the **SolarConverter®** system. The **SolarConverter** system has been designed to effectively harvest sunlight and manage the factors that could divert photonic energy away from the fuel pathway. Through gas management, turbulent mixing and channeled tubular configuration, the design optimizes energy and CO2 conversion to realize high productivities. The process eliminates the requirement for cultivated feedstock and the intrinsic costs of processing. Omitting process steps and extending process periods dramatically lowers costs and multiplies annual productivity.

Upon global commercialization, this technology can achieve the scalability, volumes and costs required to make carbon-neutral mobility a reality.

*The Helioculture process overcomes many of the challenges associated with traditional biomass batch approaches:*

- Directly converts solar energy and industrially produced waste CO2 feedstock to fuel
- Yields a pure product that is fully compatible with existing fuel infrastructure without additional refining or processing
- Operates photobiocatalytically, enabling a continuous process with 8-12 week production cycles; Does not use a biomass feedstock or batch processing
- Uses a common cyanobacterium (unlike eukaryotic algae) as a base chassis for extensive metabolic engineering
- Applies proprietary metabolic pathways via strain engineering for direct fuel production and regulation of carbon partitioning from fixed CO2 to fuel with 95% efficiency
- Minimizes energy and carbon losses to biomass growth or other competing metabolic processes
- Far surpasses the fuel productivities of all biomass-reliant processes, e.g., oils from algal and vegetable sources, sugars from plant cellulose or starch.
- Uses non-arable land, no displacement of food crops
- Uses brackish or sea water
• Provides a domestic source of transportation fuels that can contribute toward meeting the goals of the U.S. Renewable Fuel Standard and reducing the nation’s dependence on foreign oil
• Achieves >70% reduction in CO₂ (90% with PV power) to meet EPA RFS standards
• Provides a carbon utilization solution for industrial emitters faced with existing or pending carbon regulations

The Helioculture Process

The potential of algal and cyanobacterial phototrophs as production systems was recognized more than 75 years ago. A large body of knowledge has developed on their energy and carbon metabolism, physiology, genetics and cultivation. The US Department of Energy has sponsored a long-term Algal Biomass Consortium to explore all aspects of the industrialization of algal biomass for biodiesel production and published a comprehensive look-back report¹.

The DOE Summary Report as well as other expert assessments have recommended a number of critical advances necessary to overcome low photosynthetic efficiencies and unattractive economics that have hindered industrialization of photosynthetic fuel processes¹,²,³,⁴. The suggestions are summarized in Table 1 relative to Joule advances.

<table>
<thead>
<tr>
<th>EXPERT RECOMMENDATION</th>
<th>JOULE TECHNOLOGY</th>
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<tr>
<td>ENGINEERED ORGANISM</td>
<td>• Proprietary engineered pathways for synthesis of drop-in fuels: Ethanol or C₁₁ n-alkane</td>
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<td>• Carbon switch to control carbon flux from CO₂ to either biomass or to fuel pathway</td>
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<td>• 95% CO₂ conversion to fuel</td>
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<tr>
<td>MINIMIZE ENERGY LOSSES</td>
<td>• Operation at high CO₂ prevents up to 45% energy diversion by photorespiration</td>
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<td>BIOCATALYTIC PRODUCTION</td>
<td>• Biocatalytic process with 10-12 week process cycle times</td>
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<td>• Continuous product synthesis and secretion vs batch processing</td>
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<tr>
<td>OPTIMIZE PHOTOSYNTHETIC EFFICIENCY</td>
<td>• Directed evolution generates strains with improved photosynthetic efficiency (PE)</td>
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<td>• SolarConverter design optimizes light management, mixing, gas delivery, thermal control</td>
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<tr>
<td>CONTROL BIOBURDEN</td>
<td>• Proprietary process design that minimizes contaminant penetration</td>
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<td></td>
<td>• Cleaning regime for long-term axenic operation</td>
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<td>• Proprietary, in situ bioburden control solution</td>
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Table 1: Summary of productivity and economic advances inherent in the Helioculture process.

The Helioculture process operates outdoors within a closed, controlled photobioreactor (the SolarConverter® system) that circulates culture medium, controls pH, temperature and CO₂ and O₂ concentrations, and ensures efficient exposure to sunlight.

² National Algal Biofuels Technology Roadmap. (2009)
Under these conditions, the engineered cyanobacteria act as photo biocatalysts, producing fuel, but not biomass. They are also able to secrete fuel through their cell walls, enabling continuous operation and recovery of fuel product without harvesting or processing the cell biomass. The process operates at a steady state for many weeks, reducing time lost to process turn-arounds and productivity lost to biomass formation. Since the SolarConverter system is constructed in a 10-acre modular configuration, it has the potential to scale to any size without changing the basic process operation.

Figure 1. Comparison of biomass-dependent fuel production vs continuous synthesis by an engineered, product-secreting biocatalyst.

Joule has reported the productivity potential of its closed Helioculture process in a 2011 refereed publication and, in support of the publication, experimentally demonstrated that the solar energy conversion potential of its strain is up to 5 times that of biomass-dependent processes see (see Figure 8). In lab and in outdoor pilot scale reactors, productivities have been demonstrated that far surpass those of competing technologies (Figure 2)

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Figure 2. Comparison of processes and productivities for biomass vs Helioculture technologies

**Principles of photosynthesis and CO₂ fixation**

The sun is the source of >95% of all energy on earth. Organisms have evolved to capture and convert that energy into life as we now know it, using the process of photosynthesis. Photosynthesis is the biological energy capture and delivery system that ultimately drives all cellular processes. It appeared >3 billion years ago in microbes living in a non-O₂, high CO₂ atmosphere. As it evolved, a highly efficient version that efficiently captured and converted the widest range of solar energy arose in Cyanobacteria. It used CO₂ and released O₂ and created the O₂-rich atmosphere we experience today.

Solar radiation insulates the earth in the form of packets of energy called photons. For this energy to be used to drive cellular metabolism forward, the photon packets must be efficiently converted into “high energy” chemical...
forms, ATP and NADPH, which deliver chemical energy packets to catalyze individual enzymatic transformations. The reactions these chemical packets drive forward are termed endergonic or “uphill”. Exergonic reactions are catabolic, or “downhill”, and require no driving force. The exer- and endergonic reactions form the web of metabolic reactions that maintain a photosynthetic cell at a steady rate of energy and CO₂ conversion and determine the rates of growth, or in the case of Helioculture technology, the rate of synthesis of a fuel product.

Figure 3. The photosynthetic architecture for solar energy transduction.

The photosynthetic energy absorption and delivery system is composed of four multi-protein transmembrane complexes that have evolved to catalyze the sequential conversions of photonic energy in what are termed the “light reactions”. The transmembrane complexes have an architecture of redox-active cofactors evolutionarily selected and electrochemically tuned to catalyze very efficient, step-wise energy conversions. ATP and NADPH are the ultimate chemical products of this process. They are used to drive the energy requiring reactions in downstream metabolism. The efficiency of this process is nearly 100%.

Cyanobacteria have multiple transport systems to capture and concentrate CO₂ around Rubisco, the enzyme that initiates the dark reactions of the CO₂ fixation cycle. Given its universal use in oxygenic photosynthesis, Rubisco is the most abundant enzyme on earth.

CO₂ fixation is the process by which the carbon of CO₂ is built into a three-carbon metabolic intermediate, 3-phosphoglycerate (3PG). The cycle is active in all cyanobacteria, algae and plants. To incorporate 3 CO₂ molecules, the cycle must turn over three times, each cycle consuming the ATP and NADPH synthesized by the photosynthetic
machinery. 3PG joins the cell’s intermediate metabolism leading to the metabolic offtake points for the engineered pathways to either ethanol or alkane.

**Choice of platform organism**

Several criteria were used to choose a base photosynthetic organism for metabolic engineering and process performance:

- Unicellular, free-living oxygenic phototroph
- Straightforward genetics
- Rapid doubling time
- Concentrate CO₂ to overcome photorespiration energy losses
- Function in brackish, saline, sea or fresh water
- Function for weeks in closed culturing system
- No biofilm or process fouling issues

Algae are eukaryotic while cyanobacteria are prokaryotic, e.g., they are true bacteria. Algae compartmentalize their genome in multiple organelles; a membrane-bounded nucleus and chloroplasts and mitochondria, making genetic engineering very difficult. Cyanobacterial genomes are not compartmentalized or surrounded by a membrane, making them straightforward to take up and integrate foreign DNA. Algal doubling times are very slow relative to cyanobacteria, limiting their product yield per unit time.

Given the qualities desired for a genetically engineered, continuously producing biocatalyst, base organisms from the genus of unicellular *Synechococcus* were chosen as the chassis for development.

![Comparison between ultrastructures of prokaryotic cyanobacteria and eukaryotic algae](image)

*Figure 4. Comparison between ultrastructures of prokaryotic cyanobacteria and eukaryotic algae*
**Biological routes to fuels**

Strains of cyanobacteria have been genetically engineered to produce enzymes to catalyze the chemical conversion of the natural metabolite pyruvate to ethanol via acetaldehyde, or acyl-ACP enzyme of natural fatty acid synthesis to alkane via fatty aldehyde.

![Diagram showing enzyme pathways for synthesis of either ethanol or C₁₁ n-alkane](image)

**Figure 5: Enzyme pathways for synthesis of either ethanol or C₁₁ n-alkane**

Each gene was chosen from a large family of DNA sequence homologues in the public database, GenBank, to code for an enzyme with catalytic rate, substrate specificity and cofactor identity commensurate with efficient, concerted synthesis of the fuel intermediates and final product in the cyanobacterial chassis. The chosen genes are rapidly synthesized and incorporated into an operon. A regulatory gene element is also included to initiate pathway gene expression. The engineered DNA is taken up and incorporated into the cyanobacterial genome at a precisely chosen genome locus via double homologous gene recombination.

**Controlled carbon flux; Synthetic carbon switch between biocatalyst grow-up and fuel production.**

The *Helioculture* process is designed to enable continuous synthesis, secretion and recovery. The *Helioculture* photobiocatalyst has a synthetic carbon switch. The ability to control the magnitude and direction of carbon flux significantly improves the pathway product yield relative to the amount of fixed CO₂. Continuous process operation for 8 – 12 weeks reduces time lost in process turnarounds and boosts annual plant yield. Note that the biomass produced in the grow-up phase continues to produce ethanol biocatalytically.
Figure 6. Photobiocatalyst growth followed by switch induction and re-routing of carbon to ethanol. A similar mechanism is used for carbon diversion to C_{11} alkane.

<table>
<thead>
<tr>
<th>Ethanol production rate</th>
<th>Total energy conversion rate</th>
<th>C-partition efficiency</th>
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<tbody>
<tr>
<td>KJ L^{-1} h^{-1}</td>
<td>KJ L^{-1} h^{-1}</td>
<td>%</td>
</tr>
<tr>
<td>0.52</td>
<td>0.55</td>
<td>95</td>
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Metabolic engineering strategies have successfully routed 90 – 95% of fixed CO\textsubscript{2} to ethanol and are currently being applied to similarly optimize alkane pathway flux.

Figure 7. Depiction of the engineered photobiocatalyst showing offtake metabolites, engineered pathways and synthetic switches to direct carbon flux. The figure is a composite; photobiocatalysts are constructed for only one product each, either ethanol or C_{11} n-alkane.

The SolarConverter System

The Helioculture process takes place within a specially designed outdoor reactor, the SolarConverter system (Figure 8). The SolarConverter capsules are transparent arrays of channels that optimize the transmission of photosynthetically active radiation (PAR), reflecting infrared, and performing thermal management and mixing. The modules circulate culture medium in a down-and-back intra-unit configuration with subsequent circulation to the next adjacent channeled capsule. Each SolarConverter module maintains a high surface-to-volume ratio of culture medium, with cells maintained at a high operating culture density and mixing rate.
In operation, the SolarConverter field receives waste CO\textsubscript{2} from a nearby industrial source such as a power plant or a cement plant. The waste CO\textsubscript{2} is mixed with air to a 2% volume fraction and sparged through each SolarConverter module, providing both a source of carbon for fuel production and motive force for circulating the culture through the modules. Mechanical pumping can also be used to power mixing. The process is optimized by varying the culture density, depth, and surface area to efficiently convert the CO\textsubscript{2} and to maximize utilization of incoming solar illumination. As individual cells travel through the channels, they are deliberately and rapidly cycled between the light and dark areas of the capsule to most efficiently maintain energy balance, CO\textsubscript{2} fixation, and metabolism of carbon to product.

![Image of a SolarConverter system]( Capsules.jpg)

**Figure 8. Joule’s outdoor SolarConverter system, Hobbs, NM**

The Hobbs, NM facility currently uses liquefied CO\textsubscript{2}. Future facilities will use industrial waste gas streams, such as those from coal-fired power plants, cement plants, etc. We have tested the photobiocatalysts using mock flue gas and have also investigated the impact of heavy metals on photobiocatalysts with positive results.

**Photosynthetic efficiency (PE)**

Photosynthetic efficiency expresses the fraction of total solar energy incorporated into any metabolic product, e.g., biomass, ethanol, alkane. The photosynthetic system has evolved a metal-cofactor architecture to use light energy between 400nm (blue) and 700nm (red), or 48% of the total solar spectrum striking the earth’s surface. The solar energy available to drive metabolism is referred to as photosynthetically active radiation or PAR. From this PAR energy, certain physical factors, e.g., reflection, refraction, as well as the energy costs of carbon metabolism reduce the amount of energy ultimately converted to fuel product. We have calculated a maximum conversion percentage for PAR of 6.6%.

There are other energy drains that can erode PE, primarily photorespiration and high light-induced photoinhibition leading to photodamage. These are the two greatest contributors to energy diversion. Photorespiration is a condition where O\textsubscript{2} competes with CO\textsubscript{2} for reaction with Rubisco and diverts carbon and energy away from the engineered pathway. Given the multiple systems for CO\textsubscript{2} concentration in cyanobacteria, as well as a high (2%) CO\textsubscript{2} concentration used in the closed Helioculture process, photorespiration is largely avoided and the energy, up to 45% otherwise lost, can be dedicated to fuel production.

Photoinhibition occurs when cells are exposed to high photon flux as solar intensity increases to solar noon. When photon flux density exceeds the abilities of photosystems to process it, defensive energy quenching mechanisms are mobilized to process and dissipate the excess photonic and electrochemical energy, again diverting energy from fuel production. If high light exposure exceeds the capacity of the quenching mechanisms, photo-oxidation damage can occur via the formation of oxygen radicals near the water splitting reaction center associated with PSII and at PSI.
Following screening of large mutational libraries, strains with improved light management capacity and thus higher productivity have been isolated. Other genes coding for enzymes that destroy the oxygen species have been added to the genome for increased protection and culture longevity.

The SolarConverter system design and performance is also critical to PE. Physical design, optimized flow and gas transfer can improve light and dark exposure frequencies dynamics.

Figure 9 is a summary of energy diversions and how they affect photosynthetic efficiency in an open pond algal biomass process vs the closed Helioculture process. Green circles indicate points of significant advantage in photosynthetic efficiency. Data for algal biomass from Wyer, et al.

Figure 9. Comparison of open algal pond for batch biomass production vs closed, continuous conversion via Helioculture technology. Atmospheric CO₂ concentration is 0.03% for the algal pond while the closed Helioculture process uses 2%. The energy available following a loss is expressed as megajoules/m²/sec and the fraction of the total is expressed as a percent.

To test the inherent efficiency of the strain chassis used for engineering, an experiment was done to simulate mixing over a range of light/dark exposure frequencies in a photobioreactor. Delivery of light pulses to charge the photosynthetic system followed by a dark period, and varying durations of each is virtually identical to mixing into light and dark zones of a photobioreactor. Though literature measuring PE-PAR generally concludes that PE is 2-6%, we can demonstrate that a closed, well mixed culture can avoid photoinhibition and reach very high efficiencies. When durations are out of the optimum range, the experimental culture experiences over-reduction i.e., photoinhibition, followed by photooxidation and photodamage and a significant drop in PE (Figure 10).

Figure 10. Photosynthetic efficiency vs light and dark zone sampling frequency

**Biological and process improvement to increase efficiency**

Figure 11 illustrates gains in ethanol production for a randomly generated single mutant strain operating under two sets of process conditions. The mutant alone had dramatically improved PE-PAR. Adjusting SolarConverter system parameters further enhanced performance. Joule has a growing library of improved mutants to be stacked for stepwise improvement in productivity and additional process improvements to maximize fuel productivity.

**Bioburden control**

Control of microbial contaminants is critical for success of any biological process, particularly those where a product is secreted to the medium and available as a carbon and energy source for competing microorganisms. Joule has implemented strategies to limit foreign microorganism incursion, to clean the process system between multi-week
BIOBURDEN CONTROL
- Process contamination by foreign organisms can quickly lead to consumption of product
- Joule has engineered its biocatalyst for competitive advantage over contaminants
- Ethanol producing strains with the bioburden mitigation construct limit contaminant growth
- No ethanol is consumed

BIOBURDEN PREVENTION
- Novel process plant design limits penetration points
- Pre-production cleaning and sterilization procedures eliminate contaminants

Figure 12. Demonstration of contaminant mitigation via engineered strain advantage

**Engineering the chassis for production of value-added chemicals**

Similar to fuel producing photobiocatalysts, enzyme pathways for the diversion of metabolic intermediates to industrial chemicals can be constructed in the same chassis. Figure 13 depicts some of the molecules and chemical products that could be produced with *Helioculture* technology. As POC, Joule has built and tested 8 discrete pathways. In each case the *Helioculture* process design is the same, with the exception of molecule-specific recovery.

Figure 13. *Helioculture* technology for the production of industrial chemicals
SUMMARY: HELIOCULTURE TECHNOLOGY ADVANTAGES:

1. **Does not use a biomass feedstock**: Uses CO₂ feedstock from waste flue gas.

2. **Uses an engineered photobiocatalyst**: Light management capability and resistance to reactive oxygen species.

3. **Yields a pure fuel fully compatible with existing infrastructure**: Ethanol passes DIN testing; C11 n-alkane meets ASTM diesel performance standards up to 50% blend with conventional diesel.

4. **Controlled partitioning of fixed carbon and solar energy to product or biomass**: Under control of a synthetic switch mechanism, the continuous process devotes only ~5% of the culture period to biomass formation and then operates at a steady-state production level, to convert 90-95% of its energy and carbon to product.

5. **No energy loss contribution of subcellular organelle metabolism**: Eukaryotic algae have mitochondrial sub-compartments with metabolic roles in the cell. Under atmospheric conditions, algal mitochondria perform respiratory metabolism, dissipating a percentage of their energy. Prokaryotic cyanobacteria used in *Helioculture* process do not have intracellular organelles and do not perform respiration to any significant degree under insolation.

6. **No dissipation of energy due to photorespiration**: Prokaryotic cyanobacteria have evolved multiple mechanisms for CO₂ concentration in proximity to the Rubisco enzyme to minimize photorespiration. Moreover, the *Helioculture* process operates at CO₂ concentrations more than 50X higher than atmospheric, enough to supply the Rubisco enzyme and obviate nearly all photorespiration loss.

7. **Photobioreactor design that minimizes photoinhibition and optimizes productivity**: The combination of short light path, high operating cell density and high mixing rate in the closed *SolarConverter* system optimizes light/dark cycling frequency and maximizes the efficiency of photosynthetic energy conversion to product.

8. **Modular design of process units for linear scaling**: The *Helioculture* process design incorporates identical *SolarConverter* units arrayed in 10 acre circulation fields served by upstream inputs and downstream recovery operations. The circulation units can be repeated over large acreages to achieve desired outputs with linear incremental relationship to capital cost.

9. **Capital/operational costs balanced by productivities realized through organism and reactor design**: Critiques of photobioreactor designs have focused on scalability and capital cost. Given the productivities realized by direct production, secretion, continuous operation and reactor design, a modularly scaled process using a photobiocatalyst can realize economically favorable cost targets.

10. **Achieves high yields on a relatively small footprint**: Productivities are up to 10X higher than biomass feedstock dependent processes.

11. **Avoids competition with fresh water**: Uses brackish or sea water.

12. **Avoids competition for farmland and food**: Uses non-arable land.
Appendix 1: Definition of terms

SOLAR ENERGY

• **PE-PAR**: (Photosynthetic Efficiency on Photosynthetically Active Radiation): Efficiency of conversion of visible light energy to product by the catalyst
• **PE-SOLAR**: Photosynthetic Efficiency on Total Solar radiation
• **Photosynthetically Active Radiation (PAR)**: The portion of the solar spectrum available for photosynthesis, ~48%
• **Micro-Einstein, µE**: A measure of light intensity, e.g., Phoenix noon = ~2000µE/m²/sec

PHOTOSYNTHESIS

• **Photosynthesis**: Natural process for converting solar energy to matter
• **Photorespiration**: Condition where oxygen competes for energy with CO₂ fixation; Lowers PE-PAR
• **Photoinhibition**: Condition of energy overflow at high light intensity; Lowers PE-PAR
• **Photoxidation**: Damage processes of ROS
• **ROS**: Reactive Oxygen Species; Reduced forms of oxygen produced during light-induced stress

PHOTOBIOCATALYST ENGINEERING

• **Photobiocatalyst**: Photosynthetic organism engineered to continuously catalyze a chemical transformation without change to itself
• **Gene**: A sequence of DNA that codes for a protein or enzyme
• **Genome**: An organism’s full complement of genes
• **Pathway**: An enzyme or group of enzymes that catalyze chemical transformations of metabolism
• **Promoter**: A natural DNA element that controls gene transcription
• **Clone**: A strain with a unique genome sequence, e.g., following mutation
• **Mutant**: A single cell, i.e., clone with DNA alterations
• **Library**: A large collection of mutant clones; 10³ – 10¹⁰ discrete clones
• **Selection**: A primary method for probing a large library of clones for a desired feature
• **Screen**: Secondary method to further characterize multiple clones
• **Carbon switch**: A synthetic DNA sequence that turns on/off the production of product

**SolarConverter System**

• **Capsule**: Thin film plastic reactor vessel; 25 – 300 meter length
• **Channel**: A single tube of the multi-channel capsule
• **Header**: Capsule supply interface to central plant
• **EWER Capsule (Energy water efficient reactor)**: a capsule with integrated heat exchange and storage

**HELIOCULTURE PROCESS**

• **VLE** (Vapor liquid equilibrium): A sterilization process utilizing hydrogen peroxide in reactors
• **MEB** (Mass and energy balance): An accounting of all energy and mass inputs and outputs of the process, used as a basis for plant design, optimization and economics
• **LCA** (Life cycle analysis): A technique to assess environmental impacts associated with all the stages of a product’s life from-cradle-to-grave
Appendix 2: Assumptions considered in determination of photosynthetic efficiency

SOLAR IRRADIATION
- Ground-level radiation from NREL clear sky datasets (1991-2005) corrected for cloud cover and diffusion
- Future radiation characteristics will be consistent with historic values

SolarConverter
- Reflection and refraction are accounted for in photon transition through specific plastic reactor material
- Solar capture efficiency of stationary SolarConverter system is dependent on angle of incident radiation

PHOTOBIOCATALYST
- Photosynthetically active radiation (PAR) is 47% of total solar spectrum at ground level
- Photon requirement for any pathway is based on its associated redox/energy cofactor balance
- Production rate is linear with radiation intensity
- High CO₂ concentration (50X atmospheric) negates loss due to photorespiration in cyanobacterial metabolism
- No mitochondrial respiration in cyanobacterial metabolism
- Bacterial resting cell maintenance energy = 5% energy diversion
- Culture reflection and non-utilization account for 15% photon loss

PROCESS
- PAR is converted only when SolarConverter system is at operating temperature (10% loss early and late day)
- Continuous production and limited downstream processing = 95% process operational cycle time
- Culture mixing rate maximizes irradiation of individual cells
- Helioculture technology nonproductive area = 5% photon loss