

ENERGY SELF-SUFFICIENCY

Catalyst for Energy Agnostic Global Economy

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ABSTRACT

The concept of eAGE is easy to grasp if one appreciates the analogy of the **distributed** ability of computing at the hands of any individual who owns an iPad or notebook **computer** versus the ENIAC ¹ which weighed 30 tons. We propose development of energy products which could **distribute** the ability to **manufacture energy** in the form of domestic appliances to usher in **micro-energy autonomy** which may evolve as a segue to eAGE or energy agnostic global economy. Micro-energy autonomy may relieve the volatility linked to the price of fossil fuels, petroleum in particular. We propose to create tools and mechanisms which may not be restricted by intellectual property (IP) rights and disseminate the technology worldwide as a small business innovation.

INTRODUCTION

If individuals, households and small businesses are **equipped to manufacture** non-fossil renewable energy (for example, butanol) which is adequate for their needs (to power appliances and automobiles, lighting, heating, cooling) then we may suffer less from the vagaries currently associated with energy and fossil fuels. Carbon-neutral non-fossil energy sources may also help sustainability by reducing excessive emission of green house gases. A key outcome of **microscale energy production** capability is a potential paradigm shift where sourcing and distribution of energy is no longer controlled by a few global behemoths or cartels.

CENTRAL THEME

We propose ² **energy self-sufficiency** or microscale energy autonomy as a pragmatic approach to distributed energy production through manufacturing of butanol ³ and related liquid fuels. Microscale energy production may not be a panacea and may not alleviate all the ills we associate with fossil fuels but its impact on the environment may be quite significant. Microscale energy production can serve the global domestic demand of 7+ billion people and pave the way for energy self-sufficiency, albeit, in part. It is possible to implement microscale energy production with tools at hand. The potential of microscale energy production encourages us to remain cautiously optimistic about the scalability of the process which may eventually unleash macro-scale manufacturing of non-fossil fuel. The latter may boost an emerging **energy agnostic global economy** where development and freedom may be free from economic woes due to energy volatility and may no longer held hostage by the availability of energy resources or the threat of environmental embargo.

¹ <http://en.wikipedia.org/wiki/ENIAC>

² <http://dspace.mit.edu/handle/1721.1/59804>

³ Nielsen, D., *et al* (2009) Engineering alternative butanol production platforms in heterologous bacteria. *Metabolic Engineering* **11** 262-273

RENEWABLE TOOL KIT

We have the ability to use solar energy to produce liquid fuel in the form of butanol from microorganisms which are photosynthetic bacteria or micro-algae capable of growing in photo-bio-reactors. Therefore, it does not require any vegetative (corn, sugarcane, biomass) food source for production of butanol. Atmospheric carbon dioxide trapped to produce butanol (four carbon atoms in each molecule of butanol) removes carbon dioxide from the environment. When the chemical energy in butanol is converted to electrical energy (to charge your electric vehicle or generate power for your domestic appliances) or mechanical energy (if used in the internal combustion engine of your automobile) the carbon is released to the environment in the form carbon dioxide and other 'green house' gases. Hence, butanol as a fuel is **carbon neutral**. Vehicles including flex fuel vehicles (FFV) can use butanol as a liquid fuel without modifications to existing internal combustion engines which currently use gasoline or petrol or some combination of gasoline with added ethanol.

SOLUTION AMID CONTROVERSY

Butanol (or related products such as pentanol) produced by microorganisms were engineered to optimize production. But, the yield of butanol from photo bio-reactors (uses sun light as the source of energy) is low. Hence, the debate rages on whether the method is **scalable** for mass production. **The suggestion here is to transform this handicap into a key advantage**. Small scale or microscale energy production serves the **distributed** concept of energy self-sufficiency. If every household or unit product produced some energy or enough, then, scalability may not be an impediment. Excess energy may be sold or auctioned by individuals (cooperatives) to the smart grid, where available, in a manner envisaged for local wind or geothermal energy producers. Bio-energy tools at hand offers an immense potential to grow an **energy cottage industry** which may liberate the economies of the developing world and improve the lives of 80% of the global population whose ability to earn even a basic living is eviscerated by and is at the mercy of fuel prices.

NEW COMMODITIES for ENERGY SUPPLY CHAIN

The developed and industrialized nations where sunlight is less abundant (low insolation zones in US and EU) may view the dependence on solar energy with chagrin. At hand, there is an elegant alternative which may be a driver for the next generation of energy supply chain. The solution is glucose, a molecule with six carbon atoms and the universal currency for energy in most biological systems. It is established that glucose can be converted by bacteria to butanol without sunlight. Photosynthetic microorganisms (cyano-bacteria) can produce glucose in the presence of sunlight. Hence **glucose**, instead of butanol, may be produced by bacteria in high insolation zones. Glucose (instead of liquid butanol) may be transported (solid) to low insolation zones where it may serve as the key commodity for **solar-independent** microscale butanol production.

It is neither elusive nor requires any imagination to visualize the economic growth potential in the tropics from new lines of business which may spawn in high insolation zones capable of manufacturing energy, either as butanol or glucose using renewable sources (sunlight, carbon dioxide). Glucose as a commodity in the energy supply chain is non-perishable and amenable to storage. Hence, glucose serves both as a currency for energy and as an ammunition against economic volatility due to energy uncertainty. Taken together, the energy cottage industry may accelerate the development and economic freedom of developing nations on the continent of Africa, South and Central America, parts of South-East Asia, China and the Indian sub-continent, that is, most of the world. From a marketing perspective, the latter is also the market for this product(s).

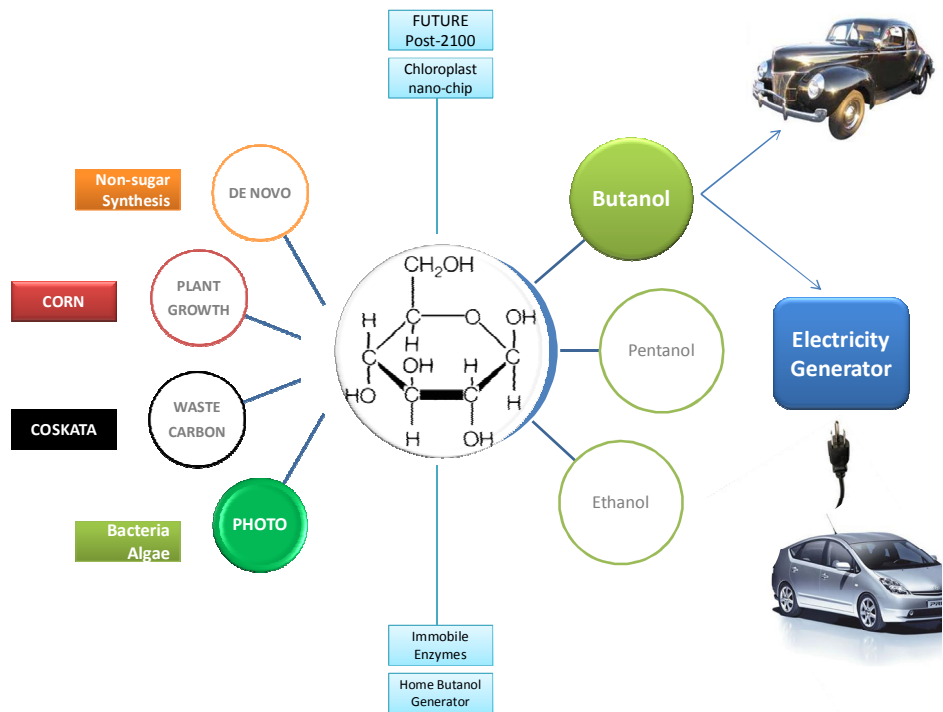


Illustration 1: Glucose – The New Petroleum?

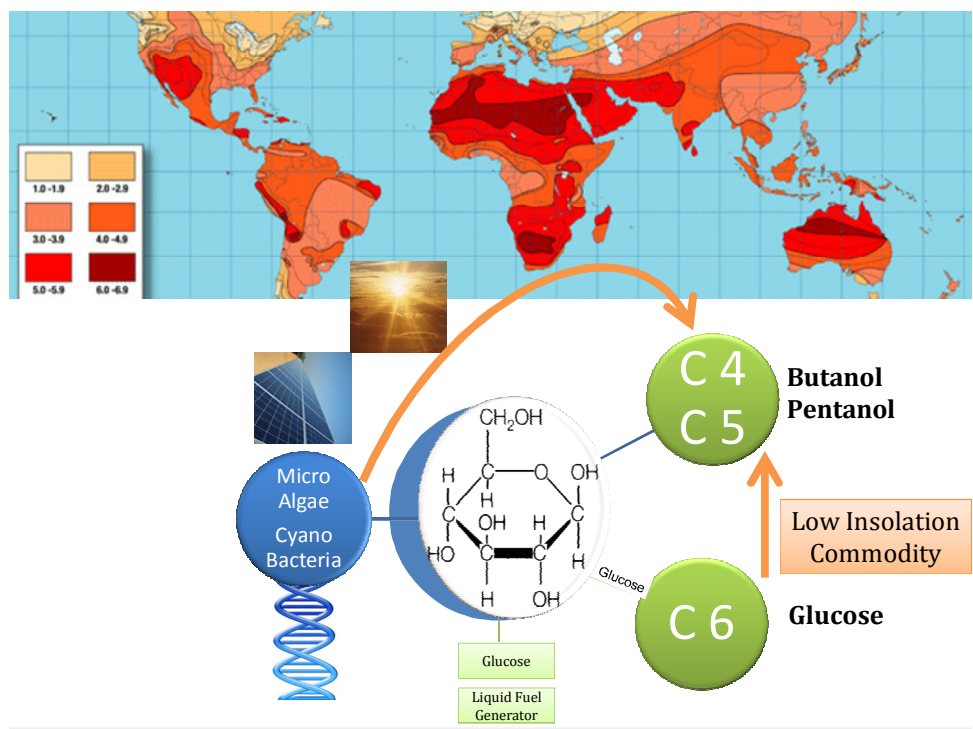


Illustration 2: Sun Light – necessary but not mandatory (alternative commodities in the energy supply chain)

RATE LIMITING STEPS

This transforming energy solution and lucrative small or medium business and business services opportunity can create new jobs, globally. But, it is still does not feature in the main stream. There may be several reasons but the key may be the lack of vision in appreciating what distributed microscale energy manufacturing may be able to accomplish if the tools and technology are actively disseminated wherever there is an interest. To many it may appear too-out-of-the-box to assimilate the fact that energy can be produced in a household by methods other than sourcing from the utility industry. Microscale energy autonomy may seem “foreign” to people because of the grip of the utility industry behemoths not only on our wallets but on our minds.

From a pragmatic perspective, few individuals are familiar with the science and engineering of bio-energy production. Basic scientists who have engineered the microorganisms are perfecting the science and pursuing other optimizations. The convergence of energy bio-technology with metabolic and chemical engineering may also experience growing pains associated with migrating energy solutions from the bench to the business. Investors will push for macro-scale mass production volumes. Hence, the penchant for domestic, low-cost, microscale energy production in the form of a kitchen appliance or a garden variety generator may not be on the agenda. Above all, the cost per kilo-watt-hour of electricity generated from an unit (liter or gallon) of butanol or glucose may be intensely debated and models analyzed for risk when estimating potential for profitability. The latter could contribute to the canonical paralysis by analysis disguised as due diligence.

Patent protection of intellectual property (IP) rights may also stifle dissemination of work in progress. It may reduce options for other groups to pursue cooperative funding from semi-altruistic investors. The principles of butanol or related liquid bio-fuel (pentanol) production in bacteria are based on a vast body of existing scientific literature. Theoretically, any biotech expert ⁴ can optimize butanol or glucose producing bacteria or micro-algae using tools of recombinant DNA or create bacteria (without IP) using metabolic engineering, RNA interference techniques (to silence diversions to unwanted pathways) and synthetic genomics. Adaptation or modification of photo bio-reactors for micro-scale bio-energy production and extraction of liquid fuel may not be a hurdle for an innovative team of chemical and mechanical engineers. Using the liquid fuel in generators to convert it to electricity may use off-the-shelf products in commercial use, even in the developing nations.

THE NUMBERS

In 2010, global energy consumption was about 1.5×10^{13} Watt (15 teraWatt) or 1×10^{21} Joules and 80-90% of the energy was derived from fossil fuels. 1 gallon of butanol releases 90% of the energy equivalent released from one gallon of gasoline (1.3×10^8 Joules per gallon of gasoline). If we do not exceed the current rate of consumption of about 2.2 kW per person per day (Japan and Germany average 6 kW per person while US is 11.4 kW per person; India uses 0.7 kW but neighboring Bangladesh has the lowest consumption with 0.2 kW per person per day) then a conservative estimate indicates that we may need 10^{13} gallons of butanol per year if it were the sole source of energy. If scalability enables a butanol plant to manufacture 1 million gallons per day it will be equivalent to about 10 million barrels of butanol per year (compare with crude oil production in excess of 30,000 million barrels per year). If 10,000 butanol plants works non-stop, it may help to maintain the average global energy consumption of 2.2 kW per person per day. With moderate penetration of electric vehicles over the next decades in India and China, there may be 300 million *more* automobiles demanding energy (1 vehicle for 10 individuals for a combined population of 3 billion in these two countries assuming a global population of 8 billion but more likely to approach 12 billion by 2050).

⁴ www.iitgn.ac.in/faculty/chemical/pub-gkalyan.pdf

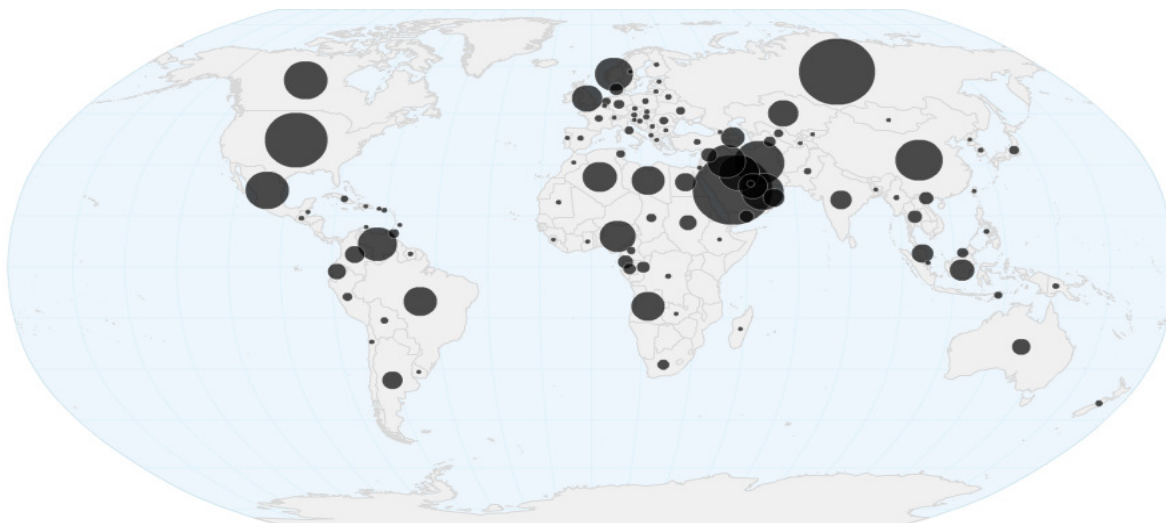


Illustration 3: Global Oil Production ⁵

RISK VS REWARDS

Investors are concerned about risks which are primarily one of scalability. The principle of photo-production of butanol by microorganisms is well documented. Successful scalability to levels indicated in the previous section may transform this vision from the lab bench to the reality of mass production necessary to satisfy the corporate vision of using butanol as an alternative and profitable commercial liquid fuel.

Risk managers deciding on this proposal must re-visit the legacy of recombinant human insulin which is now mass produced by bacterial fermentation. It started with one bacteria capable of synthesizing molecules of human insulin which offered hope to diabetics. The use of *Synechococcus elongatus* ⁶ or other microalgae for mass manufacture of butanol in photo bio-reactors ⁷ may follow and succeed along the same lines of using *E. coli* to mass produce human insulin, albeit on a scale far larger than the largest bioreactors for human insulin.

In our opinion, the risk is perceived and not real because micro-scale energy autonomy can be accomplished irrespective of the success of commercial scalability that (only) investors may demand to maximize their profitability and optimize return on investment (ROI). The lack of scalability to very large volumes from a single unit (1 million gallons/day) is certainly not necessary for an energy agnostic global economy practicing micro-scale energy autonomy. The reward from very low volume (1 liter per hour) butanol photo bioreactor operational at about 50% efficiency for 8 hours a day may yield 1 gallon of butanol which generates about 1×10^8 Joules. An average household of 4 may use 150 kWh/day in USA or 5 kWh per day in India and China. A domestic very low volume butanol photo bio-reactor (VLVC4PBR) appliance generating 1×10^8 Joules per day may offer sustainable domestic energy self-sufficiency in India and China (5 kWh = 1.8×10^7 Joules) while in the US an array of 5 such VLVC4PBR appliances per average household may suffice.

⁵ <http://chartsbin.com/view/yp7>

⁶ Shota, A., Higashide, W. and Liao, J.C. (2009) Direct photosynthetic recycling of carbon dioxide to isobutyraldehyde. *Nature Biotechnology* **27** 1177-1180

⁷ Kunjapur, A.M. and Eldridge, R.B. (2010) Photobioreactor Design for Commercial Biofuel Production from Microalgae. *Ind. Eng. Chem. Res.* **49** 3516-3526

WIN-WIN SCENARIO

Our key assumption is the presence of sun light for production of butanol by photosynthetic microorganisms. But, large areas in the industrial world are without sufficient solar energy (low insolation zones) and sun light is not always available in the manner that may be required for the operation of VLVC4PBR.

There is an alternative which is a win-win scenario. It promises to be an economic revitalizer for the tropics and create new lines of commodities business for the energy supply chain. In addition to butanol, the solution is to produce glucose⁸ from photosynthetic microorganisms in countries with high insolation (solar energy).

Several methods⁹ are currently used to produce butanol, ethanol and pentanol from metabolic engineering of bacteria without the need for sun light as long as they are provided with a source of glucose as the primary raw material. Corn, sugarcane and other food sources as well as biomass (waste) are vegetation-dependent raw material that are currently used for production of mainly ethanol and potentially butanol from bacteria. Vegetation-dependence has caused much consternation and ignited the food versus fuel debate as the price of food continues to increase since food sources are used for manufacturing of high value molecules (ethanol).

Bio-technology similar to photo production of butanol can be used to produce glucose as the metabolic end product in cyano-bacteria assuming the availability of sun light. Therefore, zones with abundant sun light may manufacture butanol for domestic use and glucose as a cash crop for sale as an energy commodity to countries in low insolation zones with high demand for energy (for example, most of the EU). Industrial nations or corporations may lease high insolation real estate and set up glucose plants in the Sahara Desert or entrepreneurs in South America may use the Atacama Desert¹⁰ as a glucose factory. Packaging and transport of solid or semi-solid glucose is an easier and less expensive logistical operation than transfer of liquid fuel. Stockpiles of glucose with its long shelf-life offers much needed energy security.

BARRIERS TO SCALABILITY

The arguments, insistence and emphasis on micro-scale butanol production in VLVC4PBR may seem odd. One would rather wait for the success of scalability to create the next butanol behemoth. Scalability of biological systems is intrinsically different from mechanical or purely chemical systems. The reactants and products in an enzyme catalyzed metabolic pathway operating in a bacterial cell producing butanol is subject to many parameters some of which may not scale because the reactions are not always additive. Increasing the rate of a reaction to increase yield is not always a linear relationship. The secretion and accumulation of butanol in the culture (growth) medium and the toxicity of butanol as well as the threshold of tolerance of the organism to butanol are further complicating factors which will impact yield. Extraction of high value molecules, butanol [C₄H₉OH] or butyraldehyde [CH₃(CH₂)₂CHO], are chemical engineering milestones likely to affect efficiency. Photosynthetic processes require atmospheric carbon dioxide and sufficient energy from specific wavelengths in the sun light. Both may be limited in a high volume scenario.

⁸ Niederholtmeyer, H., *et al* (2010) Engineering Cyanobacteria to Synthesize and Export Hydrophilic Products. *Applied and Environmental Microbiology* **76**, 3462-3466

⁹ Zhang, K., Sawaya, M.R., Eisenberg, D.S. and Liao, J.C. (2008) Expanding metabolism for biosynthesis of nonnatural alcohols. *Proceedings of the National Academy of Sciences (USA)* www.pnas.org/cgi/doi/10.1073/pnas.0807157106

¹⁰ http://cosmos.ucdavis.edu/archives/2010/cluster2/LIU_Jonathan.pdf

Hence, optimizing the ratio of exposed surface area to volume of the photo bio-reactor will be a mechanical engineering innovation to maximize the capture of solar energy by the photosynthetic micro-organisms. Successfully re-engineering, adapting or innovating flat front photo bio-reactors will determine efficiency and production volume. These issues are not automatically solved for micro-scale energy production even if we have the correct strain and optimized it for metabolic engineering to produce butanol. We speculate that in the micro-scale approach these problems may be solved sooner than in the macro-scalability approach.

Investors agonizing over cost of scalability (per kilo Watt hour) may review the history of RAM and VCR. 1MB RAM in 1957 cost \$411 million. In 2010 it declined to 1 cent per 1MB RAM. The first VCR manufactured, by AMPEX in 1956, cost \$50,000.00 each. VCR production ceased in 2006 due to decline in price and profit.

TEMPORARY ADVANTAGES

Micro-energy self-sufficiency, therefore, is neither a virtual concept nor an experiment. It is possible, here and now. The road to success depends on leadership with a vision which empowers the **distribution of energy generation** rather than consolidating it in the hands of a few or restricting diffusion due to IP rights or restrictions. Hence, this is a call for visionary investors or organizations to fuel teams who can deliver the products aimed at **distributing** bio-energy **manufacturing** and help build capacity for energy autonomy.

Despite the global gains from liquid energy manufacturing, no matter how disruptive the IP-free distributed concept may seem at present these advantages are temporary and may cease to deliver value in 100 years or less. In addition to the known unknowns and the not-known unknowns, the following may also change or influence the nature of energy and the global economy:

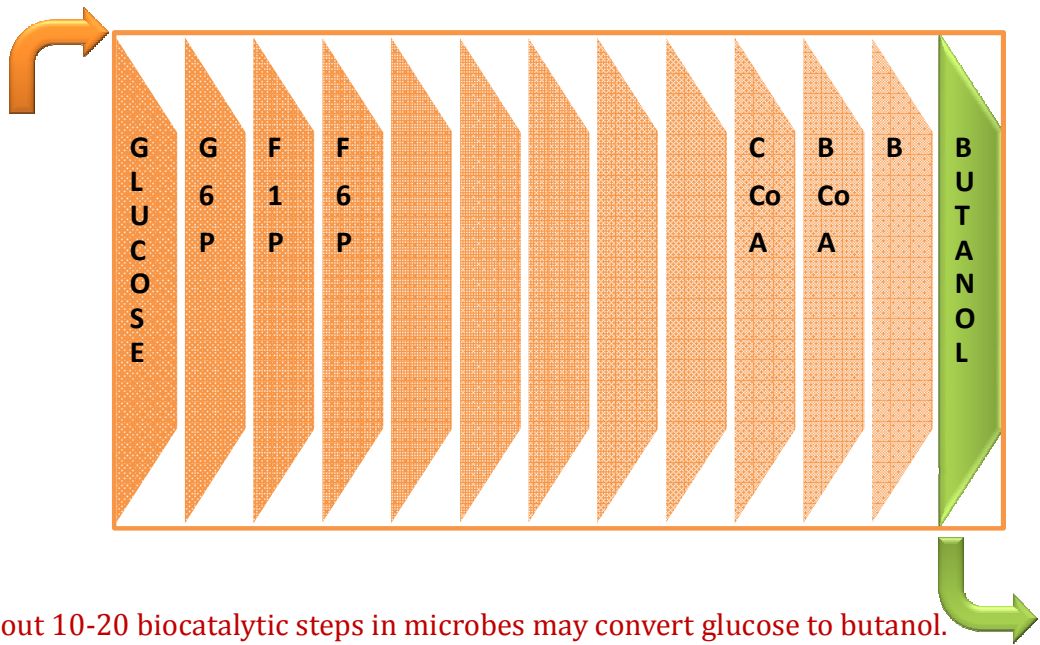
- ☑ Nate Lewis, Codexis, Joule Unlimited
- ☑ optimization of solar energy capture or use
- ☑ rapid and safe deployment of fission reactors
- ☑ commercialization of laser-ignited fusion reactors
- ☑ bio-inspired mechanisms (electron transport chain)
- ☑ nano-material battery power storage with non-zero perishability
- ☑ energy capture by photo-voltaic films to directly generate hydrogen
- ☑ reproduction of photosynthesis in vitro or on-a-chip with appreciable efficiencies

FUTURE RESEARCH

It may be possible to engineer or synthesize a genome (for example, *Mycoplasma genitalium*, a microbe which dwells in the human urinary tract and has the smallest genome of only 517 genes) with the array of genes necessary for photosynthesis of C4 or C5 or C6. The long term view includes photo-activated ¹¹ enzymatic bio-catalytic production of C4-C6 on nano-chip. In the near future enzyme immobilization may produce the hypothetical “butanol battery” (Illustration 4) which may produce butanol when supplied with glucose.

¹¹ Cardoso, M.B., Smolensky, D., Heller, W.T., Hong, K. and O'Neill, H. (2011) Supramolecular Assembly of Biohybrid Photoconversion Systems. *Energy and Environmental Science* **4** 181-188 DOI: 10.1039/C0EE00369G

Hypothetical Immobilized Enzymatic Catalysis of Glucose to Butanol Butanol Battery 2020



About 10-20 biocatalytic steps in microbes may convert glucose to butanol. These enzymes immobilized on substrates may form a multi-layer cube. If functional, the cascade may convert glucose (commodity) directly to butanol.

Illustration 4: Future of energy generation through convergence of nano-chemistry with bio-engineering.

CONCLUDING COMMENTS

Micro-scale energy autonomy is feasible and may segue to the energy agnostic global economy where growth will no longer find it necessary to depend on energy availability and price volatility. The semi-altruistic *modus operandi* suggested here to implement eAGE does not rely on existing patents or exclusive efforts currently underway. Cooperative or public investment may be a mechanism to lower the IP related barrier to market entry. Rapid dissemination of the science to improve society is preferred over the re-creation of behemoths or cartels which may control energy and hence economic growth. Distributed bio-energy manufacturing by developing photo bio-reactors to manufacture butanol (VLVC4PBR or LGEN¹² as mentioned elsewhere) and glucose (VLVC6PBR) is one solution for the energy portfolio. What we can accomplish with microscale energy manufacturing may be comparable to the transformational changes that followed when women gradually secured the right to vote in the 20th Century. Distributed micro-energy autonomy empowers global citizens to pursue development and economic freedom to build a better civilization. Indeed, the grass may be greener on the other side, in the eAGE.

¹² Datta, S., Lyu, J.J. and Jen, H-C. (2011) Bio-Inspired Energy Future: Quest for Efficient Intelligent Mitochondria and New Liquid Fuels. *International Journal of Electronic Business Management* 9 1-10