BIO-INSPIRED ENERGY FUTURE: QUEST FOR EFFICIENT INTELLIGENT MITOCHONDRIA AND NEW LIQUID FUELS

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ABSTRACT

Energy policies based on empirical assumptions without a foundation in granular real-time data may be limited in scope. It may sputter ineffectively in its role as the engine of energy economics. For energy efficiency and conservation, it is increasingly necessary to invest in systems, tools and practices that can facilitate bi- or multi- directional flow of energy to control homeostasis or balance consumption in order to reduce the carbon footprint. The central dogma of an energy oligopoly and uni-directional distribution through the electricity grid is poised for a radical overhaul. An "internet" of electricity capable of executing differential distribution strategies from capacity generated by micro-supplier networks and conventional electricity producers may evolve from the proposed Smart Grid. The future intelligent Grid (inGrid) is imminent although it may be neither adequate nor sufficient to address the root cause. Development of methodologies using technologies based on rigorous scientific standards must be coupled with effective dissemination of tools and adopted by consumers who will allow the acquisition of granular real-time data to enable feedback decision support for resource optimization. Automation driven by intelligent decision systems is key to efficiency. We advocate a partial mimicry of the natural physiology of energy dynamics and call for the emergence of a mechanical mitochondria and convergence of innovation through service science. It may be an amorphous nexus of engineering and management with the needs of society, industry and government. Higher levels of decision support, necessary both for strategists and engineers may be impotent or without global impact if we fail to promote diffusion of a grass-roots approach to seed one or more methodologies necessary to acquire data from a critical mass of users (in each environmental category from each major geography). Intelligent Energy Transparency (iET) should evolve to provide decision makers a secure mobile dashboard for real-time multi-directional equilibrium. The latter calls for an exploration of the root cause. Hence, the quest for new carbon-neutral energy sources including liquid fuels in the post-2050 era.

Keywords: Intelligent Grid, Mitochondria, Energy Efficiency, Metabolic Engineering, Dynamic Pricing, Glucose-on-a-Chip

1. INTRODUCTION

1.1 Background

Climate change is a global phenomenon with profound local impact. However, the relatively slow rate of climate change in combination with the nature of factors responsible for the problem, in part, makes it difficult for managers to invest their limited resources to implement the technologies necessary to address environmental responsibility. In addition, due to the magnitude of the energy demand, the issues

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germane to greenhouse gases shall remain in the forefront of public discourse for another quarter century unless we stumble upon a transformational innovation or acquiesce to immediately profit from an abundance of electricity from nuclear fission [45]. The latter may not address all the issues but allows enough time to productize sources of energy that offers a low risk profile with better GHG emissions control. Before we arrive at the post-2050 fossil fuel free era, at least for the next few decades, therefore, it may be prudent to focus on how to optimize the use of available forms of energy to reduce green house gases (GHG) through:

(1) Conservation or waste reduction
(2) Improving efficiency (device, infrastructure and user behavior) to decrease consumption

Investment is key to adopt these measures. Return on investment is expected from:

(1) Aggregated micro-savings from decreased usage
(2) Carbon credits for reduction in carbon footprint
(3) Global certifications for sustainable efforts

1.2 Motivation

Policies to drive the mechanisms necessary to accomplish the tasks outlined above are proceeding at global organizations. Committees and task forces are framing the structure of the infrastructure to be embedded in auditing tools to mandate elements of efficiency. Carbon calculators are part of a variety of decision making platforms [40]. Tools and simulation are necessary and are evolving to accommodate local regulations.

Various forms and degrees of legislation [35] are making their way through governments either to mandate or guide emissions. The impact of regulation will extract a price which will influence cost of goods and services [13]. Science and engineering advances necessary to mitigate climate change will usher in a convergence of innovation along with a merger of service science and business management.

Figure 1: inGrid and the idea of MITOCHONDRIA

The internet was a catalyst in the information and communication revolution. Although embryonic, evolution in climate control strategy may find part of its solution in the "internet of electricity" through the intelligent grid, inGrid [23] and the future mechanical mitochondria, a hypothetical concept (Figure 1).

1.3 Evolution of the Mechanical Mitochondria

The concept of mitochondria is borrowed from the physiology and cellular energy metabolism. The model of sources and sinks of energy in the human system which optimizes the homeostatic control may aid the design of energy supply and demand.

Mitochondria is a data driven cellular organelle that regulates the formation of energy in the form of ATP (adenosine triphosphate) in response to signals (data). The signals (data) are influenced by glucose, the molecule which is key to the manufacture of any liquid fuel or bio-fuels.

By extrapolation, can data (signal) from energy measurements catalyze resource optimization and efficiency? Are economic incentives sufficient to induce prudent energy to accumulate carbon credits? Entrepreneurial environmental e-businesses may set up carbon trading options or use carbon micro-credits to offset carbon footprint but will it be profitable? Can domestic users generate energy and profit from auctioning excess capacity (electricity) on an eBay type web-service? If feasible, it may contribute to the global deal [22] to reduce GHG emissions.

Micro-generation of electricity, micro-sales and distribution via inGrid may have positive economic consequences for some rural regions and eventually, for some remote parts of the world. Rural economic revitalization commences with investment to generate energy by harvesting unused resources (wind, solar, bio-fuels) and waste [47]. Non-fossil energy from rural sources may power air conditioners in urban zones if waste-lands can grow oil weed (*Jatropha curcas*) or sell manufactured power over inGrid. The bio-inspired approach may use principles from dynamic homeostatic models in nature. Data driven signal-mediated regulation requires the mechanical mitochondria to evolve as a regulatory hub which may sense usage, forecast demand, balance priorities, determine key patterns over time, exercise intelligent control, optimize feedback efficiency and respond to emergencies.

1.4 Achieving Energy Efficiency

To focus on energy efficiency and conservation to reduce GHG emissions and carbon footprint, it is necessary to acquire high volume granular data from monitoring consumption using WSN (wireless sensor networks). Data must be auditable and provide a basis for further decision making. Physical and financial facets of the entire energy supply-demand network must be viewed in a Game Theoretic [14] approach by assigning weights to local and global factors which may influence decisions, directly or indirectly.

The use of data to provide a service valuable to the consumer is the key. It is feasible to use proper tools to monitor and reduce energy usage. Translating the reduction in consumption to monetary savings is the incentive to invest in these tools. The generalized framework for this translational carbon savings is still emerging. Ad hoc methods, often proprietary and without verifiable data accuracy, feeding a cobbled framework, may be detrimental to energy efficiency. If we can acquire a critical mass of accurate granular data, then, the data-driven tools may save money and resulting policy constructs may stand the test of time. Enlightened policies in the national and global framework may offer insight into the magnitude of the crisis, dimensions of the ripple effect and better clues to long term sustainability rather than quick fix.

The energy sector is pursuing a plethora of worthy efforts to create decision making software but the granularity of data, in some cases, is still poor or based on default assumptions or old standard models. Tools and technologies to acquire granular data and analytics to extract meaningful associations for improved decision support are necessary. Systemic methodologies that can accelerate and catalyze the widespread systems integration and dissemination of these tools in the hands of users, in high volume, are required. The volatile energy market projects Carbon as the largest financial business commodity by 2020. Principles of operations management suggest that volatility between operational stages may be due to information asymmetry [14]. If iET matures, it will call for data acquisition and sharing. iET may reduce volatility by serving as a systems integration platform for tools, analytics and data as a driver for carbon trading and reduction of global GHG.

One goal of this paper is to forward the concept that enlightened energy policy and carbon efficiency related decision support may require country-specific granular data. This lofty goal is theoretical, at best. It is entirely dependent on adoption of technologies to acquire the basic layer of granular data. Hence, the key assumptions in this article are:

(1) The market will steer manufacturers, suppliers, system integrators, consumers and regulators to work together to improve energy efficiency by deploying innovative technology such as stick-on sensors that can form ad hoc mesh networks and upload data through an authorized gateway node.
(2) Oversight from global organizations (UNFCCC, IPCC) to create frameworks and methodologies through convergence of multiple technologies to improve energy efficiency and tangible savings.

2. INTELLIGENT ENERGY TRANSPARENCY (iET) CONCEPT

The idea that the hypothetical mitochondria may manage energy through the conceptual iET originates from Homeostatic Utility Control (HUC) [39]. Such products exist today in building energy management systems [24] but the tools are device specific with only local control. It is inadequate for overall energy efficiency. HUC and the conceptual Energy Box [27] together with iET is a prelude to the hypothetical concept of mitochondria (Figure 2).

iET is expected to offer dynamic control using local device-specific real-time sensor data to generate "global" optimization, for example, savings across an enterprise. iET will fall short of its potential unless its architecture allows for future integration with inGrid (Figures 1 and 2). Existing products are sophisticated but address limited number of issues. iET calls for very low cost per node (printed wireless sensors) and systems software that can rapidly adapt to market demands when the Smart Grid or inGrid operates.

To be financially viable, iET must offer tangible return. It must be immediately useful to help generate monetary savings for investors in energy efficiency projects and respond to systemic demand volatility through ad hoc curtailment measures in near-real time for utility corporations and local energy regulators.

Figure 2: MITOCHONDRIA may use data from wireless sensors with IPv6 addressing to interface directly with the Smart Grid and the future inGrid

3. CARBON SUPPLY CHAINS

Intelligent energy transparency is expected to be accessible via web services including tools such as:

(1) Savings Optimization
(2) Carbon Footprint Audit
(3) Power Saving Automation
(4) Differential Dynamic Pricing
(5) Energy Risk Portfolio Management
(6) inGrid operating service (e.g. Globus)
(7) MITOCHONDRIA (upgrades and versions)

One component of iET is pricing, specifically, dynamic pricing. Application of operations research has demonstrated that volatility of demand is reduced by an EDLP (every day low price) strategy [7]. EDLP is in contrast to practices to attract customers using promotions and discounts using variable pricing or price based on demand, inventory, shelf-life, seasonal trends or brand marketing. The electricity market uses a constant price per kilowatt-hour that rarely changes and is not reflective of EDLP. Without any incentive to conserve, the usage patterns of consumers may remain unaffected which leads to peak periods of consumption which the energy provider is mandated to serve. Peaks and valleys mandate the need to build excess capacity to meet peak demand. Thus, excess electricity generation capacity is under-utilized for several hours each day. An electricity quota at a base price in combination with dynamic pricing (higher rate for increasing demand) may offer incentives to be efficient. Aggregated energy efficiency can reduce peak load and providers need not build capacity continuously in order to meet projected peak demand.

It is estimated that a less variable electricity demand pattern may save the US about $100 billion and a diminished need to expand capacity over the next quarter century [3]. Enabling technologies at hand can improve energy efficiency by automating the response of the consumers to dynamic pricing to substantiate the savings. Data from wireless sensor network (WSN) monitoring systems [6] integrated with savings optimization and using the proposed iET can deliver energy savings. The decision support tool may not be manually controlled or fixed at pre-set levels irrespective of other independent variables, for example, weather. There is a need for an iterative process to perform dynamic optimization and resets, perhaps every few minutes, if necessary, depending on intelligent analysis of factors and fluctuations but without compromising the service expectation, for example, human comfort inside an airport lounge.

To extract sustainable value from the future inGrid, the diffusion of iET tools and its adoption by consumers must be accelerated to create an enabled informed society [19] that can benefit from the hypothetical mitochondria. Combination of dynamic pricing with storage and distribution via inGrid (Figure 1) may spur buying and storage of electricity from providers at a low off-peak cost and re-selling stored power at peak demand. Weather permitting, the rooftop solar panel or wind turbine in the backyard may add to the portfolio and decrease demand on the grid [20]. If the grid response time is in hours, then it limits the system because weather (wind) may not be predictable several hours in advance.

Dynamic in-the-grid analytics may use cloud computing [5] (Figure 2) to deliver business services made possible through iET. Re-routing the flow of electrons (electricity) to specific addresses mimics the principles of DNS used by the internet protocol. It will benefit from an increased number of unique addressing capability made possible by IP version 6 [11]. IPv6 catalyses the possibility that individual or an aggregate of wireless sensors can directly upload data to the internet [11]. It was previously unavailable due to limitation of unique addresses in IPv4. By combining application layers and converging various data layers (WiFi, ZigBee) (Figure 2) the analytical iET engine optimizes usage. Distributing intelligence both at the edge and core is possible with deployment of vast number of wireless sensors and nodes directly connected via TCP/IP. Ultra-low power pico-radios [38] and low power networks (6LoWPAN) enable seamless routing of data from edge to core for bi-directional control of individual wireless sensors.

4. FRAMEWORK FOR iET

Integrating a plethora of independent variables in a repetitive and sequential decision tree may use variations of stochastic dynamic programming (SDP) for most optimization needs [2]. Decisions will take into account the stages, states, transitions, policies and forecasts or conditions prevailing at the time. Approximation or accuracy of SDP will depend on or may be limited by dimensionality or state-space. In simulating or controlling a device, the input value of some of the independent variables may be selected from a distribution or to simplify, discrete values may be used. Classical linear regression modeling may suffice for some types of time-varying forecasts but other situations may benefit from application of autoregressive moving average or other advanced econometric techniques (Figure 3 and 4) [15] used in forecasting.

The value of an iET engine relies on the ability to be modular and host a variety of algorithms that may serve general as well as specific functions which vary between verticals (industry, hotels, hospitals, domestic, public and commercial). iET may be best served by a intelligent differential decisioning engine. Building intelligence using learning algorithms based on the principles of artificial neural networks (ANN) may be worthwhile. Over time it may evolve to an 'intelligent' mitochondrial decision support.

For data driven energy efficiency and savings, the following criteria may be applicable in context of assets in logistics, transport and supply chain issues:

(1) Audit : Energy Usage
- Accuracy and types of data
- Data collection, analysis and integration
- Efficiency of carbon footprint algorithm
- Savings optimization vs energy efficiency

(2) Objectives : Carbon Savings
- Calculate and compare carbon footprint
- Control automation for energy savings
- Optimize carbon credits for business units
- Reduce carbon emissions
- Increase carbon trading opportunities
- Value-add over existing technologies

(3) Parameters: Carbon Footprint
- Fuel: fossil, renewable, carbon-neutral
- Consumption in kilo-watt-hours per unit area
- Location, weather, volatility and uncertainty
- GHG emitted (tonne per kwh) vs energy cost
- Calculate carbon credits (barrels of oil saved)

(4) Recommendation : Decision Automation
- Actions to reduce transaction cost (TCE)
- Offer choices of materials, materials origin, manufacturing process
- Compare dynamic pricing, energy use and carbon status with sector specific practices

$$y_{1t} = \beta_0 + \sum_{k=1}^{K} \sum_{i=1}^{N_{X_{kt}}} \alpha_{ki} X_{kt-i} + \varphi_{11} y_{1t-1} + \varphi_{12} y_{2t-1} + \varepsilon_{1t}$$

$$y_{2t} = \beta_0 + \sum_{k=1}^{K} \sum_{i=1}^{N_{X_{kt}}} \alpha_{ki} X_{kt-i} + \varphi_{21} y_{1t-1} + \varphi_{22} y_{2t-1} + \varepsilon_{2t}$$

$$\sigma_{1t^2} = \theta_0 + \sum_{i=1}^{q} \theta_i \varepsilon^2{}_{1t-i} + \sum_{j=1}^{p} \tau_j \sigma^2{}_{1t-j}$$

$$\sigma_{2t^2} = \theta_0 + \sum_{i=1}^{q} \theta_i \varepsilon^2{}_{2t-i} + \sum_{j=1}^{p} \tau_j \sigma^2{}_{2t-j}$$

Figure 3: Analytical Models (Datta and Granger)

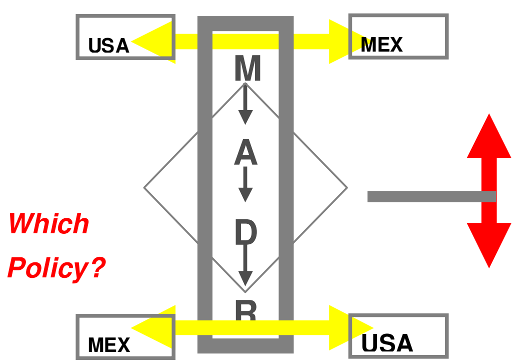

Figure 4: Analysis and Policy reflects "different strokes for different folks"

5. APPLICATION OF iET

Diffusion of iET, inGrid and the concept of hypothetical mitochondria may enable institutions or business leaders to seek appropriate combinatorial solutions. Every CEO and heads of agencies must get acquainted with demand response and tools necessary to implement and evaluate energy savings as well as carbon trading options. iET shall provide decision makers a secure mobile dashboard to deal with near real-time carbon footprint reduction, energy savings and trading (as an asset or a liability). Based on the granularity of data, iET can be used in a hierarchical manner businesses, municipality, city, state, country (Figure 5). In some countries, legislation exists to address the issue of energy risk management. US Congress approved the Sarbanes-Oxley Act (SOX) in 2002 [9] which require businesses to assess types of risk that may be associated with its operation (SOX 409). This "risk" may now extend to include energy or carbon footprint. A form of clearance that may be required in the future may be based on the format of CDM (Clean Development Mechanism, UNFCCC). The importance of carbon footprint was magnified by the introduction of the "polluter pays" principal in the form of financial costs for generating carbon dioxide. GHG emissions, thus, emerges as a financial liability. CFO's must implement measures or strategies to limit these costs. Comprehensive energy usage audit may enable carbon liabilities to be balanced against reduced energy usage by improving efficiency of use.

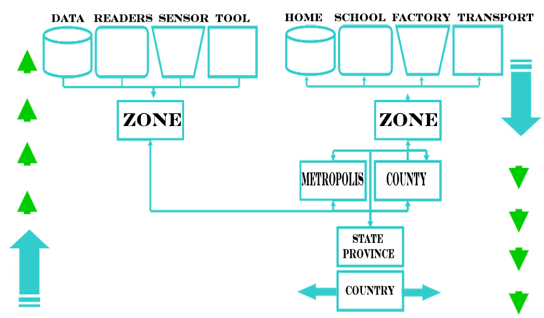

Figure 5: Flow of granular data, aggregated by operational hierarchy, may improve power systems management and emergency response planning[26]

Rewards for saving energy may be a marketing asset as well as a financial incentive. Carbon credits have been trading on the market for about US$30. One credit allows the owner to release 1 ton of carbon dioxide. The value of the carbon credits is predicted to soar. The City of London predicts that current sales of £30 billion may exceed £1 trillion by 2020 [21]. Many governments are keen to increase revenue and carbon tax is no longer a novel idea but represents a lucrative resource in the current recession to help resuscitate national treasuries. However, carbon tax may be a long term economic baggage rather than a solution. Controlling climate change via enabling technologies may be better received, globally.

Bi-directional secure wireless sensor (Figure 6) data communication is key to the "sense and respond" triggers necessary to execute effective secure control. Use of WSN to monitor energy usage and optimize energy efficiency through control (Figure 7) is one component in a portfolio of technologies that may drive the development of iET. Except for purposes of audit from a supply side, the data from monitoring energy usage is almost worthless to improve energy efficiency unless accompanied by control automation to reduce consumption without compromising the function, for example, optimum temperature in an enclosed space for human comfort. The granularity of continuous monitoring may not deliver any value unless the streaming data is able to fine tune the devices in order to optimize energy efficiency. The visualization of the data and controls must offer different "views" based on the user and factors that are of importance to users: housekeeper, building manager, financial controller, energy authority, power distributor, state regulator. The ability of the iET engine (for example, IDDE) to "learn" preferences of users and characteristics or patterns of energy usage is crucial for intelligent decision support. iET may integrate hardware-associated visualization software with an operational logic layer executing artificial neural network routines which continuously improve performance using learning algorithms in IDDE.

The strength of this granular approach for data acquisition and utilization is exemplified by the ability of a local or state electricity board to issue an online command to reduce consumption in buildings or premises using an iET type system integration. In this approach, systemic commands may be deployed with a short lag time (minutes) at multiple levels or hierarchies (Figure 5). The fact that this system can re-distribute power and reduce consumption on demand, may be an important tool for planning and designing, consumption prediction, power supply generation, power demand volatility and emergency or security options. Integrating successive layers of data in local, municipal, state and country models in the framework is necessary for development of policy and planning for the future. Global organizations can use this data to better design the tools and instruments to monitor and audit carbon emissions or credits. In reality, this approach will not materialise simply by pontificating its value. It may require the following:

(1) Transparency of aggregated consumption data
(2) Granular data acquisition tools are used
(3) Investment necessary for adoption of tools will depend on incentives rather than goodwill
(4) Adopters seeking return on investment will seek monetary savings from reduced energy charges
(5) Standards necessary for secure installation and rapid "go live" execution
(6) Modeling tools and technologies to profit from emissions trading as they evolve [10,28,4].

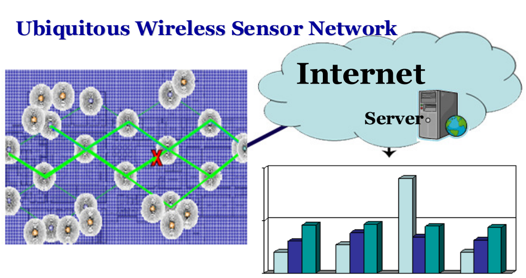

Figure 6: Two way wireless sensor network (WSN)

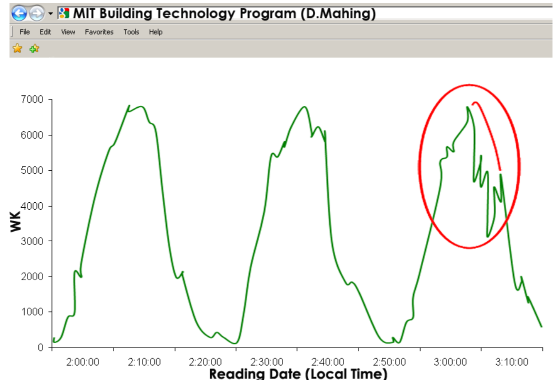

Figure 7: Energy usage data shows aggregated consumption and automation to reduce consumption (optimized to decrease demand by pre-set amount)

6. BIO-INSPIRED LIQUID FUELS

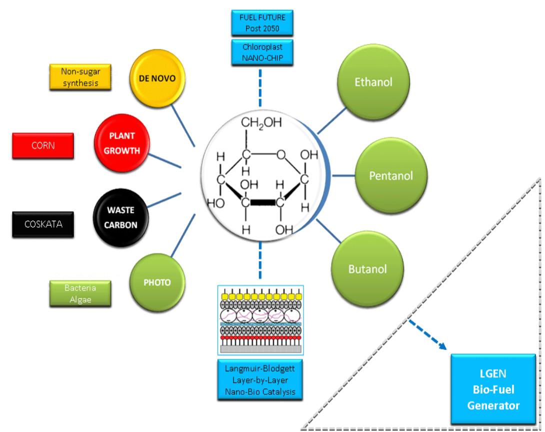

Figure 8: By 2050, energy demand will create new business services and products, for example, LGEN.

Most of the suggestions in this article, thus far, depend on innovation in conservation and efficiency. The future calls for exploration of sources of energy which will present new lines of business hitherto unknown. We propose that manufacturing of glucose and its trade as a commodity may assume an even greater significance than carbon trade [13].

It remains to be seen how glucose (Figure 8) may influence energy related inventions and process innovations. Post-2050, energy from nuclear fission and fusion may predominate the structured delivery of grid-based power to immobile assets. But, liquid fuel demand may catapult glucose manufacturing as a robust and lucrative new line of business for small and medium enterprises in the liquid energy supply chain for mobile assets and emergency response systems. It will create new services and products, for example, LGEN (see section 8). The future role of glucose in commodities trading in the value network of carbon remains unchartered. To avoid the food vs fuel debate [29] it is wise to use gas directly [30] or indirectly [36] or manufacture glucose *de novo* [43] without using a “prior” form of glucose [42]. Using waste [47] is useful but the heterogeneity of waste may reduce efficiencies from economies of scale.

We have at hand the convergence of carbon from algae [31] or bacteria [32] to feed metabolically bio-engineered yeast [1] or bacteria [33] to secrete ethanol or butanol which can be extracted [34]. The scaling of this process holds immense potential.

The next scenario is in an amorphous nexus of invention and innovation with respect to synthetic chlorophyll [46]. Energy business and its geo-politics may be subject to disruptive innovation [8] if we can oscillate-on-demand the form factor of solar energy. Solar energy is either (1) directed to heat water and let the steam run a turbine to generate electricity or, (2) produces electricity directly using photovoltaic cells. In either form, the electricity generated must be transmitted (as much as 60% loss of energy during transmission) or used rapidly to prevent degradation since storage is still inefficient. This “physical” form of energy is at the heart of the issue of energy waste due to its perishability factor. From an energy supply chain perspective, the problem is similar to the shelf-life of fresh bananas in the produce section of the grocery store. Therefore, changing the “form” or “state” of energy may help storage and transmission.

Engineering catalytic protein and lipid-protein layers to simulate choloroplast activity on wafers may create nano-machines to trap solar energy in chemical bonds and produce glucose-on-a-chip from carbon dioxide and water (nano-irrigation). Thin layer films and Langmuir-Blodgett method [41] may be useful for production of such nano-chips [44]. Wafers containing trillions and trillions of such nano-chips may replace solar-synchronized mirror stations. This mode of solar energy capture enables long term storage (as glucose) and facilitates transportation to bio-fuel generators (Figure 8). The form of energy captured from solar sources is thus converted from “use it or lose it” perishable state to “chemical” form in the chemical bonds of glucose. The conversion is essential for the global energy supply chain logistics.

Vast expanses of deserts (Libya, Somalia) may become glucose factories. Manufacturing glucose as a commodity or cash crop is likely to fuel economic growth and may even partially alleviate some of the economic woes of nations in the Equatorial belt.

Convergence of knowledge from the principles of transcriptional regulation in biology [17] and medicine [16] is enabling metabolic engineering in yeast [25] and microorganisms [37] to unleash the vast potential of manufacturing non-fossil renewable liquid bio-fuel. Fusion-fission (FuFi) [12] and the hydrogen economy may not eliminate the need for liquid fuel in the post-2050 era when what could be left from the halcyon days of petroleum may be found only at the bottom of the barrel.

7. CONCLUSION

We propose an intelligent Energy Transparency model and a bio-inspired hypothetical mechanical mitochondria to optimize energy efficiency. iET seeks learning algorithms to build intelligence in order to pursue carbon-based savings. Unlike inGrid and its long term impact, an intelligent Energy Transparency (iET) portal may yield value within a short term. Profits from energy efficiency may not materialize without implementing the tools. Without quantitative analysis, policy provides poor guidance. With the help of analytics, policy issues may be formalized and aid the development of future intelligent systems. Development of data driven decision criteria and tools to interface with inGrid may in turn influence the evolution of the mitochondria. Building artificial neural networks (ANN) based tools may empower iET mediated pattern analysis for decision support.

Non-vegetation related manufacture of glucose may emerge as a lucrative future line of business with further advances in metabolic engineering [18]. Nano chloroplast aided glucose-on-a-chip production may change the physical state of electricity from solar energy to the chemical state (chemical bonds). It may enable storage and transmission with minimal loss. This bio-inspired in vitro photosynthetic nano-chip may emerge as a disruptive innovation in solar energy capture and distribution. Hence, glucose, in some form or the other, may be essential as a carbon source for metabolically bio-engineered bacteria to produce non-fossil renewable liquid fuel for the future as we approach the fossil fuel depleted post-2050 era.

8. EPILOGUE

Approaching 2050, with a global population of about 12 billion, it is easy to predict that new forms of supply chain management paradigms will emerge. The distribution of grid-based electricity will undergo changes and may even allow bi-directional flow. But, individuals may not invest the capital necessary for self-reliance using alternative green fuels and the programs may not make economic sense. However, small or medium businesses may develop innovative fuel related products and business services which may be used in addition to grid-based electricity. We predict at least one such supply chain to include the potential development of nano-scaffolds with embedded photosynthetic cores for producing glucose-on-a-chip using sunlight and atmospheric carbon dioxide. It may evolve as an economic revitalizer for Africa, where energy supply and demand are skewed. In the post-2050 scenario, synthetic glucose may fuel metabolically engineered microorganisms to secrete extractable liquid fuel rather than scavenging for complex waste as the source of carbon. Layered deposition or embedded enzyme active centers on immobile surfaces may produce chips which may be manufactured in high volume for glucose synthesis in solar friendly environments. Linked to an efficient microbial fermentor, the glucose may be converted to produce bio-fuel. Alternatively, glucose (paste or gel) can be added as the carbon source to the fermentor. Hence, transforming to reality, albeit in part, one vision of renewable energy from liquid bio-fuel generators (LGEN). By the middle of this century, one may find a miniaturized LGEN as a standard fixture in the garage or utility room or in the kitchen of the future alongside other LG, GE or Tatung home appliances.

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