Systems Analysis and Recommendations for R&D and Accelerated Deployment of Solar Energy

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Executive Summary/Abstract

A Systems Analysis for the solar energy industry and solar R&D is presented to identify key positive reinforcements that can accelerate the adoption of solar technologies through a process of *solar value creation*. Such an analysis can also identify constraints that can decelerate solar technology adoption, as well as points of leverage where investment and R&D can have the most positive impact. The approach can also be useful for explaining solar energy to a wide range of decision makers and to the public. It emphasizes two major, related challenges in achieving widespread, rapid adoption of solar energy technologies in time to have a significant impact on global energy and environmental problems. The first concerns integration of solar-generated electricity with the electric grid and this is facilitated by a “Smart Grid” infrastructure. The second challenge involves the means to continue to drive down manufacturing and deployment costs for solar energy systems and to expand manufacturing capability in order to accelerate deployment of solar energy systems. This is closely tied to market supply chain transformation that considers each step in the technology’s manufacturing and installation. The Systems Analysis suggests that there are three high leverage points: research on Solar Energy Grid Integration Systems (SEGIS), Systems Dynamics Modeling, and a Solar Industry Supply Chain Consortium. Although such an analysis is now widely accepted in the telecommunications industry, it has yet to be applied to the solar industry until now.

Introduction

To more rapidly reach its full potential in terms of job creation and power production, as well as economic and environmental benefits, the fledgling Solar Energy Industry must consider *solar value creation* on a global scale. Although there are several definitions of economic value, we shall utilize the idea that the value of an object or condition is the perceived benefit to well-being or happiness associated with its creation, consumption or use. Table 1 shows *value migration* as civilization has advanced through the ages. Value migrates from outmoded economic models to designs that are better able to satisfy a society’s changing priorities and perceptions of its needs. Many believe that we are migrating towards a Sustainable Energy/Information Intensity era with characteristics that are outlined in the table. The transition will present us with significant new market opportunities as well as challenges. For example, our current infrastructure for transmitting electricity (the Grid) is designed to supply energy to a distributed set of recipients from large central power plants, which was adequate when society’s main perception of the value of electricity was focused on its use in new appliances and applications.

In the Sustainable Energy/Information Intensity era, a *Smart Grid* will transmit and distribute electricity in many directions, allowing customers to supply renewable energy to their utility, or to other locations where it has its highest value. This will allow the system to respond to new consumer priorities that barely existed in the first years of electricity generation. Examples may include:

- the value of reducing an individual's carbon and pollution footprint by having greater control over their energy supplies;
- more knowledge and control over how one spends money on energy;
- differentiating the quality and reliability of power one wants and being able to acquire it through the energy system in return for either higher rates, with more quality and reliability, or lower rates, with less quality and reliability.

The term *Smart Grid* is often used, but not always adequately explained. A full discussion of it is beyond the scope and intent of this paper and is confounded by the fact that it is only just being envisioned. It is clear, however, that it is more than just the use of *Smart Meters* or the inclusion of *net metering*. In short, a fully functioning Smart Grid will feature sensors throughout the electricity transmission and distribution grid to collect data so that real-time, two-way communications will move that data and electricity between utilities and consumers. When fully developed, the Smart Grid will enable informed participation by customers, accommodate all generation and storage options, enable new products, services and markets and provide the power quality for a range of needs. It will optimize the efficient utilization of all energy sources while operating resiliently by handling many disturbances in the grid automatically. To accomplish this, embedded, low-cost computing power is necessary for both power sources and consumer applications to allow for efficient generation and transmission at lower overall costs.

Some descriptive terms being used for the future Grid include: self-configuring, self-healing, and smarter. These are biological terms, suggesting that we are shifting from a machine-like linear economy to a web-like economy. The new infrastructure will change and evolve in ways similar to natural biological and ecological systems. Like natural systems, information and energy systems will possess emergent properties that we have yet to comprehend. Some factors that have been used to describe the driving forces behind the transition include: costs, capital competition/cooperation, China, consumers, climate/carrying capacity and convergence. The latter term represents an increase in, and ubiquity of, computing power. Clearly, a framework and tool is needed for understanding the transition to a Sustainable Energy/Information Intensity economy and assessing the opportunities and resources required for the complex, inter-related bottlenecks facing the solar industry.

Table 1. Value migration through the various eras (ages) of human economic development. Drivers are inputs, resources or commodities that are available to allow that phase of economic development to occur. Indicators are measures that the society values as a proxy for well-being.

Economy	Economic Drivers	Infrastructure	Economic Indicators	Environmental Protection
Agrarian (before 1800)	Land and Crops	Dirt roads and couriers on horseback	Commodity prices	No
Industrial Revolution (1760-1900)	Cheap steel, coal, textiles	Railroads, shipping, telegraph, steam engine	Coal and pig iron production, cotton consumption, railroad operating income	No
Mass Production (after 1900)	Cheap energy, especially oil	Highways, airports, telephones, broadcasting, electric power grid	Retail sales, auto sales, housing starts, industrial production, capacity utilization, Gross Domestic Product	Command and control, development of State and Federal regulations
Technology/ Information (after 1980)	Ever-cheaper semiconductors and photonics, R&D programs, rapid technology change, software, direct electronic access to knowledge	Satellites, fiber optics, networks, wireless, distributed power, Worldwide web/the Internet	Book to bill ratio, computer sales, deflation in high tech prices, high tech trade balance, employment in knowledge intensive industries, Gross Domestic Product	Pollution prevention, industrial ecology, international standards and agreements
Sustainable Energy/ Information Intensity Era (after 2010) Convergence of Electric Power and Information Technology	Global energy and information networks, large economies of scale for renewable energy, ubiquitous embedded low-cost computing power and monitoring	Smart Grid/Energy, internet, renewable energy, smart residential and commercial buildings for electricity generation and storage, smart electric vehicles for transportation and electricity generation and storage	Measurements of global electrification, global population stabilization, employment in clean energy technologies, Global Warming Potential (GWP), energy intensity, CO_2 emitted per unit of economic activity	Sustainable, market-based and integrated approaches that foster incentives, innovation and consider carrying capacity and rates of growth

Luckily, such a framework exists and has proven itself in other high-technology industries. It is based on *Systems Analysis* or *Systems Thinking*, which leads us to a process for estimating or inferring how local policies, actions, or changes influence the state of other parts of a system. A system is a group of interacting, interrelated, and interdependent components that form a complex and unified whole. Systems include R&D departments in organizations, or the circulatory system in your body. Examples of Systems Analysis are numerous in Supply Chain Design, Program Management, and in Biology and Ecology. Systems Thinking shows how events that are separated in distance and time can interact, how the rules of the system drive its behavior and how small things can cause large changes in complex systems. One goal of Systems Thinking is identifying "leverage," that is, seeing where actions and changes lead to sustainable improvement. This approach was applied successfully in the telecommunications industry by Alcatel-Lucent and is now widely accepted in that industry. A graphical way to display such Systems Analysis includes the *Senge Diagram* and this is shown for the solar industry in Figure 1. This diagram and the application of Systems Analysis to both solar R&D and the solar industry are the central and novel aspects of this paper.

Figure 1a: Senge Diagram of a Systems-focused U.S. Solar Industry. SEIA is Solar Energy Industries Association. SEPA is Solar Electric Power Association. SEMI is Semiconductor Materials International. ASES is American Solar Energy Society. SEGIS is Solar Energy Grid Integration Systems. GAO is the Government Accountability Office. CRS is Congressional Research Service. DOE is the Department of Energy.

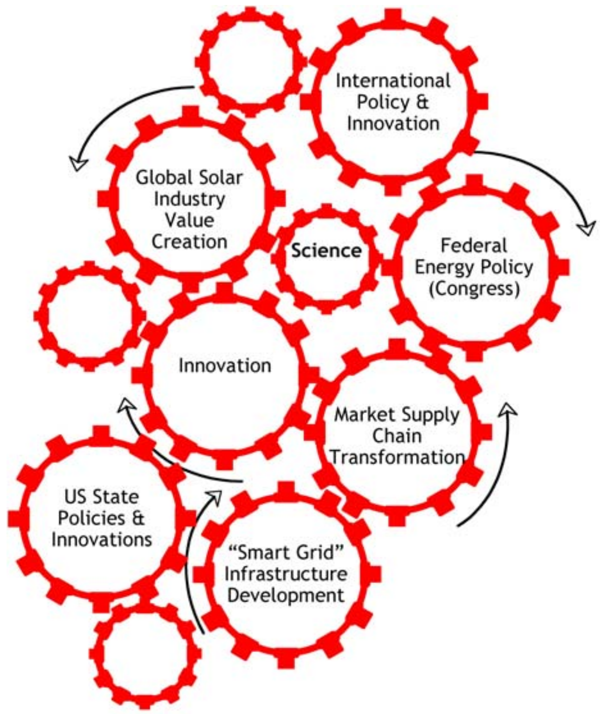

Figure 1b: Gear-based representation of Figure 1a applied to the international arena. Blanks represent unforeseen factors such as the U.S. Stimulus Package (ARRA), education and workforce development or the rise of LED-based solar lighting applications.

There are several interrelated cycles in the Senge diagram that influence one another like gears in a gearbox. These include: innovation supported by agencies such as the Department of Energy (DOE), Federal Policy, the Global Solar Industry and its target market. Feeding into these cycles are various types of analyses, investments and industry groups such as the Solar Energy Industries Association (SEIA), Solar Electric Power Association (SEPA), and the Semiconductor Equipment and Materials International (SEMI). Delays are represented by breaks in the cycle and these are places where leverage is most important to consider for removing (or minimizing) barriers and bottlenecks. If all the cycles are considered as a whole, the gears move faster and the solar industry can enter a "virtuous cycle" of lower cost, higher value, new technology and expanded markets. Viewing the solar industry from a Systems Perspective using a Senge diagram can yield useful insights and produce valuable recommendations. This is the goal of this paper. Rather than discuss the specific prospects, potential and promise of solar energy systems and technologies (for this, see the literature cited and bibliographic entries,) this paper will focus on Systems Thinking as a method for understanding and managing the development of these technologies so that they can live up to whatever potential that they can ultimately attain.

Challenges for Photovoltaics

Solar-generated power is seen as both a distributed resource (e.g. on buildings) and a large-scale central source deployed for (or by) utilities. Both have roles in the overall energy mix of a region or nation. There are two major challenges to the deployment of solar energy systems at large scales and on a schedule adequate to make a major impact on global energy and environmental problems: integration with the electric grid and innovation along the whole supply chain. Many utilities and developers argue that solar energy systems must compete with central station generation on the same terms as fossil fuels when it comes to dispatch, transmission and reliability. The intermittent nature of solar energy is often cited as a major obstacle.

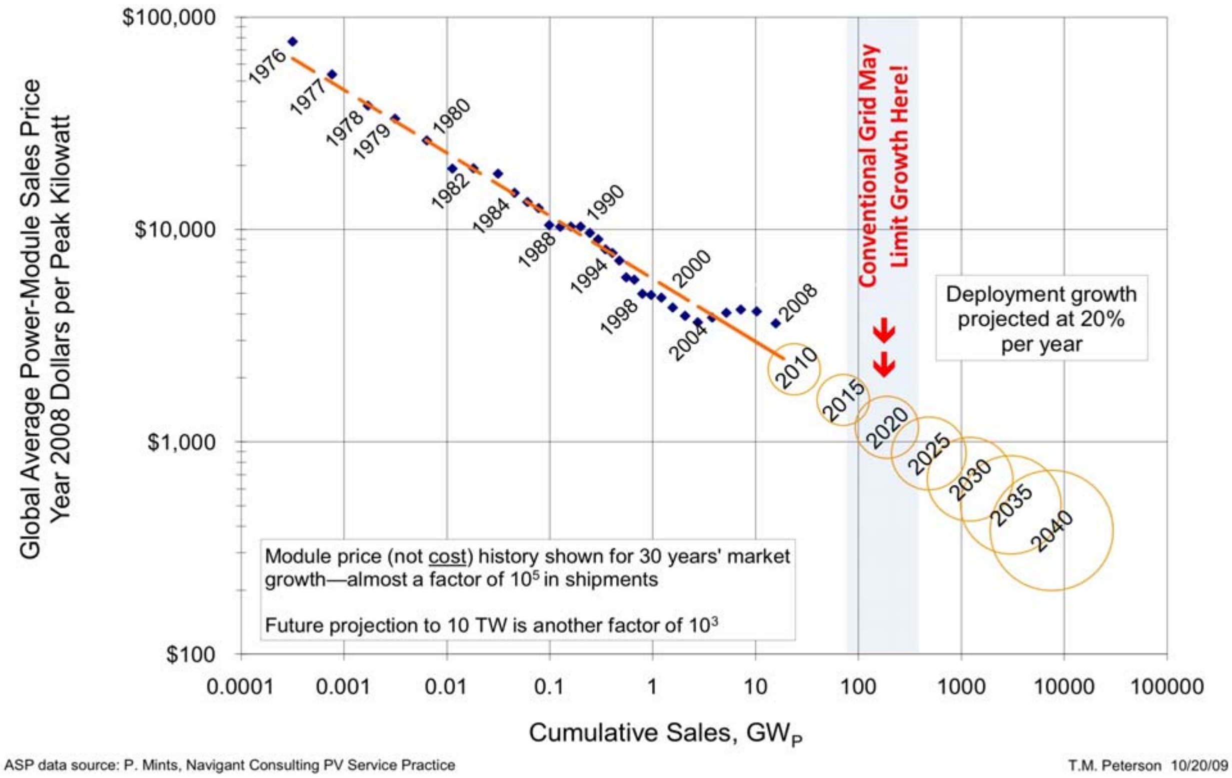

Figure 2: PV module price experience curve and a projected PV price scenario. The mnemonic for this plot is the number 20. That is, for each doubling of cumulative production, the average module price decreases by about 20% percent. For the projections at the right, similar to the long-term historic value of 20% per year is assumed. If these trends continue, silicon-based PV will reach costs comparable to the least-cost conventional options by about 2030. This will occur as PV grid penetration reaches approximately 20%.

Another challenge involves producing enough PV modules and bringing them together with mounts, wiring and power conditioning electronics (e.g. inverters) to make an impact on a nation’s energy generating capacity. PV modules are created by assembling many types of materials into an integrated package that must withstand long-term outdoor exposure. A PV supply chain is a system of companies, people, technologies, information and resources involved in moving a solar product and its energy output from its supplier to a customer. Supply chain activities transform natural resources, raw materials (such as glass, silicon or tellurium) and other components into a finished product that is delivered to the end customer. As the photovoltaic (PV) experience and growth curve shown in Figure 2 illustrates, PV module costs approximately equivalent to those of fossil fuels may not be very far in the future. Deviation from the historic trend during 2005-2007 is known to be due to a temporary shortage of purified silicon, coupled with installation incentives in Germany and Spain. This imbalance between supply and demand is resolved and this is borne out in preliminary data for 2009 from Navigant Consulting. Not shown in Figure 2 are the so-called *Balance of Systems* (BOS) costs, those that are other than the PV module costs, but are necessary to complete the installed PV system so that it can deliver energy to the consumer. PV systems have followed the trend of a 50:50 cost breakout between PV modules and BOS costs for nearly 30 years and there is no compelling evidence to suggest that this will change anytime soon. Also indicated in the figure is an estimate of the constraint on the penetration of solar-generated power from PV into the existing grid, which is not designed to manage large quantities of intermittent energy supplies.

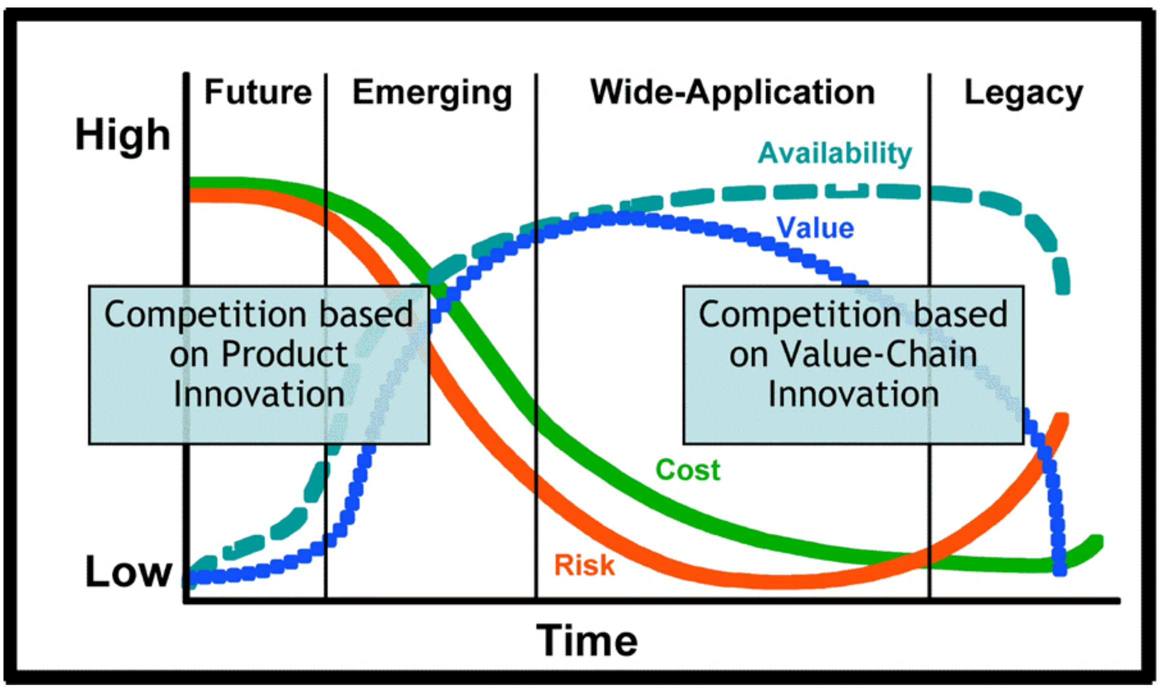

Figure 3: Technology Life Cycle Factors obtained from several hundred different non-solar technologies and products. PV and solar technologies would currently be in the future and emerging portions of the figure, but are expected to advance to the right.

This generally occurs on conventional grid systems when PV penetration reaches 15% to 25%. For more on this, and for current ideas regarding storage and an energy mix that includes wind, solar, hydroelectric, geothermal and conventional sources, refer to literature cited at the end of this paper. Additional challenges for PV are listed as bottlenecks in the Senge Diagram in Figure 1a.

PV systems have an expected life of 20 years or more, so it is difficult to predict how markets will evolve and displace earlier generations based on actual market experience. In biology, scientists study changes over generations of fruit flies as a proxy for studying human evolution and biology. Similarly, technologies and industries with rapid product cycles can be used as “industrial fruit flies” to understand how technologies and industries like PV may evolve. Figure 3 illustrates an analysis of the life cycle of over 300 different (non-solar) technologies and products that provide insights on how PV technologies may evolve. The curves are not theoretical; they are based on data from several industries. They show how cost and risk (on the y axis) decline as technologies move from future and emerging stages to wide application and, finally, legacy deployment. The value to a company that introduces the products at first rises and then peaks as a technology moves from emerging to wide application. It then declines sharply as the product moves completely into wide application and eventually legacy status. It is important to understand where different solar technologies are in their life cycle and where to focus research and development (R&D) on issues that are the most relevant to solar energy’s success, and to national interests. As solar technologies move toward competition based on value-chains in supply and manufacturing, agreements between industry participants on standards for raw materials, manufacturing equipment and processes will become essential for rapidly expanding manufacturing capacity and deployment.

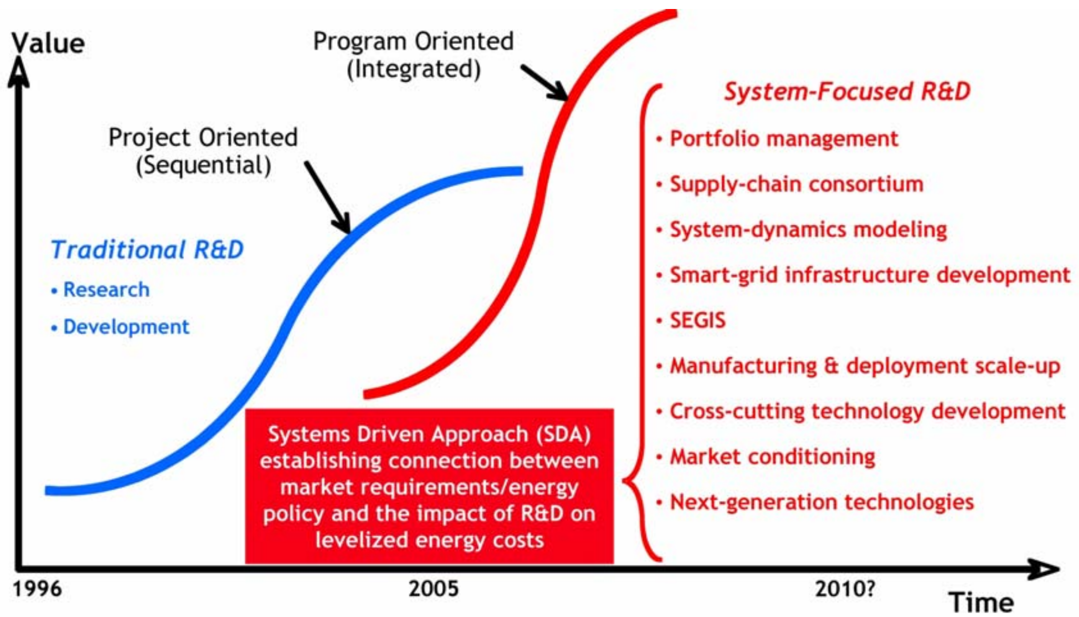

Figure 4: Value for Project and Program Oriented Solar Research. Solar Technologies are currently in the sequential and traditional R&D portions of the figure, but can be pushed into the more rapidly expanding systems-focused R&D curve to the right.

Solutions

Based on Systems Analysis represented by Figure 1 and a consideration of such technology life cycle factors, Figure 4 summarizes the desired progression of solar R&D from a project to a program focus with system-focused R&D. Three broad solutions emerge regarding the challenges previously described. These solutions are: SEGIS research, systems dynamics and modeling, and the creation and nurturing of a PV supply chain consortium.

Solar Energy Grid Integration Systems (SEGIS) Research

DOE's Solar Energy Grid Integration Systems (SEGIS) focuses on developing intelligent hardware that interconnects PV systems to an evolving "Smarter" electrical grid. Our Systems Analysis suggests that programs such as SEGIS can ensure that the Smart Grid adequately addresses opportunities for solar technologies such as PV. Key SEGIS research includes:

- Energy storage. This ranges from small capacity, quick discharge, devices to deal with the short-term impact of transient clouds on power output to longer capacity storage so solar generation can more completely cover periods of peak demand;

- Communications. Embedded computing power at generation sites and communication networks between sites are needed to make PV more effective in responding to instantaneous grid and weather conditions. For instance, avoiding automatic PV cutoff when it would harm grid stability, or shifting PV to recharging (e.g. in conjunction with plug-in hybrids) when its output is less valuable to the grid;

- Standards. Improving national and international standards for PV modules and BOS elements in a Systems Thinking framework can allow PV systems to be combined with other generation sources to alleviate problems caused by PV's intermittent output. As will be discussed shortly, this can lead to consortiums that can foster collaboration between PV module makers and integrators.

In this context, large-scale (so called high penetration) PV systems are being explored worldwide. For example, at a subdivision in Rancho Cordova, California, over 91 solar *Smart Homes* are each equipped with 2 kW of PV that feed into the grid. Other test sites include the 8 MW PV Plant in Alamosa, Colorado, and the 14 MW PV Plant at Nellis Air Force Base in Nevada. Such SEGIS research is also critically important to improving utilities' management of traditional energy generation and demand-side resources and for improving the utilization of their existing infrastructure. Overcoming grid integration limits for PV depends heavily on utilities and their regulators. Their concerns need to be addressed through continued and expanded research into technologies that will ease PV grid integration, accompanied by strong outreach and collaboration to better define issues and arrive at solutions that make both technical and economic sense.

Energy System Dynamics and Modeling

For System-focused development, it is important to use platforms, processes, tools and methods to rapidly test ideas that can effectively integrate solar energy into our economy. Stakeholders can build and maintain system models that are used throughout the development lifecyle shown in figure 3. One such tool is the Solar Advisor Model (SAM) that allows an analysis of the impact of changes to the physical system on the overall economics (including the levelized cost of energy, LCOE). It handles residential to utility-scale systems and a variety of technology-specific cost models for several and, eventually, all solar technologies.

The Utility industry needs models to understand local variations in solar resources and how this impacts PV output over large geographical scales (e.g. southwestern U.S.). This can allow an understanding of how widespread PV can be managed across the entire system. Detailed modeling of interactions can help improve grid operating strategies and approaches. For example if scattered clouds are shadowing a large solar field in one location, this can be rapidly communicated to adjacent solar, wind or conventional power plants and can, perhaps, be mitigated. This is only possible by combining energy systems with embedded computing power and communications networks.

Understanding and modeling system dynamics can also help explain solar energy to a wide range of decision makers and to the public. For example, while the term sustainability is often invoked to support solar and other renewable energy technologies, it is almost always loosely defined and rarely quantified.[1] An analysis that considers the greenhouse gas emissions of a technology over its life cycle can make sustainability more quantifiable and comparable between technologies. Global economic output ($25.4 trillion/year) can be related to global carrying capacity for carbon emissions (for the sake of argument, 8.6 trillion kg Global Warming Potential [GWP]), which is the maximum amount of carbon that can be emitted if climate change is going to be managed effectively according to Intergovernmental Panel on Climate Change (IPCC) analysis. This type of methodology quantifies sustainability and makes it a comparative metric by relating economic value – measured in dollars, just like GNP – to the carrying capacity of the environment for emissions. This results in a measure of sustainable productivity of approximately $3/kg GWP. If a business or industry's economic output is less than $3/kg GWP it emits, its production is not sustainable. This example is for GWP, but the approach has been applied to other emissions and environmental problems (see references).

Systems dynamics and modeling can also quantify the life cycle analysis of solar energy technologies in terms of Energy Return on Energy Invested and Energy and CO_2 payback times. Fthenakis and co-workers have published comparisons of emissions from solar and other energy technologies and have formulated a detailed plan to integrate solar energy into the U.S. electricity grid. Considering emissions provides a quantitative economic basis for environmental and economic comparisons of solar technologies with other energy technologies and industries.

Solar Industry Consortium to Address Supply Chain Challenges

Supply chain issues are going to be increasingly important if PV is going to maintain the growth rate it needs to have a significant impact on global energy use (see Figure 2). Without major innovation in the supply chain to keep improving costs and performance, maintaining the 20% growth curve will be very difficult. In addition, there are concerns about the availability of highly

[1] Work done in collaboration with David Dickinson. Additional technical papers and examples of the (STM) methodology are listed in the references.

pure thin film absorber materials such as Cadmium Telluride (CdTe) and Copper Gallium Indium Diselenide (CIGS) necessary for Terawatt (TW) deployment of PV. Although these aspects have yet to be fully addressed, it should be pointed out that, until recently, demand has not warranted sufficient exploration to positively identify reserves and resources.

With these aspects in mind, Systems Analysis suggests that the PV industry needs PV supply chain consortiums. One example may be taken from Sematech, organized by the semiconductor industry to develop and maintain a roadmap for standards and goals for equipment development. Sematech started with an emphasis on processes, but that effort soon slowed because of intellectual property issues concerning different manufacturers' formulations and methods – just as a PV consortium would likely break down over each company's "secret recipe" for their materials and cells. When competition is dominated by product innovation, collaboration is difficult. Where Sematech found its first success was in equipment standards and goals and competition focused on the value-chain. This will probably be the case for PV as well.

Crystalline silicon PV technology is moving into the stage of market development where supply chain innovation is the key to continued expansion and competition (see Figure 3), while solar cells utilizing thin-films are just entering this stage of development. Manufacturing line equipment for the crystalline silicon PV technologies that currently lead the market, and the supply chains that provide their materials and components, are the most promising near-term opportunity for an industry consortium. There is common interest in standardizing processing and handling equipment in order to gain economies of scale from equipment and material suppliers. The industry also needs tools to effectively monitor and optimize manufacturing while the manufacturing process is occurring, rather than relying on end-of-the-line diagnostics that identify problems too late to avoid large production losses.

Newer PV companies may be overestimating the value of protecting their trade secrets compared to what could be gained through collaboration; successful first steps by a consortium focused on crystalline silicon PV could persuade them to overcome their reluctance to collaborate. Such a consortium should possess objective technical expertise so that it can form a consensus on standardization and crosscutting research on supply chain issues.

Equally important as collaboration and consortia is *peer review*. This is the process of subjecting an idea, work, or research plan to the scrutiny of others who are among a community of experts in the same or similar field. The process of performing a meaningful and impartial review should itself be viewed as a cycle in the Senge diagram of Figure 1, and plays an essential role in a Systems Approach aimed at achieving high quality R&D in a minimum amount of time. This is because supply chains cannot be developed internally, and peer review breaks down barriers that collaboration on standards and equipment, and supply chain consortia, cannot address.

Conclusions

PV markets are growing rapidly, but from a very small base. Annual growth of approximately 20% will need to continue for solar to have a major impact on generating capacity in the U.S. and the world. Obstacles to overcome include achieving grid integration at high market penetration and the shifting of the focus from product innovation to supply chain innovation. The results from the PV experience curve strongly suggest that major breakthroughs are not required. However, targeted research for sustaining innovation is needed, as well as more effective industry collaboration. These will allow solar deployment to follow its past trends for cost and performance improvements through 2050, the time frame necessary to address climate change. Systems Thinking techniques may be used to study any kind of system: natural, scientific, engineered, human, or conceptual. Solar Energy R&D and Industry Drivers should be considered in the context of Systems Analysis and such perspectives lead to a multidisciplinary, collaborative approach. Although the analysis presented in this paper has focused on non-concentrator solar photovoltaic systems, it can, in principle, also be applied to concentrator PV (CPV) and concentrating solar power plants (CSP). It can explain and optimize the engine of growth for the fledgling solar industry to identify areas where spending and support can accelerate this value creation process. This will create a new economic era for the 21st century.

This new economic era will involve a modification of society comparable in scale to only two other changes: the Agricultural Revolution and the Industrial Revolution. Sustainable Energy and Information Intensity are two essential technologies for this transformation. Sustainability will be a major driver of technological innovations such as the Smart Grid. This, in turn, will be a product of the Internet and energy management of sustainable energy sources made possible by low cost and embedded computational power in energy-generating and energy-utilizing devices.

Literature and Acknowledgements

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