Ad Lucem: Modeling Market Transformation Pathways Workshop

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Ad lucem **– Latin for toward the light – captures the essence of the SunShot Initiative. We seek to accelerate the global transition to clean, abundant solar energy by expanding our understanding of the technology-society-economics nexus. The ability to control energy resources is the enabler for growth, development, and opportunity. The diffusion of low-cost solar energy technologies allows us to re-imagine and re-evaluate the interface between energy and humanity. In this workshop, we will identify potential pathways for solar market transformation and discuss methods for studying their consequences.**

Workshop overview

The *Ad Lucem* workshop will bring together a diverse group of researchers and technical experts to discuss solar market dynamics and market transformation pathways. Just as biophysicists are making great advances in the life sciences using tools adapted from the physical sciences, dialogue between economists, psychologists, sociologists, anthropologists, mathematicians, and physicists is leading the development of innovative methods to comprehend the complex relationships between technology, behavior, and decision-making. An interdisciplinary approach affords us the opportunity to study such issues with unprecedented breadth and depth. This one-day workshop will comprise a series of talks, debates, and brainstorming sessions. The primary objective is to identify potential research areas that may effectively inform SunShot Initiative activities. A background description and possible workshop discussion topics are provided below.

Background

In 1965, Gordon Moore, who would later co-found Intel Corporation, extrapolated from five data points that transistor density on integrated circuits would continue to double roughly every two years [1]. Moore's law – a roadmap which predicts the rate of technological progress – has remained accurate for nearly fifty years. The elegance exhibited by Moore's law lies in the story it captures about human innovation, social organization, and economic investment. Science and engineering are quintessentially human endeavors. There exists an extraordinarily complex set of couplings between consumers' decisions to adopt a product, the rate of that product's diffusion within a population, decisions to invest in further research and development, and technological advancements and cost-reduction. It is remarkable that such a simple exponential curve can summarize these interdependent processes; implicit to Moore's law are basic verities about the dynamics of human learning, effort, and experience.

Photovoltaic modules – the semiconductor devices that convert solar photons into electricity – have historically followed an *experience curve*, a trend closely associated with Moore's law[†]. The unit price p (in U.S. dollars per

[†] The experience curve relationship (Wright's law) is equivalent to Moore's law when production increases exponentially with time, as is the case for photovoltaics, transistors, and numerous other technologies [2].

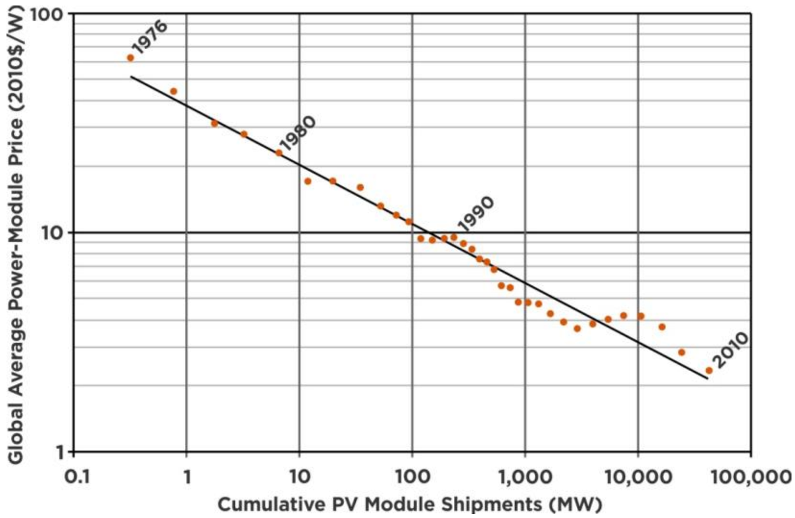

Fig. 1: Photovoltaics experience curve, 1976-2010 [3-5].

watt) follows a power law relationship with cumulative production q (in watts), $p \propto q^{-\alpha}$, where α is the learning coefficient. In Fig. 1, the experience curve relationship is evident over more than four orders of magnitude for cumulative production. From the time when photovoltaics were of limited application used almost exclusively for powering space satellites to the present when solar panels are moving toward wide-scale terrestrial adoption (40 gigawatts of cumulative production through 2010), global average module price has declined roughly 95 % from about $60/watt in 1976 to about $2/watt in 2010 (adjusted for inflation). Economists have termed this observed power law relationship *learning-by-doing*, a concept reflecting a number of underlying processes including advancements in research and development, economies of scale, worker productivity, and manufacturing efficiency [6].

The Moore's law relationship between a performance metric and time and the experience curve linking a performance metric with production are necessarily coupled via a trajectory for production in time. The production trajectory is driven by underlying consumer demand. A relatively simplistic approach to adoption dynamics was presented by Frank Bass in 1969 [7]. With few assumptions, one can use the Bass diffusion model to construct a forecast of adoption behavior. In Fig. 2, projected adoption curves are plotted for four different solar cost reduction scenarios[§]. The projections, of course, are reflections of the model and assumptions. The Bass model is relatively simplistic and does not describe a series of known consumer preferences including perceived advantage, compatibility, complexity, trialability, and observability [8].

[§] The projections for adoption of photovoltaics on residential and commercial rooftops in the continental United States were obtained using a bottom-up, market penetration model (NREL's SolarDS model) which incorporates Bass diffusion along with regional solar resources, capital costs, electricity prices, utility rate structures, and federal and local incentives [9]. Utility-scale photovoltaic adoption was modeled with NREL's Regional Energy Deployment System linear optimization model which deploys conventional and renewable electricity generation technologies to meet customer load at the lowest cost, subject to model constraints and scenario assumptions [10].

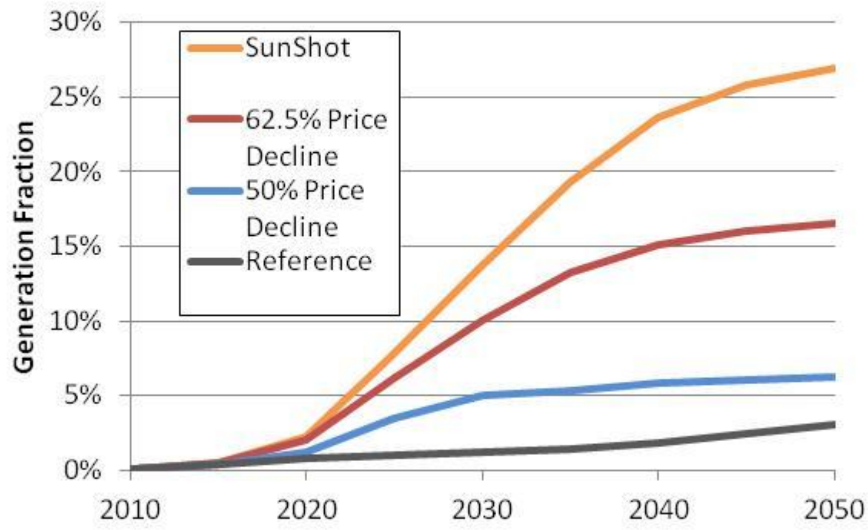

Fig. 2: Projected solar market diffusion (including photovoltaic and concentrated solar power).

Moore's law, the experience curve framework, and the Bass diffusion model are powerful and practical tools in fields as diverse as management science, economics, public policy, and engineering. However, they have little to no explanatory power, thus limiting their roles in informing decision-making of an applied technology program. A deeper understanding in this area can provide guidance for billions and billions of dollars of private and public investments.

In February 2011, Secretary Steven Chu announced the SunShot Initiative – a collaborative national effort to drive down the cost of solar energy technologies to be competitive with conventional sources of electricity by the end of the decade. Like the Apollo program of the 1960s, there are a finite set of engineering challenges which are necessary to overcome in order to meet this aggressive target. For instance, these challenges include developing higher efficiency devices using thinner, earth-abundant materials. Unlike the space program, technological and engineering advances alone will not be sufficient. In the case of solar energy, improved understanding of the non-technical costs (so called *balance of systems* or *BOS* costs) and adoption dynamics will be critical for achieving the SunShot goals. Thus one cannot neglect social patterns and economic forces that must be understood to develop a rudimentary picture of the energy landscape.

In essence, the SunShot Initiative strives to accelerate the rates of technological progress and adoption associated with solar energy technologies. To achieve the SunShot, it is necessary to develop a comprehensive picture of the social, behavioral, and economic components of solar energy. Fortunately, powerful new analytic and computational tools developed by network scientists, cognitive scientists, and behavioral economists are enabling new discoveries and insights that can be leveraged in this context.

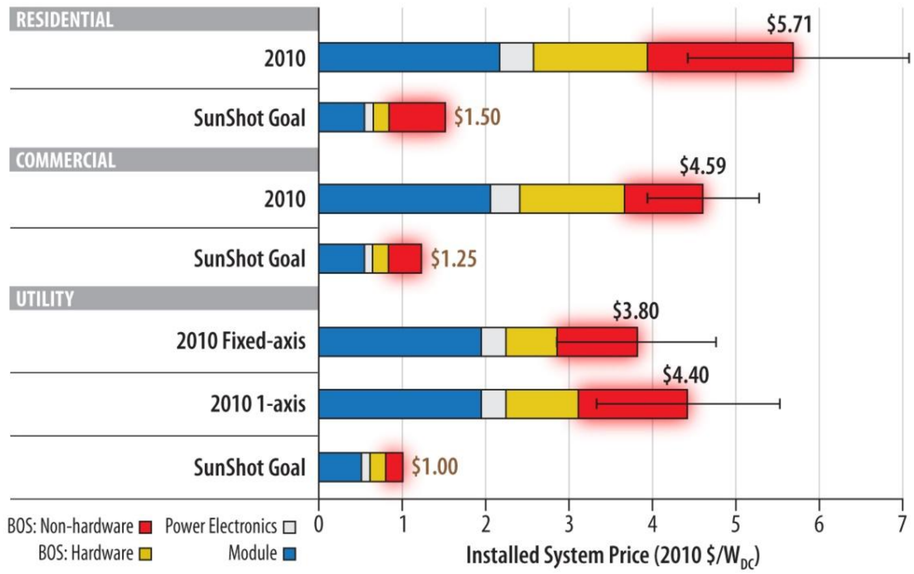

Fig. 3: Non-hardware BOS costs are represented by red bars. Prices are based on national average U.S. labor rates and exclude system operation, maintenance, and financing costs [11].

For example, new research has begun to decouple the myriad causes and effects found within complex dynamical systems. As access to population-size datasets that organize individuals into collections of social networks grows, scientists are increasingly able to study the spread of information, services, or products with unprecedented precision and granularity. Thus, we are currently well positioned to draw insights from a growing body of literature focused on these topics, identify how these insights can specifically be applied to solar technology, and incorporate specific research into the Department of Energy portfolio that will yield new insights. In this workshop, participants will discuss incorporating such basic and applied science into the SunShot research portfolio.

The need for market transformation research is not strictly theoretical. As the price of photovoltaics and power electronics hardware has dropped, the costs associated with non-hardware BOS – including permitting, inspection, labor, customer acquisition overhead, financing, sales tax, and system design – have begun to account for a larger share of the installed system price. These non-hardware BOS costs can account for about one third of the installed system price for an average installation as of 2011 (Fig. 3) and are a key barrier to widespread adoption of solar energy technologies. To achieve the SunShot, market structure innovations must be designed, studied, and implemented. For example, innovations – such as third-party ownership models, group buys, and community solar projects – could reduce the BOS costs by modifying the ways in which solar systems are bought, sold, operated, and maintained. In the *Ad Lucem* workshop, potential market transformation pathways will be identified and discussed.

Selected workshop topics

| 1 | Solar energy technology market dynamics

The diffusion of innovations within a population is a social process. To fundamentally and enduringly change a target market, one requires a basic understanding of the complex relationships between market participants and the underlying market structure. Solar energy technologies are characterized by a unique set of market forces and motivators that do not fully overlap with those of other current or past innovations. It is instructive to identify parallels with markets for hybrid electric vehicles, energy efficiency technologies, and consumer electronics, but it is commensurately important to identify and understand the differences between these products and solar energy technologies. In this workshop, we will discuss directed applications of network science, agent-based modeling, and other methods to better understand the external drivers and interdependencies present within the solar market. Questions for discussion include:

- What is the relationship between mass media and patterns of peer-to-peer communication?
- How does information and persuasion propagate in a social network?
- What is the cause for spatial and temporal clustering of solar installations?
- What are key leverage points that, when modified, have the greatest impact?
- Can a technology be developed and diffused to trigger greater socioeconomic equality?
  How can we expand the adoption of solar energy systems into new geographic areas and demographic groups?

| 2 | Customer acquisition

Market observers often fail to recognize the complexity of an individual's decision-making process leading to product adoption. Upfront cost and relative advantage for a given product are seldom the main motivators, especially for an early adopter during the nascent stage of a technology. As the solar market expands, anticipating how a potential adopter's decision-making process might evolve will become increasingly important. Questions for discussion include:

- To date, what role has symbolic meaning played in a customer's adoption patterns, and how might this factor evolve as solar technology moves from early to more mainstream adopters?
- What communication strategies might be used to effectively and efficiently educate and inform consumers about solar technologies?
- How can community solar programs or similar innovations transform solar energy technology market dynamics into an interactive process that leverages group adoption processes?
- How does solar adoption fit into the larger context of an individual's entire energy-usage behavior (*ripple* and *rebound* effects)?

| 3 | Technology evolution

Energy lies at the intersection of technology, economics, and society. Technology evolution is affected by many drivers, including measures to reduce cost. Other factors such as aesthetics, environmental impact, and the human-technology interface play critical roles in molding products into those that we encounter on the store shelf. A fundamental understanding of the process of technology evolution will provide much-needed insight to address questions such as the following:

- How can we increase the rate of technological progress?
- What are the best strategies for investing in portfolios of energy generation technologies?
- What are the primary mechanisms for spillover (e.g. standardization, the use of common components) between both individual firms and entire industries?
- Can spillovers be optimized to benefit both consumers and industry?
- What are the primary non-cost drivers for decision-making with respect to investing in solar energy technologies?
- Can strengthening feedback mechanisms between human preferences and product design increase rates of technological evolution and adoption?

The policy implications resulting from research in this area reach far beyond the boundaries of the SunShot Initiative.

Closing remarks

The *Ad Lucem* workshop will explore a broad spectrum of questions on the human dimensions that underlie innovation and the innovation-adoption process, with a specific focus on insights that can be leveraged to achieve the SunShot goals. The workshop will be dialogue-driven, and we strongly encourage creative exploration. Innovation is not limited to the laboratory bench; through this workshop, we hope to identify novel techniques for analyzing and modeling market dynamics that can provide insights into practical pathways for transforming the solar energy technologies market.

References

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