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Industrial Symbiosis of Very Large Scale Photovoltaic Manufacturing

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Abstract

In order to stabilize the global climate the world's governments must make significant commitments to drastically reduce global greenhouse gas (GHG) emissions. One of the most promising methods of curbing GHG emissions is a world transition from fossil fuels to renewable sources of energy. Solar photovoltaic (PV) cells offer a technically sustainable solution to the projected enormous future energy demands. This article explores utilizing industrial symbiosis to obtain economies of scale and increased manufacturing efficiencies for solar photovoltaic cells in order for solar electricity to compete economically with fossil fuel-fired electricity. The state of PV manufacturing, the market and the effects of scale on both are reviewed. Government policies necessary to construct a multi-gigaWatt PV factory and complimentary policies to protect existing solar companies are outlined and the technical requirements for a symbiotic industrial system are explored to increase the manufacturing efficiency while improving the environmental impact of PV. The results of the analysis show that an 8-factory industrial symbiotic system can be viewed as a medium-term investment by any government, which will not only obtain direct financial return, but also an improved global environment. The technical concepts and policy limitations to this approach were analyzed and it was found that symbiotic growth will help to mitigate many of the limitations of PV and is likely to catalyze mass manufacturing of PV by transparently demonstrating that large scale PV manufacturing is technically feasible and reaches an enormous untapped market for PV with low costs.

Keywords: solar photovoltaic; industrial ecology; industrial symbiosis

1. Introduction

The global climate destabilization underway is primarily due to human combustion of fossil fuels for energy and the resultant greenhouse gas (GHG) emissions [1,2,3]. There is a large consensus among scientists that if current trends continue in climate

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destabilization, the earth will reach a point of no return [4]. The challenge of reducing atmospheric GHG like carbon dioxide (CO₂) emissions is significant – with the Kyoto Protocol an entire order of magnitude below those values necessary to stabilize the global climate [5]. To obtain a stable climate, GHG emissions would have to be reduced to a point equal to the natural absorption of CO₂. After this stabilization occurs, the level of natural absorption will gradually fall as the vegetation sink is exhausted so GHG emissions would need to fall to the level of ocean uptake alone. This level is not well quantified, but may demand emissions reductions to 5 Gt CO₂ eq./year (more than 80% below current levels) by the second half of the next century [6].

One of the most promising methods of curbing continued GHG emissions and concomitant global warming is for the world to transition to renewable sources of energy. Solar photovoltaic (PV) cells, which convert sunlight directly into electricity, offer a technically feasible and environmentally sustainable solution to our enormous future energy needs [7]. PV fabrication does entail use of energy and with the current energy blend this is equivalent to GHG emissions, but the energy payback time for modern solar cells is a fraction of their total lifetime so they are net CO₂ sinks [8]. With existing technologies, readily available materials, and current conversion efficiencies found in manufactured modules, an insignificant fraction of terrestrially available sunlight is needed to power the global society [7]. Unfortunately, due to the currently small manufacturing facilities, PV has not reached an economy of scale able to compete economically with conventional energy sources and remains a small but growing niche in the energy market.

This article explores utilizing industrial symbiosis to obtain economies of scale and increased manufacturing efficiencies for PV cells in order for solar electricity to compete economically with fossil fuel-fired electricity. This set of technical concepts and policies can be viewed as a medium term investment by a government interested in speeding the advance of renewable energy, which will not only see financial return directly, but also an improved global environment, enhanced national energy security, and international favor. First, the state of PV manufacturing, the market and the effects of scale on both will be reviewed. Next, the government policies necessary to construct a multi-GigaWatt (GW = 10⁹W) PV factory and complimentary policies to protect existing solar companies will be discussed. The technical requirements for a symbiotic industrial system will be outlined to increase the manufacturing efficiency while improving the environmental impact. Finally, how this system could act as a catalyst and the limitations to this approach will be analyzed and conclusions will be drawn.

2. Solar Photovoltaic Manufacturing

2.1 Photovoltaic Production

Although PV electricity production is a technically feasible method of providing for the world's energy needs and mitigating human interference with the climate, the technology will not be more than a boutique energy source until economic costs are driven

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down to be directly competitive with fossil fuel-fired electricity. There is intense interest and often government support throughout the world for PV. Although the well-intentioned government programs [9] including: government-funded research, information/education campaigns, national renewable energy plans, regulations/standards, guaranteed markets, green pricing such as the 'standard offer' to buy solar electricity at a premium by the Ontario government [10], and financial incentives such as 100,000 roof program in Germany [11]), expanded the manufacturing of PV, they are largely inconsequential in the energy budget of an expanding world. Both industry and government are moving slowly towards the solar energy transition, but PV electrical production still makes up much less than 1% of the total world energy market. A catalyst to speed the up scaling of PV manufacturing is needed [12,13]. Most global governments are financially secure enough to take advantage of this opportunity and become this necessary medium of change.

There has been significant progress in the last 30 years in the performance of solar PV. Solar cells made from a variety of materials have demonstrated efficiencies of over 10% and are currently manufactured globally. In the U.S., the PV industry has grown at average of ~20%/year, a growth rate comparable to that of the semiconductor and computer industries [14]. This growth rate, while large, must be viewed in context of the global energy market; in 2004 the peak electrical generation capacity in the world was 3,736 GW [15] while the total global installed solar PV was only 1 GW.

2.2 The Photovoltaic Market

The market for solar PV continues to expand rapidly. World solar photovoltaic market installations rose to 1.46 GW in 2005, representing annual growth of 34% and leading to a cumulative installed solar PV electricity generating capacity of 5GW (up 39%) [16]. As the production volume of PV has increased, the price per module fell rapidly [17]. This trend continued for several years with prices in dollars per peak Watt ($\$/W_p$) dropping to $\$4.94/W_p$ in May 2004 in the U.S. [18] and then beginning to climb to $\$5.47/W_p$ as of December 2006 as the worldwide demand for PV outstripped the supply of purified silicon used in the majority of "1st Generation" solar modules. The market will eventually correct this problem as more silicon feedstock factories scale up and more "2nd Generation" factories are built that use small quantities of amorphous silicon in thin films or non-silicon based PV technologies. The rapid increases in PV even at values over 25% per year are not enough to make a serious run at fossil fuel supplies for decades. This limit to the growth is largely because the cost of solar electricity fully installed at even $\$3/W_p$ is $\$0.09/kW\text{-hr}$ is just competitive with the average retail price of electricity (in the U.S. in 2006 it was $\$0.1047/kW\text{-hr}$ [19]). It should be noted that to secure significant market share PV will need to compete with wholesale electricity rates, which are considerably lower than retail rates. The cost of the PV module represents 50-60% of the total installed cost of a PV system so the cost of solar electricity will only enjoy market dominance if the price of installed solar systems can be brought down to about $\$1/W_p$ after enormous scale up in manufacturing. At this price, the payback from savings for a consumer's electric bill is

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about five years in locations with utility costs of more than \$0.12/ kW-hr. This will greatly increase the demand for solar PV panels on residential and commercial rooftops.

2.3 Scale and Photovoltaic Production

This ambitious target of \$1/W_p can be reached by one of two ways. The first method would demand a major scientific breakthrough – a radically new and efficient method of converting light into electricity. There continues to be world wide effort in new “3rd Generation” [20] types of solar cells that improve upon existing cell designs and recruit new materials/nanotechnology that have potential to do this. Such unknown breakthroughs are not necessary if the second method is employed, which utilizes a massive scale-up of PV manufacturing facilities. A “Solar City Factory”, a factory capable of making 2.1-3.6 GW of solar cells per year would achieve new economies of scale to reduce the price by the necessary ~3X factor [21].

It is not enough just to build a 3GW factory to obtain the necessary cost reductions. The Solar City Factory would achieve such cost decreases by utilizing five key principles to drive down the cost of “2nd Generation” solar cells [21]. First, all materials including the substrate, packaging, and materials would need to be designed to last for > 25 years in realistic environmental conditions so that the capital cost of the modules can be sufficiently amortized. Second, the transportation and handling of substrate materials should be minimized and automated similar to the design of semiconductor chip facilities. This reduces the steps for fabrication based on cleaning, and thus also reduces breakage and costs to improve yields. Third, all of the material inputs entering the solar cell factory should be optimized for solar cell production. This can only occur if the demand for the materials is large enough to warrant a dedicated line. For example, substrate glass specifically manufactured without iron for solar cells can increase the sunlight entering the cell by about fifteen percent. At current solar PV manufacturing lines for thin films altering the glass recipe for small batches is uneconomic, but this would be reversed at scales of 100X current PV manufacturing lines. Fourth, multiple lines of identical equipment with rotating planned downtime for cleaning and maintenance could be used to minimize unplanned downtime and reduce the cost of maintenance and operations. Finally, the need for the most expensive constituent materials could be minimized by increasing the utilization rates for high purity input materials, which will both reduce costs directly and improve availability of rare materials for some types of solar cells (e.g. indium).

These improvements and the massive scale up necessary to make them, require an enormous capital investment in a single plant of ~ \$600 million [21]. To put this level of investment into perspective, it is helpful to note that investment in new plants to manufacture solar cells exceeded \$1 billion in 2005 globally [16]. This money was primarily invested in 1st Generation (poly-silicon and single crystal silicon) PV manufacturing plants, which, while they benefit from larger scales, do not have the economic advantages of 2nd Generation PV technology and can not obtain the economic leverage outlined by the plan above.

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Although both the semiconductor and flat panel display factories cost well over \$1 billion each, even large companies have been reluctant to invest so much into a single plant, because solar PV is often viewed as a somewhat risky investment. The government support that has helped the solar PV industry substantially and conventional energy prices have historically been unstable. A large investor able to reduce the risk is needed to invest the money necessary to build a multi-GW solar PV manufacturing facility.

3. Multi-GW Solar PV Production

3.1. Government Policies for multi-GW PV Production

Most of the world's governments are well positioned to take advantage of this opportunity to be the investor that produces the first multi-GW PV fabrication facility. Any government with the necessary political stability and available cash flow could look at the production facility as an investment in the same way that government reserves are kept in banks to earn interest. The investment would yield direct financial return after the facility was producing solar panels for public sale. The government would enjoy national benefits including a good reputation throughout the world, increased national energy security and long-term economic growth [22].

Increases in national energy security would come from both an increase in domestic supply of energy (and thus a reduction in present and future energy imports), but also an increase in national electric grid robustness. PV has been established to be part of the solution to deliver firm, dependable power during extreme peak conditions leading to outages [23]. Solar PV electric production has the advantage over more conventional forms of electricity supply of being a distributed energy source – solar PV systems can be located near the consumer by placing solar panels on any surface that is exposed to sunlight without large shading losses during the day. As a distributed electrical generation source, this technology acts as a network (much like the Internet), and is therefore much less susceptible to large-scale power outages caused by natural or manmade disasters.

Long-term economic growth would come first from domestic reduction of electricity costs, which would drive down the cost of most products; and second by providing a technological head start in a job-intense industry with an enormous and growing international demand. There is considerable evidence that the integration of PV into the electric supply could reduce electricity costs for all consumers. This is a consequence of the fortunate solar irradiance-demand correlation, where most human activities tend to follow the sunlight cycle. For example, residential PV installations in New England have shown that ~60% of the total daily output from PV systems is supplied during the utility peak period when the utility system load is $\geq 95\%$ of the maximum load reached during the day [24]. Solar PV thus provides value to the grid by displacing generation from conventional units that use higher-cost fuels. At low solar electricity percentages, or penetration levels, the least efficient and most costly sources of conventional electricity can be removed. This would drive down both economic and environmental costs for the entire electrical production system.

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Many utilities have actively tried to prevent any transition to a more distributed grid because it would represent a reduction in revenue from sales of their principle product. In addition, they have been particularly unenthusiastic for intermittent renewable energy sources such as solar PV. This is due to the fact that at certain penetration levels the savings offered by intermittent generations could be offset by the increase in costs of partial loads of reserves, making it uneconomic. Particularly in the case of solar energy, the high costs have prevented the large distribution of solar electricity on purely economic grounds.

In the case explored here, where large scale production of PV drives down the costs to be competitive with conventional sources, only technical criteria (e.g. intermittency) are valid for the determination of PV penetration levels. Although higher penetration levels of PV generation can be problematic, corrective measures such as assigning more generating units to regulating duty or installing fast-response combined-cycle generators have been available for decades [25]. The problem of fluctuating cloud conditions can be solved simply by deploying solar PV over a larger area; if a network of PV installations is dispersed over 100 km² the tolerable penetration increases to 18.1%, and if the area is 1,000 km² the limit is 35.8% [26]. In a review of several studies, an upper penetration limit of PV generation of 16% is estimated for a system load set by the worst-case cloud pattern [27]. Combined, these factors have enormous potential economic return for any of the world's governments. The first plant at 2GW/year would have revenues of \$2 billion/year and as additional plants replicate the first successful demonstration the positive effect on even the largest developed economies could be staggering. With construction of this single plant, the country would be the dominant PV manufacturer in the world, out-producing the aggregate of global manufacturers. The country would have a firm technological lead in large-scale PV manufacturing, which it can leverage to rapidly deploy several multi-GW plants to feed the enormous global market, which could have a powerful effect on most country's balance of trade. Even within the country, any energy source supplanted with PV would increase the number of people employed with solar, as investment in solar PV produces substantially higher levels of employment than equivalent investments in conventional energy supplies [28]. A study for Environment Canada found that for every \$1 million invested, an average of 17 jobs are created in the PV energy sector compared to only 7.3 jobs created from the same investment in conventional energy [28].

The overall investment of \$600 million is relatively modest compared to the budget of most of the world's governments or even yearly expenditures in a single class. For example, >70 countries spend more than \$600 million/year on their military budgets each [29]. A developed government could also raise money for the multi-GW PV plant investment from the following sources: i) reallocation of the international aid for a single year, ii) increased taxes or decreased spending by a fraction of a percent, iii) a donation drive to get each of citizen to donate a modest amount. This donation could also be in the form of a "solar bond" that would pay dividends to citizen investors. In developing countries \$600 million represents a larger relative investment, but it still within the reach of

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most countries. There is significant public support for environmental protection [30] and based on the public's recent historical environmental record and opinion data [31], considerable public support for such a bold initiative would be expected in many countries.

3.2. Policies To Protect Domestic PV Manufacturers

It is understandable that any proposal to have a government directly interfere in a market to the point of becoming an actual competitor would be a major concern – particularly for solar cell producers. The concern would focus on the probability of disrupting the market and destroying small, medium, and even large businesses if they were slated to compete in solar cell production with the government, which has significantly larger resources. Based upon relatively well-founded estimates of the modules produced in a very large multi-GW facility, it is likely that the government's PV modules will be a 3X less expensive and, given the scale of the plant, provide ~ 50%-100% of the global market. This would necessarily drive many producers out of business if these cells were immediately placed on the market. In order to avoid this problem, the government could purchase all of their own PV cells for the time that is necessary to begin production from another multi-GW manufacturing plant by existing national PV companies. The government-manufactured cells could be integrated into the roofs of all government buildings and then, when roof space had been completely exhausted, PV could be integrated into south-facing highway sound barriers and into carports constructed over all government parking lots. Similarly, off-grid government electrical applications could be completely solar powered (e.g. highway signs, buoys, bus stops and street lights). Again, this would be an investment for the government. Purchasing solar panels at such a low cost per W_p has a very competitive return because of the avoided electrical costs. For example, utilizing conservative assumptions such as 2.4 hours of peak sunlight on average per day, a 1kW system would output 876kW-hrs worth \$70 at \$0.08/kW-hr and have a simple payback of 14 years. Over the lifetime of the system, estimated at 25 years, this is a rate of return > 5%. This return on investment, while a conservative estimate because it assumes that the price of energy escalates at the rate of inflation, is competitive with mortgage rates.

During this transition period where the government could set a future date when the PV from the facility would be put on the open market (e.g. 2-4 years). By giving the PV industry enough lead time to ramp up their own production facilities, the government will not be directly competing against them for customers because the demand will far outstrip the supply of a single digit multi-GW plant at such low $$/W_p$ prices [32]. Domestic manufacturers would i) know that it is technically feasible to produce inexpensive solar cells in such a large plant, ii) receive government technical support with designs and construction of multi-GW factories based on the lessons learned in funding, building, and operating a plant, and iii) an enormous incentive to scale up immediately before being driven out of business by not only the government fabrication facility, but also manufacturing plants being built by their competitors.

3.3. Industrial Symbiosis in PV Production

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In order to increase both the economic and environmental performance of the manufacturing sector, the government could introduce a second set of policies with the large scale PV manufacturing in order to facilitate the widespread adoption of industrial symbiosis. In industrial symbiosis, traditionally separate industries are considered collectively to gain competitive advantage by instituting the mutually-beneficial physical exchange of materials, energy, water, and/or by-products. Such a system collectively optimizes material and energy use at efficiencies beyond those achievable by any individual process alone. The key benefits of industrial symbiosis are collaboration and the synergies offered by geographic proximity [33]. Industrial symbiotic systems such as the now-classic network of companies in Kalundborg, Denmark have spontaneously evolved from a series of micro-innovations over a long time scale. In order to accelerate the process and demonstrate the possibilities for mutually-beneficial collaboration, the government could engineer the design of the new solar PV manufacturing plant using industrial symbiosis.

The multi-GW PV factory could sit at the center of a next generation eco-industrial park. The eco-industrial park would be made up of at least 8 symbiotic factories as seen in Fig. 1. These could be located outside of a major population center to provide raw materials, labor, and a ready market. The first factory would be a conventional recycling facility (1). In this way, the glass and aluminum needed to fabricate the solar cell could be recovered from recycled materials and thus have a lower embodied energy (95% lower for aluminum and 20% for glass) [34].

The raw glass from the recycling plant will be fed to a sheet glass factory (2) and melted using natural gas. Generally, the high quality requirements of flat glass prohibit the use of post-consumer waste glass [35]. However, the glass industry is exploring a method to eliminate problems with color contamination by using thin plastic coatings, which can be made with a variety of colors and that would vaporize during re-melting without affecting the quality of the new glass [36]. This would benefit the industry considerably because using recycled glass, called cullet, has several important benefits that include: i) lowering the consumption of raw materials, ii) reducing the release of CO₂ formed in the chemical reaction of raw materials, iii) increasing the life of the furnace by up to 30% due to lower melting temperatures, iv) reducing energy use during the melting stage of production and thus reducing additional GHGs and operating costs, and v) reducing the costs associated with pollution abatement due to lower emissions of NO_x, SO₂ and particulates [35,37,38]. The factory will output cut sheets of 3 mm thick glass with seamed edges and low iron content in order to obtain a high solar transparency. Finally, the glass will be tempered for mechanical strength and coated with a transparent conductor such as tin oxide, zinc oxide, or indium tin oxide to be used as the substrates.

The production stages in the glass factory that utilize large amounts of heat will have integrated thermal recovery to provide lower grade heat for the other facilities and a greenhouse complex (3a). In the greenhouse complex, exotic plants can be grown year

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round in even northern climates utilizing the waste heat from the manufacturing plants in the eco-industrial park. Similarly, waste heat could be utilized to provide grow rooms for mushrooms (3b). In both agricultural plants, the food or other agricultural products will be sold outside of the park and the growing medium will be provided by the recycling facility (1), compost for the greenhouse (3a) and wood pulp or compost for the mushroom growing facility (3b). In warmer climates, the waste heat could be used to drive absorption chillers perhaps providing cooling for an office park.

The substrates will then be fed directly into the PV module plant (4). Then a group of semiconductor and metal thin-film deposition systems will create and pattern the active layers of the solar cells. All waste semiconductors and metals will be captured and returned to a semiconductor recycling plant (5) to supplement the incoming and generally expensive high purity materials going into the deposition systems. The output of the PV deposition and patterning lines will be PV solar panels ready for protective coatings and packaging.

The aluminum extracted from common drinking cans in the recycling center (1) will be fed to an aluminum fabrication factory (6) that will produce coated aluminum rails for holding the glass solar panels. The aluminum rails will be extruded and used to provide a simple and inexpensive means of attachment to rooftops, ground mounted systems, or building integrated PV. In addition, the extruded aluminum rails could be designed into ground and flat roof mounting balance of system components. Similar to the glass manufacturing plant (2), waste heat will be recovered and used in the symbiotic collective or to heat the greenhouse (3a) or mushroom grow rooms (3b).

Next, in the packaging factory (7), the solar panels are interconnected if necessary and are sprayed with a protective polymer coating to seal them to the environment. The primary constituents of the polymer coating could again be acquired from the recycling plant (1) and common plastics. The panels would then be wired with quick connects so they can be easily installed in the field by connecting to each other, an inverter, or battery bank.

Finally, the panels would be packaged for shipment to prevent damage in cardboard boxes and cushioned with shredded newspaper. The newspapers would again come from the recycling plant (1) and the cardboard could come from a cardboard plant (8), which would gain its raw materials from the recycling factory (1).

By co-locating these factories in the eco-industrial park, the transportation costs and energy between them can be minimized and many of the inputs for the solar PV plant can literally come from waste products in the surrounding population centers. It should be noted that each factory will be scaled appropriately for the symbiotic system and should be individually profitable so that independent businesses can replicate this model by co-locating and benefit from industrial symbiosis in future facilities.

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3.4. The Catalytic Effect

The primary focus of this technological/policy assemblage is to provide a reproducible demonstration of large-scale mass manufacturing of PV. This demonstration and the accompanying policies will provide a fertile ground for companies already experienced in PV manufacturing and those businesses considering the PV industry (e.g. GE) to begin large-scale mass production themselves. Both the technical demonstration and the secure business environment will help reduce the financial risk that prospective multi-GW manufacturers face when considering such large investments. Following the policy suggestions, numerous multi-GW PV facilities would be built. This in turn would drive further private sector investment in the complimentary industries such as power conditioning (inverters and charge controllers) and storage (batteries). In order to target the primary global issue of climate change, the country would either need to be the supplier for the electrical production equipment for the entire world or, more likely, spread the concept to other nations. This expansion could take place following existing models such as country to country collaborative work to solve environmental problems such as the Canada-China Cooperative Project in Clean Production [39].

3.5. Limitations to Approach and Potential Solutions

Photovoltaic electricity production is not the complete solution to global energy requirements, nor will it single-handedly deliver us from the potential enormous harm of destabilizing the global climate. PV can, however, tip the balance into a renewable distributed energy future where many green technologies and aggressive conservation can lead society towards a sustainable state. PV cannot do it alone because there are inherent limitations to PV technology itself. The most important of which is intermittency; PV does not produce useful quantities of electricity at night and under heavy cloud conditions. There are two approaches that can be used to mitigate this limitation.

First, a form of storage can be used in which electricity is produced in excess during the day and stored for use at night in devices such as batteries. This drives up both first costs and recurring costs from maintenance/battery replacement (~ 5 years for current technologies). Solar cells themselves operate maintenance-free and are normally warranted for 25 years or more. To avoid the need for chemical batteries, it is also possible to couple solar cells with other conventional sources. For example, in a solar PV-hydro hybrid system, the solar modules produce power during the day with the hydro plant holding the water in reserve until the night, when it takes over power production [39]. In addition, at night or during cloudy weather, electrical demand can be met by retaining the existing fossil fuel power stations, which are already built and largely paid for, and starting them up as required. The cost of using existing power stations in this way is surprisingly low since the vast majority of the cost of running a power station is the fuel cost.

Second, with low PV penetration levels solar arrays can eliminate the need for batteries by utilizing an inverter to use the grid as a storage medium. This method is limited

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to about 20% before the grid will have to be altered to adapt to intermittent sources. Studies have shown that penetration limits usually are not technical limits but economic limits where additional operational costs are greater than the added value of intermittent renewable energy technologies – so the 20% rule of thumb should be viewed as a moving target [27]. An added economic advantage for utilities using solar for symbiotic energy production with other sources, rests on fortunate daily and yearly solar timing. When electrical demand is highest for many electrical suppliers (during the summer for air conditioning) PV power output is at or near its peak. Thus, solar power facilities can be used to mitigate peak demand and thus hold down costs for current energy suppliers. Unfortunately, for this same reason, as the solar penetration level is increased, some of the economic benefits disappear as an increasing number of conventional generating units are partially loaded to add load-following capability and operating reserve to the system. This can be detrimental to overall grid efficiency because of the increased cycling duties and decreased efficiency caused by the partial loading of these generators, which will increase fuel consumption and maintenance costs.

In the long term, to move to a more renewable and thus intermittent energy mix, the grid must be transformed. Electricity-producing units that can quickly power up and down to meet the demand not handled by intermittent sources like PV and wind need to be developed. Technologies such as gas-fired microturbines, fuel cells, other combined heat and power (CHP) devices, and plug-in hybrid vehicles all combined or working independently offer possibilities to overcome the technical challenge of penetration limits.

4. Conclusions

This paper has shown that the first multi-GW thin film solar PV facility at the heart of a government sponsored eco-industrial park could be an enormous benefit to both the economy and environment. The main objective of the policies outlined here, however, was not to benefit from the output of a single multi-GW PV plant. Rather, the primary focus of these procedures is to provide a reproducible demonstration of large-scale mass manufacturing of PV to encourage domestic PV manufacturers to scale up production and thus drive down production costs globally. Both the technical demonstration and the secure business environment provided by the technical and policy assembly outlined here will help reduce the financial risk that prospective multi-GW manufacturers face when considering such large investments and help catalyze a true renewable energy transition.

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Figure Captions

Figure 1. Graphical Representation of the Eco-Industrial Park to produce multiple GigaWatts of Solar PV

