

Study of Potential Cost Reductions Resulting from Super-Large-Scale Manufacturing of PV Modules

**Final Subcontract Report
7 August 2003–30 September 2004**

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*Hewlett Packard
Palo Alto, California*



NREL

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Operated for the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
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Executive Summary

Technology investments by the U.S. government Dept. of Energy, National Renewable Energy Lab (NREL) and others over the past 30 years have positioned the Solar Energy industry to undergo an inflection. The technology is now very close to good enough. The key issue is cost.

Like the DRAM industry of the middle 1980's, we will see large companies invest around \$0.5 B in capital to create large, optimized and automated factories that will achieve dramatically lower costs for solar panels. These lower costs will finally enable solar energy to compete economically with the cost of producing electricity by conventional means, enabling the market to explode.

We have created a design for a "Solar City" factory that will produce 2.1 – 3.6 GW of solar panels per year—100x the volume of a typical, thin-film, solar panel manufacturer in 2004, and about 4x the volume of the entire solar panel industry in 2004. We have shown that with a reasonable selection of materials, and conservative assumptions, this "Solar City" can hit a price target of *\$1.00 per watt* (6.5x - 8.5x lower than prices in 2004) *as the total price for a complete and installed solar energy system*. This breakthrough in the price of solar energy comes without the need for any significant new invention. It comes entirely from the design of a large factory and the cost savings inherent in operating at such a large manufacturing scale.

At the price of \$1.00 per watt for a complete and installed system, the payback time in states like California is under 5 years. Therefore, we expect the demand for solar energy systems to explode. At this price, there will be demand for small solar energy systems installed on residential rooftops (4 - 6kW each), much larger systems on commercial rooftops (0.5 MW each) and even larger systems for the regional and wholesale generation of electricity at competitive regional and wholesale rates (10 – 100 MW each). Eventually, we envision hundreds of these "Solar City" factories distributed across the U.S. and around the world to serve local markets.

We detail the design principals for creating a "Solar City" factory that is large enough to obtain dramatic breakthroughs in manufacturing costs, small enough to be affordable in capital cost, and small enough to be well matched to the needs of local markets. We then detail the design of the 5 sub-factories that make up the "Solar City". Inputs to the "Solar City" are raw materials in bulk form that are easy and inexpensive to transport. Outputs are finished solar panel products (with multiple PV modules), ready for simple installation. All intermediary steps are on-site.

Finally, we have developed a list of key technical challenges that must be addressed to make this possible. The challenges appear to be solvable, but will require focused R&D investments in these areas over the next few years.

Introduction

Technology investments by the U.S. government Dept. of Energy, National Renewable Energy Lab (NREL) and others over the past 30 years have positioned the Solar Energy industry to undergo an inflection. The technology is now very close to good enough. The key issue is cost.

This study will show that the photovoltaic solar panel industry is on the verge of a major inflection point that will be characterized by the following:

1. Large companies who are willing to make large investments of around \$0.5 B in plant and equipment will be able to achieve new economies of manufacturing scale and much lower prices per installed watt for photovoltaic (PV) solar panels.
2. The trigger point in *price* per watt, estimated at about \$1.00 per watt for an installed system, can be met at these new economies of scale. Improvements will be made in the design of the **manufacturing equipment** and in the **design for low cost installation**—both enabled by the new economies of scale. No new inventions or technical breakthroughs are required.

At this price, the payback from savings in one's electricity bill will approach 5 years in states like California (at \$0.10 per kWhr) and much shorter times in countries like Japan and Germany (at \$0.20 per kWhr). This will create explosive growth in market for PV solar panels on residential and commercial rooftops.

In addition, with a 30 year lifetime, assuming 6% interest, a solar farm costing \$1.00 per peak watt (installed) will generate electricity at \$0.02 per kWhr in the southwest desert and \$0.03 per kWhr throughout much of the southwestern states. These large solar farms and their attractive cost per kWhr will further enable solar energy to become a substantial part of the total energy supply for the U.S. and the world.

3. Large companies outside the U.S. are motivated to invest strongly, supported by their respective government rebates for solar electricity installations and by the 2x cost of producing electricity in those countries, which makes solar electricity generation even more competitive.

In the mid 1990's, the DRAM industry (which supplies memory chips for computers, etc.) went through a similar inflection point. Before the inflection, the industry was based in the U.S. and dominated by many small manufacturers. Factories were modest in capital cost and were used flexibly to manufacture a large variety of semiconductor chips in addition to DRAM's.

In the mid 1990's, several companies in Japan invested heavily to create highly automated DRAM factories. Each factory was completely dedicated to producing only one product and to produce that product in very high volumes: DRAM's. The equipment was specialized

for DRAM's, the manufacturing processes were tuned and tuned again—just for DRAM's—and the operations were tuned for DRAM's. As a result, manufacturing costs came down dramatically and product yields went from under 50% that was typical in the U.S. to over 90% in Japan. By the end of the decade, all U.S. manufacturers had left the business with the exception of Micron Technologies. Micron followed the Japanese companies in building dedicated and highly automated factories. They also petitioned the U.S. government for price protection. Recently, the PV industry has seen the Sharp company in Japan enter the solar panel industry, grow rapidly and take roughly a 50% share of the worldwide market in just a few years. This is clear evidence that the inflection point is near.

In this study, we will present a design for a dedicated, optimized, photovoltaic solar panel factory that is 100x larger than those in existence in 2003. Whereas current factories typically produce about 20 MegaWatts (MW) of solar panels (rated at their peak power), our design will be for a factory that will produce 2.1 – 3.6 GigaWatts (GW) of solar panels (rated at their peak power). Estimated capital costs for these large plants range from \$0.4 - \$0.6 B.

In effect, our factory is a “Solar City”. Steel factories were steel cities that manufactured coke from coal, iron from iron ore and coke, and then steel from the iron ore. Finally, the steel ingots were fabricated into finished products. For our “Solar City” factory, starting with raw materials, each of the components or sub-assemblies necessary for a solar panel will be produced in an on-site, sub-factory with equipment and processes that are sized, dedicated and optimized to produce only PV panels. The factory will be highly automated with significant savings and yield improvements gained by eliminating transportation and handling of sub-assemblies. The large factory will have 100 identical lines, each a clone of the next. This results in substantial savings in capital cost per line and in operations, compared with a small factory that has only one, custom-developed, manufacturing line.

The significant breakthroughs in design concept and manufacturing cost will be presented at high level in the body of this report. The design of the solar factory and of the packaging for simple and inexpensive installation of solar panels will be presented also in two power point presentations that are attached. In all, there are five appendices with additional details and supporting references:

1. Two presentations: one on the design for our “Solar City” factory and one on the design for inexpensive packaging and installation of solar panels.
2. Two case studies of other industries whose products are somewhat similar to PV panels and that have gone through the inflection point to large investments in factories and/or dedicated equipment and processes.
 - Flat panel, TFT Liquid Crystal displays for notebook computers
 - Low emissivity coated glass (a.k.a., low-e window glass)
3. The cost and availability of the thin-film materials required for the layers that convert sunlight to electricity. Presented in spreadsheet form are the designs for three archetype, single junction, solar cells (amorphous silicon, CdTe and CuInGaSe₂), with the amounts of high purity materials needed for each, their costs, and an estimate of the current and potential world-wide supply of these materials.

Design principles for a dedicated, optimized “Solar City” factory

Our purpose is to show the cost savings that can be achieved by creating a factory at a much larger scale than the scale of PV factories today. We have chosen a representative set of technologies that are simple and well characterized. With these simple designs, we were able to estimate the improvements in manufacturing costs as we moved to large-scale manufacturing. We have not attempted to optimize any of the designs—not the substrate, the active layers nor the packaging. We expect that further optimizations from these simple designs will lead to further improvements in cost.

The manufacturing process and cost depend on the choice for the active layer that converts sunlight into electricity. The efficiency by which sunlight is converted into electricity can range from 7% to 15%. This parameter has a large effect on the overall price per watt. There are other impacts, as well, and we have attempted to capture them without creating undue distractions. Our primary purpose is to demonstrate the impact of large-scale manufacturing. This impact is largely independent of the choice of active layer. It is not our purpose to compare the pro’s and con’s for various types of active layers.

Significant improvements in cost per watt can also come from scientific advances in active layers that lead to higher efficiency. But, again, our focus is on manufacturing gains and not on the potential advances in the basic technology.

Our “solar city” factory was designed based on the following principles:

1. Select substrate (or superstrate), packaging and mounting materials that are known to survive for 25 - 30 years on the outside of buildings, exposed to full sun and in all climates of interest. Our choices are the materials used in metal frame windows: sheet glass, coated aluminum and a polymer seal between the sheet glass and the aluminum frame.
2. Minimize transportation & handling; eliminate middlemen. Automate all handling within the factory to improve yields. Use clean tunnels between equipment rather than clean rooms. Thereby, obtain lower costs, less breakage, less cleaning, and higher yields.
3. Dedicate and optimize production for exactly what is needed for solar panels. Improve equipment utilization, process optimization and yields.
4. Use multiple lines of identical equipment with rotating planned downtime for cleaning & maintenance and minimal unplanned downtime. This will reduce the cost of the equipment, and the cost of maintenance and operations.
5. Achieve very high utilization rates for high purity input materials—both to reduce costs and to improve availability of rare materials (e.g. tellurium, selenium and indium).

Discussion—choice of materials

Reliability and long life are keys to the economic success of any PV solar panel system. One cannot recover the cost of solar panels unless they have a long lifetime over which they generate electricity. We have set our goal at 25 - 30 years and looked for materials and examples of products that can last 30 years on a rooftop in all climates of interest. This poses some significant but solvable challenges. The materials must survive UV exposure, temperature cycling, freezing and thawing, high and low humidity, exposure to pollutants, corrosion, hail, high winds, sandstorms and other forces of nature. Nevertheless, several materials and products exist today that could meet these stringent requirements. Obvious candidates are materials and products already used on roofs and south facing walls, such as: shingles, windows (skylights), urethane polymers and silicone polymers. Window glass packaged in coated aluminum frames is a great example of a group of products that survive well in all climates of interest.

We have chosen sheet glass to be our superstrate or substrate for our solar panel factory. Other choices might work just as well. For example, we could use a stainless steel or a polymer substrate with a transparent polymer overcoat through which the sunlight enters the device. However, in outdoor environments, especially for the first surface exposed to sunlight, glass is well known to last—much more than 30 years. Also, when tempered, it has acceptable mechanical strength and can be cheap enough when made in an on-site, dedicated plant at high volume.

Today, 95% of the solar panels produced use either crystalline silicon or cast poly-silicon that is cast into a brick and then sawed into thin wafers (250 - 300 um). These wafers are then processed using standard silicon techniques, interconnected into a string of 36 and then mounted into a sandwich, consisting of glass, a compliant polymer (Ethy Vinyl Acetate or EVA), the interconnected wafers, another layer of compliant polymer (EVA) and finally a back sheet of glass. (Some modules replace the back sheets of EVA and glass with sheets of EVA and Tedlar.) Crystalline or poly-silicon solar panels have been favored because reasonable reliability and lifetime has been easy to obtain.

Unfortunately, this approach uses 500 – 1000 times more silicon than a thin-film approach and only delivers 1.5 – 2x the efficiency of thin-film silicon, CdTe or CuInGa Se₂. Silicon is both expensive and requires a lot of energy in its production.

Today, the solar panel industry is using scrap silicon that is a by-product of the semiconductor industry at a cost of about \$25 per kg. But, consumption for solar panels is approaching 25% of the silicon industry's total production in 2004. Therefore, the cost of silicon for the solar industry is expected to rise to close to \$50 per kg in the next few years, which is the current price for non-scrap silicon.

Even assuming that some “solar” grade of silicon can be created that will only cost \$25 per kg for non-scrap, the authors could not develop a model, even at 30 million sq. meters of panels per year, that would yield a price per installed peak watt of less than \$2.00. Thus, we conclude that for applications where space is limited and high efficiency is critical,

crystalline or poly-crystalline silicon is a good choice. But, for the majority of applications, where the cost per installed peak watt is the critical factor, one of the thin-film approaches is the best choice. Lifetime for thin-film solar panels is one of important technical areas that will need some additional attention. (See our section on technical challenges.)

Discussion—eliminate transportation and handling

The basic input materials for a “Solar City” factory are sand and energy to make sheet glass, small volumes of high purity elements to deposit the thin, active layers, aluminum ingots from which the frame is extruded and barrels of coating material to coat the aluminum. All of these materials are easy to transport, do not easily break, cannot be easily contaminated, and do not require special cleaning. Intermediate products such as sheet glass, aluminum extrusions, and intermediate steps in the deposition and patterning process are exactly the opposite. Transport at these stages is expensive, must be clean, creates yield loss due to contamination and breakage, and requires extra cleaning steps.

Therefore, we have designed the factory to have all of the ‘delicate and sensitive’ intermediate stages completely contained within the factory. Transport within the factory will be over short distances, will be completely automated to reduce yield loss and, will be within clean tunnels to reduce contamination and avoid the need for re-cleaning. This approach has the additional advantage of eliminating middlemen (distributors, wholesalers, retailers and fabricators) with their transportation costs, handling costs, marketing costs, breakage and profit margins.

Discussion—dedicated production

We have designed the factory so that a full scale set of equipment and a well-tuned process can be dedicated to exactly the needs for the components to make a solar panel. Many of components used today for manufacturing solar panels are made in low volumes by job shops that specialize in low volume, custom orders. For example, the amount of sheet glass used by a 20 MW solar plant is about 3.6 days of production for a glass factory. The solar plant can either use standard sheet glass (with iron) that blocks about 15% of the sunlight and reduces conversion efficiency, or they can request that the glass plant shut down, re-load their ovens with low iron glass, operate for 3.6 days, then shut down and re-load again. The cost for this is very high, including the cost of the shut downs and the cost of storing one year’s volume of glass until it is needed. In addition, this special process is never as well optimized as a dedicated process that is run every day throughout the year.

For example, in 2003, the price to a 20 MWp solar panel factory for normal 3 mm thick sheet glass (i.e. with Fe added) that has been processed to seam the edges, coated with SnO₂ and then tempered for mechanical strength is about \$23.60 per sq. meter. This high cost is a direct result of the low volumes required. The sheet glass is manufactured by a float glass plant and then is packed and shipped to a specialty glass finisher, who finishes

the glass. The specialty glass finisher tools up for a short run to cut the glass to the desired size, seam the edges, deposit the sealing layer and the SnO₂ transparent conductor and, finally, heat strengthen or temper the glass. With low volumes, the finisher has the cost to set up the equipment for this short run, and then the cost of take-down. Finally, since even this “short run” represents one year’s consumption for a 20 MWp factory, there is also the cost of packing and storing the glass for one year. These costs are significant and get spread over a very small volume of material.

At high enough volumes, we can create a dedicated, on-site, glass float line to manufacture the raw glass. We also create an on-site, dedicated, post glass finishing equipment line that seams the edges, applies the sealing and transparent conductor layers and, then, finally, tempers the glass for strength. Both the glass float line and the finishing line are operated continuously without the need for set up and take down. Both are optimized for the specific glass needed for solar panels. For only a 10% premium, we can manufacture low Fe float glass that improves the overall efficiency of converting sunlight to electricity by about 15%. We also eliminate packing, shipping, breakage, storage, cleaning, re-cleaning, and handling costs—plus the profits of middlemen.

For sheet glass, made on-site and specifically designed for our solar factory (with low Fe, cut to size, with seamed edges, coated with a sealing layer and a SnO₂ transparent conductor, and, finally, tempered for strength), we would have a price (included profit) of about \$4.62 per sq. meter. This price compares favorably with almost any other substrate or superstrate that one might consider. In addition, it offers a longer lifetime in outdoor environments than any other superstrate that we can produce at this price.

Discussion—identical sets of cloned equipment

Finally, the semiconductor and flat panel display industry have shown the benefit of designing a factory with multiple, identical equipment sets (see the attached appendix on the flat panel display industry). Typically, a plant for flat panel displays will have 3 – 5 identical sets of equipment. We intend to expand this approach one step further. For the design of our factory, we have chosen to use at least 100 identical fabrication and patterning lines (like ‘looms’ in cotton plants).

These factory designs could take the form of 100 long or large, in-line systems similar to the fabrication lines used by PV manufacturers today. Or, they could be clusters of equipment, with many, many identical and independently operated deposition systems, clustered with appropriate numbers of independently operated patterning systems to form a balanced cluster. In the cluster design, if one piece of equipment is inoperable, the cluster can still function, albeit at a slightly lower rate.

The use of multiple, cloned sets of identical equipment offers several advantages:

1. We can expect substantial savings in the cost of the equipment. A standard learning curve model with a learning rate of 0.8 would predict that at a volume of 100 sets of identical, cloned equipment, each would be about 4.4x less expensive

that at a volume of 1. There are many examples of learning curves for various industries and the learning rate is often very close to 0.8.¹ We know that the learning curve model applies well to cost savings in moving from volumes of thousands to volumes of millions. But, the learning rates are often much higher, when one moves from the very first piece of custom designed equipment to a volume of 100.

Most of the cost for a custom designed deposition equipment and for a custom designed deposition and patterning line is the engineering to design, de-bug, re-design, and develop the process for the system. Once the system is working well and the process space has been understood, then, the cost of replicating the system is small compared with the cost of the engineering. The replication cost is only the cost of a metal shop making the deposition chambers and of accessories like power supplies and vacuum pumps. These numbers are highly proprietary and closely held. We were unable to find a manufacturer who would give us their numbers for the record. But, after informal discussions with vendors and subject matter experts we estimate (off the record) that the ratio is typically in the range from 8:1 to 10:1.

For example, a typical thin-film solar panel factory has spent about \$20M in total for their unique, custom-built equipment set². In designing an equipment set that will be replicated 100 times, the non-recurring engineering (NRE) costs of design, process characterization and de-bugging, will be larger, perhaps as much \$30M. Done well, this extra investment will make the replication costs even less. Also, in replicating 100 identical sets of equipment, one can invest in simple tooling for manufacturing and one can buy materials and components in larger quantities.

With a volume of 100 sets of identical equipment, the NRE costs become insignificant and the total cost is dominated by the replication costs. For example, using the unofficial estimates of 8:1, we have:

$$\begin{aligned} \text{Total cost per 100 identical lines} &= \text{NRE cost} + \$2.5 \text{ million per line} \\ &= \$30 \text{ M} + 100 \times \$2.5 \text{ million} \\ &= \$280 \text{ M} \\ &= \$2.8 \text{ M per line} \end{aligned}$$

This represents a cost reduction, per line, of about 7.5x. In the appendices, we substantiate this hypothesis with two examples of industries that have moved from a very small set of custom designed equipment to a larger set of optimized equipment.

¹ For example, see “Facilitating Widespread Deployment of Wind and Photovoltaic Technologies”, by Robert H. Williams, in **The Energy Foundation Annual Report for 2001**, San Francisco, CA. pages 19-30.

² The a-Si factory was \$19.9M. The CIGS factory was \$20.9M. The CdTe factory was less expensive, about \$15.5M. For the purpose of the general discussion, we have used \$20M. For calculating the costs per watt for solar panels with the various active layers, we will use the above numbers.

For the low-e glass industry, in moving from 6 to 40 equipment sets, world wide, the cost per coated volume has been reduced by 3x. This represents a learning curve rate of 0.7. Extrapolating, for our case, with an increase of 100 to 1, we would have a cost decrease of 10x. For the equipment used in the flat panel display industry, the learning curve rates were much more dramatic and would predict cost decreases of at least 10x. Nevertheless, to be conservative, for our cost and capital equipment estimates throughout this study, we will assume a 5x improvement. This number is close to the improvement predicted by a standard learning curve model with a learning rate of 0.8.

Please note: the learning curve is a model that observes and predicts that manufacturing costs will decrease as the cumulative volume increases. With volume, one accumulates experience. The experience, together with investment, leads to better ways to manufacture and therefore, lower costs. Achieving these lower costs will require new equipment designs for this larger scale and the use of higher volume manufacturing tooling and techniques. This will not just happen by itself. It requires a focused development program and significant investment. Please see our section on technical challenges.

2. With identical equipment, the operations can be highly optimized. Maintenance routines are identical. Scheduled maintenance can be rotated so that the factory is always running and only one of many identical pieces of equipment is down at any time. Unplanned downtime can also be handled more efficiently since no single piece of equipment is on the critical path without an alternative.
3. Processes are identical throughout the factory. They can be highly optimized for very high yields (95%) and for low operating cost.

Discussion—achieving high utilization for high purity input materials

We have designed our factory with an on-site material recycling facility, with the goal of achieving 75% utilization of high purity input materials. Small factories cannot afford recycling. It is not cost effective at small scale. But, for a large factory, recycling is profitable.

For some processes, like sputtering or evaporation, utilization tends to be high without recycling—circa 50 - 75%. Standard practice is to add new material to the targets without wasting the material that has been left on the target. On the other, some of the input material is deposited on the shields of the deposition chamber rather than the substrate. With the large substrates needed for solar panels, the amount of material deposited on the shields instead of the panel can be minimized. Even so, some recycling of these materials may improve the utilization even further. For other processes, like PE-CVD process to deposit silicon from silane, the initial utilization is low, circa 10 - 15%, and the recycling process is more complex. (See technical challenges.)

High utilization rates are critical for active layer designs that use rare materials like tellurium, selenium or indium. Otherwise, the world's supply of these materials would be an issue. It is also important for achieving our overall costs. Including the additional cost of the recycling process, our goal is to add less than 10% to the purchase cost of our high purity input materials.

All of the recycling may be done on-site. This has the advantage that recycled material can be returned to exactly the process from which it came and will not pick up impurities from other processes. Alternatively, it may be effective to collect and then ship the recycled material back to the material supplier for one or more process steps. Efficient and low cost recycling is an aggressive goal and is listed in the section on technical challenges.

Discussion—selecting the factory size

Based on the four design principles above, we have selected a design center of 2.1 – 3.6 GW³ for our “Solar City” factory⁴.

- First, this will enable us to take a full-scale sheet glass factory (500 – 600 metric tons of glass per day) and dedicate it to producing low Fe glass with the fabrication tailored for solar panels. It will eliminate almost all shipping, handling, breakage and marketing costs.
- Second, this is 100x times the size of a typical thin-film solar panel factory in the year 2003. This will enable us to realize the cost and other advantages offered by using 100 lines of identical equipment.
- Third, our requirements for fabricated and coated aluminum to package the solar panels (60,000 metric tons per year) will put us at or above the volumes of very large aluminum coaters and fabricators around the world. Again, unlike the fabricators, who must have very flexible production equipment, we will dedicate our fabrication and coating exclusively to the requirements for solar panels.

For a 2.1 - 3.6 GW factory, we do not have enough volume to purify the materials needed for the thin-film depositions. Our materials requirements are in the range from 40 metric tons to 400 metric tons per material. Efficient production facilities are in the range of

³ All power references for PV solar panels are in peak watts. In sunny areas such as California with 270 sunny days per year, solar panels of 4 kW (peak) will generate an average power of about 1kW, when averaged for an entire year over day and night, sunny and cloudy days. Desert areas in the southwest U.S. will be higher, about 1.3 kW.

⁴ The factory design point is at 30 million sq. meters of sheet glass per year. This is the output of a full scale, on-site glass sub-factory. Depending on the choice of the active, thin-film layer, and assuming the use of low Fe glass, the output of the factory in peak watts will be 2.1 GWp for amorphous silicon (7% efficiency), 3.3 GWp for CdTe (11%) and 3.6 GWp for CuInGaSe₂ (12%).

1000 to 2000 metric tons per year. However, these materials are easily transported in bulk at minimal cost (less than 0.5%).

For a 2.1 – 3.6 GW factory, we do have the volumes to recycle materials, where necessary. Recycling will include:

1. Reconditioning sputtering and evaporation targets by adding new material without wasting any of the unused material from previous operation.
2. Removing the shields from the deposition chambers and recovering the input material that was deposited on the shields.
3. Recycling of partially used silane and other input gasses from a PE-CVD silicon deposition process. Techniques exist for recycling silane and should be applicable at the scale for our factory⁵. (See technical challenges.)

Discussion—why not even bigger factories?

For the design principles above, bigger is better. But, there are several factors that might advocate for a smaller size factory. First, would be the capital cost. We understand that the sheet glass factory would have a capital cost of about \$125 M. In PV plants of 2003, a single, 20 MW, deposition and patterning line costs between \$15 M and \$21 M, depending on the choice for the active layer. With a learning curve rate of just under 0.8, one would predict that this cost would come down to \$3 M - \$4 M with a volume increase of 100x. Taking the worst-case numbers, we would have an additional capital investment of \$400 M.

Finally, we have the material recycling for the thin-films and the aluminum extrusion and coating. Aluminum extrusion and coating is not very capital intensive, especially since we are only producing one or two designs. Because the activities for our factory are so specialized, we do not have good estimates. We would guess \$50 M for the aluminum fabrication and less than \$25 M for the recycling.

In total, our “Solar City” factory would require a capital investment of \$600 M. This is a very large investment, but not inconceivable for a large company, ***when the market risk is low***. Semiconductor and flat panel display factories cost well over \$ 1B each. However, reducing this investment is greatly desirable. With a focused development program to lower the cost for each of 100 identical deposition and patterning lines by 10x, we should be able to hit the range of \$125 M + \$200 M + \$75 M = \$400 M capital investment. Please note that this is still a very large investment. The market risk must be low.

The second issue advocating for a smaller factory is the size of the local market. We needed assurance that our 2.1 – 3.6 GW factory will have a market for its product within a

⁵ The simplest process would recycle only the silane used to deposit the intrinsic silicon layer (about 90% of the total used). It could be filtered to remove particles and then chilled to - 20 °C. At this temp, the higher order silanes (e.g. Si₂H₆) will liquefy and can be easily removed. Then, the reconditioned silane + hydrogen can be returned to the deposition chamber.

reasonable transportation distance. As is the case for aluminum frame windows, local factories and local transportation of finished goods are preferred to global transportation. Otherwise, transportation and handling costs can become too large. A single 2.1 GW factory would supply a combination of 0.4 million homes per year with a 5 kW solar rooftop, 4000 installations per year of 0.5 MW on the roofs of large commercial buildings (about 7000 sq. meters of solar panels at 7% efficiency) or 80 installations per year of 25 MW regional power generation stations (600 m x 600 m).

At the 2003 prices of \$6.50 (commercial) to \$8.50 (residential) per installed watt, we would not have these markets. But, at \$1 per installed watt, in states like California (with electricity priced at \$0.10 per kWhr), the breakeven time would be less than 5 years. Then, we would be confident that the market would support several factories of this size in the U.S. It is our vision that with a lifetime of 30 years, an installed cost of \$1.00 per peak watt and assuming 6% interest rates, solar panels will offer a compelling price for generating electricity of \$0.02 - \$0.03 per kWhr. Then, there will be hundreds of our large-scale, 2.1 – 3.6 GW factor modules, located at several places in the U.S. and around the world to meet the demand.

Design details for the dedicated, optimized “Solar City” factory

The “solar city” factory has 5 sub-factories:

1. A sheet glass factory
Major input materials are sand (soda, lime, silica) and natural gas.
Output is cut sheets of 3mm thick, low iron glass with seamed edges, coated with a transparent conductor such as SnO₂, and tempered for mechanical strength.
2. A thin-film deposition and patterning factory to create the active layers
Major input materials are high purity elements.
Output is PV solar panels ready for protective coatings and packaging.
3. A recycling factory to recover high purity elements not deposited on the PV panels and inexpensively recycle them so that they can re-enter the process.
The goal is 75% of the high purity materials delivered to the plant will become part of finished solar panels. Only 25% will be wasted.
4. A packaging factory in which the panels are interconnected, are sprayed with a protective polymer coating to seal them to the environment, are packaged with coated aluminum rails and then are wired at each end for connection to a power converter upon installation on a rooftop.
5. An aluminum fabrication factory that produces the coated aluminum rails for packaging the panels. Major input materials are ingots of aluminum and barrels of coating material. Outputs are extruded and coated aluminum rails that hold the glass solar panels and provide for simple and inexpensive attachment to rooftops.

Sheet Glass Sub-Factory

The sheet glass sub-factory is a set of float-glass manufacturing lines followed by a set of glass processing or finishing lines. For PV solar panels, for low cost, for good sunlight transmission and for inertness at deposition temperatures, the choice of glass is low-iron, soda-lime glass. Compared with normal sheet glass, low-Fe glass transmits about 15% more of the incident sunlight and enables both silicon and CdTe solar panels to operate with an improved efficiency. For window glass, iron is added to make the glass easier to melt. Obtaining low-iron glass at the volumes of a 20 MW factory is very expensive. The total, yearly needs for a 20 MW plant represent only 3.6 days of production for a sheet glass factory. To make the low-iron glass, the manufacturer would have to shut down the line, clean the oven, restart with low iron constituents, run for 3.6 days, shut down again and then restart normal production. Once made, the low-iron glass would have to be stored for a year.

With a dedicated, low-iron, sheet glass plant and a solar panel factory that uses 100% of its output, the incremental cost of low-iron glass is 10%. For low-iron glass, the ovens are

operated at a higher temperature. For normal glass, the ovens are operated for 10 years and then re-lined. For low-iron glass, they must be re-lined every 9 years. Similarly, the low-iron glass requires about 10% more energy to melt it.

Even greater savings are achieved in finishing of the sheet glass. With the small volumes required for a 20 MW plant, sheet glass is manufactured on the float-glass line and then sent to a specialty glass finisher. The specialty glass finisher sets up his equipment and tooling for the requirements of PV panels, runs for a few days and then re-sets for the next job. As a result, equipment utilization is poor and depreciation charges per piece are high. Every job is different; it is difficult to optimize the process and the yields are low.

With on-site, dedicated glass finishing, glass coming off the float line is cut to one size. Very little glass is wasted. All handling is automated and designed for this one size. In an on-line process, the glass edges are seamed (smoothed), a textured SnO₂ transparent conductor is applied by APCVD at high temperature and then the glass is cooled at a controlled rate to heat-strengthen it. Ideally, the glass proceeds steadily down in temperature from molten to cool. No re-heating is necessary for the CVD or for the tempering processes. The finished glass is then moved in clean tunnels directly to the deposition lines. Hence, cleaning is minimized or eliminated entirely.

The price of glass (incl. profit for the glass manufacturer) is estimated as follows:

Low volume glass manufacturing, finishing and storage (20 MWp per year):

Soda-lime float glass	\$10.50
coated with an SiO ₂ sealing layer	
then coated with SnO ₂ transparent conductor	
Packing and Transportation to the finisher	\$ 1.50
Glass Finishing	\$ 5.00
cutting to size, smoothing the edges	
and heat strengthening	
Breakage Losses	\$ 1.00
Profit Margins	\$ 5.62
Total price per square meter	\$23.62

On-site, glass manufacturing and finishing (2.1 – 3.6 GWp per year):

Low iron, soda-lime float glass (with SiO ₂ and SnO ₂)	\$ 3.17
Packing and Transportation	\$ 0.10
Glass Finishing (edges & tempering)	\$ 0.50
Breakage Losses	\$ 0.10
Profit Margins	\$ 0.75
Total price per square meter	\$ 4.62

Deposition and Patterning Sub-Factory

For example, with amorphous silicon based, thin-film technology, as described above, the deposition and patterning factory is designed to have 100 identical lines, each processing 300,000 sq. meters per year. Assuming operation for 7500 hours per year (10% planned and 5% unplanned downtime), the throughput would be 40 sq. meters per hour. If the substrate size is 0.5 meters x 1 meter as depicted in the appendices, then the throughput would be 1 substrate every 45 seconds—or 80 substrates per hour.

There has been much work over the last 10 years to improve the rate at which silicon, in particular, can be deposited using PE-CVD or other techniques, such as hot wire. These improvements would be welcome and would contribute strongly to the efficiency and cost per watt for our 2.1 GW factory. However, our cost models and capital investments make no assumptions of these improvements.

Systems in 2003 that are manufacturing single junction, amorphous silicon, PV solar panels have compensated for the slow deposition rates by making long deposition systems (10 meters or more) consisting of many deposition chambers with the substrates moving through them. The cost of these long systems is included in our estimate for the total line cost in a 20 MW plant of about \$20M. We still expect that in making 100 such lines, we will reduce the cost per line to be in the range of \$2M - \$4M.

The display industry started with long deposition systems, but switched to the cluster design. The clusters were easier to maintain and cheaper to operate. If one part of a long system was inoperable, then the entire line was down. But, if a part of a cluster was inoperable, the cluster continued to operate at a slightly reduced rate. For our factory, as an alternative to a long deposition system consisting of many deposition chambers, each of the 100 lines could have a cluster with 30 or more, short deposition systems. Each deposition system would be short, only a few chambers. Each one would be slow. PE-CVD for silicon deposition is probably the worst case and might take 1000 seconds to coat a sq. meter with a thickness of 0.4 um at 0.5 nm per sec. But, the large number of identical, small and slow systems would result in an adequate coating rate for the line. The line would also include patterning systems that might operate at much higher rates. The ratios of patterning and deposition equipment would be balanced to achieve the overall production rates for each line.

Please note that for the purpose of this study, we expect to reduce the cost of these systems rather than focus on possible improvements in their productivity. However, any productivity breakthroughs would be a welcome upside.

Patterning is an area where additional R&D could yield some additional gains. In the flat panel display industry, patterning on large glass panels (2 meters by 3 meters in the latest generation) is accomplished by modifications of conventional semiconductor techniques. A typical process is: deposit a layer of material, apply a layer of photo-resist, expose a pattern using optical projection, develop the resist, and, finally, etch the pattern using either wet chemical or plasma etching.

The PV industry already recognizes that PV solar panels need little patterning (i.e., most of the total area is not patterned). In addition, the feature resolution required is only about 200 μm . Today, various companies are using laser ablation techniques to pattern a solar panel into a series connection of about 25 - 50 diodes. Combinations of laser ablation and printed materials may offer additional cost savings and yield improvements. The goal is to have no wet chemical processing. Research groups at NREL and in other companies around the world are working on these techniques under the general subject area of: Printed Electronics.

Sub-Factory for Recycling of thin-film materials

Our goal is to achieve high utilization of high purity input materials used to create the active layers. For CdTe or CuInGaSe₂ active layers, the deposition processes start with good utilization rates, approaching 50%, and sometimes better. Nevertheless, since the input materials (e.g., Te, Se and In) are expensive and/or rare, we would like to drive this number up to at least 75%. For these active layers, the recycling process has two components:

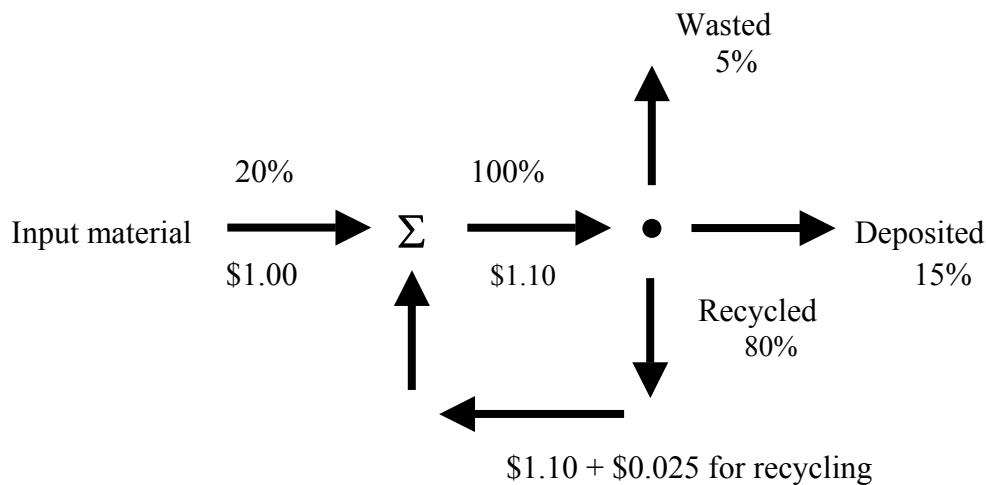
1. Recondition sputtering or evaporation targets by heating the target and then adding new material onto the old. If a printed ink or slurry can be used for the initial depositions, then this step will be unnecessary.
2. Reclaim material that is deposited on the shields of the deposition chamber, by stopping the system, removing the shields and then, using either a chemical or electrochemical process to recover the input material.

For a silicon active layer, the commonly used PE-CVD deposition process has a low utilization rate—typically less than 15% of the input silane is used. In addition, as above, some of the material is deposited onto the shields instead of onto the substrate. For a silicon active layer, the recycling process would include the two steps above, plus:

3. Reclaim input gasses, such as silane, that are only partially utilized during the deposition process. The technology to recycle silane exists, but has not been applied to present day factories due to the low volume of consumption⁶. The key issues are to remove the long chains of higher-order silanes that form in a plasma and to remove impurities that leak into the deposition chamber. Silane gas mixtures used to deposit intrinsic silicon, p-type silicon and n-type silicon must be recycled separately.

Finally, the total cost of the material used is very sensitive to the cost of recycling the wasted material. For example, for the case of recycling silane:

⁶ For possibilities for silane recycling, contact John P. de Neufville, president of Voltaix.....



The model above accomplishes our goals of 75% material utilization and of adding less than 10% to the cost of our materials. But note that the cost of recycling must be very low, less than 2.5% of the cost of the input material. Therefore, the recovered material must require only the slightest processing.

Re-conditioning a sputtering target by heating it and adding new material is a good example of a very low cost recycling process. Recovering material from the deposition chamber shields requires more processing and therefore, presents more of a cost challenge. Finally, recovering silane with very low additional cost is the most challenging. Because the recycling must be accomplished at a very small fraction of the cost of purifying the material initially, recycling is a technical challenge and is listed in the section on Technical Challenges.

Without recycling, the cost per watt for the panels would increase by the following:

Active Layer Material	Utilization without recycling	Cost per sq. m at 75% utilization	Added cost per watt
amorphous silicon	10%	\$ 0.13	\$ 0.01
dual-junction silicon	10%	\$ 1.17	\$ 0.06
CdTe	50%	\$ 2.31	\$ 0.01
CuInGaSe ₂	50%	\$ 9.31	\$ 0.04

In assessing the value of recycling, we need to compare these numbers against the total cost of \$ 0.15 per watt for an unpackaged panel. The increased costs for single-junction, amorphous-silicon, and for CdTe panels are small—only about one cent per watt. But, as we see above, one design for a dual-junction silicon cell with a thick layer of micro-

crystalline silicon⁷ would use up to 9x more silicon and would be more strongly affected. Only for CuInGaSe₂ and the dual-junction silicon active layers would recycling be essential based on cost⁸. However, for CdTe and for CuInGaSe₂, the most critical issue is not only the increase in cost, it is the availability of several of the materials. At a volume of 30 million sq. meters per year (3.3 - 3.6 GWpeak), recycling is critical for an adequate supply of rare materials like indium, selenium and tellurium⁹.

Packaging Sub-Factory

The packaging is designed to be inexpensive, provide a 30-lifetime in all climates of interest and allow for trivial installation. All assembly and interconnection is done at the factory where tools and scale facilitate low cost and high yield. The large volumes should make it possible to automate the assembly process entirely. In the assembly process, finished solar panels are assembled into groups totaling 2.5 sq. meters.

First, the panels are mounted into coated aluminum rails and sealed into the rails with a polymer that fits between the glass and the aluminum—just like window glass is sealed into coated aluminum windows. Next, each panel is interconnected to its neighbor with either an aluminum foil or a dozen short wires distributed along the width of the panels. Rather than use connectors, the foil or wires are welded directly to the metal layer of the thin-films. Next, long, #20 gauge stranded aluminum wires are attached to the ends of the assembly that will connect the assembled panel over a distance of up to 6 meters to a power converter¹⁰. Finally, for amorphous silicon or CdTe solar panels, the back surface of the panel is coated with a spray-on, polymer, sealing layer that protects the thin-films from corrosion in an outdoor environment. For CuInGaSe₂, the sealing layer is applied to the front surface and must also be highly transparent and stable under strong exposure to sunlight and ultra-violet.

The design presented in the appendix is intended to be illustrative of the possible packaging costs at high volume. We have made no attempt to optimize the design for packaging cost vs. ease of handling. There are many packaging alternatives.

First, the solar panel could be designed to be a single sheet of glass, 0.5 m x 5 m. This would eliminate the interconnections between the small sheets of glass. The disadvantages would be lower yield and the difficulty of processing a long and narrow sheet of glass.

⁷ See “Intrinsic Microcrystalline Silicon: A New Material for Photovoltaics”, Vetterl, et. al., **Solar Energy Materials and Solar Cells** 62 (2000) 97 – 108. The authors report a dual-junction cell with 320 nm of a-Si:H as a front cell and 3.2 um of uc-Si:H as a back cell. The combination is 9x thicker than a convention single junction a-Si:H cell. The reported efficiency is 12% in the lab.

⁸ See appendix on the design of a factory for detailed material costs for a-Si, CdTe and CuInGaSe₂.

⁹ See appendix on the materials requirements and worldwide availability for each material.

¹⁰ See appendix on packaging and installation.

Second, the assembled panel could be shorter—maybe 3 meters long instead of 5 meters. Shorter panels might be easier to handle and easier to lift up onto a roof, but they require more connections to the power converter. Also, the packaging costs would increase slightly, by about 4%. Today, homebuilders use special trucks to transport pre-fabricated roof joists that are more than 6 meters long. Each truck includes a small crane that lifts bundles of joists onto the roof. A similar approach might favor a panel length of 5 meters rather than 3 meters.

Third, the panels could be the same area, but more square. This might make them easier to handle. But, when mounted at an angle on a flat roof, they rise further off the roof and might be more susceptible to wind damage.

Finally, the assembled panel could use two sheets of glass, one for the front surface and one for the back, with a polymer, sealing layer in between. The development of a sealing layer should be easier than a back coating layer and much easier than a front coating layer. The first disadvantage of this approach would be the cost of the second sheet of glass. It would not require low Fe glass and would not have to be coated. But, it would require edge seaming and tempering. This second sheet of glass would have a price (including profit) of about \$3.65 per sq. meter and would add \$0.03 - \$0.05 per watt to the panel manufacturing cost. The second disadvantage would be weight. A 0.5m x 5m packaged panel weighs about 50 lbs. A second sheet of glass would increase that weight to about 90 lbs. A 4 kW system on a roof would then be 1800 lbs plus the weight of the power converter.

The process for welding aluminum foil or wires directly onto the thin-film metal layer is an area that requires development and is listed in the section on Technical Challenges later in this report. The spray-on polymer most likely will be derived from urethanes, silicones or other polymers that will withstand outdoor environments and offer protection to the thin-films against humidity and pollutants. The spray-on polymer for the back surface is less demanding. It can be opaque and will not experience much, if any, exposure to ultra-violet light. The front surface coating is technically much more difficult to develop. It must be highly transparent and will be exposed to strong ultra-violet light. It is required for CuInGaSe_2 , and also is required for any PV product made on a non-transparent substrate (e.g., polyimide or stainless steel). The development of the spray-on, protective, coating is also listed in the section on Technical Challenges.

Sub-Factory to extrude and coat aluminum

The aluminum rails, into which the solar panels are mounted, are made on site. Ingots of aluminum are simple and inexpensive to transport. Barrels of the materials to coat the aluminum are also simple and inexpensive to transport. Aluminum rails are awkward to transport and more easily damaged. Raw aluminum is \$.60 per pound. Extruded rails, coated and cut into 6 meter lengths cost about \$ 1.38 per pound (as quoted in large lots by a large aluminum fabricator). Part of a fabricator's price reflects the versatility of the equipment in their shop to handle the diverse requirements of their customers. Another

part is the packaging, shipping and handling of the thin, long rails so that they will not be damaged in transit. Finally, another part is the fabricator's gross margin.

This sub-factory will also make the mounting stands used on flat roofs to mount the panels at an angle to the roof and secure them in high winds. There are many possible designs for the mounting stands. One design would use extruded aluminum rails or tubes that are welded together and then coated.

We used the quoted price of \$ 1.38 per pound for the coated aluminum rails in our cost estimates for packaging the solar panels. We do not have access to the internal costs of an aluminum fabricator. On the other hand, this sub-factory will have only two products: the rails to package the panels and the mounting stands for mounting the panels at an angle onto a flat roof. With only two products, each produced in volumes at or above the volumes of a fabricator, we would expect that the price for coated, extruded rails will be lower than the quoted price of \$ 1.38, perhaps as low as \$1.19. This would take \$.03 off the price for 7% efficient panels and \$.02 off the price for 12% efficient panels.

Price model to achieve \$1 per watt for installed solar panels

A model summarizing the manufacturing cost and building the total installed retail (or contractor) price is presented below. All the numbers are derived in the two appendices on the Solar Factory and on the Packaging of Solar Panels.

	Price per watt		
	7% a-Si	11% CdTe	12% CuInGaSe ₂
Basic pricing model for a 6 kW roof installation			
Panel Price¹¹			
Panel Cost			
Substrate	\$.071	\$.045	\$.041
Active layer			
depreciation and operations	\$.065	\$.034	\$.038
thin-film materials (75% utilization)			
amorphous silicon single junction	\$.005		
CdTe single junction		\$.023	
CuInGaSe ₂ single junction			\$.083
Packaging of panels ready for installation	\$.161	\$.103	\$.094
Manufacturer's gross margin (50%)	\$.300	\$.210	\$.260
Total Panel Price per watt	\$.60	\$.42	\$.52
Installation Price¹²			
Power converter (wholesale cost, 225 v dc in, 220 v ac out)	\$.120	\$.120	\$.120
AC wiring (220 volt, 30 amp, breaker, disconnect, conduit, 2 hrs labor)	\$.027	\$.027	\$.027
Installation (approx. 4 hours labor at \$75 per hour)	\$.050	\$.033	\$.030
Retailer's total gross margin (20%)	\$.200	\$.150	\$.180
Total Installation Price per watt	\$.40	\$.33	\$.36
Total price per watt at retail			
or from a contractor (for an installed system on a sloped roof)	\$ 1.00	\$.75	\$.88
Mounting pedestals (only required for flat roofs)	\$.050	\$.033	\$.030
Total price per watt at retail			
or from a contractor (for an installed system on a flat roof)	\$ 1.05	\$.78	\$.91

¹¹ These numbers include the effect of an overall process yield of 93%. Efficiencies include the enhancement obtained by using low Fe glass for a-Si and for CdTe superstrates.

¹² These numbers are for residential installation of a 6 kW solar system. Commercial installation of a much larger system, 0.5 MW, should result in lower costs for the power converter, the AC wiring and the installation. Overall, the price might be lower by \$0.06 per watt.

Technical challenges and opportunities for focused investment

There are several technical challenges noted in the appendices and summarized here. We do not believe that any of these require a new invention. But, we do believe that it will take a focused and significant investment in R&D to solve them.

Cornerstone Challenges—critical to success

1. Design of the deposition and fabrication lines so that they can be replicated 100 times for a capital cost of \$2M - \$4M each (or less). Design must include simple maintenance, automatic measurement and feedback control to keep the process parameters within acceptable limits, automated handling and operations, and high machine uptime (7500 hours per year).
2. Development of an inexpensive, spray-on polymer that can be used to seal the solar panels and protect them from the environment, and especially from penetration of water vapor, in all climates of interest, after completing the welding of the interconnects and wires to the panel. For amorphous silicon and CdTe, this will be a back coat. It can be opaque and will not receive much ultra-violet exposure. For CuInGaSe₂, the protective coating must be highly transparent to sunlight and will receive full ultra-violet exposure.

An alternative would be to use front and back sheets of glass with a sealing layer in between that protected the panels from the environment. Edge sealing is somewhat less demanding of the sealing material than a back coating, and much less demanding than a front surface coating. The first disadvantage would be the high cost of the second piece of glass (\$3.65 per sq meter or \$ 0.03 - \$0.05 per watt). This would increase the manufacturing cost by about 15%. The second disadvantage would be the additional weight. The weight would roughly double to about ½ lb per watt.

Additional important challenges

3. Recycling of high purity thin-film materials to achieve 75% utilization without incurring more than 10% additional costs over the cost of the material, initially. This should be routine for materials like CdTe or CuInGaSe₂ that can be printed from inks, slurries, evaporated or sputter deposited. The key issue will be to recover material from the chamber shields. For silicon, the key issue is to recycle unused silane. Techniques exist for re-cycling silane, but have not been implemented for solar panel depositions.
4. Development of dry, atmospheric, low-cost patterning using laser ablation and/or printed electronics techniques to achieve low cost and high yield.
5. Development of a welding technique to reliably attach aluminum foil and wires to a thin film of aluminum on the panels. Key issues are corrosion under steady dc current and mechanical strength.

6. Design of the automated transport to move the panel within and between the “Solar City” factories.
7. Development of low-cost mounting assemblies for mounting solar panels on a flat roof or on the ground with good resistance to high winds and with 30-year lifetime in all climates of interest.
8. Study of the durability of the active layers under conditions of steady dc current with various choices for transparent conductors and metal interconnects. Key issues are cathodic or anodic corrosion and possible de-lamination under outdoor conditions.
9. Development and acceptance of new building codes for 225-volt dc systems on rooftops.
10. Technology-specific issues for each thin-film option:
 - a. **Amorphous Si**
 For generation 1, develop PE-CVD deposition equipment to meet the cost goal of \$2 - \$4 million per deposition and patterning line.
 For generation 2, and for achieving further cost reductions, develop 10% efficiency (currently at 7% on low Fe glass for single-junctions) using improved light trapping¹³, combinations of amorphous and micro-crystalline silicon or a-Si and a-SiGe. Improve deposition rates to 0.5 – 1.0 nm per second.
 - b. **CdTe**
 For generation 2, make thinner layers with light trapping to lower materials costs (down to 1 micron or less).
 - c. **CuIn(Ga)Se₂**
 For generation 2, make thinner layers with light trapping to lower material costs. This may require an alternative seed layer, since Mo has very poor reflectivity (50%). Thinner layers can lower the installed price per watt by as much as \$0.17 from \$0.88 to \$0.71. Possibly use Cu/In inks to replace sputtering or evaporation to raise materials utilization efficiency and reduce feedstock costs (avoiding sputtering or evaporation targets); developing recycling for targets, if their use is maintained.
 - d. **All**
 - i. Incorporating cheap, process & materials controls—specific in-line diagnostics and controls for yield and a tight distribution of product quality (for cost and yield).
 - ii. Assuring outdoor reliability with innovative and low cost packaging schemes and module/panel/mounting designs.

¹³ *High-efficiency amorphous and “micromorph” silicon solar cells*, J. Meier, et. al., University of Neuchatel, to be presented at WCPEC-3 (Osaka, May 11 – 18, 2003).

Summary

We have created a design for a “Solar City” factory that will process 30 million sq. meters of glass panels per year and produce 2.1 – 3.6 GW of solar panels per year—100x the volume of a typical, thin-film, solar panel manufacturer in 2004. We have shown that with a reasonable selection of materials, and conservative assumptions, this “Solar City” can produce solar panels and hit the price target of \$1.00 per peak watt (6.5x - 8.5x lower than prices in 2004) as the total price for a complete and installed rooftop (or ground mounted) solar energy system. This breakthrough in the price of solar energy comes without the need for any significant new invention. It comes entirely from the manufacturing scale of a large plant and the cost savings inherent in operating at such a large manufacturing scale.

At the price of \$1.00 per peak watt for a complete and installed system, the payback time in states like California is under 5 years. Therefore, we expect the demand for solar energy systems to explode. At this price, there will be demand for small solar energy systems installed on residential rooftops (4 – 6 kWp each), much larger systems on commercial rooftops (0.5 MWp each) and even larger systems for the wholesale generation of electricity at competitive wholesale rates (10 – 100 MWp each). With a 30 year lifetime, assuming 6% interest, a solar farm costing \$1.00 per peak watt installed will generate electricity at \$0.02 per kWhr in the southwest desert and \$0.03 per kWhr across much of the U.S. Eventually, we envision hundreds of these “Solar City” factories distributed across the U.S. and around the world to serve local markets.

Finally, we have developed a list of key technical challenges that must be addressed to make this possible. None appears to require a new invention, but focused R&D investments in these areas for a few years will be necessary.

List of Appendices

- Appendix I Optimized, Large Scale, Solar Panel Factory
- Appendix II Inexpensive Packaging and Installation for Solar Panel
- Appendix III Case Study: Flat Panel Display Industry
- Appendix IV Case Study: Low-emissivity glass industry
- Appendix V Thin-film Materials Cost and Availability

Appendix I – Optimized, Large Scale, Solar Panel Factory

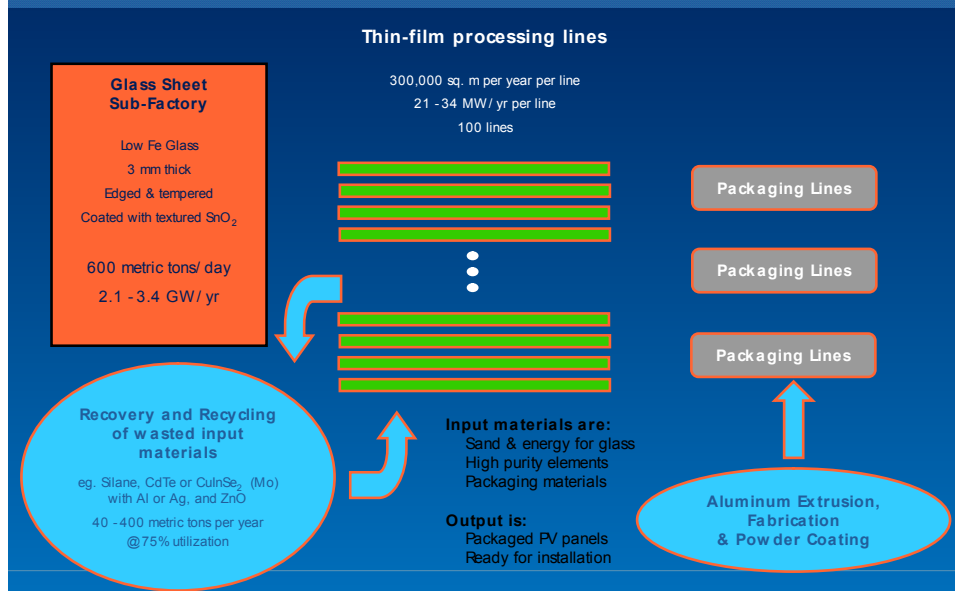
Appendix I Optimized, Large Scale Solar Panel Factory

Designed for \$1.00 per (peak) watt
total installed system price

2.1 - 3.6 (peak) GW per year
30 million square meters per year
1/2 million residential rooftops per year

Marvin Keshner and Rajiv Arya
September 21, 2004

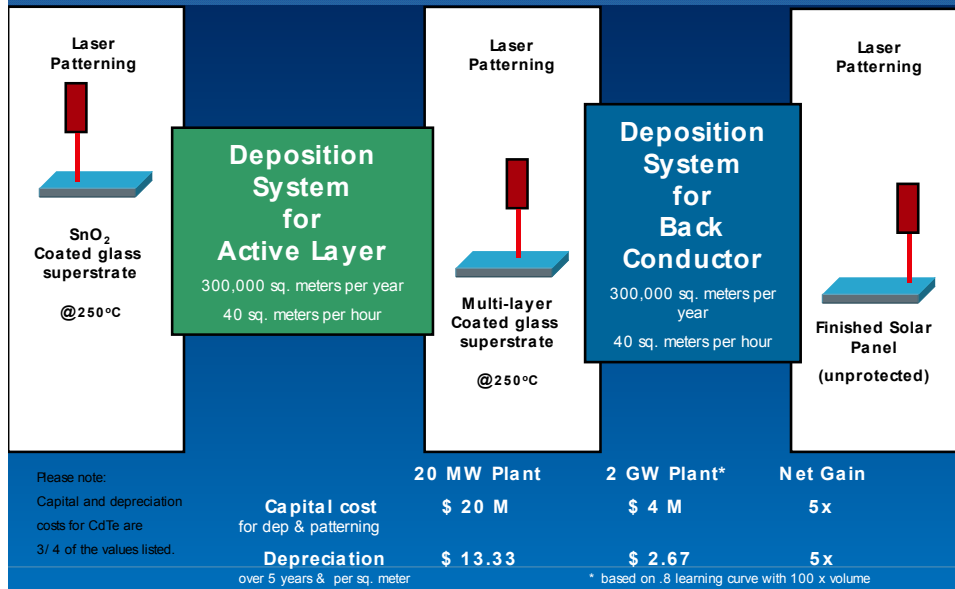
Factory Design for low cost PV panels 2.1 - 3.6 GW per year



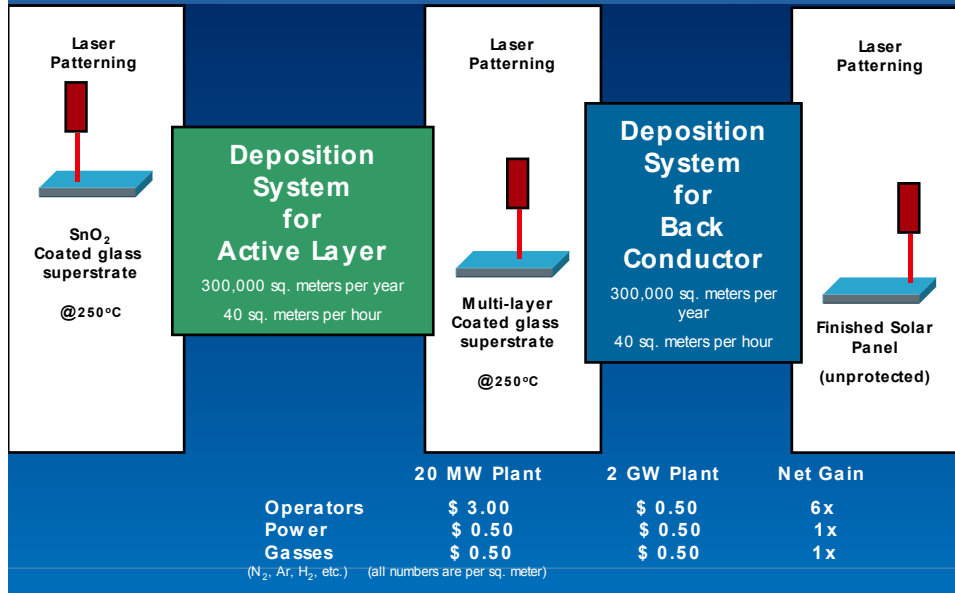
Glass Sheet Sub-Factory



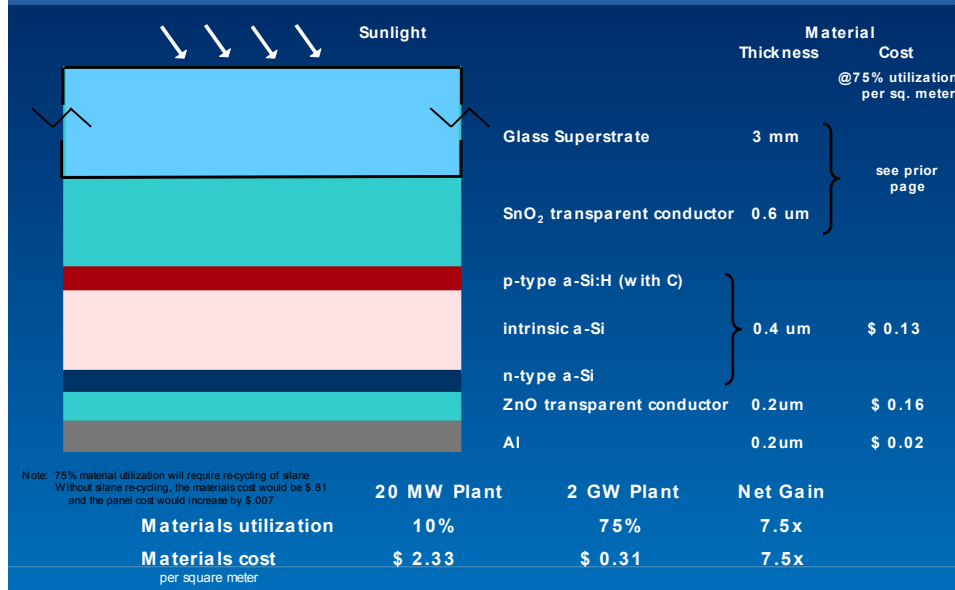
Deposition, Patterning, Vias and Interconnect Capital and Depreciation costs



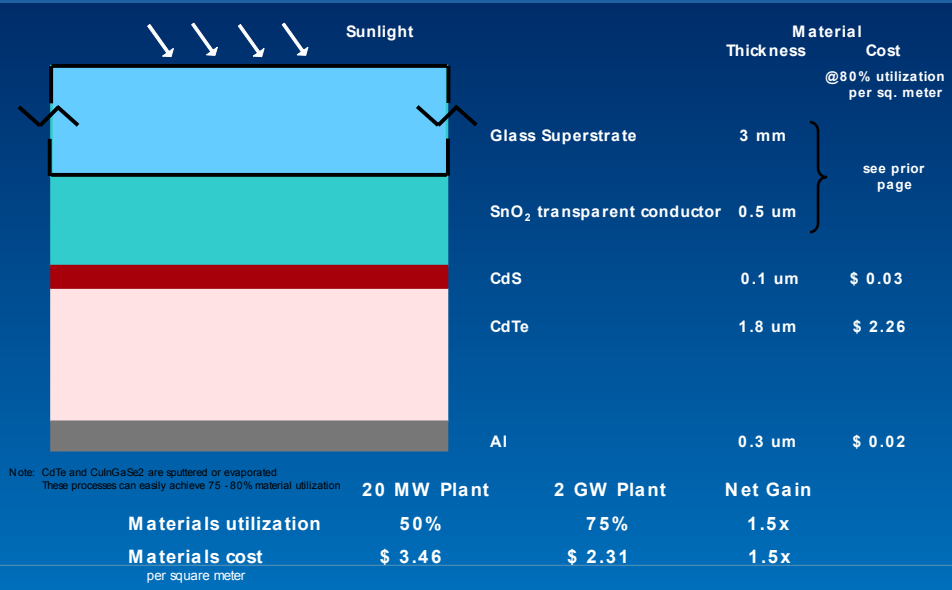
Deposition, Patterning, Vias and Interconnect Operating costs



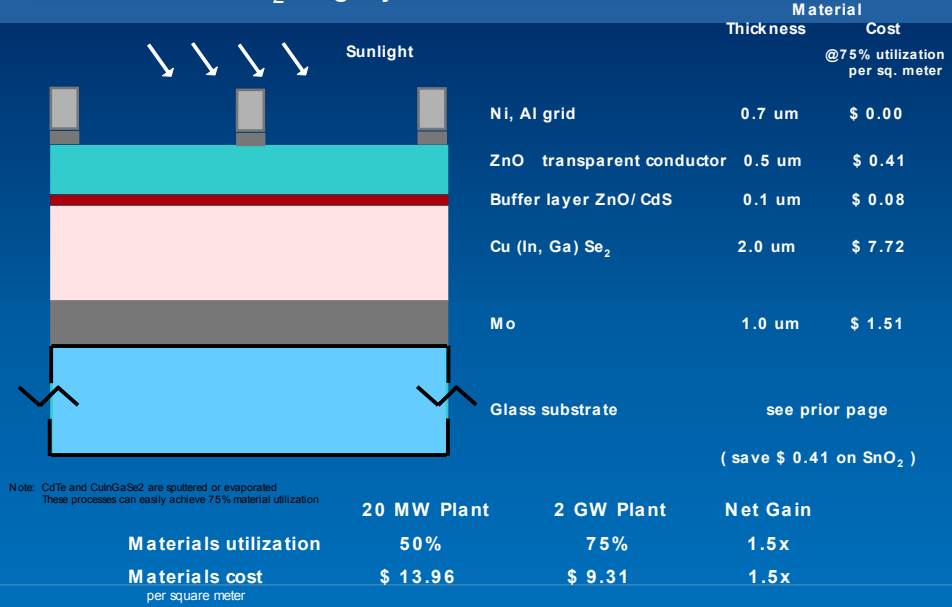
Materials for Active layer and Back Conductor for amorphous Si single junction cell



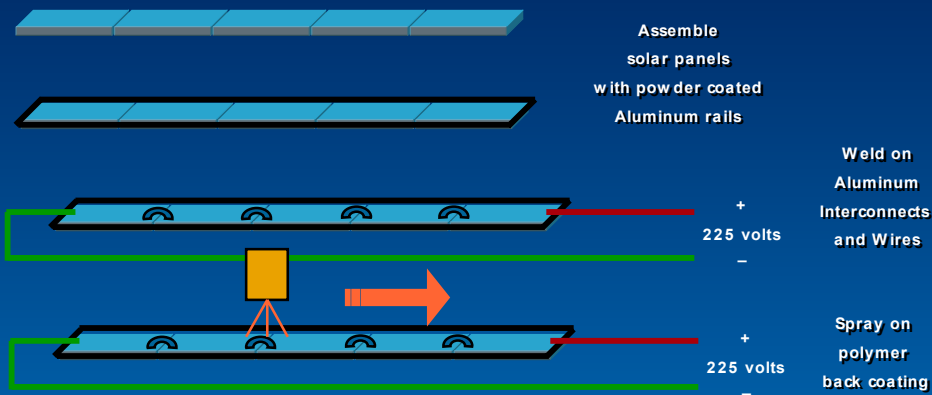
Materials for Active layer and Back Conductor for CdTe single junction cell



Materials for Active layer and Back Conductor for CuInGaSe₂ single junction cell



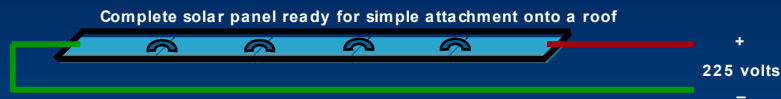
Packaging and Final Interconnect (Si or CdTe)



Note: for details, see appendix on Packaging Solar Panels.

	20 MW Plant	2 GW Plant	Net Gain
Packaging and Interconnect cost per sq. meter	\$ 41.71	\$ 10.50	4x
	(savings from high volume materials and automated assembly)		

Solar Factory Module Cost Comparisons for Completed Solar Panels



Cost Summary	20 MW Plant	2 GW Plant	Net Gain
(all numbers are per sq. meter)			
Coated Glass	\$ 23.62	\$ 4.62	5 x
Operating Expenses	\$ 4.00	\$ 1.50	2.5x
Materials and depreciation			
a - Si	\$ 2.33 + \$ 13.35	\$ 0.31 + \$ 2.67	5x
CdTe	\$ 3.46 + \$ 10.00	\$ 2.31 + \$ 2.00	7.5x
CuInGaSe ₂	\$ 13.96 + \$ 13.35	\$ 9.31 + \$ 2.67	7.5x
Assembly, Packaging & Interconnect	\$ 41.71	\$ 10.50	4x
Overall process yield	60 %	93 %	1.55x

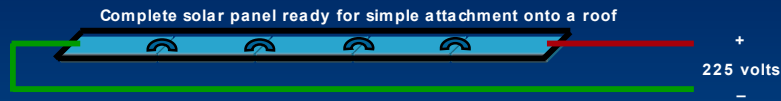
Total manufacturing cost per watt

a - Si	(7%)	\$ 2.02	\$ 0.30
CdTe	(11%)	\$ 1.25	\$ 0.21
CuInGaSe ₂	(12%)	\$ 1.34	\$ 0.26

Notes: If CdTe and CuInGaSe₂ could use effective light trapping and be reduced in thickness to 0.4 um like a-Si, then their cost per Wp would be \$.19 and \$.19, respectively.
If a-Si could use a second junction of a-SiGe or uc-Si, its efficiency would be circa 10% and its cost per Wp would be \$.21.

Solar Factory Module

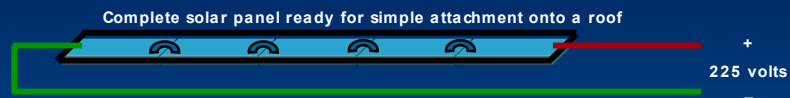
Cost Comparisons for Total Installed Solar System



Cost Summary (all numbers are \$ per watt)	20 MW Plant	2 GW Plant	Net Gain
Solar Panel Manuf Cost			
a - Si	\$ 2.02	\$ 0.30	7x
CdTe	\$ 1.25	\$ 0.21	6x
CuInGaSe ₂	\$ 1.34	\$ 0.26	5x
Manufacturer's margin	\$ 1.75	@50%	6x
Sub-total for panel	\$2.90 - \$3.75	\$0.42 - \$0.60	6x
Power Converter (wholesale)	\$ 0.40	\$ 0.12	3.3x
Complexity and cost of installation	Medium to High \$ 1.20 - \$2.50	Very low \$ 0.10	12 - 25x
Retailer's or Contractor's Margin	\$ 1.40 - \$2.10	\$ 0.18	8 - 12x
Total Installed Price	\$ 6.50 - \$ 8.50 (2004 market price)	less than \$ 1.00	7x

Solar Factory Module

Technical Challenges



• Technical Challenges

- design deposition and patterning lines
 - minimal planned downtime; 8000 hours per year operation
 - very high yield approaching 95%
 - low system replication cost: 20% of a custom system
 - low facilities costs: minimize need for clean rooms
 - highly automated; feedback to control processes; minimize operator and operations costs
- develop low cost, spray-on polymer coating to seal panel
- for silicon, re-cycling of silane to achieve 75% utilization
 - use the large volumes to achieve low cost of recycling

Appendix II -- Inexpensive Packaging and Installation for Solar Panels

Appendix II Inexpensive Packaging and Installation for Solar Panels

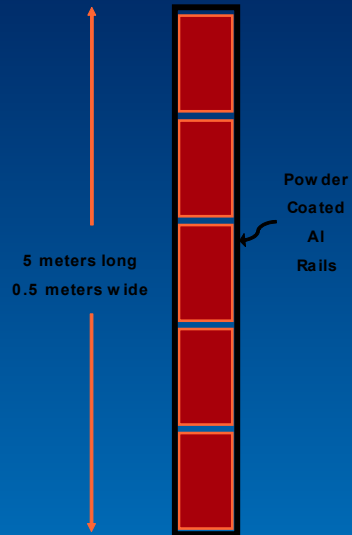
-- Marvin Keshner and Rajiv Arya
September 21, 2004

Basic Packaging Concept

- **Use the technology developed for metal frame windows**
 - powder-coated aluminum frames
 - rubber-like polymers to seal the glass into the aluminum frame
 - windows are mechanically strong and capable of surviving tough outdoor environments for 30 years
- **Use an on-site, large scale factory to reduce costs**
 - dedicated to manufacturing one simple product at the lowest possible cost
 - extrude the aluminum, powder coat, fabricate and then assemble
- **Assemble the product in the factory**
 - minimize assembly in the field to keep installation costs low

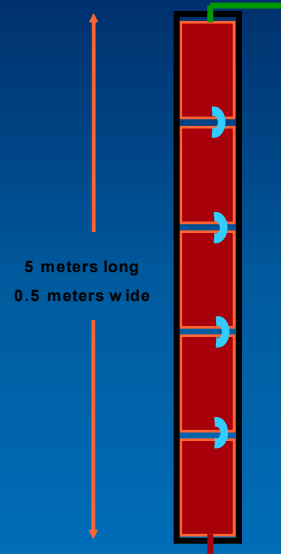
Basic Packaging Concept

- **PV panels 50 cm x 100 cm**
 - back coated with a spray-on polymer for an environmental seal
- **Avoid connectors**
 - they are expensive, unreliable and vulnerable to corrosion
 - use factory welded wires instead
- **Assemble 5 panels together**
 - 225 volts @ 0.8- 1.4 amps
 - Powder-coated Al rails hold panels and attach directly to roof

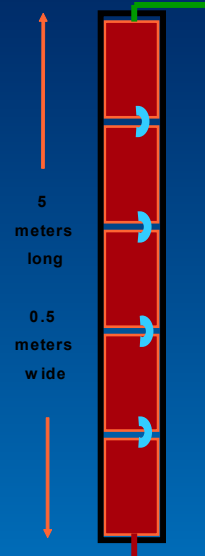
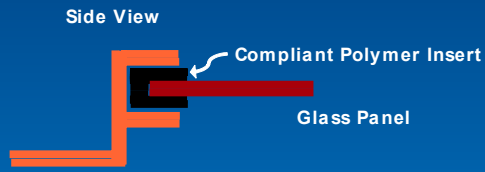


Interconnects

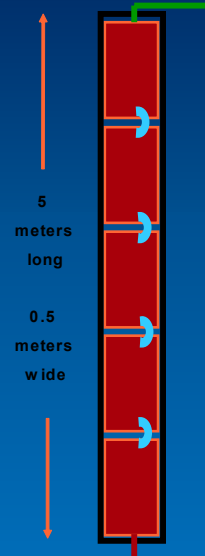
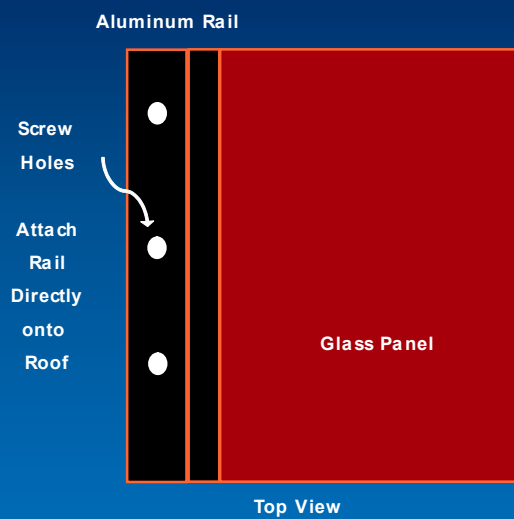
- **Weld Aluminum wires to interconnect the 5 panels**
 - either many thin, insulated Al wires distributed across the 0.5 meter width
 - or, a thin sheet of insulated Al foil 0.46 meters wide and 4 mils thick
- **Weld insulated, stranded Al wire on the ends that connect directly to the power converter**
 - # 20 gauge, stranded Al
 - insulated for 300 volts, 0.8 - 1.4 amps
 - 7.5 meters long at one end
 - 12.5 meters long at the other end



Aluminum Rails -- Detail

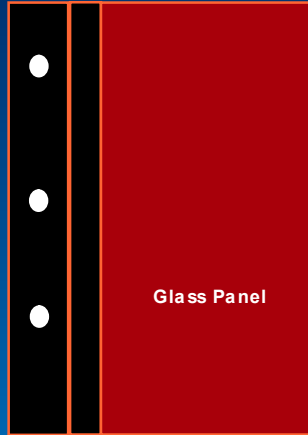


Installation Detail for a 30° sloped roof



Installation Process for a 30° sloped roof

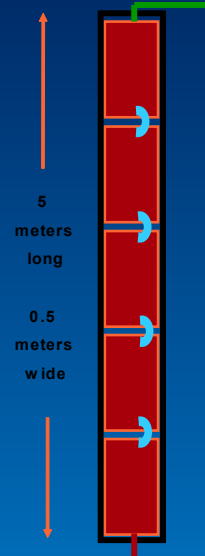
Aluminum Rail



Top View

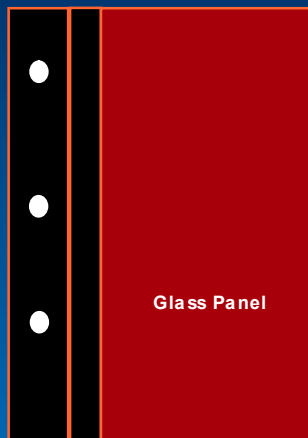
Installation Process

- hoist panel assemblies onto roof (50 lbs each)
- position on roof
- attach to roof with screws every 12 - 18"
- mount power converter
- attach wires from panels to power converter
- connect power converter output to 220 V AC



Installation Process for a flat commercial roof

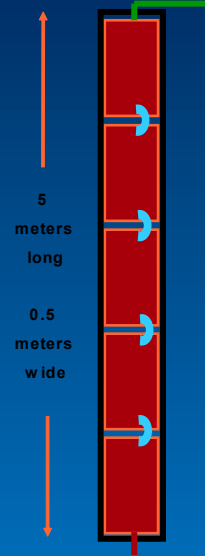
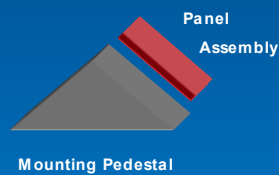
Aluminum Rail



Top View

Installation Process

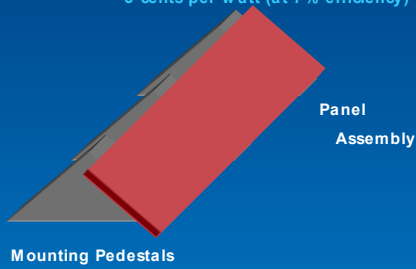
- hoist panel assemblies onto roof (50 lbs each)
- position on roof
- position 3 mounting pedestals approx. 1.5 meters apart
- attach mounting pedestals to roof with screws
- attach panels to mounting pedestals with screws
- mount power converter
- attach DC wires from panels to power converter
- connect power converter output to 220 V AC



Mounting Pedestal for Solar Farms and Flat Roofs

Solar Farms

- Ground level installation
- Concrete pedestals; 165 lbs each
- Concrete cost: \$50/m³
- 30 degree angle
- 60 cm x 70 cm x 35 cm and 30 cm thick
- .032 cubic meters per pedestal
- \$5 for 3 pedestals
3 cents per watt (at 7% efficiency)



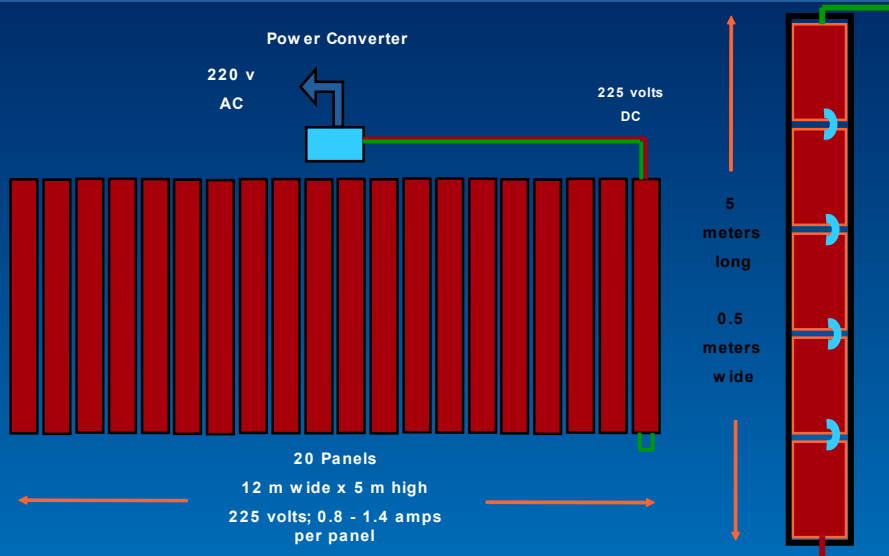
Flat Roofs

- Minimize weight; attach to roof
- 3 pedestals; Tetrahedron in shape
- 30 degree angle
- each beam is a powder coated aluminum 2.5cm x 2.5cm x 3mm angle iron 1.4 sq. cm in cross section
- total length = 35 cm x 3 + 60 cm x 3 = 285 cm
- weight approx. = 2 lbs each
- \$8 for 3 pedestals
5 cents per watt (at 7% efficiency)



Note: Cost of pedestals will be included as part of the installation cost

Example Installation for a 3.5 - 6 kW roof top system



Total Packaging Cost

- **Simple Al extrusion**

- 5 kg or 11 lbs total
- \$1.18 per lb for Al extrusion (* quote) \$13.00
- \$0.20 per lb of Al for powder coating (* quote) \$2.20
- \$0.07 per foot for polymer insert 36 ft. \$2.55
- 5 minutes assembly (\$30 per hour) \$2.50
- Total = \$20.25

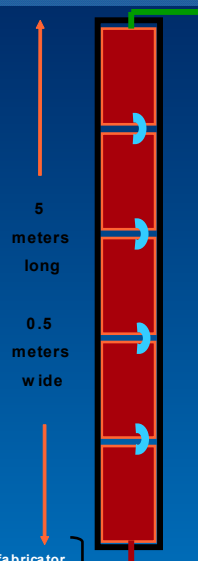
- **Wires and spray back coat**

- 20 meters #20 stranded Al (\$3.00 per lb) \$0.45
- 6 welded interconnects \$3.00
- spray-on polymer back coat (\$1 per sq m) \$2.50

- **Total Packaging Cost \$26.20**

- \$0.15 per watt for 7% efficiency panel

* Quote from an aluminum fabricator
On-site manuf would be .8x the cost



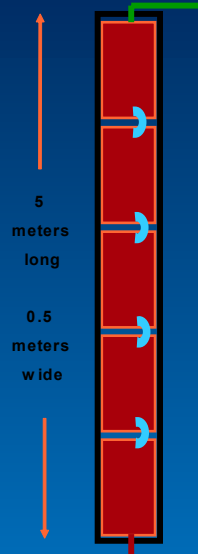
Challenges

- **Technical Challenges**

- Inexpensive spray polymer back coat for Si or CdTe active layer and front coat for CuInSe_2 active layer
- Corrosion induced by steady DC current through a stack of dissimilar materials
- Welding technique for attaching Al wire or foil to thin-film Al on panels
- Design for wind tolerance and for 30 year lifetime

- **Engineering issues to solve**

- Protect integrity of roof
 - avoid creating ice dams
 - avoid holding wetness next on roof
 - avoid water channels via screws through the roof
- Building codes for high voltages on roof
- Design and manufacturing for mounting pedestals



Appendix III – Case Study

The Thin-Film-Transistor Liquid Crystal Flat Panel Display Industry goes through its inflection point

based in part on an interviews with
Larry Hubby
Hewlett-Packard Labs
hp's expert on the display industry

Bob Myers
Hewlett Packard
Notebook Computer Business

Introduction

The TFT, liquid crystal, flat panel display industry is an example of an industry that has moved through the inflection point from small factories, with equipment adapted from other industries and low product volumes, to an industry with very large factories, with dedicated equipment specifically designed for this industry and with very large volumes of product. As we shall see, as the industry went through its inflection point, the improvement in the productivity was huge—much larger than a typical learning curve model would have predicted.

In 1989, 1990 and 1991, the first TFT, liquid crystal, flat panel displays became available for notebook computers, with the size, color & image quality, and reliability that would make an acceptable product. The price of these first, 10.6” and then 13” diagonal displays was over \$3000—all that the notebook computer market would pay¹⁴. Rumors were that the manufacturing cost was much greater. Yields were terrible, less than 10%. The manufacturing process for the back-plane that included the transistors, addressing lines and addressing logic used a long tunnel of vacuum systems (sputtering systems and PE-CVD systems), interconnected by load locks. The displays were made on sheets of high temperature glass just slightly larger than the size of the finished display, 0.24 m x 0.33 m. Total industry volume for active matrix, TFT, liquid crystal, flat panel displays was on the order of 120,000 displays per year¹⁵.

In the year 2003, well on the other side of the inflection point, the industry is about to build its generation VII factories. These factories will process 2.1 m x 1.9 m sheets of

¹⁴ Interview with Bob Myers, hp purchasing for notebook computer displays

¹⁵ Bob Myers, also extrapolation from EE times articles in March 15, 1993 and Sept, 1993.

glass and will make 45" diagonal, 16:9 aspect ratio displays to replace home TV sets, 6 at a time on a single sheet of glass. The factories have dedicated sets of equipment with the equipment and processes designed exclusively for making displays. Gen V factories (1.1m x 1.25m glass substrates) now cost just over \$ 1 B with the gen VII factories estimated at about \$ 1.5 B. Prices for notebook computer displays are now down to under \$200 for a 15" diagonal display. Flat panel display volumes continue to grow and are now about 80 million per year¹⁶. Flat panel displays are now replacing CRT's on desktops, small screen TV's and are about to compete with large screen TV's, as well. Manufacturing cost for a 45" diagonal display is estimated to be \$1200 several years from now. If the industry can hit the projected costs and take on the large screen TV business, then industry volumes are expected to build toward 18 million sq. meters per year by 2005¹⁷.

Productivity improvements

Every industry takes a unique path to productivity improvements. In the semiconductor industry, we have:

1. Develop the resolution and uniformity for the next generation of feature size.
2. Obtain high yields
3. Improve throughput (processed area per minute) per capital cost for the equipment.

For the semiconductor industry, every time the feature size can be reduced by a factor of 2x, the number of transistors per unit area goes up by 4x, the speed of the transistors improves by 4x and so on. Therefore, job 1 is feature size.

For the display industry, the path to increased productivity has been:

1. Obtain high yields
2. Reduce costs per area processed.
3. Move to larger and larger display sizes

The number of pixels in a display has increased dramatically since the very early days and is now 1 - 2 million pixels per display.

In the early 1990's, the big issue was very low yields, below 10%. The cause was found to be large particles created in the sputter depositions and especially in the machines for depositing CVD dielectric. During the deposition processes, material would deposit on the walls of the machines as well as on the display substrate. Eventually, this material would build up and begin to flake off the walls, creating particles that landed on the substrates and produced defects or shorts. Displays are especially sensitive to defects or shorts, since a single defect can take out an entire row or column in the display and make it worthless.

¹⁶ Current and historical prices and unit volumes, also the estimates for the cost of fabs, are from Stanford Resources. For example, see Stanford Resources, Display Insight, Global LCD Supply/Demand Q2, 2002

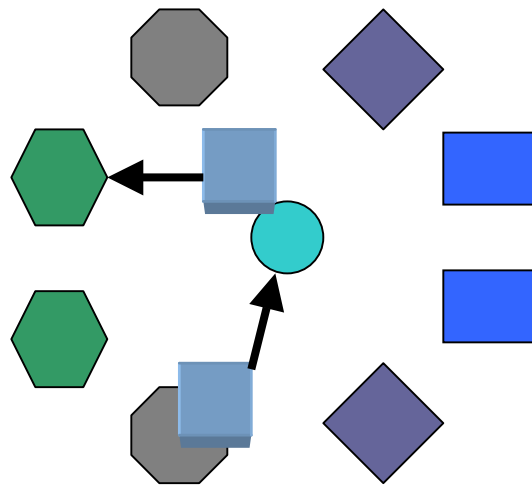
¹⁷ Coping with the Downturn by Chris Hall, **Electronic news**, September 17, 2001 page 41.

The second big issue was low up time for the deposition system. Since the deposition system was a single, long, string of depositions all in series, when one part of the system went down, the entire system was down. This design made the system availability low. It also made the system difficult to service and restore, since working on any part required working on the entire system, to some extent.

To solve these problems, the industry took a novel approach. They developed a cluster tool, depicted below. A cluster tool is a ring of separate pieces of equipment with a robot loader in the center. The robot handles one substrate at a time. It removes the substrate from a piece of equipment and inserts the substrate into the next. A single ring of equipment has more than one system of each kind, so that if one fails, the system can continue to process substrates, albeit, at a reduced rate. Similarly, maintenance can work on one piece of equipment at a time without affecting others.

Cluster Tool

Robot in center
Process equip surrounding it
Duplicate equipment
in the event of a breakdown
Robot loads and unloads
substrates to and from
processing equipment



The other novelty was to clean the walls of each piece of deposition equipment after each and every single substrate. At the time, this was unheard of. Systems were only cleaned after days or weeks of continuous operation. A gas mixture was developed that would clean any deposited material off the walls, leaving them pristine. Material could not build up, flakes would not develop and the number of particles deposited onto the substrates would be reduced.

The combination of these two approaches worked brilliantly. Yields went from well under 10% to over 90%. Equipment availability went from under 50% to about 80% (7000 hours per year). Manufacturing costs dropped and the prices of displays for notebook computers were now attractive. The volume of displays (and of notebook computers) soared.

In the middle 1990's, now in generation III, the industry was stalled. The manufacturing costs per sq. inch were not getting cheaper. They were still a factor of 2.5x off in price to be able to challenge CRT's for desktop computers and small TV's. The industry assembled and developed an overall game plan with its equipment suppliers. They took several approaches:

1. They beat on component suppliers for better prices
2. The equipment was designed to handle larger glass sheets, at the about same number of sheets per minute and about the same cost for the equipment.
3. They identified operating costs as the key area to work on.

Unlike many other industries, the cost of flat panel displays had become dominated by the cost of operating materials¹⁸. The cost of the gas to clean the deposition systems after each substrate was 3 – 4x the cost of the silane used for the silicon deposition. With the ever-larger substrate sizes, the cost and the waste of spinning or spraying on photo-resist became another major cost item.

The cleaning process was tuned to use less gas and less-expensive gases. A roller coating process was developed to apply a uniform thickness of photo-resist with little or no waste. More recently, this has evolved to extrusion coaters that extrude a thin, uniform, ribbon of photo-resist.

Initially, for their silicon deposition, the display industry used the PE-CVD process and equipment developed for the photovoltaic solar panel industry. As described above, because displays are much more sensitive to defects than solar panels, the display industry moved to a set of specially designed equipment that could be cleaned after every substrate. Now, the display industry has moved to sputter deposited poly-silicon and laser annealing to get acceptable mobility (100 – 200 cm² per volt-sec) for the thin-film transistors.

Equipment sets

Like the semiconductor industry, the display industry has a small number of expensive fabs (\$1B each), each of which produce displays in high volumes. For Gen IV and V, there are 11 and 2 fabs worldwide, respectively. Each has 3 identical modules, for a total of about 40 modules worldwide. Each module has at least two pieces of every type of equipment. Each of the three modules in the Gen V factories is being designed to process about 0.3 million sq. meters per year. For all generations, the total number of fabs worldwide is 42. The total area processed by all generations of fabs is about 10 million sq. meters per year)¹⁹.

For comparisons, the low-e coated glass industry coats about 10x as much glass—100 million sq. meters per year in about 40 sites worldwide. A single line of the 100 identical lines in our design for a “Solar City” factory module will process 0.3 million sq. meters of

¹⁸ iSuppli/Stanford Resources Flat Panel Display Manufacturing Cost Model

¹⁹ Stanford Resources, Display Insight, Global LCD Supply/Demand Q2, 2002, pages 43-44.

glass. A “Solar City” factory will process about 30 million sq. meters, in total. With 100 “Solar City” factories worldwide, the area of solar panels would be 30x the area of low-e glass, produced worldwide, and 300x the area of flat panel displays, produced worldwide.

Productivity gains and learn curve rate

The productivity gain from the 10.6” and 13” diagonal displays of the early 1990’s (at a price of \$ 3000) to the 15” diagonal displays in 2003 (at a price of \$ 200) is 20x – 30x (in price per area). The lion’s share of this gain was the improvement in yield from under 10% to over 90%, approximately 10x. The remainder came from productivity improvements in the equipment and the cost savings in the materials utilized in the process.

The unit volumes (in 15” display equivalents) went from about 60,000 per year (10,000 10.6” displays per month) to about 80 million per year, an increase of 1300x. From the first 10.6” diagonal displays in 1990 to the 15” displays now manufactured in very high volumes, we have a price improvement of 30x. Therefore, the learning rate is about **0.72**.

These very high learning rates are common in going from the early days of an industry, through the inflection point to a mature industry. In the early days, no one can afford specialized equipment and dedicated production processes. After the inflection point, productivity benefits enormously from equipment designed exclusively for the industry and from factories and processes dedicated and optimized only for one specific type of product.

Improvements on equipment productivity with experience and volume

Our purpose in studying the flat panel display industry was to see the improvements in the productivity of the equipment as the industry moved from low volumes of product and small factories, to high volumes of product, and large, dedicated factories. In the early 1990’s, the flat panel display industry had to use equipment borrowed from other industries. It was too small to have equipment specially developed for its needs. The substrate size was just a bit bigger than a 12” diameter silicon wafer and much of the equipment was the same as or was adapted from semiconductor processing equipment. The thin-film silicon deposition was PE-CVD and was taken from the solar panel industry.

Once the display industry went through its inflection point and became large and well established, equipment was designed for and dedicated to its needs. The first big push was for high yields. For semiconductors, a defect may take out only a small chip or part of a chip. It cannot take out an entire wafer. For displays, a single, major defect on a display panel can easily make the entire display worthless. Therefore, yield was a more critical issue for displays than it had been for semiconductor wafer processing. To solve this issue, deposition equipment for the display industry was designed to clean itself completely after every substrate. An aggressively reactive gas would be circulated within

the chamber to completely etch any deposited material off of the walls. With no build-up on the walls, particles of materials would not form, could not fall onto the substrates and could not create defects.

Once yields were good, the next big push was for bigger substrates and higher productivity, measured as the area processed per cost of the equipment. To illustrate this effect, we will track the productivity improvement in one piece of equipment: dry etching. We have chosen dry etching because it was already a mature technology widely used in the semiconductor industry with many 100's of units installed. Nevertheless, as we will see, by creating dedicated equipment for the display industry and by manufacturing that dedicated equipment in significant unit volume, further productivity gains were possible. This is exactly what we need and intend for our "Solar City" factory module.

Included below is a table showing the improvement in dry etch equipment as the display industry has progressed.

Dry Etch equipment productivity²⁰

Generation	Gen I	Gen II	Gen III	Gen IV	Gen V	Gen VI	Gen VII
Substrate size	.24 x .33	.37 x .47	.55 x .65	.68 x .88	1.1 x 1.25	1.5 x 1.8	1.8 x 2.1
Substrate area (in sq. meters)	.08	.17	.36	.60	1.38	2.7	3.78
Capital cost		\$1.7M	\$2.5M	\$3.0M	\$3.4M	\$4.2M	
Throughput (substrates per hour)		27	46	50	54	36	
Productivity (sq. meters per hour - \$)		2.7	6.6	10	22	23	
Equipment (units per factory)		12	12	12	12	12	
Total Factories ²¹ (world wide total)		13	16	11	2		
Total Units (per generation)		156	192	132	24		
Total installed Units (for all generations)				504			

As the industry progressed from generation II fabs to generation V fabs, the productivity of dry etch equipment improved from 2.7 to 22 sq. meter per hour. When divided by the increased capital cost of the equipment, we get an 8x net improvement. The cumulative

²⁰ iSuppli/Stanford Resources Flat Panel Display Manufacturing Cost Model

²¹ Stanford Resources, Display Insight, Global LCD Supply/Demand Q2, 2002, page 43.

volume of units shipped increased from 150 to 500, or 3.3x. These numbers would give a learn curve rate that is way off the usual scale, about **0.3**. For a typical learning curve rate of .8, we would need an increase in the total units of more than 600x.

From this information, we draw two conclusions. First, the learning curve model is very good for describing the improvements in price when going from volumes of thousands to millions. It is not very good when going from volumes of a few to a few hundred. Second, the productivity gains in going from a few units to a few hundred can be very dramatic—much greater than a typical learning curve rate would predict. In the specific case of flat panel displays, increasing the substrate size was a very, very effective way to increase the total productivity of the equipment.

Conclusion

The active matrix, thin-film transistor, flat panel display industry is a good example of an industry that has gone through its inflection point. It started as a small industry with small factories and with equipment and processes adapted from other industries. It has moved to an industry with large dedicated factories. The equipment used is designed exclusively for this industry. The processes are exclusive, as well. Each factory is dedicated and optimized for one type of product: Active Matrix, TFT, flat panel displays.

The productivity gains as the industry went through the inflection point were much larger than would have been predicted by a learning curve model. Learning curve models predict well the continued evolution of a high volume business. They do not predict well the gains in the very early stages and through the inflection point. Whereas, typical learning curve rates are often **0.80**, the learning curve rate for the price per unit area of AM, TFT, flat panel displays was **0.72**. The learning curve rate for a typical piece of equipment, a dry etching machine, was off the scale, at **0.30**.

This study strongly suggests that the gains in cost per unit area processed for the deposition and patterning equipment in our “Solar City” factory module will exceed the learning curve rate of 0.8. With a learning curve rate of 0.8, in moving from a single fab line to 100 identical lines, we would predict a decline in cost of about 4.4x. Based on the information above, we have some confidence that the decline in cost will be much greater, in the range of 5x – 10x.

Appendix IV – Case Study

Productivity gains for the Low-e Coated Glass Industry

**Interview with Donoho Hall
Formerly of Libby Owens Ford
and BOC Coating Technology
Now with ADG Associates, LLC.**

(510) 521-3828

In this narrative, we will track the impact of increasing unit volume on the cost of a specific product and on the cost of the equipment used to make that product. We will focus on low-e or low emissivity glass used in both commercial and residential applications to improve energy efficiency by reducing the infrared energy that is transmitted through a window. This material is not available in the public literature and was obtained by an interview with Dan Hall, who was formerly with Leybold and has been in this low-e glass business since its onset.

Low-e window glass for commercial and residential use is fabricated in three groups of process steps:

1. Making sheets of glass by a float glass process.
2. Fabricating the glass in specific sizes, possibly with edge seaming or tempering.
3. Vacuum coating of the glass with a series of very thin layers that reflect heat eg. ZnO, Ag, ZnO.

We will be discussing only the vacuum coating process step and only for the application of low-e coatings.

Price and Unit Volumes of low-e glass

Both the price and unit volume estimates for low-e glass are based on the experience and private communications of our interviewee. Price includes the manufacturers margin and profit, which was large in the early days and is much smaller now. Manufacturing costs are highly guarded and could not be obtained. Nevertheless, we have seen the price for just the coating for low-e coated glass drop from \$1.50 per sq. ft in the early days to about \$0.40 per sq. ft in 2003. This is a decline in price of a little more than 3.75x.

During that period, the low-e glass product has changed from a 3 - 4 layer coating stack to a 9 – 10 coating stack—about a factor of 2x in thickness. Therefore, if we measure the price divided by the coating thickness, then the decline is about 7.5x from the early days until 2003. Some of this decline was a dramatic decline in margins as the business moved from boutique to mainstream. We guess that the margin decline may have gone from 60%

to 20% gross margins, i.e., the manufacturing cost was 40% of the price initially and has increased to 80% of the price today. This accounts for about a factor of 2x in the price decrease. Based on this, we can estimate the drop in manufacturing cost to be about $7.5x * .5x = 3.75x$.

Unit volume has increased as follows. In the early days of vacuum coating of glass, there were about 6 coaters world wide, running about 2000 hours per year and coating at a rate of 100 sq. ft. per 60 seconds per coater. This gives a unit volume before yield and loading losses of about 72 million sq. ft. per year. After yield and loading losses, this might be 40 million sq. ft. per year. In 2003, there are 40 coaters operating world-wide. The newest coaters operate up to about 6400 hours per year, and coat 100 sq. ft (with the entire 9 – 10 layer stack) in 20 seconds, with an 80% load factor and approximately 96% yield. (The load factor is the percentage of the 100 sq. ft. that is used by mixtures of different size glass.) Thus, we have a capacity for the new coaters of about 80 million sq. ft. per year from which about 55 million sq. ft. is actually produced. Since the industry has a mix of new and old coaters, the average is about 30 million sq. ft. per coater. With 40 coaters world-wide, we have a unit volume of about 1.2 Billion sq. ft. Thus, the unit volumes have increased by roughly 30x.

Progress in the equipment and process

In the mid-1990's, people attempting to coat large window glass with a series of thin film layers switched to vacuum coating and, specifically, to sputtering as the preferred approach. At that time, sputter coating was a mature technology—widely deployed in the semiconductor and disk drive industry to coat 8" diameter wafers and 3.5" diameter disks. But, it had not been applied to coating large areas of glass with the goal of very low coating costs. From the early days of sputter coating for low-e glass, the number of equipment sets has gone from about 6, world-wide, to about 40 in 2003. Several areas of improvement have increased the productivity of the equipment, as described below.

In the early days of sputter coating of glass, the low-e coating consisted of 3 or 4 layers of thin films such as ZnO, Ag, ZnO. The coating area was 100" wide and 144" long and could be either a single sheet of glass or a holder of the same size into which cut glass was arranged to fill the space. The equipment was an in-line system that did all 3 or 4 layers at a rate of 1 holder (i.e., 100 sq. ft.) every 60 seconds. The purchase price for the equipment was about \$6 M.

In 2003, the coatings are more complex, 9 – 10 layers and roughly equivalent to two of the early coating stacks and about double in total thickness. The equipment has improved in productivity. It is a much larger in-line system that coats all 9 – 10 layers at a rate of 1 holder (102" x 148") or about 100 sq. ft. every 20 sec. Since the layers have twice the total thickness, this represents a 6x improvement in throughput in units of $\mu\text{m} - \text{sq. ft. per second}$. The cost of these much larger and faster systems has increased as well to about \$19 M—a 3x increase. Therefore, the net improvement in equipment productivity divided by equipment cost is about 2x.

A second area of improvement has been the utilization of the equipment. This has three aspects. First, downtime for cleaning the system and other maintenance has been improved. For the early systems, they would run Monday morning to Friday evening, and then would be shut down over the weekend to replace targets, clean shields and then pump down the system. Now, the systems are designed to run for 11 or 12 days and then shut down for one day for the same operations. Therefore, system availability has improved from 64% to 92%--almost an additional factor of 1.5x gain in productivity.

Second, in the early days, there was not enough demand for coated glass to keep the machined running all the time. A typical installation might run about 2000 hours per year out of the then available 6000 hours. Now, a typical installation will run the coater about at about 80% of the available time, or about 6400 hours per year of the 8000 hours per year that the system is available.

Third, the utilization of the coating area has improved. In some installations in Europe, the glass sheets (3.2 meters x 6 meters) are coated and then cut. Often in the U.S., the glass sheets are first cut, then loaded onto a 100 sq. ft. holder and then coated. In both cases, when the volumes are large, it is possible to get a higher percentage of the coated area to be finished product rather than waste. We do not have a good estimate for this increase, but we believe that it is small, maybe 1.1x.

In 2003, yields tend to be very, very high: 98%. We do not have information about the yields in the early days. But, sputtering was a mature process even in the early days of low-e coatings. Only the application was new. Therefore, we are assuming that the yields were high in the early days, as well. We will estimate the improvement in productivity from yield improvement to be about 1.1x — from 90% to 98%.

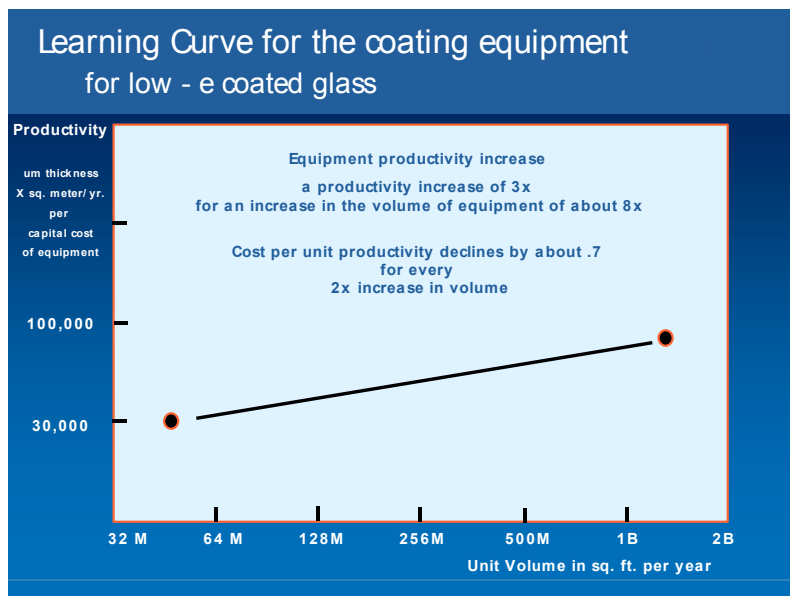
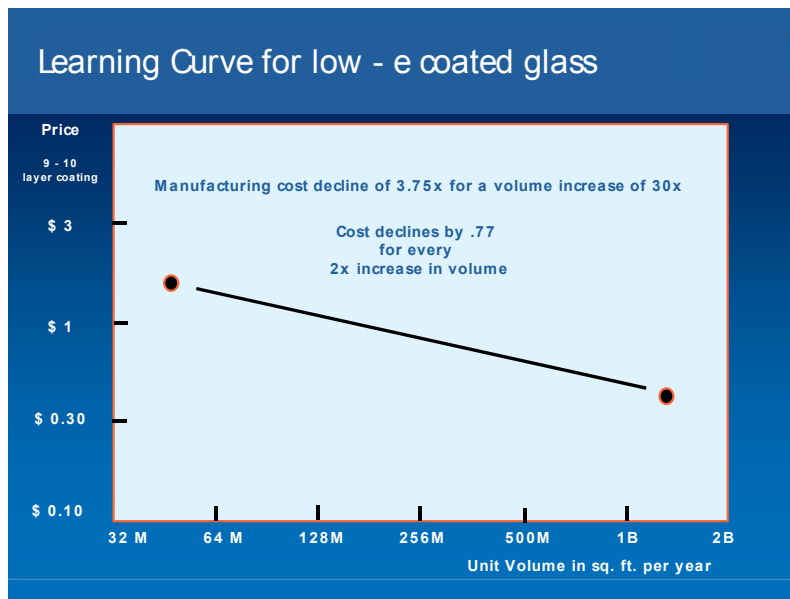
Adding up all of the productivity improvement estimates, we have:

Equipment throughput divided by cost	2x
Equipment availability	1.5x
Availability utilization	2.2x
Area utilization	1.1x
Yield improvement	1.1x
Total	8x

Note that these numbers only represent the improvement in the productivity of the process, utilization and equipment. These will contribute to a decrease in the amount of equipment depreciation that is a part of the total cost per sq. ft. coated. Other costs would be the materials and operating expenses. Given that the layers of the coating are very thin, the materials costs are very low. Also, the infrequent maintenance suggests that this cost is low, as well. Nevertheless, it is reasonably consistent that an 8x improvement in equipment productivity would translate into a 3.75x improvement in overall manufacturing

cost. Better estimates than these are not possible with the data that is available to the public.

The learning curve rates are .77 for the decline in the product price vs. unit volumes shipped. The learning rates are 0.7 for the increase in equipment productivity vs. the unit volumes of equipment shipped. We can apply the second number to estimate the likely reduction in cost for the deposition and patterning equipment in our large scale solar factory. Compared to a single factory, we would have 100x the number of equipment sets. With a learning rate of 0.707, this would predict a 10x reduction in the cost of the equipment. In our calculations for the design of the large scale solar factory, we were more conservative and assumed a 5x reduction in the cost of the equipment.



Appendix V – Thin-film Materials Cost and Availability

Cost of materials for thin-film active layers

21-Sep-04

Marvin Keshner and Rajiv Arya

Device	Material	Specific Gravity gm per cm ³	% of layer by formula weight	layer thickness um	Material Utilization via recycling	amount used gm/ sq. meter	amount used metric tons per year at 30 M sq. meters per year	price per kg lots of 10 metric tons	net cost per sq. meter
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Amorphous Silicon Single Junction

a-Si:H	2.3	100%	0.4	0.75	1.23	37	\$110	\$0.13
Zn in ZnO	5.6	80%	0.25	0.75	1.49	45	\$110	\$0.16
Al	2.7	100%	0.3	0.75	1.08	32	\$18	\$0.02
Total Cost								\$0.32

Additional or Alternate materials

Ag	10.4	100%	0.3	0.75	4.16	125		
Sn in SnO ₂	6.9	79%	0.5	0.75	3.63	109		
Ge	5.3	20%	0.4	0.75	0.57	17	\$1,150	\$0.65

CdTe Single Junction

CdS	4.8	100%	0.1	0.75	0.64	19		\$0.03
Cd	4.8	78%	0.1	0.75	0.50	15	\$60	\$0.03
S	4.8	22%	0.1	0.75	0.14	4	\$18	\$0.00
CdTe	6.2	100%	1.8	0.75	14.88	446		\$2.26
Cd	6.2	49%	1.8	0.75	7.29	219	\$60	\$0.44
Te	6.2	51%	1.8	0.75	7.59	228	\$240	\$1.82
Back contact or Al	2.7	100%	0.3	0.75	1.08	32	\$18	\$0.02
	2.7	100%	0	0.75	0.00	0	\$18	\$0.00
Total Cost								\$2.31

Cu (In .85 Ga .15) Se₂ Single Junction

Formula weight = 332

Mo	10.3	100%	1	0.75	13.73	412	\$110	\$1.51
Cu (In, Ga) Se₂	5.8	100%	2	0.75	15.47	464		\$7.72
Cu	5.8	19%	2	0.75	2.94	88	\$30	\$0.09
In	5.8	30%	2	0.75	4.64	139	\$1,200	\$5.57
Ga	5.8	3%	2	0.75	0.46	14	\$2,200	\$1.02
Se	5.8	48%	2	0.75	7.42	223	\$140	\$1.04
ZnO / CdS	5.6	100%	0.1	0.75	0.75	22	\$110	\$0.08
ZnO	5.6	100%	0.5	0.75	3.73	112	\$110	\$0.41
Al grid	2.7	10%	0.7	0.75	0.25	8	\$18	\$0.00
Savings on materials from SnO ₂ glass coating step								(\$0.41)
Total Cost								\$9.31

Notes:

The density for CuInGaSe₂ is an estimate. CuSe = 6.0; GaSe = 5.03; InSe = 5.7. The formula average is approx. 5.8.

The cost of CdTe and Cu (In,Ga) Se materials could be reduced by developing a 5x - 10x thinner layer (0.2 -- 0.4 um) with light trapping to achieve adequate light absorption.
 Limitations to the light trapping effectiveness might be the low reflectivity (50%) of the Mo back contact for Cu (In,Ga) Se

Availability of materials for thin-film active layers

Marvin Keshner and Rajiv Arya

21-Sep-04

Device	Material	Amount Required for 30 M sq. m per yr. metric tons per year	Abundance in Earth's crust parts per billion	Current Amount mined world wide metric tons per year	Potential Production based on % abundance metric tons per year	% of Current Production	% of Potential Production	Limit by current prod GW per year	Limit by potential prod GW per year
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Amorphous Silicon Single Junction

a-Si:H	37	282,000,000		4,100,000	73,723,260,000	0.0%	0.0%	222,826	4,006,698,913
ZnO	45	70,000		8,700,000	18,300,100	0.0%	0.0%	388,393	816,969
Al	32	83,200,000		127,000,000	21,750,976,000	0.0%	0.0%	7,839,506	1,342,652,840

Additional or Alternate materials

				see note below					
Ag	125	70		18,300	18,300	0.7%	0.7%	293	293
SnO2	109	2,000		283,000	522,860	0.0%	0.0%	5,192	9,592
Ge	7	5,400		44	1,411,722	15.9%	0.0%	13	403,349

CdTe Single Junction

CdS	19								
Cd	15	200		18,700	52,286	0.1%	0.0%	4,121	11,521
S	4	2,600,000		58,000,000	679,718,000	0.0%	0.0%	45,312,500	531,029,688
	0								
CdTe	446								
Cd	219	200		18,700	52,286	1.2%	0.4%	282	789
see note Te	228	1		130	2,000	175.1%	11.4%	2	29
Back contact	32								
Al	32	83,200,000		127,000,000	21,750,976,000	0.0%	0.0%	13,096,875	2,243,069,400

Cu (In .85 Ga .15) Se2

Mo	412	1,500		112,000	392,145	0.4%	0.1%	979	3,427
Cu (In, Ga) Se2	464								
Cu	88	55,000		13,200,000	14,378,650	0.0%	0.0%	539,020	587,150
see note In	139	100		335	26,143	41.6%	0.5%	9	676
see note Ga	14	15,000		70	3,921,450	19.9%	0.0%	18	1,014,168
see note Se	223	50		1,500	4,000	14.8%	5.6%	24	65
ZnO / CdS	22								
ZnO	112	70,000		8,700,000	18,300,100	0.0%	0.0%	279,643	588,218
Al grid	8	83,200,000		127,000,000	21,750,976,000	0.0%	0.0%	60,476,190	10,357,607,619

References: <http://www.mbandi.co.za/indy/ming/p0005.htm>

USGS mineral commodity summaries

Tellurium and Selenium descriptions can be found at : <http://minerals.usgs.gov/minerals/pubs/commodity/selenium/831798.pdf>

Indium description can be found at: <http://minerals.usgs.gov/minerals/pubs/commodity/indium/490303.pdf>

Notes: This chart presents the issue that for In, Ga, Se and Te, current production will be a limitation and additional production will need to be developed.

"Potential production" is an order of magnitude estimate based on the ratio of silver production to silver abundance in the Earth's crust
Abundance in the Earth's crust is an order of magnitude estimate and only an indication of possible mining production.

Se and Te are both by-products of Cu refining and are not economical to mine directly.

Cu anode slimes are 41,000 metric tons annually world wide with an average of 5% Te and 10% Se

Thus, Se production could be increased to 4000 metric tons per year and Te production to 2000 metric tons per year (Ref. USGS commodity summaries--see above))

Indium is currently a by-product of Zn refining, which is declining year to year.

Re-cycling of indium is important to meet current demand

Although the abundance numbers suggest indium production could be increased, it tends to be found only in low concentrations with base metals such as Zn, Cu

Therefore, increasing production may be very difficult without a substantial increase in price

Gallium is produced mostly from aluminum production. It is also a by-product of Zn production. In addition, there are a small number of other mineral deposits (100ppm).

The availability of In, Ga, Se and Te could be greatly extended if the films could be made 5x - 10x thinner, 0.2 -- 0.4 um, with light trapping to enhance light absorption in the thinner layer. Limitations to the light trapping effectiveness might be the low reflectivity (50%) of the Mo back contact and seed layer for Cu (In,Ga) Se2

Form and purity of materials for thin-film active layers

21-Sep-04

Marvin Keshner and Rajiv Arya

Device	Material	Form	Purity
Amorphous Silicon Single or Dual Junction			
	Silane	Gas	UHP Grade 99.9996 vol.%
	Trimethylboron	Gas	Electronic Grade 99.5 min. vol%
	Phosphine	Gas	MOCVD Grade 99.9995 vol.%
	Methane	Gas	UHP Grade 99.998 vol.%
	Hydrogen	Gas	Research Grade 99.999 vol.%
	Argon	Gas	Research Grade 99.999 vol.%
	Germane	Gas	UHP Grade 99.999 vol.%
	Diethyl Zinc	Liquid	96.2 wt %, Min. Zinc 51%
	Diborane	Gas	UHP Grade 99.99 vol.%
	Nitrogen	Gas	Research Grade 99.999 vol.%
	Aluminium	ingots, powder	100.00%
CdTe Single Junction			
	Cadmium telluride	Poly pieces, powder	99.999+%
	Cadmium sulphide	Powder	99.99+%
	Thio Urea	Powder	99+%
	Cadmium Suphate	Liquid	99+%
	Nickel	Pellets	99.99%
	Silver	Pellets	99.99%
Cu (In .85 Ga .15) Se2			
	Copper	Pellets	99.9990%
	Gallium	ingot, pellets	99.9990%
	Indium	Pellets	99.9990%
	Selenium	Shots	99.9990%
	Molybedenum	Pellets	99.9990%

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