Luminescent, Quantum Dot-based Anti-reflective Coatings for Crystalline Silicon Photovoltaics

by

Garrett Bruer

Submitted to the Department of Materials Science and Engineering
in partial fulfillment of the requirements for the degree of
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Abstract

This thesis demonstrates and evaluates the potential application of luminescent quantum dot/polymer solutions on crystalline silicon photovoltaics. After spin coating the QD/polymer onto silicon photodiodes, an increase of 3% in current density was observed. This performance improvement was used to determine the impact application would have on the crystalline silicon photovoltaic supply chain. Supply chain costs were modeled to estimate the segment costs for Sharp's NU-U230F3 230W module. The benefits realized by use of cells coated with the QD/polymer solution were then estimated at both the module and the cell segments. Finally, an installation cost model for the residential market was built to determine the impact an increase in efficiency had on total system costs.

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Title: Associate Professor of Electrical Engineering and Computer Science

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During my limited time at MIT I have met several people, but none were more helpful than those I mention here.

To my friends who were always ready to go out and experience Boston and the region. Our many coffee hour conversations and weekend excursions will be missed and will never go out of style. Plus, there is never enough Pho to go around.

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To the members of the ONE lab who were extremely helpful in obtaining measurements of my devices. To Geoffrey for enlightening my life with British humor and cooking ideas. To Alexi who was profoundly knowledgeable about the photovoltaic market and performance of different technologies regarding both engineering and finance. Alexi was always willing to help even when trying to open stuck vacuum chambers! To Tim who will always be interested in eccentric and awesome technical topics and is willing to talk about anything that improves our lives. Our personalities jive too well.

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Contents

List of Figures

List of Tables

1 Technology

1.1 Introduction to Photovoltaics

Photovoltaic devices are a popular form of electronic device used in many electronic products from cameras, to remote sensors. The most well known of its applications is in the form of solar energy production, or solar cells.

In the design of a simple solar cell, a *p-type* and an *n-type* semiconductor material will united to form a metallurgical junction. Sunlight incident to the solar cell surface that passes between the metallic contact grid will be absorbed within the region of the junction. Upon absorption by the *p-n* photodiode, the light is transformed into an electron-hole pair called an exciton. Each doped layer acts to separate the pair and transport the charges to their respective electrodes. This process results in a current from which solar power is derived. Recombination of excitons will not contribute to the current produced by the cell.

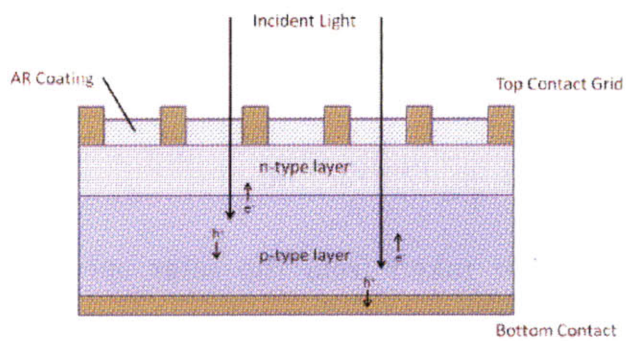

Figure 1–1. Diagram of a solar cell.

When connecting the cell to an applied voltage source, current can be extracted at small voltages. This current is the short-circuit current, I_{SC}. When the voltage is increased, the recombination current (from the recombination of excitons) of the cell considerably increases and the current drops. The open-circuit voltage, V_{OC}, is defined as the point where the current drops to zero. The V_{OC} and the I_{SC} define the rectangle whose area is the ideal *I-V* curve for a solar cell. The maximum power current, I_{mpp}, and maximum power voltage, V_{mpp} are derived from the maximum power point. This point defines the rectangle whose area is the largest rectangle on the *I-V* curve. The ratio of the area of this rectangle with that of the ideal *I-V* curve gives another figure of merit called the fill factor, *FF*. The fill factor is a measure of the squareness of the solar cell's *I-V* curve and is always less than one.

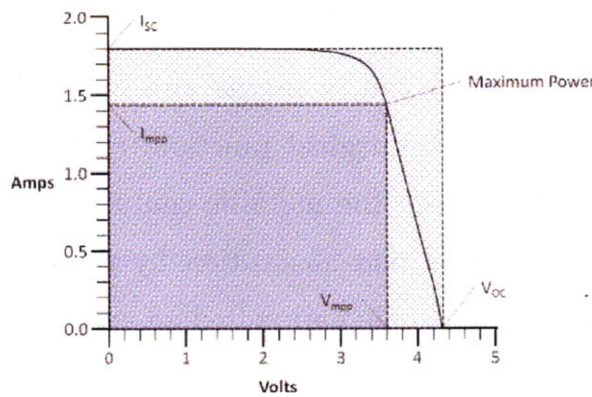

Figure 1–2. Current-voltage characteristic curve of a solar cell.

One of the most important parameters that define solar cells is its power conversion efficiency, or η, defined as

$$\eta = \frac{FF * V_{OC} * I_{SC}}{P_{in}} \qquad [1.]$$

with P_{in} as the incident power taken from the solar spectrum. The external quantum efficiency, *EQE*, is defined as the maximum possible photocurrent if all photons with energy larger than the bandgap energy that created excitons were collected. It follows that

$$EQE = \frac{I_{SC}}{I_{ph}} = \frac{I_{SC}/q}{P_{in}/E} \qquad [2.]$$

where E is the energy of the incident photon and q is the charge of one electron.

The predominant materials used in industry to manufacture single and multi-crystalline photovoltaics are silicon and gallium arsenide. One might expect GaAs photovoltaics to be the popular choice given its higher efficiency. GaAs has a bandgap 1.4eV (compared to Si with a bandgap of 1.1eV) and falls within the optimal range for peak power conversion efficiency of 1.4-1.6eV.[1] Assuming an air mass of 1.5 (AM1.5), the theoretical optimal conversion efficiency for GaAs and Si are 29% and 26% respectively.

1.2 Why Silicon

Silicon makes up about 90% of the solar cell market [2] which includes mono and multi-crystalline (mono c-Si and multi c-Si) silicon cells. Because of the high electronic quality of mono- and multi-crystalline silicon (diffusion lengths in the range of 100's of μm) cells with stable and reasonably high efficiencies (ranging from 14-25% - although commercially available can be 12-18% efficient) can be realized in these materials. [3]

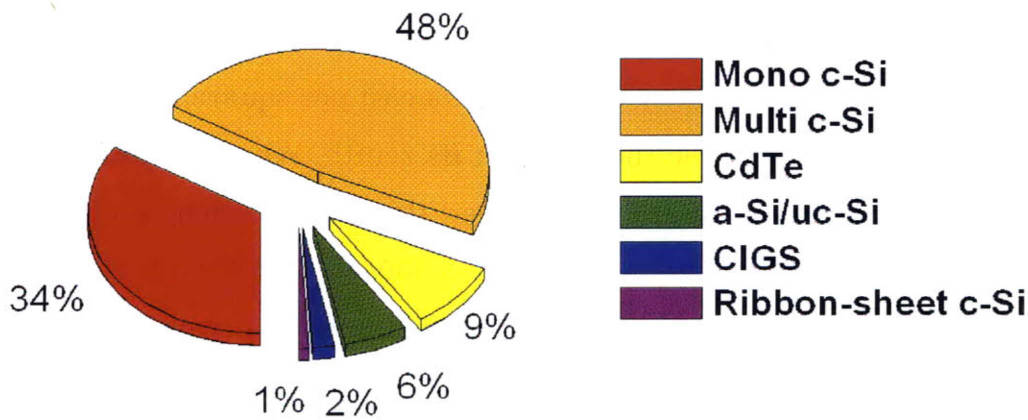

Figure 1–3. Cell technology shares in 2008. [3]

However, the high cost of ultra-pure Si combined with a large material consumption (200-300 μm wafer thickness) results in a high cost of finished PV module. Therefore, significant research effort has been focused on solar cell fabrication on very thin substrates and on Si ribbons, which consume much less

Si per unit area. Although thin-film technologies have been considered as promising candidates for low cost PV power for a long time, none of them have so far had a real breakthrough in efficiency and mass production capability, and bulk crystalline silicon appears likely to dominate the photovoltaic field for at least a decade.

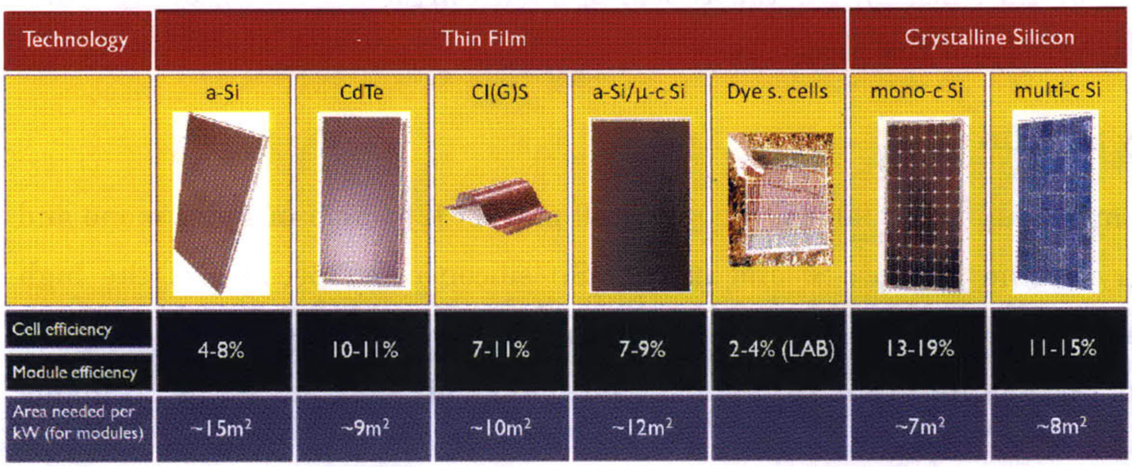

Figure 1–4. Commercial module efficiency based on standard test conditions. [3]

Yet, silicon photovoltaics dominate the crystalline solar cell market mostly because of their cost-efficiency. A typical crystalline silicon photovoltaic cell can have an energy conversion efficiency of 12% with a cost per square meter of $300. [4] This comes out to $3.5/W when the sun is at its zenith. When compared to the cost of GaAs at $10,000 per square meter, even the most efficient photovoltaic made of GaAs would still have a cost of $3,350/W. [5] This high cost is attributable to the rarity of gallium, which is rarer than gold. Because of the high cost of GaAs, most applications of GaAs are found in concentrated photovoltaics and used in the space industry where weight is the predominant decision factor. For perspective, the cost to launch a pound into space can range from as low as $3600/lb for low earth orbit, to as high as $11,200/lb for geosynchronous transfer orbit. [6] As a result, efficiency gains from GaAs outweigh production cost gains from using Si.

With silicon's dominant position in the solar cell market, significant research has focused on branch development of Si photovoltaics to improve their performance through use of concepts such as luminescent solar concentrators and surface texturing. [7][8] One simple manner to improve device performance is to apply thin films on the surface that minimize loss of light due to reflection. These films define the anti-reflective coating market, which find applications in solar cells, optics, electronics, sun glasses, and windshields.

1.3 Introduction to Anti-reflective Coatings

Most semiconducting material used in photovoltaics (Si or GaAs) has a high refractive index, larger than three. With the refractive index of air about one, the difference in refractive indices can lead to significant reflection at the interface and therefore less light absorbed by the photovoltaic.

Typical anti-reflective (AR) coatings use the basic concept of destructive interference to minimize light reflected to the environment. In this concept, a thin film with the thickness one quarter the wavelength of the incident light is applied to the surface of the semiconducting material. This type of interference minimizes reflection of this wavelength with the reflected light 180° out of phase with the incident light.

To minimize reflection due to refractive index differences, one can apply an AR coating with an index intermediate between the substrate and the environment.

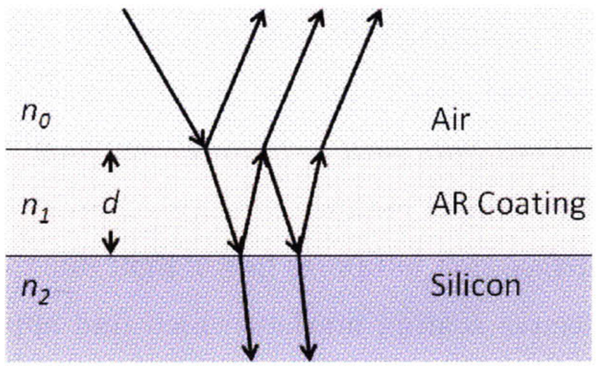

Figure 1–5. Quarter wavelength interference effects.

The expression for reflection of an incident beam on a surface covered by a transparent thin film of thickness d is given by

$$R = \frac{r_1^2 + r_2^2 + 2r_1 r_2 \cos 2\theta}{1 + r_1^2 r_2^2 + 2r_1 r_2 \cos 2\theta} \qquad [3.]$$

with r_1 and r_2 defined as

$$r_1 = \frac{n_0 - n_1}{n_0 + n_1} \qquad r_2 = \frac{n_1 - n_2}{n_1 + n_2} \qquad [4.]$$

where n_i represents the real part of the index of refraction for each layer. θ is defined as

$$\theta = \frac{2\pi n_1 d}{\lambda} \qquad [5.]$$

Reflection reaches it minimum value when

$$R_{min} = \left(\frac{n_1^2 - n_0 n_2}{n_1^2 + n_0 n_2}\right)^2 \qquad [6.]$$

This value becomes zero when the index of refraction of the AR coating is the geometric mean of the substrate and the environment.

$$n_1 = \sqrt{n_0 n_2} \qquad [7.]$$

Therefore, for a silicon photovoltaic (n_{Si} = 3.8), the optimal refractive index of the AR coating is 1.9.

1.4 Project History and Development

The key to this quantum dot (QD)/polymer coating technology lies in the material itself, the QD/polymer solution. This solution is manufactured by an MIT startup, QD Vision, which has identified several markets for their technology.

QD Vision was founded in 2004 by MIT doctoral graduate Seth Coe-Sullivan. Their initial target was to commercialize QD-based displays. In 2006, QD Vision demonstrated a proof-of-concept QD display with bright emission in the visible and near infra-red part of the spectrum. QD Vision states that as much as 30% more of the visible spectrum could be used by QD-LED (quantum dot-light emitting diode) displays when compared to a standard cathode ray tube (CRT). [9]

However, it was quickly realized that the technology was still too nascent to realize a positive cash flow at an acceptably early stage to sustain the company. [10] A logical springboard product for the company became application as a color filter in LED lighting. Over the following five years, the company continued to work on development of its product partnering with Nexxus Lighting to introduce the Lighting Array Quantum LED™ R30 which is currently commercially available.

QD Vision's current focus is in the LED (light emitting diode) lighting market taking existing LED technology and crafting a niche product for retail and commercial lighting. This product can be used to light object displays such as those in department stores, grocery stores, museums, showrooms, galleries, conference rooms, board rooms, and restaurants among other areas where color balance is a priority for the consumer.

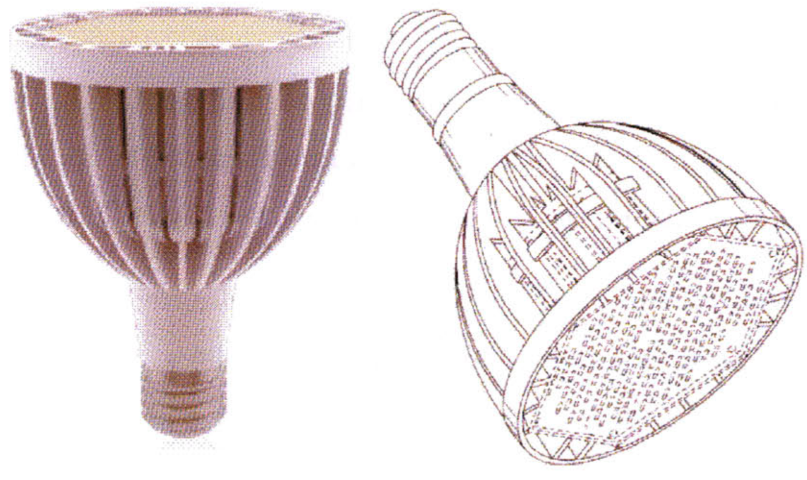

Figure 1-6. Nexxus Lighting Array Quantum LED™ R30. [11]

The new light bulb merges two technologies: white LEDs which function as normal bulbs, and a new filter of quantum dots that capture and re-radiate the light from the LEDs. This filter turns the LED's light from a 5000K daylight white to a "warm white" of 2700K, typical of incandescent lights. This product uses energy efficient LEDs while offering a less offensive means of illumination. Moreover, in using LEDs, the bulb offers a 50% increase in light per Watt at 61lm/W compared to a typical incandescent rating of 42lm/W. Their founder, Seth Coe-Sullivan, expects the cost of the bulbs to be around $100 when they are released in the near future. [12] Dr. Coe-Sullivan believes there to be ample space for their product to carve out its niche in a $700 mil. market as of 2009.

In conversations with QD Vision, the company was not willing to share information pertaining to their method. QD Vision has obtained several patents key to the production of the quantum dots and the QD/polymer coating itself. Probable methods for production of this technology are further described in the IP Landscape section.

QD Vision has been primarily focused on developing their lighting and display products. However, a potential application of the technology has been identified in the photovoltaic industry for use as an AR coating.

A simple photodiode uses the same principle as photovoltaics to turn light into electricity. When light strikes the diode, an electron-hole pair is created. If the exciton is created in the depletion region, the carriers are taken from the junction by the built-in field of the depletion region caused by the *p-n* junction. Holes migrate to the anode and electrons move to cathode creating a current. Under zero bias, this diode operates under the mechanisms of photovoltaics and current flows out of the device. [13] Therefore, research in improving the performance of photodiodes can be directly applied to improvements in the performance of silicon solar cells.

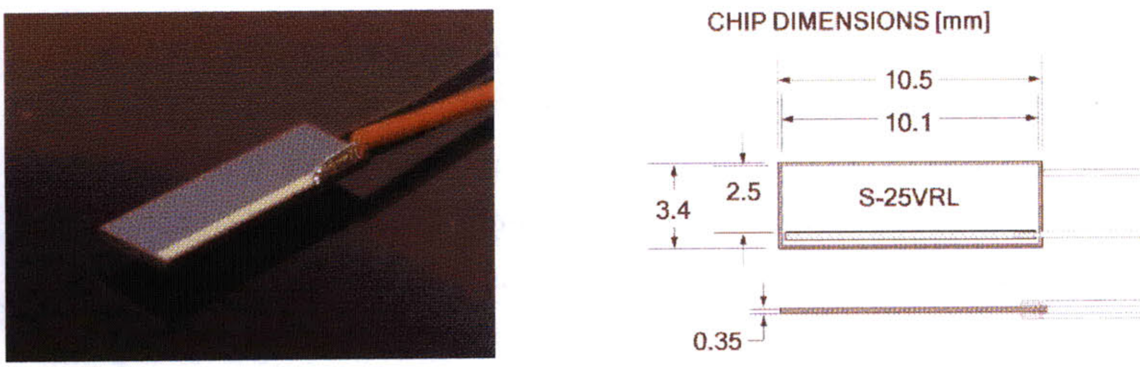

Figure 1–7. Solderable silicon photodiode used in research from OSI Optoelectronics. [14]

Silicon itself has a high refractive index in the UV part of the spectrum and thus a lower responsivity in the UV than visible. However, the responsivity of silicon photodiodes can be optimized for various parts of the spectrum including 'red', 'blue', and 'UV'. The primary difference between each type is the thickness of the silicon oxide layer applied to the surface of the active region.

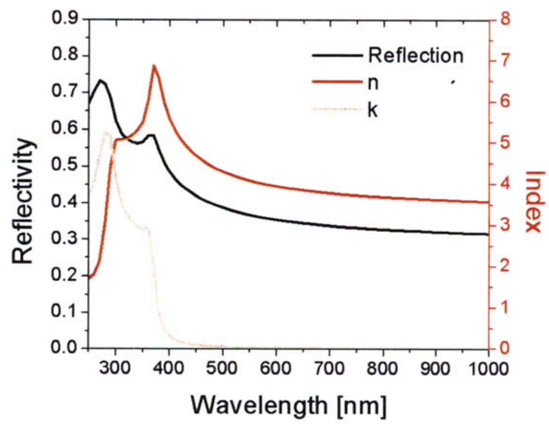

Figure 1–8. Reflectivity and real and imaginary indices of silicon.

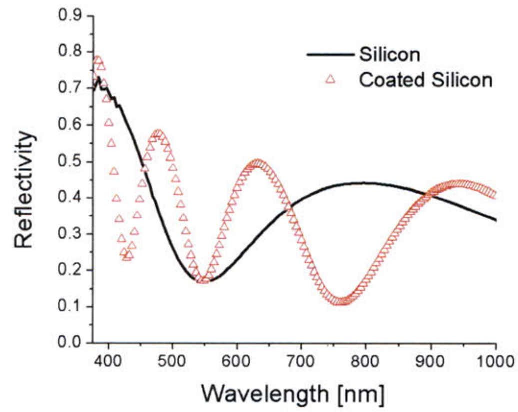

Figure 1–9. Reflectivity of silicon and silicon coated with QD/polymer coating.

Thinner layers of silicon oxide allowed for an increase in the photodiodes responsivity in the bluer and more energetic parts of the spectrum. However, the device cost increases by a factor of 10 when going from 500nm to 200nm thick layers of silicon oxide (typical for 'red-' and 'UV-enhanced' photodiodes respectively). [15] With silicon's high reflection coefficient in the UV and concomitant low responsivity, it is desired to capture this reflected energy and better couple the light into the photovoltaic for conversion into electricity. Therefore, applying a thin layer of QD/polymer material to the surface of the device for use as an AR coating at wavelengths where the device has a higher responsivity can increase power conversion performance.

To demonstrate the AR properties of the film, the QD/polymer solution was spin-coated onto silicon with a SiO_2 thickness of 300nm. A comparison of the reflectivity of the silicon with and without the coating is shown in Figure 1–9. A marked decrease in reflectivity is observed in the region 700-800nm.

Past research has included investigation of photoluminescent AR coatings using organics. [16] These thin layers of luminescent organic material acted as anti-reflection coatings in that the organic absorbs in the UV part of the spectrum and demonstrates visible emission helping to couple light into the active region of the photodiode. These organics drastically improved the external quantum efficiency (EQE) of the photodiodes, especially in the UV. This offered a simple solution to improving the responsivity of photodiodes.

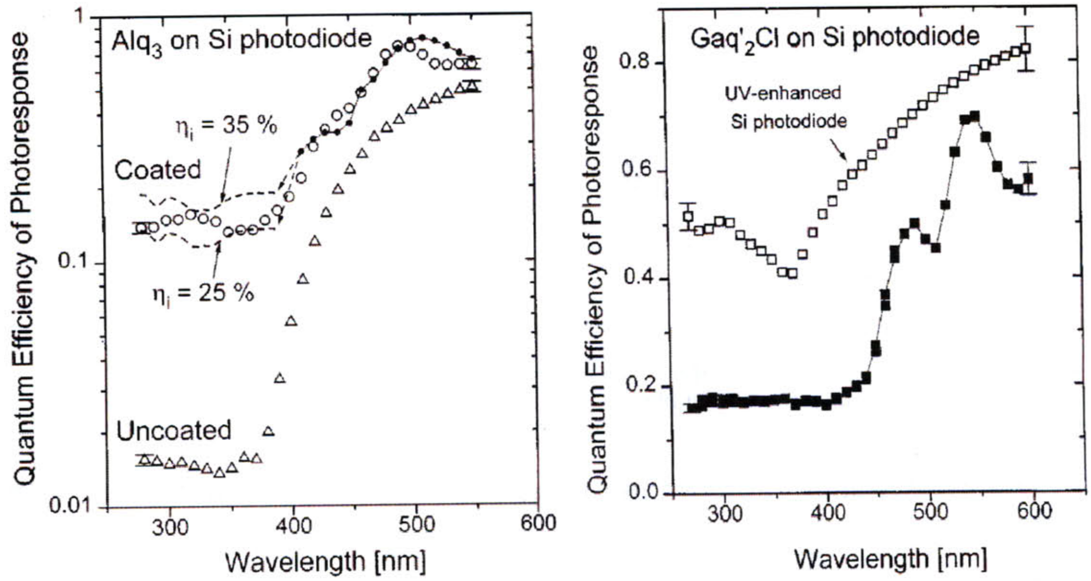

Figure 1–10. At left, the enhanced EQE of a silicon photodiode with application of Alq_3 anti-reflective coating. At right, the EQE of a silicon photodiode coated with Gaq'_2Cl. [16]

Quantum dots offer a similar solution absorbing strongly in the UV and emitting in the visible. In recognizing QD Vision's QD solution as a potential AR coating for silicon photovoltaics, several similarities were drawn from the past research that used organic films. The primary mechanism to improve the performance of the silicon photodiodes is absorption of high-energy UV light and conversion into visible light, a part of the spectrum where silicon has lower reflectivity. This affords stronger coupling of the light with the photodiode.

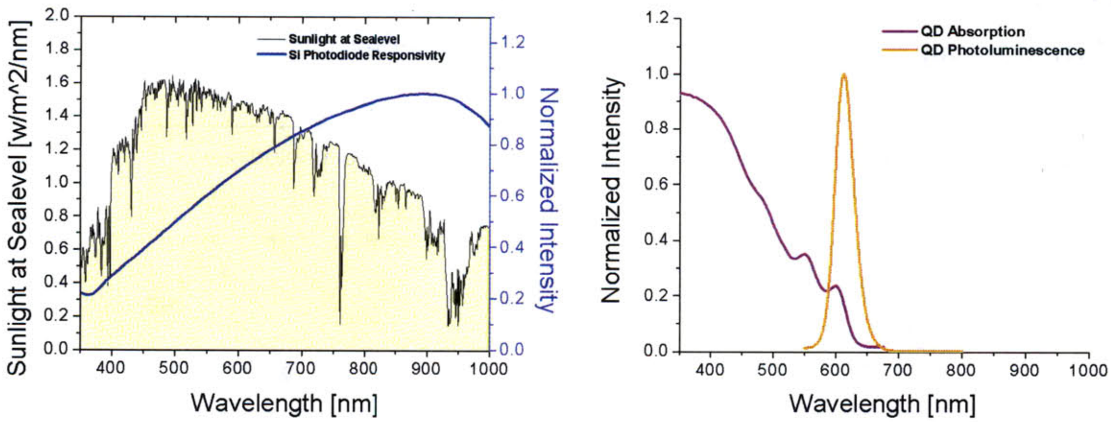

Figure 1–11. At left, the AM 1.5 solar spectrum paired with the normalized responsivity of a silicon photodiode. At right, the QD solution absorbs UV light and emits in the visible allowing for better coupling of the UV part of the spectrum into the silicon photodiode.

Moreover, QDs are more stable than organics in ambient environments and their photoluminescence efficiency improves with time when subject to light.

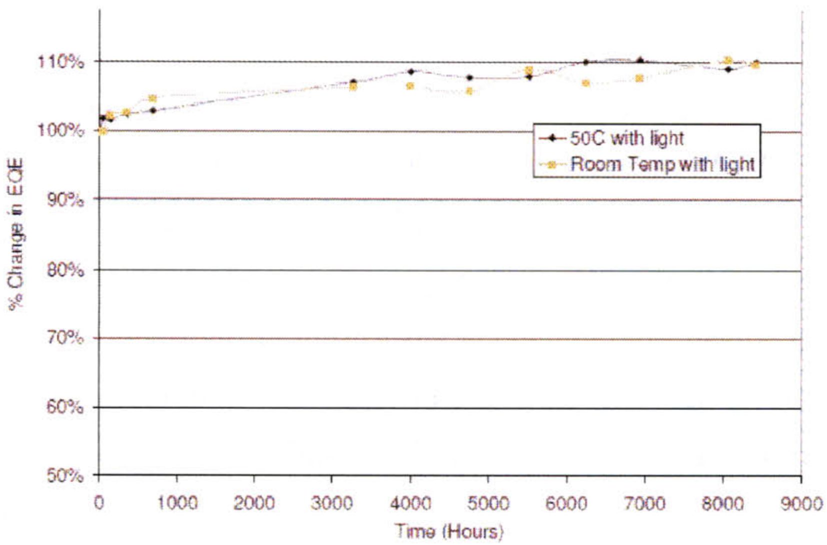

Figure 1–12. Quantum efficiency of QD Vision quantum dots over a solar simulated equivalent period of six months. [11]

1.5 Current Research Results

In research, the QD solution (CdSe quantum dots in an acrylic polymer swollen with toluene) was spin-coated and cured on commercially available 'red-enhanced' silicon photodiodes to form a QD/polymer coating. An increase in the photodiode

External Quantum Efficiency (EQE) in the UV compared to what was seen from the original 'red-enhanced' photodiode. Moreover, an increase in the short-circuit photocurrent density by 3% was observed.

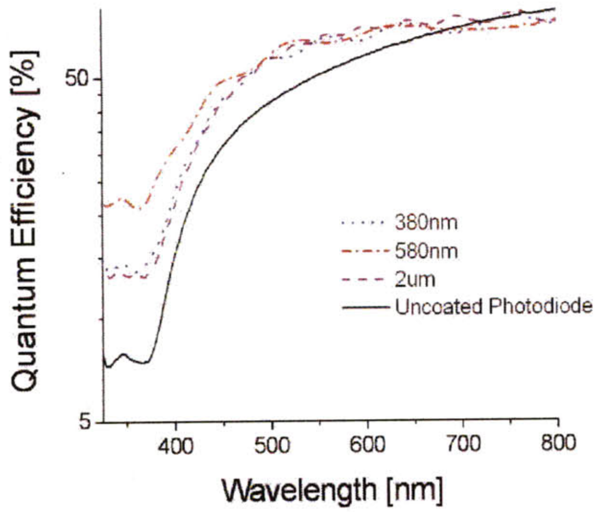

Figure 1–13. Experimental data for device EQE as a function of wavelength.

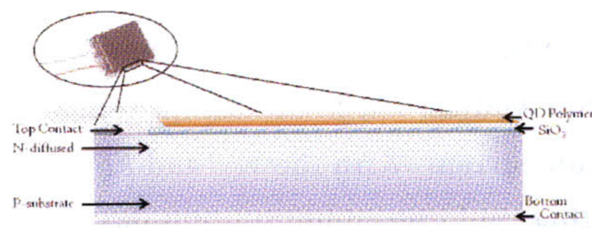

Figure 1–14. Illustration of QD/polymer coated silicon photodiode.

The EQE of the photodiode is significantly increased in the UV and across the visible spectrum allowing for better light coupling with the device and overall improvement in photocurrent density as seen in Figure 1–13. However, at wavelengths higher than 700nm, the EQE of the coated photodiode is reduced below that of the uncoated photodiode. The photodiode has a silicon oxide layer whose thickness (approximately 500nm from conversations with OSI Optoeletronics) has been optimized for absorption in the red part of the spectrum. Coating the device with the QD/polymer solution enhances device performance at wavelengths below 700nm, but is reduced beyond this point due to reduced silicon absorption.

To calculate the short-circuit photocurrent density, it is necessary to integrate the expected solar spectrum intensity at sea-level multiplied with the device external quantum efficiency by wavelength,

$$J_{SC} = \int \frac{P_{in}\lambda q}{hc}(EQE)d\lambda \qquad [8.]$$

where J_{SC} is the total short-circuit current, P_{in} is the solar irradiance at sea-level, and q, c, and h are standard constants of a Coulombic point charge, the velocity of light, and Planck's constant respectively.

To obtain the overall device power-conversion efficiency, η, the spectral open-circuit voltage (V_{OC}) and fill factor must be multiplied by the spectral short-circuit current. With the V_{OC} and FF unchanged after addition of the QD/polymer coating, and assuming these parameters are more or less constant across the part of the spectrum in question (300-1000nm), we find an overall power conversion efficiency improvement of 3% over the reference cell. This means the QD/polymer coating helped convert an additional 3% of the photons into current. This QD/polymer coating can be used as a cost-effective solution to enhancing crystalline silicon photovoltaic performance through the post-processing addition of a luminescent anti-reflective layer.

1.6 Risks and Further Development

The most identifiable risk to implementation of this technology is application to commcercial photocells. Experimentation has not been done on existing photocell technology to ascertain the resulting improvement in power conversion efficiency. Those cells whose technology has been design with better responsivity in the UV may not benefit as much from application of the QD/polymer. Moreover, the experiments were conducted with photodiodes whose base power conversion efficiency was 8.2%. It remains to be seen if scaling the application of this coating is achievable through means proposed in this paper.

A basic demonstration of the coating was conducted and it would be desirable to optimize the performance of the coating through experimenting with different dilution techniques, solvents, and coating methods in addition to determining the optimal coating thickness. This thickness could be specified through modeling of the layer structure. Optimization of this coating may reveal higher performance improvements resulting in a change of economics as described later.

Lastly, change of the emission wavelength of the QDs in the polymer solution may also improve the performance efficiency. By changing the synthesis process to grow QDs with a different emission wavelength. The emission may pair with an observed trough in reflectivity of silicon better coupling the emission light with the photovoltaic device.

2 IP Landscape

The company currently producing the technology, QD Vision, has obtained several patents and licenses for its products and production methods. The patent for its first product, the Lighting Array Quantum LED™ R30, is held by Nexxus under US patents D590,077 S and D601,276 S. QD Vision in a non-exclusive relationship with Nexxus in the production of their LED filters. QD Vision only makes the filters and Nexxus acts as a customer and primary advocate for its adoption. [10]

The key to QD Vision's product is its 90% efficient quantum dots. They are the industry leader in producing the most efficient quantum dots based upon patented methods developed at MIT. There are several patents which have been granted that pertain to QD Vision's technology. However, a limited set that is relevant to QD Vision's capability includes the following:

Table 2-1. US patents relevant to QD Vision's technology.

Patent Title	Patent Number
Layered materials including nanoparticles	7,332,211
***Method of preparing nanocrystals**	7,229,497
Preparation of nanocrystallites	7,138,098
****Preparation of nanocrystallites**	6,821,337
****Preparation of nanocrystallites**	6,576,291
Blue light emitting semiconductor nanocrystal materials	7,253,452
Light emitting device including semiconductor nanocrystals	7,700,200
Stabilized semiconductor nanocrystals	7,601,424
Stabilized semiconductor nanocrystals	7,106,613

* *A previous patent (App. No. 60,497,706) filed on Aug. 26th, 2003 was incorporated into this patent taking the later filing date.*

** *These patents were later expanded upon and their material was covered in the latest patent, 7,138,098.*

The "blue light emitting semiconductor nanocrystal materials" and "light emitting device including semiconductor nanocrystals" combined define the potential for QD Vision to realize a QD display product in the future.

QD Vision was not able to comment on specifically which patents it has obtained, describe those under pursuit, or development of any new IP. Patents mentioned above are simply a list of candidate patents that a company similar to QD Vision should look to pursue for development of the technology described in this paper.

2.1 Materials Technology IP

The "layered materials including nanoparticles" is a patent directly on the QD/polymer coating. This composite is a matrix material (most likely an aromatic polymer moiety as mentioned in the patent or an acrylic with a plurality of nanoparticles (most likely CdSe quantum dots again from the absorption shoulder characteristics and emission peak) in a mutually soluble solvent. This solvent is most likely non-polar as the QD/polymer coating solution was easily diluted with toluene. [17] The nanopaticles themselves have ligands bonded to their surface to avoid FRET between particles and improve optical emission efficiency of the coating. This patent sets the stage for the application of QD Vision's capability.

The patents titled "stabilized semiconductor nanocrystals" includes considerations in preparing nanocrystal with oligomerized polydentate phosphine ligands that bind strongly to the surface of the nanocrystal. This prevents ligand exchange which can quench or diminish emission from the quantum dot. This method can be seen as a way to achieve the 90% photoluminescence efficiencies demonstrated by QD Vision.

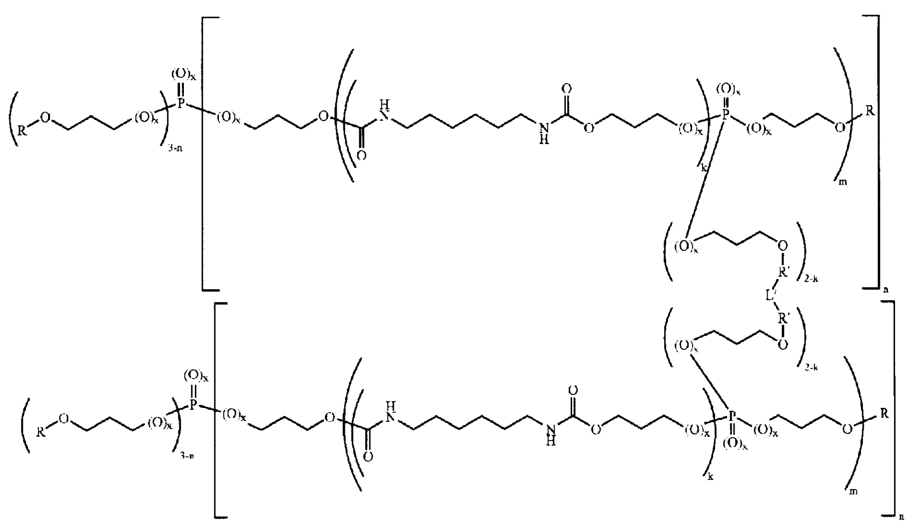

Figure 2–1. Oligomerized polydentate ligand structure of patent US 7,601,424 where L' is a bond to the nanocrystal or cross-linking group. Each R group can be a variety of polyamide group linkages.

2.2 Process IP

In order to produce these high-performance quantum dots, QD Vision has most likely secured a patent similar to the patent titled "method of preparing nanocrystals". This patent details a method to continuously produce colloidal semiconducting nanocrystals (quantum dots) as opposed to the typical method of batch processing production used in the lab or by other nanocrystal manufacturers.

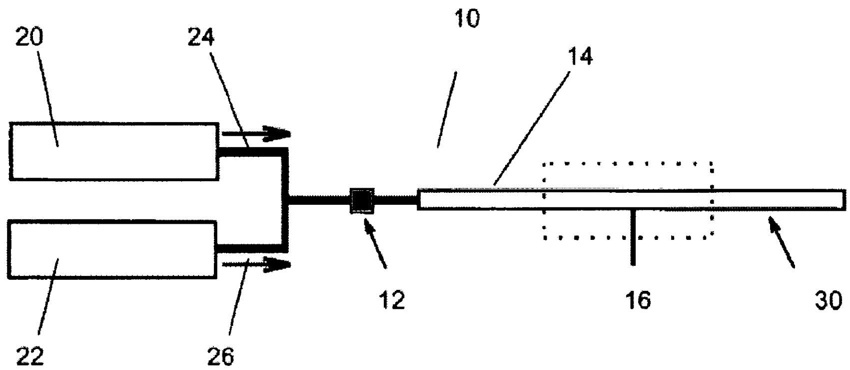

Figure 2–2. Capillary reactor diagram used in production of quantum dots as described in patent US 7,229,497.

This continuous flow reactor contains a convective mixing chamber (12) connected to a heat glass reaction channel (14) with a reaction zone (16) heated to a constant temperature T as described in Figure 2–3. M-source (20) and X-source (22) provide the precursors which flow down paths 24 and 26 respectively. The M-source precursor has an M-containing salt such as halide, carboxylate, carbonate, hydroxide, diketonate in which M can be Cd, Zn, Mg, Hg, Al, Ga, In, or Tl. The X-donor source can be O, S, Se, Te, N, P, As, or Sb. The solutions are then mixed in the mixer (12) before reaching the reaction zone (16). The reaction takes place in the reaction flow zone of 16 where constant temperature is maintained and the nanocrystals are grown to their appropriate size. After exiting the reaction zone, the mixture reaches the growth stopping zone (30) and the mixture cools limiting, or substantially stopping growth of the nanocrystals. To best control the reproducibility of the nanocrystals, it is best to use a mixing chamber with an inner diameter of 250μm and a volume of 30μL with a mixture residence time of 1-15 mins depending upon flow rate. Operation of this continuous flow production method for 8 continuous hours was demonstrated.

Following production of the quantum dots, a polymer is incorporated to form a composite of quantum dots, polymer, and mutual solvent. This composite can then be cured using a UV light source. This curing process affords better stability of the film.

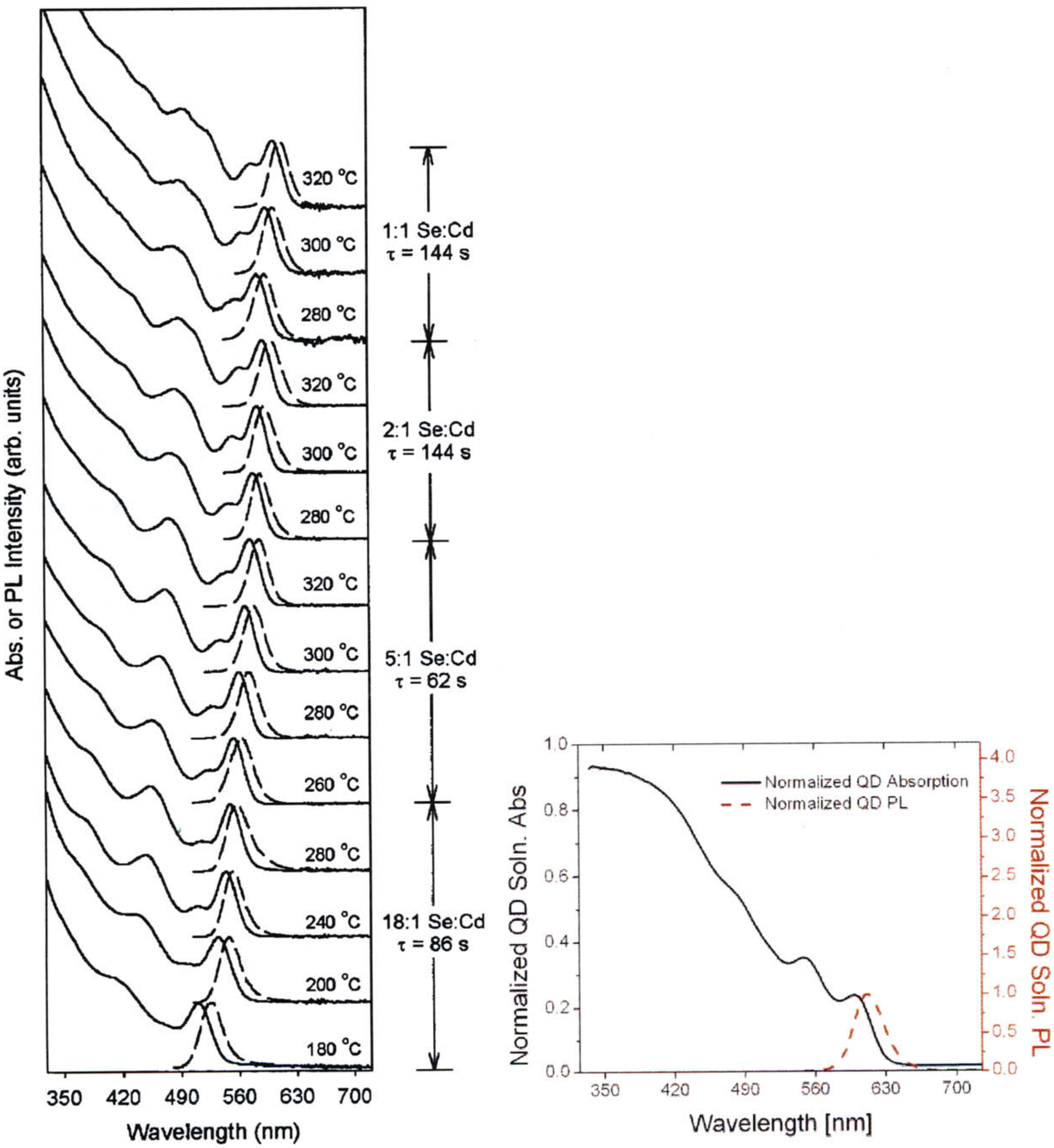

Figure 2–3. At left, the absorption and emission spectra of QDs produced using the production method described in patent US 7,229,497. At right, the absorption and emission spectra of the QD/polymer solution used in research for comparison.

From the range of quantum dot absorption and emission spectra capable of being produced by the method in patent US 7,229,497, it is apparent that from the corresponding absorption and emission spectra of the QD/polymer coating that the quantum dots can be synthesized using a 1:1 Se:Cd ratio at 300°C and heating time of 144s. This produces a CdSe quantum dot for inclusion into the polymer matrix material with absorption peaks of ~550nm, and ~600nm with an emission peak at ~610nm.

3 Market Analysis

3.1 Optical Coatings

Innovation is essential for revenue growth in the optical coatings industry. [18] New applications where coatings have a new advantage represent the fastest growth markets in the industry. Moreover, small companies will have difficulty surviving in the current economic situation. Overall sales in optical coatings are expected to be $4.6 billion in 2010 with growth to $5.7 billion by 2015 for a CAGR of 4.3%. [19] As a result of the recent economic recession, several orders for coatings were cancelled and the industry experienced significant sales decline from 2008 to 2009. Sales lost during this period are not expected to return to levels prior to the recession until sometime around 2015.

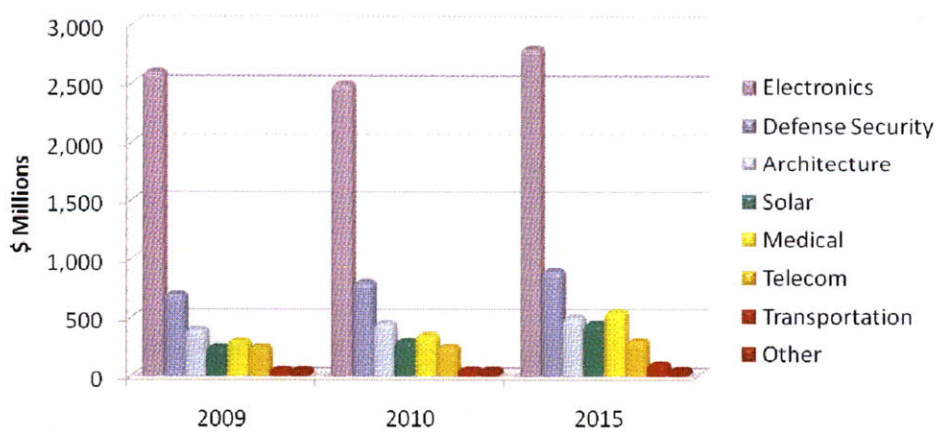

Figure 3–1. Global market for optical coatings by segment 2009-2015. [19]

The larger players in the optical coatings for solar applications market include CERAC (a subsidiary of Williams Advanced Materials, which is itself under the Advanced Material Technology and Services (AMTS) segment of Brush Engineered Materials, Inc.), Dynasil, Evaporated Coatings, Inc., Heraeus, Inc., Honeywell International Inc., Œrlikon, Praxair, Inc., Quantum Coating, Inc., Solar Applied Materials Technology Corp., Sumitomo Metals, and Xinxiang Baihe O.E. Each supplies either materials or applies the coatings themselves. The most common coatings used in this market for solar applications are TiO_2 and Si_3N_4.

Brush Engineered Materials is one of the largest in this group that serves the solar industry. It has identified that the energy market as a having significant potential for growth in its materials portfolio. [20] Sales within this market declined in 2009 as a result of the global economic climate, but the company was able to realize increased margins. Moreover, sales in the AMTS division primarily depend upon the price of metals as the company mostly passes material through and takes a margin regardless of the type of material or metal. Operating profits in the AMTS division represented 5% of external sales in 2009, better than the operating losses posted by most of their other divisions. Even so, AMTS took an operating profit of near 10% prior to the economic downturn while other divisions saw operating profits an order of magnitude lower. Brush Engineered Materials recognizes the potential growth opportunities in the solar and medical markets in their AMTS division and has acquired Techni-Met, a company specializing in the production of precision precious metal coated flexible polymeric fibers for use in mostly high-end medical applications. Brush has also invested $4.9 mil. in capital for development of Brush's capabilities in the solar market representing 0.7% of total global sales. This represented a major investment on Brush's part due to the small margins on which the industry operates.

Similarly, Honeywell's Electronic Materials division is a major player in the solar energy coatings market. Recent research investments have resulted in the release of a new AR coating product called SOLARC, which is stated to improve transmission by 3-4% over the broad spectrum (350-1100nm). [21] This product has been further improved by having self-cleaning and anti-soiling properties.

Honeywell has long distinguished itself as a market leader in quality and consistency in product. This has afforded its leading position in the market with some of the largest profit margins.

Honeywell's Specialty Materials division (which includes the electronic materials division) has chosen to focus on development of their materials portfolio for renewable energy sources, and specifically that of solar. [22] Because Honeywell enjoys large profit margins (14.6% in their Specialty Materials Division), is highly respected in industry, and emphasizes investment in new and innovative products, Honeywell might make a good partner for future distribution of the QD/polymer coating product. However, it is important to note that Honeywell has been apparently uninterested in acquisition opportunities recently as only $10 mil. in acquisitions was seen in 2008 and nothing in 2007.

Most companies in the optical coatings industry, and especially that for solar, are large and operate on very thin margins. Consequently, it is difficult for a startup to compete directly with these companies on an operations basis. The critical competitive factor to emphasize is the added benefit of the technology which will be covered in more detail in the Product and Process Assessment section. The acquisition of Techni-Met by Brush was the result of an existing relationship between the companies were Techni-Met was already sourcing much of their material from the AMTS division of Brush and Brush was looking for a new, high-margin market to enter to boost their income statement. Therefore, when looking for a potential exit strategy, acquisition by a larger materials firm in the industry may be an option. However, proving market demand is critical to demonstrate company value for acquisition.

3.2 Solar PV

Solar PV for energy production can be found or used in a variety of areas. An exemplary, but by no means exhaustive list of applications may include: watches, calculators, toys, battery chargers (portable electronics), professional sunroofs for cars, utility, grid-connected residential, grid-connected commercial, buoys, street lights, garden lights, electric fences, water pumps, radios, advertising billboard lighting, bird/bath fountains, boats, CCTV, clothing lights, railway crossing lights, remote water level meters, pool lights, etc.

The solar PV market is very bottom heavy with a few companies controlling the supply of silicon and a multitude delivering to end consumers.

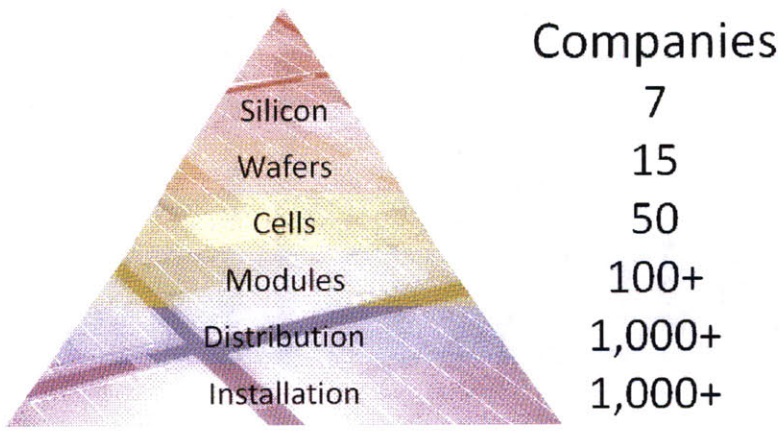

Figure 3–2. Solar PV industry supply chain in the United States. [23]

Approaching the product end-consumer directly may also be an option for obtaining a customer base. Therefore, identifying crystalline silicon cell manufacturers that would be interested in using the QD/polymer coating on their existing products would be a probable business model. In this market, there are a limited number of silicon photocell producers for solar PV end-use. In a survey of companies, there are only a handful of medium to large-sized companies based in the top four largest PV markets: U.S., Germany, Japan, and China.

However, the German market could see decline in its growth. The German government has recently announced a cut in the solar PV Feed-in-Tariff (FiT) of 16% for new rooftop installations, 15% for most open-field installations, and has completely eliminated the subsidy for farmland solar systems. [24] Even more cuts are likely in 2011 if demand exceeds the 3000MW target for 2010. This could have a broadly negative impact on the market as the current market demand subsides. Citigroup believes the industry is in a temporary period where demand can just clear supply and there has been no pressure for PV module companies to find markets to pick up the slack. [25]

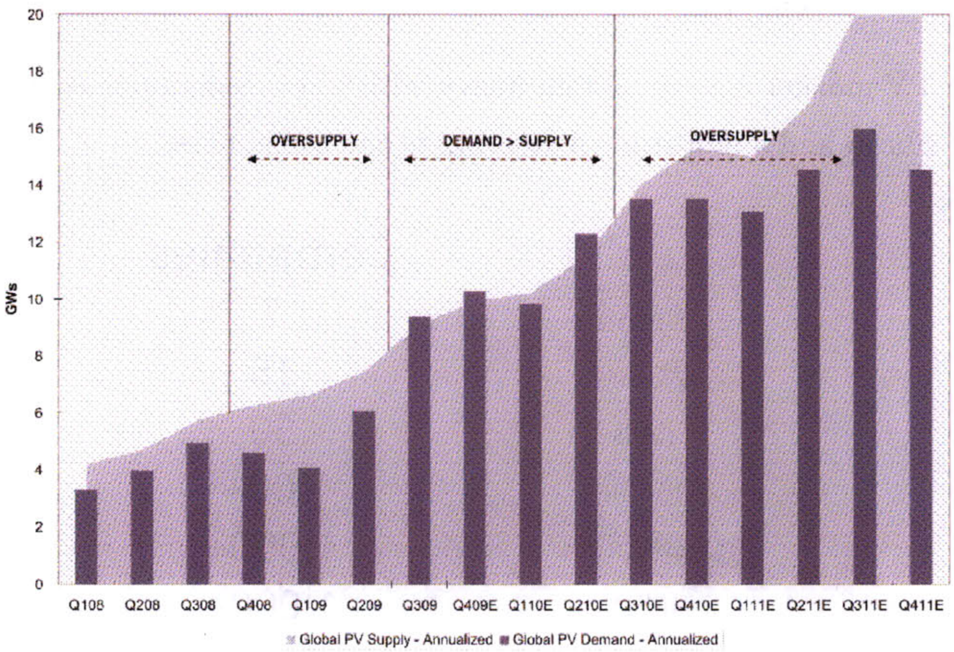

Figure 3–3. Citi quarterly global solar PV supply/demand model. [25]

Citigroup states that over-production could return by early 2011 resulting in a ~2-3GW gap, similar in size to that seen in 2009 when prices dropped significantly. However, during early 2009, manufacturers also faced a raw semiconductor-grade silicon material shortage which put pressure from the supply side as well. This shortage is described in more detail in the Photovoltaic Supply Chain section.

3.3 Photocells

The photovoltaic cell industry includes many producers none of which dominate the market. As a result, producers look to vertically integrate into silicon or modules in order to maintain control over margins and avoid being squeezed from other parts of the supply chain. As a result, some larger producers such as Suntech and SolarWorld do not sell their cells to other module producers. Most manufactures have moved to vertically integrate and keep to crystalline silicon technology. Even with the fragmented downstream module producer industry, median gross margins have fallen from 16.8% in 2007 to 11.5% in June 2009. That means cell producers have been forced to resolve higher production efficiencies due mostly to pressure from the silicon material industry. The scale and capital requirements for manufacturing lines make it difficult for new entrants to compete.

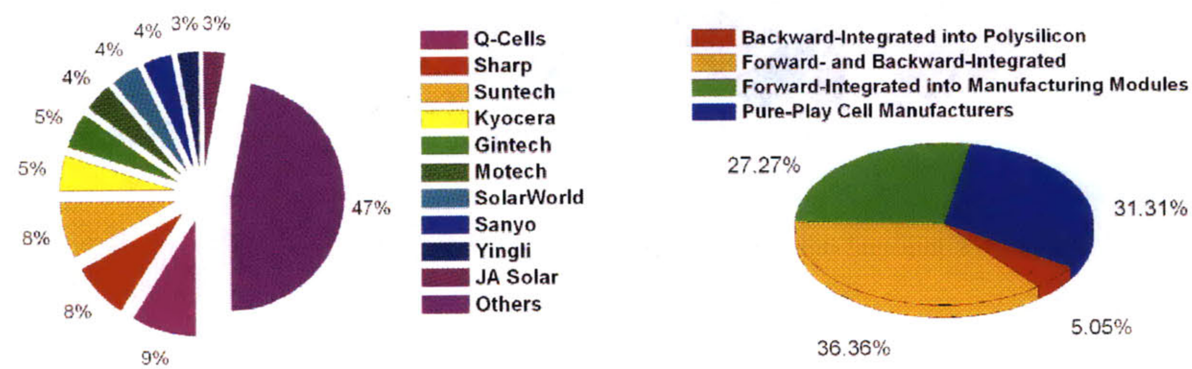

Figure 3–4. At left, photocell market share in 2008. At right, photocell vertical integration position in 2008. [26]

In a survey of 45 different countries in 2006 conducted by Energy Focus, 49% of module production companies said that solar cell manufacturer brand name was important in their consideration of product purchase. [27] When asked which brands were of high-quality, respondents said the top two producers were of highest quality with the top five of high-quality, and the remaining producers all equal. This survey indicates that working with the top two or five cell producers is essential to gaining market traction and realizing early adoption of the technology application. As a result, only the most recognized and respected producers by brand name should be approached in each market.

When looking at solar cell markets by geography, it is apparent that there are a handful of leaders, namely, Germany, China, Japan, and the U.S. The success of these regions in production development can be attributable to a set of factors including production cost competitiveness, technology knowledge and capability, and government support. The latter factor can be obscure and complex for most investors and hence requires a thorough understanding of how policy can impact the market.

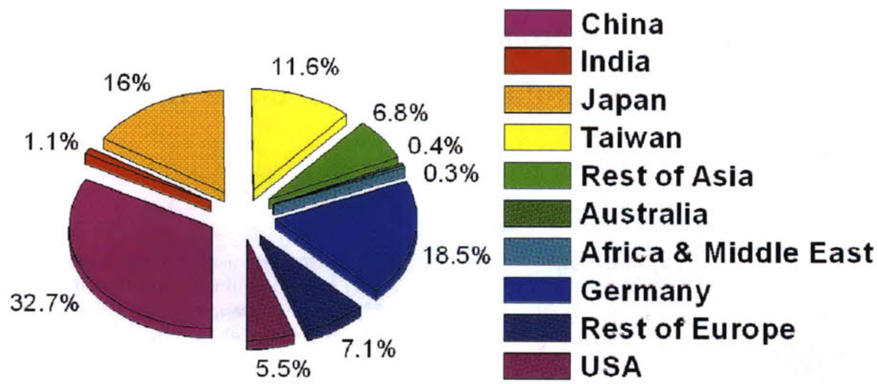

Figure 3–5. Regional shares in photocell production in 2008. [3]

3.4 PV Modules

The PV modules market is highly fragmented with several being vertically integrated into photocell manufacturing. Most module producers are located closer to their end-consumer markets as the cost of transportation is high given the weight of the glass used in module manufacture. However, for those module makers who are vertically integrated into photocells, the shipping costs saved do not justify separation of cell and module plants. [26] Hence, most vertically integrated manufacturers make cells in the same facility as their modules.

To determine the competitiveness of a module technology, analysts typically use the term $/watt-peak ($/Wp), or dollars per maximum watt produced by the module in idealized, standard testing conditions. In this sense, modules can be compared across technologies to determine which one has the best "bang-for-their-buck". Most analysts state that photovoltaics will reach grid-parity, or generate energy at the cost most currently pay for electricity, at the $1/Wp level. [28]

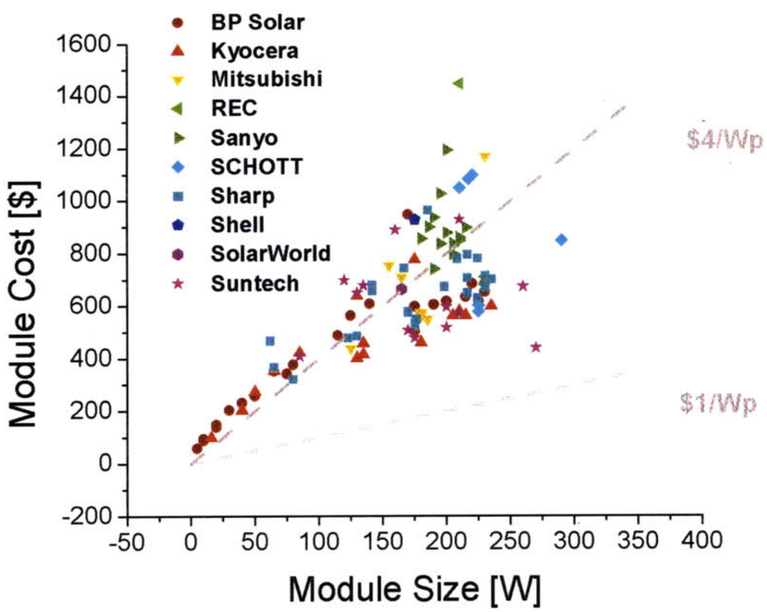

Figure 3–6. Survey of crystalline silicon module costs by rated power capacity.

In a survey of crystalline silicon photovoltaic modules, we see a clear price trend in the market with respect to cell efficiency. [29]

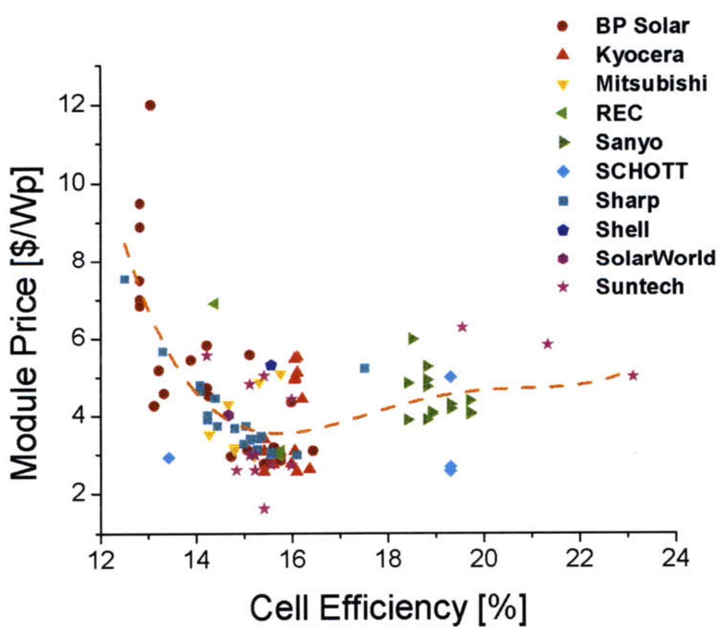

Figure 3–7. Survey of crystalline silicon module prices with their corresponding cell efficiencies and trend line superimposed.

Producers compete to produce ever more cost-efficient modules. As a result, they seek to increase module efficiency both through module design innovation and cell innovation, and reduce the overall cost of the module. In this crystalline silicon market, this can be best described as a down-rightward trend of the market average price/Wp as a function of cell efficiency. The most competitive cell efficiency range moves from the current 15-16% to 17-18%.

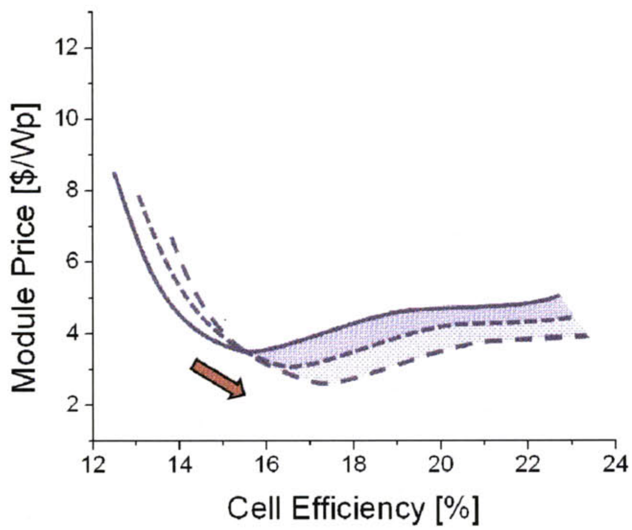

Figure 3–8. Module price/Wp versus cell efficiency trend with time.

It is Citi's view that solar module producers will see increased valuation due to fundamental demand drivers that will fuel growth above that of the S&P 500 market. [28]

Photovoltaic module industry leaders are expected to gain market share at the expense of non-differentiated companies resulting in a shake-out and consolidation of manufacturers. Those who will lose out are those with weaker balance sheets and smaller sales revenues as the industry moves closer to larger, scaled production. These companies will serve in subordinate roles to large ones. However, those with differentiated product lines could maintain market share and grow as a result of the further commoditization of the photovoltaic module.

The QD/polymer coating would allow producers to differentiate their product and maintain market share.

Even with the dramatic reduction in cost of raw material, crystalline silicon module manufactures will experience further margin compression over the coming years. Though crystalline silicon has around 90% of the photovoltaic module market, crystalline silicon cannot compete with CdTe thin-film on the modular level. With an Average Selling Point (ASP) of around $2.00/Wp, crystalline silicon modules are more than twice as expensive as CdTe modules. Moreover, installation costs of crystalline silicon dwarf that of CdTe making the installed system price close to $4.00/Wp. [25] Manufacturing efficiencies and raw material cost will not be enough to challenge the position of CdTe on a Levelized Cost of Electricity (LCOE) basis. Application of the QD/polymer coating would offer crystalline silicon manufacturers the opportunity to realize increased margins. With their high efficiency crystalline silicon product line, modules from producers such as SunPower will be able to compete effectively with CdTe at the LCOE level. Deustche Bank believes SunPower has one of the strongest positions in the market with a sustainable, long-term, vertically integrated business model from cell manufacture to energy provision. Many upstream companies will attempt to integrate downstream as market share is lost.

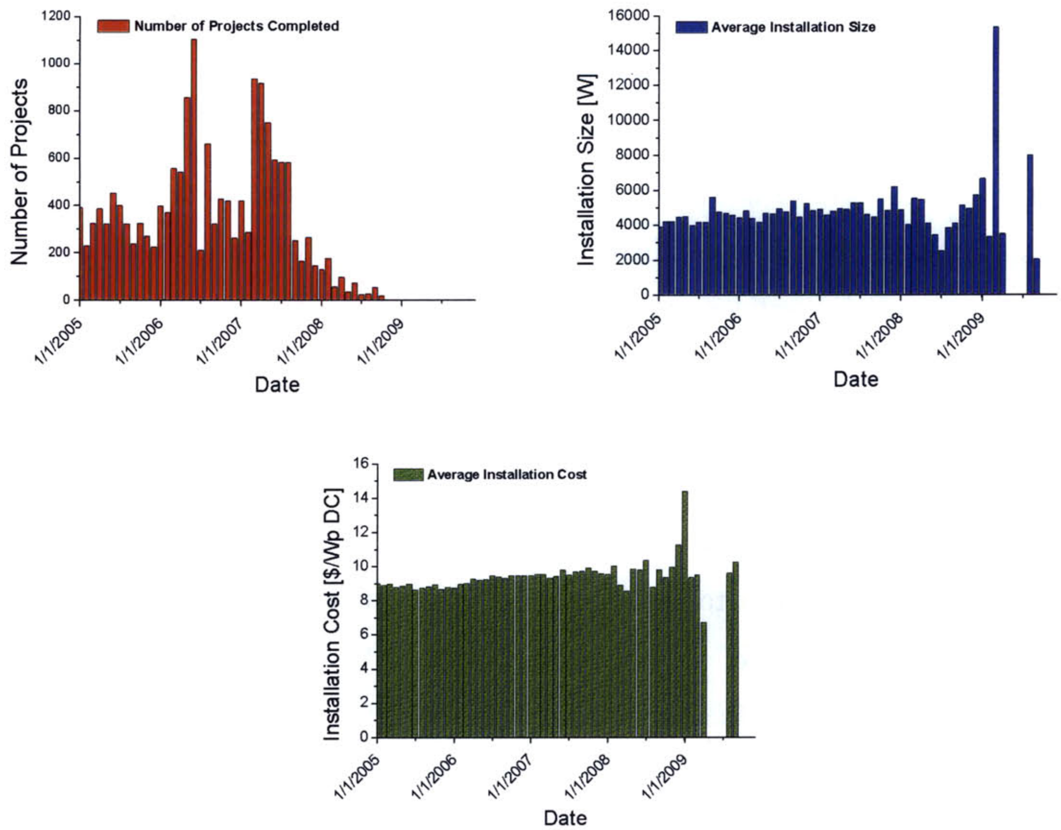

Figure 3–9. Upper-left, average number of solar PV installations by month. Upper-right, average size of solar PV installations by month. Lower-middle, average solar PV installation costs by month. All information for projects completed in the California market from January 1st, 2005 to December 31st, 2009. [31]

However, there are several risks that hinder growth of the solar PV market as a whole. Most notable are the inconsistent government policies for stimulating market demand, large upfront costs, high labor costs, customized application for varying residential and commercial installations, and the variety of competing technologies.

Key factors for success in the photovoltaics industry include a stable business model and balance sheet, overall supply chain, and supply/demand fundamentals which can be significantly influenced by the government or local authority.

3.5 PV Policy Landscape

Legislation is as much a factor in sizing the potential market for this technology as are the customers themselves. Governments provide substantial assistance and subsidies for all forms of energy production.

In consideration of grid-connected PV generation, mechanisms to increase adoption of solar renewable energy (RE) generation have been varied and diverse with the majority of countries following a core set of policy initiatives. Many of these mechanisms rely upon a liberalized wholesale energy market with generators, retailers, and consumers managed by a system operator (such as PJM, NE-ISO, CAISO, ERCOT, or MISO in the United States) to ensure the reliability and security of the overall system. In most systems, policy is designed to increase the adoption of RE in general with specific goals for each type of RE set such as those for solar or wind. When developing a product whose primary purpose is to generate energy, it is crucial to understand the government's role in creating and designing markets for energy. The following is a cursory explanation of the different mechanisms used by countries to increase adoption of RE in general with several analogies to that of solar PV.

3.5.1 Direct Strategies

Quota obligations, or commonly referred to in the U.S. as Renewable Portfolio Standards (RPS), places a specified obligation on electricity suppliers or consumers as to the amount of RE they generate or consume respectively. From the purchaser's perspective, for each MW of power they purchase from a RE generator, they get a certificate that the purchaser gives to the local authority. Companies can either get cash for this certificate, or, if they do not meet these standards, must pay a penalty for each unit of RE electricity not met. This forces the market to trade RE by requiring participants to purchase or sell RE. The idea is to reduce the costs of introducing RE resources by having market mechanisms efficiently resolve issues through competition. This method is currently used by several states in the U.S., U.K., Italy, Belgium, Austria, Australia, and Sweden. This is also an efficient way to achieve specific generation goals for the state.

However, RPS policies can hinder investment due to the variability in prices seen in the market. [30] With production fixed, the price becomes flexible and thus returns become uncertain for investors. Moreover, this mechanism supports development of RE technology that is closest to wide-spread adoption (such as wind as seen in many countries). This leads to significant investment in this single technology and leads to an unbalanced adoption of RE technologies. Lastly, the difference in design of these quota policies across states and even provinces has hindered the success of this method. For these reasons, it is difficult to implement solar in markets where quota obligations are imposed.

Contract bidding requires RE generators bid into a government auction to be awarded RE generation contracts with the contract going to the lowest bidder, and assumed most efficient. Electricity suppliers are then required to purchase energy from these awarded contractors. Auctions occur across RE sub-sectors such as solar, wind, or biomass. This gives the authority more control over the performance and mix of each technology. Moreover, competition affords a reduction in prices and the contract ensures stability in pricing.

However, several bids never lead to development as was seen in the U.K. market. This can be a result of generators making bids too aggressive, or existing conventional generators undercutting other developers with the intent to never develop and thus keep RE competitors out of the market.

Most bidding systems or quotas are beneficial to large, established companies. These companies have the financial support and political clout to implement the marginal-cost form of RE generation. They are also able to use existing assets, already fully depreciated to assist in the implementation of RE generation. In this manner, adoption of RE generation is cost-efficient. However, it does not realize the scale or diversity of RE generation technologies that policy makers may have originally intended.

Tariffs affect market adoption of technologies directly by directing the price of individual generation options. This method typically takes the form of a Feed-in-Tariff (FiT) where the price of each technology is set to compete with that of conventional sources based upon the calculated benefits and costs of adoption of certain RE technologies. The government may choose to use dedicated funds to subsidize this tariff, or require utilities to purchase RE and pass the costs off to consumers. The authority also can control the rates of adoption of individual technologies by affecting the associated tariffs directly. This is an effective form of regulation for diverse and dispersed sources of RE generation and is a good fit for small to medium-sized developers. Countries that have implemented FiTs include Spain, Germany, France, and Denmark up till 2000. [30]

Table 3-1. Wind Energy in Europe. Comparison of price regulations with quantity regulations.†

	Country	Accumulated end of Dec. 2006 (MW)	Installed in 2006 (MW)	Installed capacity per area (kw/km²)	Installed capacity per capita (Watt/capita)
Countries with price regulations (Feed-in law)	Germany	20,622	2194	57.8	251.1
	Spain	11,615	1,587	23.3	255.0
	Denmark*	3,136	8	72.8	570.8
	Sum	**35,373**	**3,789**		
Countries with Quantity regulations (Call for tenders)	UK**	1,963	610	8.13	32.0
	France	1,567	810	2.32	25.2
	Ireland	643	147	9.3	145.3
	Sum	**4,173**	**1,567**		

Source: World Wind Energy Association [31]

* *The limited expansion in the Danish market was due to a repeal of the wind FiT in 2001. This has resulted in a significant slow-down of wind development and has caused an upheaval among the general population who is in support of its development.*

** *Great Britain in comparison to the German and Spanish markets has high wind power resources. However, with quantity regulations by tendering similar to several other European nations.*

† *Wind energy development is one of the most mature forms of RE across countries and has been used in analogy to policy geared towards support of solar PV development.*

This mechanism reduces the risks for investors as returns are more predictable and sometimes tied to the performance of conventional sources. The long-term stability of capital leads to low-interest credits. This contrasts to the uncertainty of quotas (RPS) where there is significant doubt as to the quantity of electricity and certificates that will be available for capture leading to a higher interest rate and cost of capital.

Distinct disadvantages include unpredictability of market adoption, excessive developer margins, network balancing, and resource prioritization. Without caps or quotas, RE development can exceed that which is needed as exemplified recently in Spain. [32] Along a similar vein, developers can reap significant margins from these tariffs if the tariff amount is set too high. [33] Moreover, the requirement to use RE by suppliers may result in overuse and create issues for system operators in handling intermittent resources.

Use obligation requires building developers to incorporate a certain amount of RE generation in their building design when building new or refurbishing old structures. These forms of integrated-RE generation are a great method to reduce grid load and capture local sources of energy and can be used in different ways to incentivize use of specific technologies. This instrument uses existing policy such as building permitting and codes to develop the RE market and may be implemented on a local level not requiring large sums of cash from relevant authorities. The extra costs of the plan would increase building costs by 0.5-1%. [34] Hence, the impact on investments would not be significant as the upfront cost to implement would be relatively small. Examples of use of this policy include Barcelona, Spain, which, due to its success, was later adopted nationally. [35]

Preferential tax treatment or offsets can be used in a variety of ways to indirectly stimulate the development of RE generation. The benefits, and thus development, are often realized by existing market parties who stand to improve their tax situation by increasing activity in the related area. These incentives can spurn new market development, but need to have a significant impact on the tax situation of participants. New or small developers do not reap the benefits needed to compete in the market due to their small or entire lack of tax obligations. Unless the developer has other sources of income, this instrument may not be as effective as planned. In this manner, tax incentives should be used cautiously and only when regulators wish to change the behavior of an existing and developed RE market.

The U.S. has recently resolved this problem by giving developers the opportunity to opt for a direct grant equal to what they could have saved in taxes.

This is especially helpful during the current economic climate when the tax-equity market is slim or non-existent.

Accelerated depreciation is often used by regulatory authorities to allow companies to recoup upfront capital costs sooner. As a result, investors face steep and unpredictable changes in the value of their assets that can be much larger than the expected physical life of the assets implies. Typical depreciation schedules allow owners to depreciated 50% of the value of their assets in the first year, with the remaining 50% depreciated according to normal schedules. [36]

Production tax credits (PTCs) give a direct stimulus to those who produce RE in the form of remuneration per kWh. This typically will last for a period of 10 years of the facility's operation after which it is expected that the upfront capital cost will be covered and the facility's marginal costs will be competitive in the market. [37]

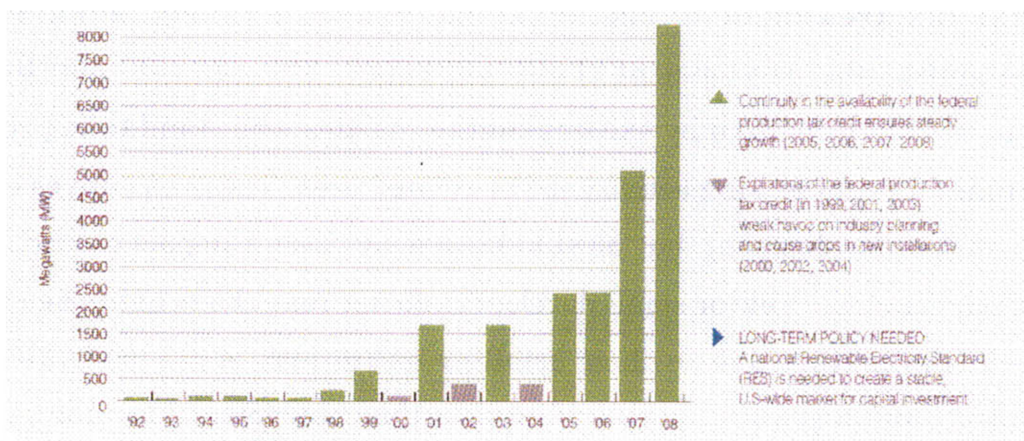

Figure 3–10. Annual installed U.S. wind capacity. [37]

This method is only used in the Unites States and has been favored by wind developers throughout its long history. The biggest issue with PTCs is that they can only be used by those who sell bulk electricity. They cannot be used by individuals who participate in distributed generation. Moreover, they require that the developer have a significant tax burden to begin with. The transient nature in which PTCs have been applied has lead to a boom-bust cycle, unsustainable for manufacturing. (This has been a primary motive for General Electric to lobby to renew PTCs by only one year, each year. This is used to deter international manufactures like Vestas from building facilities in the U.S. due to the financial uncertainty of the venture. [38]) Only those with the financial wherewithal are able to develop with this scheme resulting in a concentration of development and monopoly. Finally, PTCs cause obscure forms of ownership structures as was the case with Enron and their wind deals to maximize PTCs. It becomes very difficult to follow the exchange of money.

Manufacturing investment tax credits (MITCs) provide companies who produce RE end-product or parts or components for RE generation the opportunity to deduct a certain portion of their taxes as a result in their participation in the RE generation market. This method is currently used in the U.S. and is supported by Section 1302 of the American Reinvestment and Recovery Act (ARRA) of 2009 where $2.3 bil. were given to support $7.7 bil. in qualified new, expanded, or re-equipped renewable and advanced energy manufacturing investments. [39] The MITC allows for a 30% credit for these projects. The Department of Energy (DOE) and the Internal Revenue Service (IRS) reviews and makes determinations on the eligibility and merit of the applications.

Property tax reductions for land owners are often offered from cities or towns after the installation of certain forms of RE generation on the affected property. These include solar thermal, solar photovoltaics, wind, and central wood-fired heating systems. [40]

Value-added tax reductions come from reducing the customs import duty on equipment and services for RE generation. This is typical policy for developing countries where existing industry may not be developed or have strong standards for utility scale RE generation. Such policy has been used to increase imports and adoption of RE in places such as China. [41]

R&D tax credits are most often used by research institutes, universities, and corporations with significant R&D efforts such as IBM or Intel. These credits are applied towards research efforts beyond the base amount in a particular year. This particular instrument should mostly be used for focusing on the development of new technologies in places where existing infrastructure permits increased research. This method would not be effective in creating an entirely new research industry within a country. Other tax provisions would be more effective in increasing RE adoption than this method. [42]

Low-interest loans provide developers the opportunity to make investments in RE generation with an increased rate of return on their investment. Because of the high risk involved in RE generation development, it can be very difficult to obtain loans or financing at a low enough interest rate to make the project profitable. This is highly beneficial for smaller and newer developers who have limited reserves of cash and financing to support the kind of upfront investment needed for RE generation.

3.5.2 Indirect Strategies

Removal of conventional generation subsidies is a more direct way to resolve the RE market imbalance. Conventional generation sources such as gas, coal, and oil in many countries receive subsidies to reduce the cost of their delivery and reduce the apparent cost to the consumer. This method, however, can be very difficult to implement as existing lobby groups that support the coal, oil, and gas interests have a very strong influence on governments. This is most apparent in the U.S. where a tax on coal or oil has been regarded as easier to implement than remove of subsidies - even though they would achieve more or less the same ends!

Eco-taxes, or permits on CO_2 emissions can cause market participants to invest more in RE generation due to the reduced or zero emissions of RE. This becomes a direct method to affect the unaccounted cost most cited by RE proponents.

However, it can have other, unintentional consequences by impacting markets outside that of the electricity market. Some examples of the most impacted markets would be the cement manufacture, automobile, and airline industry. These impacts are large and complex and are ineffective in stimulating RE development for the electric wholesale market due to larger, economic consequences. For this reason, it can be hard to pass legislation on such an instrument because it impacts almost all parties, and in more than one manner.

4 Industry Structure and Business Model

4.1 Photovoltaic Supply Chain

The application of the QD/polymer coating can be seen as a post-cell processing step in production. In single or multi-crystalline photocell production, the process begins with the mining of silicon ore, which will then be later purified into high purity, semiconductor-grade silicon (typically a 0.0005ppm or 99.9999999% pure). [43] The cost of the final module product is highly dependent upon the material cost of silicon.

The period of 2004 to 2009 saw one of the most dramatic shortages in silicon. Prior to the shortage, significant demand for semiconductor-grade silicon drove up prices. With the two major consumers of silicon being the solar and semiconductor industries, computer chip makers were able swallow some of the price increases and out-bid PV wafer manufacturers due to their larger margins. In consequence, most silicon used in the PV industry during the shortage was rejected silicon wafer material from the computer chip industry. Prices went from $24/kg in 2004 to a peak of over $400/kg in 2008. [44] In response, the industry made large investments in production capabilities with the help of government incentives. The shortage issue has been largely resolved with the price of silicon falling to $50-55/kg by year-end 2009. [45] As a result of this over-capacity, the silicon material industry has looked to PV wafer manufacturers to take up supply.

Some believe the price could stay around $40/kg through 2012. [45] Consumption of high-quality silicon by the solar market surpassed that of the semiconductor industry in 2008. [45] Industry analyst Richard Winegarner of Sage Concepts believes that in 2010, 70% of semiconductor-grade silicon production will be consumed by the solar market with the remaining mostly going towards semiconductors. He projects this trend to continue with 90% going to the solar market over the coming years.

The two processes most widely used by industry to purify silicon ore; the Siemens Process, and the Fluidized Bed Process (FB). The Siemens Process produces about 80% of the silicon for use in polysilicon wafer fabrication. In this process silicon is deposited onto harpin-shaped hot seed filaments of high-purity silicon crystals from a mixture of purified trichlorosilane or silane gas with excess hydrogen. The filaments, which are connected in series as part of a circuit, are heated to 1,100-1,175°C by an external direct current. [45]

The FB process was designed in the 1980's by a program sponsored by the U.S. Department of Energy to create a less energy intensive method to make high-purity silicon. This process consumes 90% less energy than the Siemens Process and has continuous production compared to the Siemens batch method. [45]

For mono-crystalline silicon ingots, the Czochralski (CZ) process is often used which involves melting the silicon material in a crucible of quartz and introducing a seed crystal to initialize the growth of the single silicon crystal. The crystal is then pulled out of the liquefied silicon slowly to form an ingot. This ingot is then sliced into mono-crystalline wafers for later processing. Another process used in making single crystal silicon ingots is the Float-Zone (FZ) process. This method makes purer crystals than the CZ method because they are not contaminated by the quartz crucible. Typical wafer edge lengths from this process range from 100-150mm.

For poly-crystalline silicon, Directional Solidification (DS) or Electromagnetic Casting (EMC) are used. In DS, silicon is melted in a crucible and is directionally solidified in the same crucible. Silicon casting uses a separate melting crucible from which the liquefied silicon is poured into the mold crucible for casting. This process is three times as fast as the CZ method, and requires less skill, man power, and equipment than the CZ method. However, much of the material is discarded due to large defects and the brittle nature of the large grain boundaries. Ingots produced range from 125mm x 125mm to 690mm x 690mm. Most wafers, however, are made from ingots that make wafer sizes of 125-150mm.

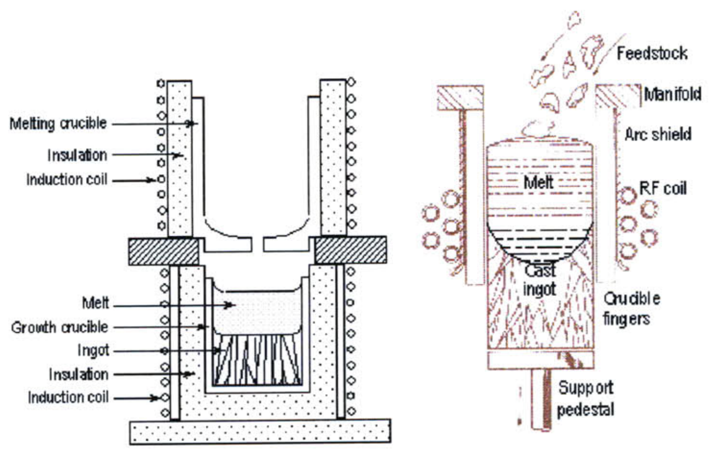

Figure 4–1. At left, directional solidification/silicon casting method diagram. At right, diagram of the electromagnetic casting method. [46]

EMC uses induction-heated cold crucible melt confinement. A parallel, vertical array of closely-spaced fingers cooled by water is used to contain the silicon melt while the cooled silicon ingot is repulsed downward. This process typically makes ingots of 350mm x 350mm.

Once the ingots are produced, they are sliced with a wire saw to form thin wafers. However, this preparation results in as much as 50% waste material known as "kerf". [47] Any damage from the sawing process is removed using an etch process.

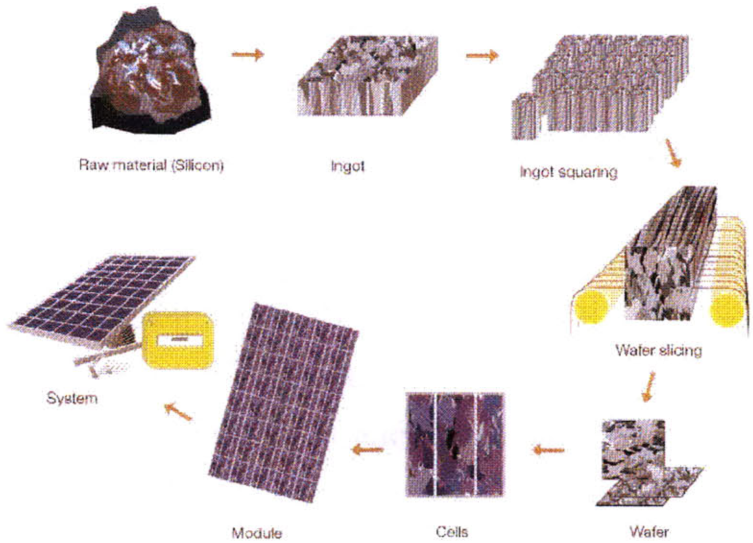

Figure 4–2. Silicon solar PV supply chain. [3]

In cell production, the wafers undergo doping, metallization of the electrical contacts, the application of the anti-reflective coating, and final testing and sorting. In doping the wafers, two methods are used. The wafers can be n^+ doped using gaseous $POCl_3$ supplied in a liquid blubber through a horizontal furnace kept at 800-900°C. [48] Similarly, the phosphorous used for doping can be applied in a paste using a screen printing process (similar to those used in LCD manufacturing). Following deposition of the paste/glass, the wafer is put through a conveyor furnace, removed, and the paste/glass is then removed. The heat diffuses the phosphorous into the silicon substrate

The contacts are placed using a screen process as well with Ag/Al paste. The branch/finger pattern is overlaid on the top of the doped wafer while the bottom is covered with the paste to form the back contact. The device is then co-fired to set the metal contacts using an IR belt furnace for rapid sintering.

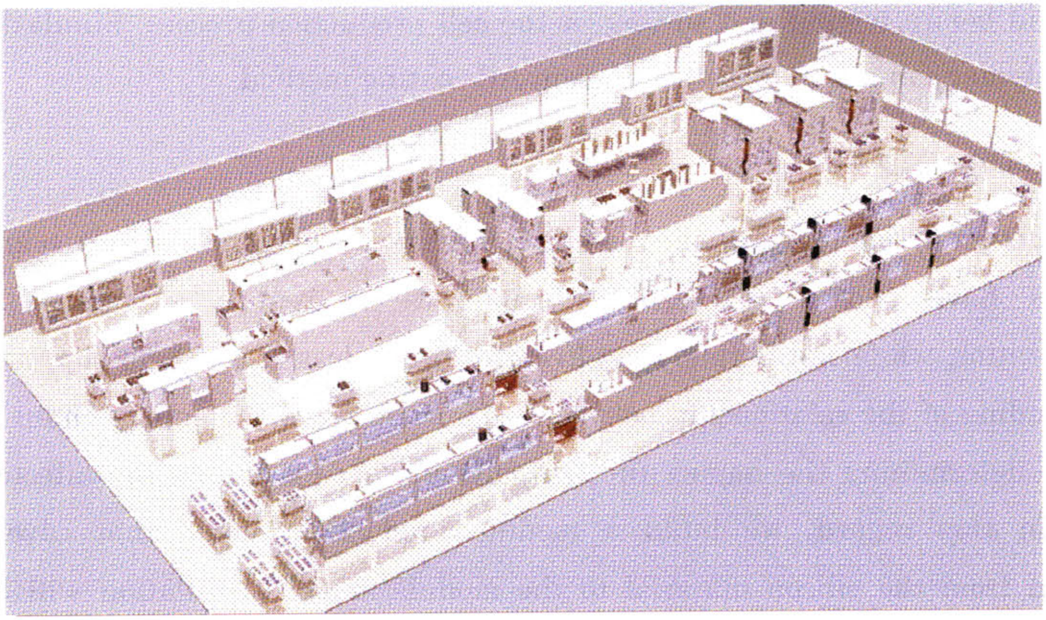

Figure 4–3. Cell process manufacturing turnkey factory. [49]

The typical AR coating of Si_3N_4 is applied using a plasma-enhanced chemical vapor deposition (PECVD) process with SiH_4 and NH_3 gases pumped into the chamber at a temperature of around 400°C. [48] An AR coating of Si_3N_4 with the desired dielectric constant is formed on the surface of the cell and contacts. TiO_2 may also be used as an AR coating. In this case, sol-gel polymeric TiO_2 films are deposited on the surface of the cell through a dip-coating process with film thicknesses on the order of 10-100's of nanometers. This process needs neither high temperatures nor vacuum environments and produces homogeneous films. [50] For cells without these AR coatings, the silicon oxide layer of between 200-500nm is left exposed to the environment.

These cells are then taken into a separate process where they are arranged on a preparation tray or frame. The cells are electrically connected, laminated, and framed into a final module. [51] This module is then shipped to a distributor or its final location where it is incorporated as part of a solar PV system for energy production.

It is seen that the optimal part of the supply chain for application of the QD/polymer coating would be following the application of the standing AR coating and before testing and sorting in the cell production process. Similarly, the QD/polymer can also replace the current AR coating method.

4.2 Production Model

The production of photovoltaic modules is a highly unified process that many companies have chosen to vertically integrate to realize economies of standardization while mitigating the effects of profit loss from their supplier. Understanding of the relationship between each segment of the supply chain is critical to determining the impact the QD/polymer coating has on the affected parties. In this regard, we build a module production model that covers production from the silicon material to the module stage. Installation will be covered at a later point.

For this model, we use Sharp's 230W modules, model NU-U230F3 with a 15.8% cell efficiency and a cost of $3.10/Wp which is seen as market average according to a survey of modules on the market.

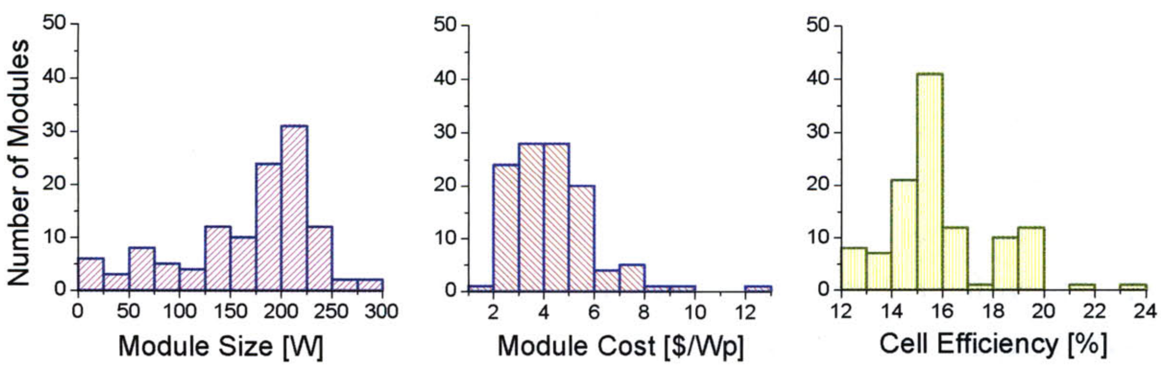

Figure 4–4. PV module sizes, costs, and efficiencies from a survey of modules. [29]

After understanding Sharp's financial position in their solar division at both the cell and module segments, we can construct a detailed picture of the specific costs of production for each segment. This will later help to understand the benefits of using the QD/polymer coating later in this paper.

Table 4-1. Estimated production costs for Sharp's 230W module. [52]

2010

	Matl's	Lbr.	Var.	Depr.	Fac. Ovd.	Corp. Ovd.	Fixed	Profit	Contrib. to Price	Cum.
Si	$0.24	$0.00	$0.24	$0.00	$0.00	$0.13	$0.13	$0.03	$0.40	$0.40
Wafer	$0.33	$0.05	$0.38	$0.06	$0.10	$0.14	$0.30	$0.08	$0.76	$1.16
Cell	$0.22	$0.06	$0.28	$0.06	$0.05	$0.13	$0.24	$0.07	$0.58	$1.75
Module	$0.59	$0.07	$0.66	$0.01	$0.02	$0.39	$0.42	$0.27	$1.36	$3.10

NOTE: All costs with units of $/Wp.

From this we see that the silicon wafer contributes an astounding 37% to the cost of the final module. This is still much lower than the industry average of 45%. [53] In Sharp's view, the decision to vertically integrate has afforded the company control over gross margins at the module segment, giving it room to adjust prices in order to retain its competitive position.

However, it takes time to implement a solution such as the QD/polymer coating with integration efforts taking on the order of a year assuming the technology is readily available in commercial scale quantities. For this reason, we look to estimate the expected costs of production at each segment.

Table 4-2. Estimated production costs for Sharp's 230W module in 2012. [56]

2012

	Matl's	Lbr.	Var.	Depr.	Fac. Ovd.	Corp. Ovd.	Fixed	Profit	Contrib. to Price	Cum.
Si	$0.17	$0.00	$0.17	$0.00	$0.00	$0.10	$0.10	$0.02	$0.29	$0.29
Wafer	$0.26	$0.04	$0.30	$0.05	$0.08	$0.11	$0.24	$0.05	$0.58	$0.87
Cell	$0.14	$0.04	$0.18	$0.04	$0.03	$0.09	$0.16	$0.02	$0.36	$1.24
Module	$0.46	$0.06	$0.51	$0.01	$0.01	$0.30	$0.33	$0.18	$1.02	$2.26

NOTE: All costs with units of $/Wp.

Production cost, price, and margin forecasts were taken from Barclays Capital industry estimates. Wafer costs as a percentage of module price increase while material and cell costs decrease. We also see the most significant gross margin erosion of 66% at the cell level where cell manufacturers will be squeezed from both the module side and materials side. [54] This effect was expected to take place for vertically integrated cell producers like Sharp as well. The most dramatic cost reduction expected is to occur on the cell level where process costs are reduce a dramatic 38% while the silicon and wafer levels decrease 29% and 23% respectively. This model is covered in more detail in Appendix B: Detailed Production Model. This understanding will allow us to better quantify the benefits realized by cell and module manufacturers covered in the Upstream Supply Chain Benefits section.

4.3 Business Models

Two unique companies utilize different business models mostly as a result of the difference in technology. The efforts of these companies may be referenced as a model for implementation.

4.3.1 XeroCoat

Started in 2005 by a professor from the University of Queensland, Australia, XeroCoat uses patented technology to reduce silicon solar cell reflectivity by 3%, and increase kWhr for a solar PV installation by 4%. [55] The company's primary application from the beginning was for use in optics. They have since focused all efforts on the photovoltaic industry including multi- and mono-c silicon, concentrating, thin film, and solar thermal. Their claimed innovation is module performance improvement along with process cost reduction. The application of the silicate-based liquid dispersion to the surface is easily scalable and less costly than current methods of forming anti-reflective coatings such as chemical vapor deposition (CVD), physical vapor deposition (PVD) or atomic layer deposition (ALD). XeroCoat advertises to current cell manufacturers and uses the reduction in costs and performance improvement as the primary selling point. [56]

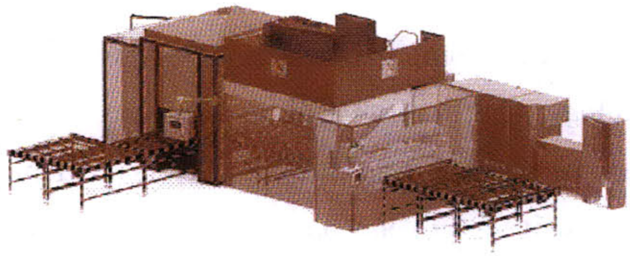

Figure 4–5. XeroCoat's turnkey coating system. [57]

In development of their business, XeroCoat realized that cell manufacturers are not in the position to develop or modify equipment for the application of their liquid coating. XeroCoat has paired with Hitachi High-Tech of Japan to develop turnkey systems for cell producer customers to purchase and install on their factory floors. XeroCoat has also partnered with Neotronics International for sales and distribution of their coating and turnkey system technology. Assembly & Test Worldwide and Air Liquide act as distributors for automation and curing system equipment and materials respectively. Pairing with experts in their respective aspects of production has been essential to the sales success seen by XeroCoat. [56]

XeroCoat has moved their business close to one of the largest photovoltaic markets in the world, California, where it can easily work with partner corporations. This move has also afforded XeroCoat the opportunity to receive U.S. government grants to further develop their technology and commercialize the existing material. In 2009, XeroCoat was one of 24 companies to receive part of a $24 mil. grant awarded by the DOE for PV Supply Chain and Cross Cutting Technologies under the Solar Energy Technologies Program. [58] This was part of a larger $300 mil. funding package from the DOE with the intent to reduce costs, emissions, and improving the green-collar workforce. Before this, XeroCoat won several grants from the Australian government and has completed rounds of venture funding from Southern Cross, Nth Power, and Uniseed.

4.3.2 QD Vision

QD Vision has been the primary company behind development of the technology in this paper. The technology itself has several applications and can be used from lighting systems to display technology. However, it is critical for a fledgling company to become cash positive as soon as possible. For this reason, choosing the application closest to being market-ready is necessary. In this regard, QD Vision has positioned itself as a materials technology company focusing on development of the base material and partnering with other industry experts to develop and deliver end-products such as the case with Nexxus. Nexxus was desirable to work with due to the number of distributors who are in several different lighting markets. [10]

QD Vision holds no exclusivity rights with their partner companies allowing them freedom to innovate into new markets and move to more experienced partners should their existing relationships not prove successful.

In their efforts, QD Vision has partnered with DTE Energy of Michigan to develop rebates for electricity customers who install energy efficient light bulbs. This was done to further stimulate the market for LED light bulbs in the hopes that customers will choose bulbs with their technology over the leading competitor. QD Vision has also secured a grant from the Department of Commerce along with venture funding from North Bridge, Highland Capital, DTE Energy Ventures, and In-Q-Tel. [10]

In their efforts to develop the market, QD Vision has participated directly in several tradeshows alongside the partner product developer, Nexxus.

4.4 Risks

The optical coatings market is highly fragmented with several leading players. Differentiation is key. Moreover, existing relationships between suppliers and customers are critical to establishing trust as margins in this industry are thin and gross margins depend upon volume sold. Therefore, finding the right partner to develop application solutions and materials distribution such as what XeroCoat has done is important. Obtaining client accounts will be a matter of trust and dependability than delivery of technological innovation.

Realizing high production volumes is also necessary to succeed in the photovoltaic coatings market as the primary component, the material, will account for a majority of the technology costs. As a result, potential customers will not be willing work with the startup should supply quantities not meet a reasonable level where application can be realized on a scale comparable to their other products.

One method to mitigate these risks is to closely monitor the performance and efforts of the next closest competitor, XeroCoat. XeroCoat has already done significant development of their technology and practices. Moreover, their efforts have created a foundation of expectations upon which potential customers will base their decisions. This can be seen as a positive or a negative for a potential startup using this technology. Customers who have had the opportunity to work with XeroCoat in the past unsuccessfully will not be keen on repeating efforts in a similar technology. Therefore, it is just as important to have direct market competitors to succeed as it is for the startup to succeed. However, market dominance is important for client account expansion and securing large client accounts will be crucial to becoming the market leader in specialized anti-reflective coatings.

5 Product and Process Assessment

5.1 Product Attributes

Module efficiency is the greatest determinant of the cost of a solar PV system in that the installed area is dependent upon efficiency. Design and installation costs vary significantly with module efficiency. Needs for wiring, racking, and connections increase with module size.

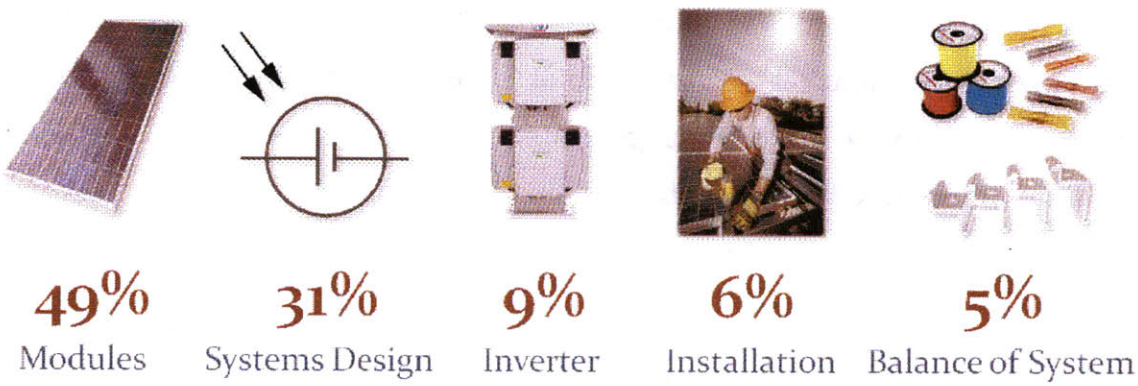

Figure 5–1. Cost breakdown of major solar PV system components. [59]

Solar PV systems mostly provide a single product, energy, which is in itself a commodity and is easily accessible in most developed countries. As a result, cost-performance of the solar PV system is essential to maintain competitiveness in the market. Consumers want energy provided as cheaply, and reliably as possible. There are several attributes of a solar PV system that end-consumers consider including visual appeal, reliability, maintenance costs, and product lifetime. However, these are secondary to the primary diver for investment which is cost-efficiency, or the lowest dollar-per-watt option. For this, attributes such as module output and upfront cost are the largest determining factors when consumers look at installing systems. Upfront costs include factors such as financing options, tax benefits, and rebates. Module output includes aspects of module efficiency and local solar irradiance. Those with deeper pockets, such as large corporations, are not as concerned with the upfront cost of the system and are instead interested in the payback period. A shorter payback period of under five years is desirable for potential commercial solar PV developers such as Hawaiian resort hotels. [60]

Table 5-1. Module product attributes.

Solar PV System End-Consumer Attributes	
Primary Attributes	Averaged module output, Upfront costs
Secondary Attributes	Visual appeal, Reliability, Maintenance costs, Product lifetime*

* *Product lifetime ends up not being much of a concern among end-consumers as most inorganic-based PV systems that dominate the market have a lifetime of 20-25 years or longer, well within the period needed to recoup the costs of the system investment.*

5.2 Product Benefits

In understanding the cost of ownership, it is important to consider the current environment for the end consumer and what the competing options include.

In consideration of the benefits realized by the QD/polymer coating at the installation level, it is necessary to construct a model that reflects the variance in costs associated with PV system construction.

In an example case, we look at a comparison between an average home in a low solar irradiance and high solar irradiance region of the United States, namely Medford, MA and Chandler, AZ. Both locations are near major metropolitan areas to avoid concerns with integration costs in rural areas or lack of space in urban areas. Both homes are built since 1990 with central, electric A/C, 2000 sq. ft., three TVs, natural gas heating, no basement or attic, two stories, and about six rooms with three inhabitants.

Table 5-2. Estimated energy consumed by average households.

	Medford, MA			Chandler, AZ		
	1222 sq. ft.	2000 sq. ft.		1222 sq. ft.	2000 sq. ft.	
Electricity rate	0.163	0.163		0.091	0.091	*$/kWh*
Similar home electric bill	127.00	145.92		124.00	160.17	*$/mth*
Similar home consumption	780.58	896.84		1361.14	1758.14	*kWh/mth*
Daily consumption	26.02	29.89		45.37	58.60	*kWh/day*
Consumption rate	1.08	1.25		1.89	2.44	*KW*
Avg. annual solar irradiance						
MA flat plate (lat)	4.6	4.6				*kWh/m^2/day*
AZ flat plate (lat + 15 deg.)				6.3	6.3	*kWh/m^2/day*
Offset						
75%	585.43	672.63		1020.86	1318.61	*kWh/mth*
50%	390.29	448.42		680.57	879.07	*kWh/mth*
25%	195.14	224.21		340.29	439.54	*kWh/mth*
Installation Size						
75% offset	4.71	5.42		6.00	7.75	*kW*
50% offset	3.14	3.61		4.00	5.17	*kW*
25% offset	1.57	1.81		2.00	2.58	*kW*

Source: Energy Information Administration, NStar, Energyguide [61][62][63]

With the expected consumption determined from this information, we can determine the expected size of the solar installation for a 50% offset to be about 3.6 and 5.2kW for the Medford and Chandler homes respectively. We assume this 50% offset to translate to the DC size of the installation, not the final output after AC conversion.

A high level approach to estimate installation costs may involve the following where it is best to minimize the size of the installation and thus associated labor and materials costs. Module efficiencies can be defined as

$$\eta = \frac{P_{peak}}{A * 1000 \, {W}/{m^2}} \qquad [9.]$$

where η is the module efficiency, P_{peak} is the optimal power output from the system, A is the system area, and 1000W/m^2 is the standard testing conditions for solar irradiance at AM1.5 (sea-level). Moreover, installation includes a fixed cost and a variable cost dependent upon the area covered by the installation. Therefore,

$$Installation\ Cost = Fixed\ Cost + (Area\ Depdendent\ Cost)\left(\frac{P_{peak}}{\eta * 1000\ {}^{W}/_{m^2}}\right) \quad [10.]$$

To reiterate, industry uses the term $/Wp to define the cost-efficiency of solar PV systems. This is an easy measure by which to compare competing products. In this sense, it is necessary to consider the total installation cost by the rated capacity of the installed system.

$$\frac{Installation\ Cost}{P_{peak}} = \frac{Fixed\ Cost}{P_{peak}} + \frac{Area\ Depdendent\ Cost}{\eta * 1000\ {}^{W}/_{m^2}} \quad [11.]$$

where the left-hand side defines the $/Wp.

However, in the case we have described above, information to develop a detailed residential model is available and we can better estimate costs with this more resolved approach. We continue with the Medford example case where a 3.6kW DC installation will be constructed with Sharp's NU-U230F3 module with a 15.8% cell efficiency.

Table 5-3. Estimated installation cost for a Sharp 230W module.[59]

Installation Size	3.6	kW (DC)
Module Size	230	W
Total Cost	$25,815.35	
Cost/Wp (DC)	$7.17	
Direct Cost	$17,344.83	
Module	$11,443.04	
Inverter	$2,189.79	
Balance of System	$1,158.26	
Installation	$1,472.00	
Indirect	$8,470.52	
Eng., Proc., Const.	$7,256.39	
Project, Land, Misc	$0.00	
Sales Tax	$1,214.14	

In this model, engineering and construction fees are determined as a function of the system size with reference points for a 3.8kW residential system, taken from NREL's Solar Advisor Model (SAM). [59] Inverter costs are determine from a survey of inverters currently on the market. These prices were then associated with a set of solar PV projects in California to determine the inverter cost-per-watt-peak. [29] These data were fit with a linear function then used to determine inverter cost-per-watt-peak as a function of system size. The balance of system (BOS) costs were determined as a function of the number of modules with a base fixed cost for connection to the grid and inverter. A reference point for this cost was taken from NREL's SAM of $2,240 for a 3.8kW system using Photowatt's 95W modules. The base fixed costs was assumed to be 20% of this total estimated cost. Installation costs were assumed to be largely dependent on labor time for module installation. Modules were assumed to take 0.13hr with one hour setup time, and three hours cleanup and wrap-up time. It was assumed three workers were used and a labor cost of $80/hr. These assumptions were referenced with a solar technical consultant at RealGoods Solar, one of the largest residential solar PV installation companies in California. [64] These costs were also cross-referenced with NREL's SAM in their example cases. These assumptions were only to be used for installation cost estimates of smaller, residential systems.

Federal rebates and credits of about $5,804 and state and local incentives totaling $3,436 may be used to decrease the overall cost of this 3.6kW system. Financing options may also allow the end-consumer to pay off the installation over a period of five years with a low monthly payment. [65]

The largest observed portion of the installation cost results from the purchase of modules. This is where the most dramatic cost reduction can be realized. What can the QD/polymer coating afford end-consumers in the market?

When looking at the expected benefits realized by a module using the QD/polymer coated cells, the module size in watts will be affected directly.

Namely, the 230W module will become a 237.6W module. For the purposes of this evaluation, we assume the module maker does not change the size of the module nor the cost per module in order to observe the effect on installation costs.

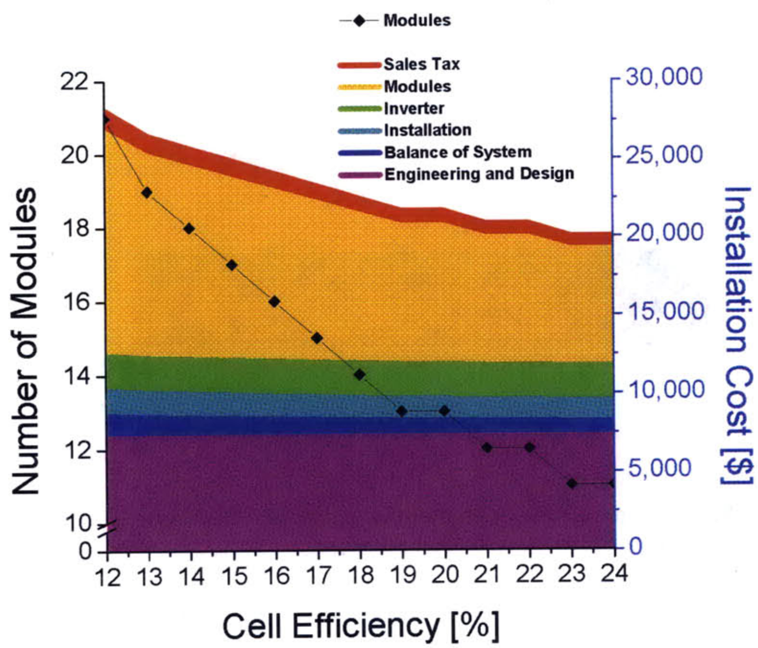

Figure 5–2. Installation cost by cell efficiency with constant module cost.

Given these assumptions, we find that installation costs do not change with the addition of the QD/polymer coating to the Sharp modules. This is mostly due to the fact that the delta in cell efficiency is not substantial enough to change the number of modules used from the current 16. The efficiency increase does not justify using fewer modules because of the 3.6kW size of the system. We may observe installation cost savings with a larger installation, either commercial or utility, where the resolution and number of modules used increases substantially. However, in this residential case, the total cost savings does not justify any costs from application of the QD/polymer coating.

Using this same installation model, we can estimate the installation costs across the market of cell efficiencies using the trend in module cost-per-watt-peak by cell efficiency that we had identified earlier.

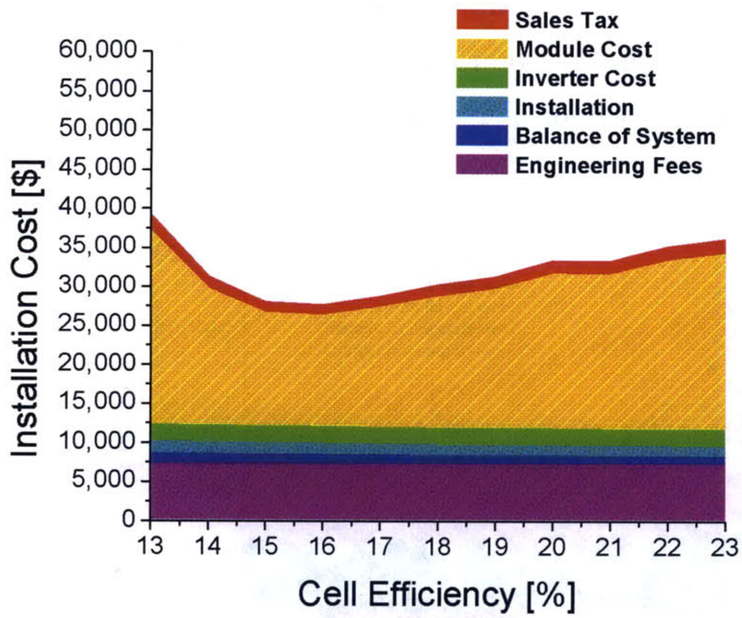

Figure 5–3. Installation costs with module prices as a function of cell efficiency as determine by a market survey.

Again, we find that the final cost of the system is largely dependent upon the module cost. In conversations with RealGoods Solar, it was confirmed that systems that use higher-efficiency modules, such as those with Sanyo's HIT technology, are generally more expensive and are used only in rare circumstances. [64] Even with a clear trend in module prices, it is difficult to estimate installation costs based upon module price.

Installation costs vary widely and are highly dependent upon individual system dynamics such as space, location, and existing infrastructure. As a result, final installed costs-per-watt-peak are difficult to determine on a generalized level. However, an increase in module performance for residential systems does not change the BOS costs substantially. The area dependent costs such as labor, racking, and wiring vary little and the engineering design fees are better correlated with installation size than module efficiency. [59] Higher efficiency modules are often used in area limited installations where every watt is needed, and command a higher price. Yet, for the majority of installations, the lowest cost-per-watt-peak is desired and this tends to be in the more competitive range of 15-16% cell efficiency range. [64]

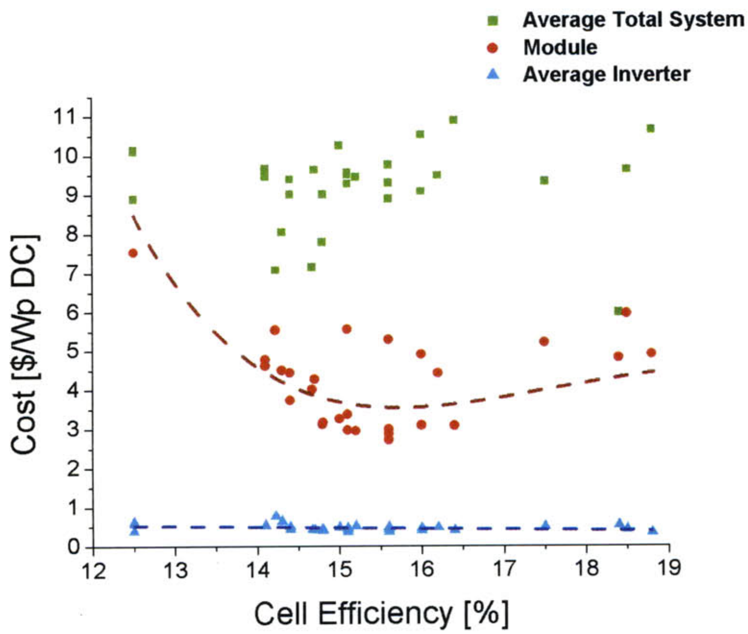

Figure 5–4. System, module, and inverter costs for a survey of PV projects in the California market from January 1st, 2005 to December 31st 2009. [29]

5.3 Process Design

In designing a system to apply the QD/polymer coating, it behooves the engineer to consider existing methods and systems to minimize costs using standardized, off-the-shelf components. For this reason, a flexographic printing system can be used to apply the AR coating in a production process.

Flexographic printers are used in many electronics manufacturing processes including application of positive and negative photoresists, application of backing adhesives, passivation of MEMS chips, and LCD manufacturing. In this process, units are taken from a loading platform and placed onto a conveyor table which transports the unit to the roll-heads. [48] One of the leading equipment makers of flexographic printers, or screen-printers, is Sakurai of Japan. Their experience ranges from small setups to large-scale production lines. Moreover, they were responsible for the equipment to make the keypad LEDs in the Motorola Razr. [66]

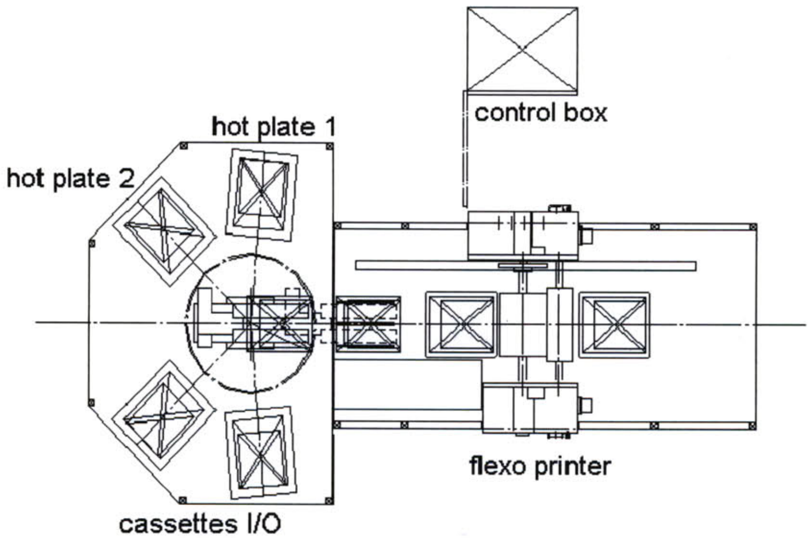

Figure 5–5. Equipment design for QD/polymer coating application. [48]

A mechanically controlled syringe releases a prescribed amount of coating onto the film roll which is then doctor-bladed to the prescribed thickness. A resin letterpress affixed to a second printing roll then takes the cutout of the coating from the film roll. This film is then applied to the photocell as it passes under the printing roll. This process results in a sub-micron (usually 40-100nm) film thickness which can be controlled based upon the doctor-blade position adjacent to the film roll. Following application of the QD/polymer coating, the photocells are taken to a UV curing system for final setting of the coating. At this stage, the photocells are ready for placement into a module or a solar system.

The QD/polymer coating can be applied to either cells with existing AR coatings such as TiO_2 or Si_3N_4 or to cells without the conventional AR coatings and directly to the SiO_2 layer. In experiments, the marked increased in performance was seen with no conventional AR coating applied. Thus, it is suggested to avoid application of conventional AR coatings prior to printing of the QD/polymer coating to achieve the expected improvements in performance.

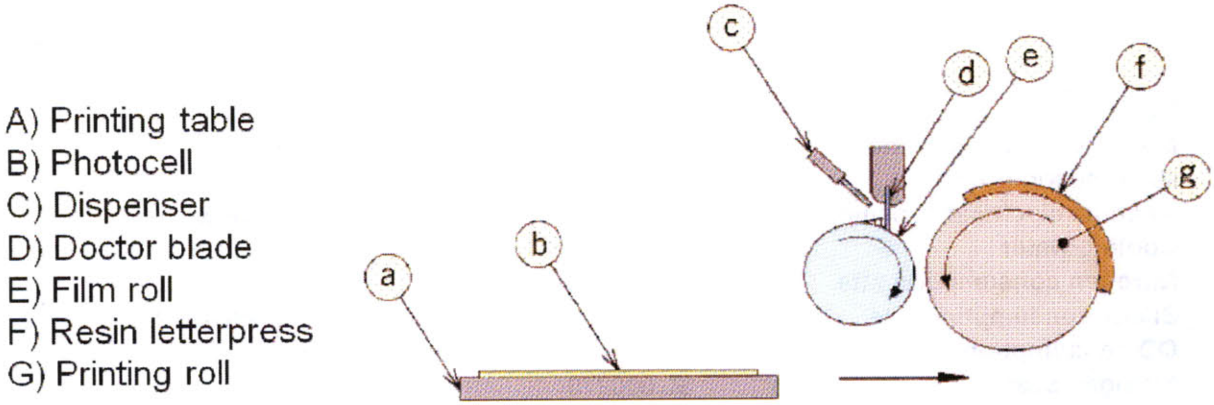

Figure 5–6. Flexo printer process for applying QD/polymer coating – side-view. [48]

Combination spin coating/UV curing systems were considered as a method to apply the QD/polymer coating. However, this process was not analyzed due to initial concerns with throughput and cycle time. Dip coating was also considered initially, but was ruled out because of concerns with film thickness capabilities. Spray coating was not considered due to uneven application of film at thicknesslevels required.

Screen printing offers the best capability in the industry to apply sub-micron, uniform films on large surfaces. Taking the system's operation into consideration, it can be compared with the cost to apply competing AR coatings such as TiO_2, or SiN_x. It is necessary to consider the added cost of the AR coating, specifically the cost-per-watt-peak of the system. Armed with this information, the added benefit can be compared with the expected cost.

5.4 Cost Modeling

To determine the cost of application of the QD/polymer coating to the silicon cells, we use the production model for a 100MW cell production facility that was previously described. In this manner, we can more accurately compare costs between application of the SiN_x coating and the QD/polymer coating.

Table 5-4. QD/polymer and SiN_x process costs comparison.

	SiN_X	QD/polymer	
Machine cost	$2,300,000.00	$230,000.00	*per machine*
Machine production rate	1500	1500	*cells/hr*
Machine footprint	18.72	18.72	*m^2*
Machine electrical consumption	80	40	*kW/machine*
Cooling water	7200	3600	*L/hr/machine*
Nitrogen consumption rate	21600		*L/hr/machine*
Silane consumption rate	360		*L/hr/machine*
QD consumption rate		24.235	*g/hr*
Nitrogen cost	$0.000270		*per L*
Silane cost	$0.003532		*per L*
QD cost		$3.00	*per gram*
Number of technicians	0.5	0.5	*per step*
Number of production workers	0.5	0.5	*per step*
[$/Wp]			
Material	$0.00199	$0.02036	
Labor	$0.01018	$0.01018	
Depreciation	$0.01645	$0.00179	
Factory Overhead	$0.01388	$0.00402	
Factory Cost	**$0.04251**	**$0.03635**	

NOTE: Corporate Overhead, which includes R&D, Sales and Marketing, General & Administrative, Plant Expansion, Insurance, Shipping, Warranty, Taxes, and Profit are expensed at the segment level and are not impacted by the above items. QD consumption rate is determined as the amount needed to cover the cells with a base amount that is not recycled.

Even with the significant material cost ($3/gram as estimated from conversations with QD Vision) from the QD/polymer coating, the added cost is still competitive with the SiN_x coating method. The primary drivers behind the potentially lower cost of the QD/polymer solution is that the cost of equipment is drastically lower than processes used to apply competing methods. Moreover, utility supply costs such as water and electricity are assumed to be significantly reduced from that of the PECVD process which requires high temperatures and low-pressure environments. Screen printing can be done in the ambient and does not require significant time between cycles. Moreover, the process is easily modeled as a complete, standalone manufacturing line similar to XeroCoat's system.

In the SiN_x coating process, wafers are removed from the chamber following deposition and pump-down. It typically takes about 50mins for a chamber with the capacity to hold four 125mm wafers to apply a 114nm coating. This puts the process at about 10-15 mins for a wafer, per system which is very labor, and time intensive. Even with scaled SiN_x processes, the method is very energy intensive translating into a relatively high cost. It was expected by industry experts that a non-materials cost difference of ten times would be seen between the QD/polymer process and the SiN_x process. [66]

However, the cost of the QD/polymer solution may be significantly higher than that which was modeled. Therefore, it is beneficial to understand how the cost contribution from the process varies with the material cost and the coating production rate.

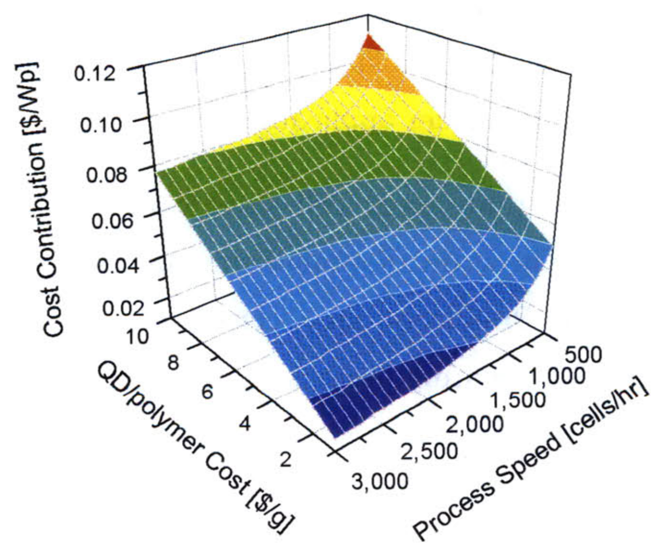

Figure 5–7. Production cost variation with QD/polymer cost and process speed.

The material cost represents the largest portion of contributed costs to the module and contributed costs vary significantly over this axis. Production speed has a relatively smaller effect.

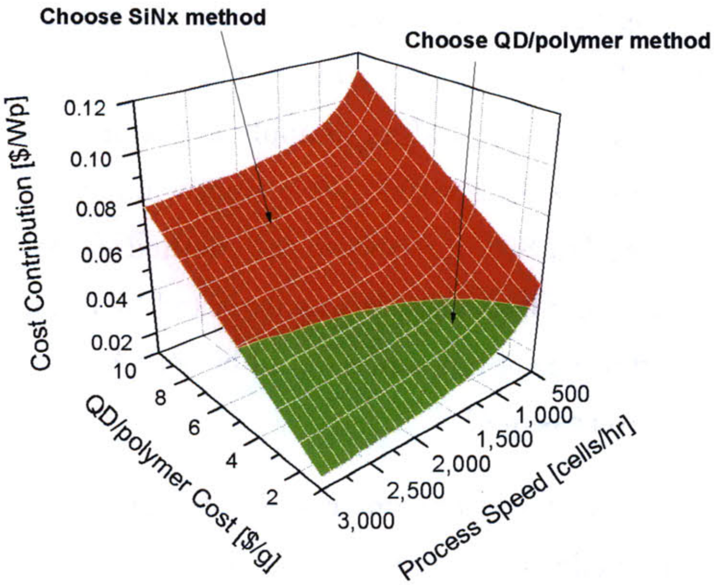

Figure 5–8. QD/polymer and SiN_x production comparison with variation in material cost and process speed.

When compared directly to the SiN_x method which contributes an estimated $0.04251/Wp, we find a set of process speeds and materials costs that define a competitive region for the QD/polymer application.

It is important to note that many cell producers currently employ SiN_x coating systems and may be hesitant to remove this process from production due to large investment costs. Producers may consider adding the QD/polymer coating directly after the SiN_x coating process. However, the interaction between the two layers has not been studied in this paper. Moreover, the added cost of the QD/polymer coating system would need to be justified by potential benefits in revenue increases as the QD/polymer would no longer replace existing technology.

Industry experts have cited that the SiN_x coating method provides the added benefit of surface passivation in addition to acting as an anti-reflective coating. [66] Therefore, it may be difficult to envision the QD/polymer coating process replacing the SiNx coating process.

Table 5-5. Production volumes for typical large production facilities making 15.8% efficient cells.

Capacity	20MW	50MW	100MW
Production volume (m^2/yr)	126,582	316,455	632,911

5.5 Upstream Supply Chain Benefits

Coating of the QD/polymer solution onto cells takes place in the middle of the photovoltaic supply chain. Therefore, it is necessary to assess the benefits realized by each segment following addition of the coating. Understanding how sequential producers are affected gives a better picture of how and if this technology may be developed and will succeed.

With the solution applied in the cell production segment, we look to see what the impact will be on cell manufacturers. The primary objective of cell producers is throughput. That is, selling more MW of cells is desirable as the MW is the unit by which performance is measured. The expected performance increase for an existing photocell technology of 15.8% should be dramatic enough to justify the associated costs. Predicted trends in the photocell market show that revenues will decrease by about 30% over the next two years. If it is possible to demonstrate how application of this technology might halt or reverse this revenue erosion, then the associated costs can be easily compared.

Table 5-6. Cell production savings with QD/polymer coated cell improvement.

Facility Capacity	100	*MW*		
Cell Size	156	*mm*		
Efficiency w/o	15.80%			
Efficiency w/	16.32%			
Cell Capacity w/o	3.85	*W/cell*		
Cell Capacity w/	3.97	*W/cell*		
	2010 w/o coating		**2010 w/ coating**	
Revenues	$174.64	*mil*	$185.12	*mil*
	2012 w/o coating		**2012 w/ coating**	
Revenues	$123.70	*mil*	$131.12	*mil*
Rev. erosion w/o	29%	$50.94	*mil*	
Rev. erosion w/	25%	$43.52	*mil*	
savings		$7.42	*mil*	

Assuming that the photocell manufacturer seeks to maximize their gains, they would seek higher prices in the market according to trend analysis done on the current market with cell efficiency increasing from 15.8% to 16.3%. Thus, commanding a higher price, they are able to realize a revenue savings of $7.42mil. in 2012. Therefore, when dealing with the potential customer of the technology, it would be necessary to keep costs at or below this savings, or $0.0718/Wp with production capacity increasing to about 103MW.

Similarly, it is necessary to evaluate the module producer's perspective in the supply chain with using QD/polymer coated photocells. In using these coated cells, the module producer may or may not choose to adjust the framing and size of the module to compensate for the increase in performance. The module maker could either use existing equipment to produce larger modules (by wattage with a 230W module becoming a 237.6W module for example), or decrease the number of photocells used and concomitant decrease in variable and fixed costs. The module maker may also choose to follow the market trend of increased prices with higher efficiency modules just as the photocell producer might command a proportional increase in photocell price as well. Thus, it is beneficial to look at the expected benefits from multiple decision points.

2010

Profit Margin Savings [$/Wp]

Size \ Price	no Δ: cell price Δ	no Δ: no cell price Δ	Δ: cell price Δ	Δ: no cell price Δ
no Δ	($0.046)	$0.000	$0.036	$0.082
Δ	($0.022)	$0.024	$0.060	$0.106

2012

Profit Margin Savings [$/Wp]

Size \ Price	no Δ: cell price Δ	no Δ: no cell price Δ	Δ: cell price Δ	Δ: no cell price Δ
no Δ	($0.032)	$0.000	$0.027	$0.059
Δ	($0.014)	$0.019	$0.045	$0.078

Figure 5–9. Module producer profit margin savings decision matrix.

In recognizing that cell producers may look to obtain a portion of the increase in prices experienced with the increase in efficiency, module producers can expect cells to cost either the same amount per Wp (no cell price change) or a price change proportional to the price change that module producers could obtain in the market. To be safe, module producers may want to limit their decisions to those which include the latter case where cell prices increase with the QD/polymer coating.

With this in mind, module producers, can look to change their own module prices on a cost-per-watt-peak basis, and/or change the size of the module, making a smaller module whose size decrease is proportional to the efficiency increase with the QD/polymer coated cells.

As a result, module producers are forced to increase the module price and realize revenue gains if they are to implement the QD/polymer coated cells. This move shows the most dramatic profit savings. Moreover, it demonstrates that with expected profit erosion over the next two years, the application of the technology allows the producer to command higher prices and thus save at least \$0.027/Wp in profits.

Table 5-7. Forecasted supply chain costs and prices. [54]

Cell Efficiency	15.8	%
Module Price	\$3.10	per Wp

Source: Sharp NU-230F3

[\$/Wp]

		Si	->	Wafer	->	Cell	->	Module
2010	Price	\$0.40		\$1.16		\$1.75		\$3.10
	Profit Margin	\$0.03		\$0.08		\$0.07		\$0.27
	Cost	\$0.38	\$0.68	\$1.09	\$0.52	\$1.68	\$1.09	\$2.83
2012	Price	\$0.29		\$0.87		\$1.24		\$2.26
	Profit Margin	\$0.02		\$0.05		\$0.02		\$0.18
	Cost	\$0.27	\$0.53	\$0.82	\$0.34	\$1.21	\$0.84	\$2.08
Margin Erosion				33%		66%		33%

Margin erosion will be experienced on all levels of the photovoltaic supply chain. The argument that avoidance of this erosion will realize benefits for cell and module producers demonstrates value of the technology application.

6 Conclusions

6.1 Project Summary

Crystalline silicon photovoltaics are the clear dominant technology in the solar PV market due to production knowledge and existing momentum. Small innovations in this market can have significant impact due to the size of this market. Using the existing supply chain, it is possible to realize improved power conversion performance through application of a QD/polymer solution. This coating has been observed to better couple UV light with the active region of the photovoltaic partly by absorbing light in the UV and efficiently converting it to a portion of the spectrum where silicon is more responsive. Moreover, the coating can be applied to large areas such as photocells through use of screen printing processes. This process avoids costly vacuum or high temperature methods. Therefore, the benefits determined in this paper may justify the substantially lower costs of application. However, success relies upon the ability to produce this material in large quantities on the order of 3,000kg per year as estimated in the production model.

In evaluating the market potential of the coating process, understanding the benefits realized by each segment of the supply chain is necessary. Photocell producers, module producers, and installation companies should realize a sales increase from use of the technology. When approaching cell and module makers, understanding the technology's impact on the company's bottom line is paramount. Benefits realized by installation companies and end-consumers is more variable and difficult to determine. Yet, the most cost-efficient method to produce energy from the sun is highly desired by residential, commercial, and utility scale customers. Quantifying these benefits is difficult given the many variables. However, a model has been proposed in this paper to understand the impact an increase in crystalline silicon cell efficiency will have on each segment of the supply chain.

It should be noted that several assumptions have been made in the development of the models described herein and developed for specific case. While the author believes the sources of information to be reliable, the author in no way represents or guarantees the accuracy of the forecasts or models described. The efforts described in this paper are an academic exercise to evaluate the potential impacts of a QD/polymer coating on the crystalline silicon photovoltaic supply chain.

6.2 Future Work

In developing a startup with nascent technology, there is no single important issue. All issues must be given equal weight and thorough consideration. [10]

First, and most importantly is to address a cost model for the production and synthesis of the QD/polymer solution. This is at the core of the technology offering and it must be determined if the material can be produced at a cost acceptable for incorporation into existing crystalline silicon photovoltaics.

Second, financial projections of the expected costs and revenues of the venture will need to be made in order to ascertain the financial opportunity and viability of the business model.

Third, speaking directly with potential customers to obtain a better understanding of their requirements is essential. Conversation should focus on product attribute values in order to develop a product attribute curve to distinguish the QD/polymer coating technology from others by appealing to the consumer interests.

Fourth, it would be beneficial to take a closer look at the competing technologies, namely that of TiO_2, SiN_x, and especially that of XeroCoat which claims similar gains in efficiency using its patented silicon oxide ARC method. XeroCoat is one of the first companies to offer a complete solution for their individualized product after they recognized that PV producers wouldn't be interested in just buying their product and figuring out a way to implement it. Even so, XeroCoat has not gained much traction in the market mostly due to the commoditization of the PV industry; cost-per-watt-peak is mostly driven down through production and business model innovation, hardly because of technology. Therefore, it will be critical to watch XeroCoat as it moves into this market and learn from its mistakes.

Fifth, only small, residential-scale installations were modeled in this paper. It would be beneficial to understand the impact the coating may have on PV systems that are much larger such as commercial and utility-scale systems. The effect the coating would have may be more dramatic than that which was predicted in the residential model.

Sixth, a physical demonstration of the screen printing process with the QD/polymer would help convince customers of the technologies viability. This would follow a more detailed building of the process to apply the QD/polymer coating. However, there are several instrument and equipment suppliers who are willing and able to assist in developing a specialized system using existing technology and equipment.

Last, the technology itself has only been applied towards silicon photodiodes on small surface areas. It is unknown if the assumed 3% power conversion increase can be extrapolated to a larger surface area, much less be repeated with the application process described above. Moreover, the performance increase may not be as dramatic for cells that have higher efficiencies than the photodiode used in research. Similarly, the performance increase may or may not be sustainable over long periods of time when the film is subject to the harsh environments PV modules typically experience. Furthermore, it would be necessary to optimize the coating thickness and emission wavelength of the QDs to match that of the lowest reflectivity point for the photovoltaic. Therefore, it is necessary to test large-area devices using this QD/polymer coating. This will give engineers a better understanding of the limitations of the technology and further focus development capabilities.

Should this application not be determined as competitive by those involved with implementation, there are several other applications of the technology. Those applications may include LED displays, cameras, fluorescent sensors, and laser materials. There are several directions that this technology might take.

However, it requires a focused effort to identify the market and a detailed implementation plan. Without definition of these two variables, the technology's success remains uncertain.

7 Appendix A: Cost Model Details

Cost model summary and assumptions of QD/polymer coating process

	SiNx	QD/polymer	
Machine cost	$2,300,000.00	$230,000.00	per machine
Machine production rate	1500	1500	cells/hr
Machine footprint	18.72	18.72	m^2
Machine electrical consumption	80	40	kW/machine
Cooling water	7200	3600	L/hr/machine
Nitrogen consumption rate	21600		L/hr/machine
Silane consumption rate	360		L/hr/machine
QD consumption rate		24.235	g/hr
Nitrogen cost	$0.000270		per L
Silane cost	$0.003532		per L
QD cost		$3.00	per gram
Number of technicians	0.5	0.5	per step
Number of production workers	0.5	0.5	per step

[$/Wp]		
Supplies	$0.00199	$0.02036
Consumables	$0.00000	$0.00000
Material	$0.00199	$0.02036
Direct Labor	$0.00765	$0.00765
Indirect Labor	$0.00113	$0.00113
Plant Overhead	$0.00140	$0.00140
Labor	$0.01018	$0.01018
Equipment	$0.01446	$0.00145
Auxiliary	$0.00184	$0.00018
Building	$0.00016	$0.00016
Depreciation	$0.01645	$0.00179
Factory Overhead	$0.01388	$0.00402
Factory Cost	**$0.04251**	**$0.03635**

QD/polymer cost	$3.00	per gram
Cd	8.65	g/cm^3
Se	4.79	g/cm^3
Polyacrylic	1.15	g/cm^3
Cd/Se ratio	1.00	by atom
Polymer/QD ratio	49.00	by mass
QD Acrylic density	1.2614	g/cm^3
Layer Thickness	0.5	um
% of Layer	100%	
Amount Used	0.6307	g/m^2
Non-recycled Mat'l	5%	

Note: Corporate Overhead, which includes R&D, Sales and Marketing, General & Administrative, Plant Expansion, Insurance, Shipping, Warranty, Taxes, and Profit are expensed at the segment level and are not impacted by the above items. QD consumption rate is determine as the amount needed to cover the cells with a base amount that is not recycled. Please reference the production model for further details not described here.

8 Appendix B: Detailed Production Model

Global assumptions

Design

Module

Input	Min	Mean	Max	Unit
Module Output Specification	218.5	230	253	Watts
Module Length		164		cm
Module Width		99.4		cm
Module Size		1.63		m2
Module Efficiency		14.1%		
Number of Cells/Module		60		6x10
Number of Strings		6		
Framed?		Y		

Wafer Technologies

Polysilicon

Input	Min	Mean	Max	Unit
Silicon Usage		8.09		g/W
% Silicon Recycled		10%		%
Polysilicon Cost	25	30	35	$/kg
Polysilicon Price	40	50	60	$/kg

Cell

Input	Min	Mean	Max	Unit
Cell Size		156		mm
Cell Area		243		cm2
Cell Finished Thickness		180		microns
Cell Power		3.83		Watts
Cell Efficiency		15.8%		%

Wafer

Input	Min	Mean	Max	Unit
Ingot Weight	250	300	300	kg
Cast Block Length (Cast polycrystalline)		84		cm
Cast Block Width (Cast polycrystalline)		84		cm
Cast Block Height (Cast polycrystalline)	20.4	24.5	24.5	cm
Brick Height		15.6		cm
Bricks per Ingot		25		
Brick Length		21		cm
Wire Saw Kerf		150		microns
Wafer Type		Silicon		

Detailed Qty Assumptions	Min	Mean	Max	Unit
Boron Doping Level	0.02	0.1	0.2	ppm
Isotexture Etch Depth		10		microns

Global assumptions continued

Economic

Input	Value	Unit
Base Year	2007	
Current Year	2010	
Inflation Rate	2	%
Working Capital Period	3	Months
Supply House Discount	85%	

Corporate Expense Defaults

(% of Sales)	PolySilicon	Wafer	Cell	Module
R&D	0.5%	1%	1%	0.5%
Sales & Marketing	1%	2%	1%	4%
G&A	5%	5%	7%	7%
Plant Expansion	12%	2%	3%	3%
Insurance	0.5%	0.5%	0.5%	0.5%
Shipping	2%	2%	2%	4%
Warranty	0%	0%	0%	3%
Taxes	12%	7%	7%	7%
Profit	7%	10%	12%	20%
Total Corporate Expense	40%	29%	33%	49%

Factory Space Ratios

Input	Value	Unit
Aisle:Machine	100%	ratio
Receiving:Machine	5%	ratio
Shipping:Machine	5%	ratio
Warehouse:Machine	25%	ratio
Offices:Machine	10%	ratio

Location dependent assumptions

Manufacturing			Polysilicon Factory	Wafer, Cell, Module Factory
	Input	Unit		
	Annual Module Production Volume	MW	495	100
	Capacity	MW	550	143
	Num Modules Annually	#	2,151,001	434,783
	Number of Shifts / Day		3	3
	Shift Length	Hours	8	8
	Line Yield	%	90%	94%
	Avg Default Uptime	%	90%	90%
	Annual Hours per Worker		2,000	2,000
	Days per Year		365	
	Hours per Day		24	
Labor Rates				
Cat.	Input	Unit		
Direct	Factory Worker	$/Hr	29.90	29.90
	Technician	$/Year	50,000	50,000
	Material Handler	$/Year	25,000	25,000
Indirect	Supervisor	$/Year	52,000	52,000
	Manufacturing Engineer	$/Year	67,000	67,000
Overhead	Director / VP Ops	$/Year	110,000	110,000
	Manager	$/Year	100,000	100,000
	Engineer	$/Year	72,000	72,000
	Scientist	$/Year	62,000	62,000
	Purchasing	$/Year	58,000	58,000
	Quality Assurance	$/Year	58,000	58,000
	Human Resources	$/Year	63,000	63,000
	Health & Safety	$/Year	52,000	52,000
	Accountant	$/Year	60,000	60,000
	Assistant / Clerk	$/Year	30,000	30,000
	Information Technology	$/Year	70,000	70,000

Location dependent assumptions continued

Estimations			
Input	**Unit**		
Material Cost	% of Factory Cost	55%	55%
Supplies Cost	% of Factory Cost	10%	10%
Consumables Cost	% of Factory Cost	5%	5%
Direct Labor	% of Factory Cost	7%	7%
Indirect Labor	% of Factory Cost	3%	3%
Overhead Labor	% of Factory Cost	10%	10%
Utilities Cost	% of Factory Cost	2%	2%
Indirect:Direct Headcount Ratio		20%	20%
Management Span Ratio	# managers/workers	5%	5%
Auxiliary Costs	(% of CapEx)	20%	20%
Installation Costs	(% of CapEx)	10%	10%
Maintenance Ratio	(% of CapEx)	4%	4%
Economic			
Input	**Unit**		
Factory Building or Annual Rental Cost	$/m2	1,400	1,400
Owned (1) or Rented (0)		1	1
Equipment Subsidy	%	0%	0%
Incoming Shipping Cost	% of Mtl Cost	4%	4%
Currency		Dollar	Dollar
Manufacturing Exchange Rate (FX)	Currency : Dollar	1	1
Equipment Depreciation Period	Years	7	7
Auxiliary Depreciation Period	Years	10	10
Building Depreciation Period	Years	15	15
Benefits Ratio		1.28	1.28
Electricity Price	$/kWh	0.068	0.068
Internal Capital Return Rate (CRR)	%	6%	6%
Financed Capex Capital Return Rate (CRR)	%	6%	6%

NOTE: Values adjusted from the Solar America Initiative (SAI) model developed by Navigant Consulting to demonstrate a common accounting framework used by Technology Pathway Partners (TPPs) [52]

Production summary

Process Flow	Cum. Yield	Matl	Labor	Depr.	Fac. Ovd.	Fac. Cost	Corp. Ovd.	Tot. Price
Cast Wafer Based Silicon PV		*$1.38*	*$0.18*	*$0.13*	*$0.16*	*$1.86*	*$1.24*	*$3.10*
Polysilicon	**78%**	**$0.24**	**$0.00**	**$0.00**	**$0.00**	**$0.24**	**$0.16**	**$0.40**
Reduce SiO2 w/C-- produce MGS	78%	$0.00	$0.00	$0.00	$0.00	$0.00		
Produce trichlorosilane (SiHCl3)	78%	$0.00	$0.00	$0.00	$0.00	$0.00		
Fractional Distillation	78%	$0.00	$0.00	$0.00	$0.00	$0.00		
H2 Reduction (Siemens Reactor)	78%	$0.00	$0.00	$0.00	$0.00	$0.00		
Package Polysilicon	78%	$0.00	$0.00	$0.00	$0.00	$0.00		
Wafer	**78%**	**$0.33**	**$0.05**	**$0.06**	**$0.10**	**$0.54**	**$0.22**	**$0.76**
Prep Silicon	78%	$0.00	$0.00	$0.00	$0.00	$0.00		
DSS Cast Polycrystalline Ingot	78%	$0.04	$0.01	$0.03	$0.07	$0.15		
Slice into Bricks	78%	$0.00	$0.00	$0.01	$0.00	$0.01		
Slice Bricks into Wafers	79%	$0.25	$0.00	$0.02	$0.02	$0.30		
Wafer Clean	86%	$0.00	$0.01	$0.00	$0.00	$0.02		
Package Wafer	84%	$0.00	$0.01	$0.00	$0.00	$0.02		
PV Cell	**86%**	**$0.22**	**$0.06**	**$0.06**	**$0.05**	**$0.38**	**$0.19**	**$0.57**
Incoming Inspection	86%	$0.00	$0.00	$0.01	$0.00	$0.01		
Isotexture Etch	88%	$0.01	$0.01	$0.00	$0.00	$0.02		
Diffusion	88%	$0.00	$0.00	$0.01	$0.01	$0.02		
HF Surface Etch	89%	$0.00	$0.01	$0.00	$0.00	$0.02		
A/R Coating	89%	$0.00	$0.01	$0.02	$0.01	$0.04		
Metal Line	90%	$0.20	$0.01	$0.01	$0.01	$0.23		
Firing Furnace	91%	$0.00	$0.01	$0.01	$0.00	$0.02		
Cell Test & Sort	92%	$0.00	$0.00	$0.00	$0.00	$0.01		
Package Cells	94%	$0.00	$0.01	$0.00	$0.00	$0.01		
PV Modules	**96%**	**$0.59**	**$0.07**	**$0.01**	**$0.017**	**$0.69**	**$0.67**	**$1.36**
Incoming Cell Inspection	96%	$0.00	$0.00	$0.00	$0.00	$0.01		
Glass Washing	97%	$0.00	$0.00	$0.00	$0.00	$0.00		
Tab & String Cells	97%	$0.01	$0.00	$0.00	$0.00	$0.02		
Module Layup	99%	$0.14	$0.01	$0.00	$0.00	$0.14		
Bussing and Inspection	99%	$0.16	$0.01	$0.00	$0.00	$0.17		
Module Lamination	100%	$0.00	$0.00	$0.00	$0.01	$0.02		
Module Curing	100%	$0.00	$0.00	$0.00	$0.00	$0.00		
Module Trim & Taping	100%	$0.01	$0.01	$0.00	$0.00	$0.02		
Frame Module	100%	$0.14	$0.01	$0.00	$0.00	$0.15		
Module Termination	100%	$0.09	$0.01	$0.00	$0.00	$0.10		
Module Power Test	100%	$0.00	$0.00	$0.00	$0.00	$0.00		
Module Safety Test	100%	$0.00	$0.01	$0.00	$0.00	$0.01		
Package and Label Module	100%	$0.04	$0.01	$0.00	$0.00	$0.05		

Process yield

Step	Rej. Rate	Proc. Step Yield	Cum. Yield	Scrap Loss	Cum. Scrap
Cast Wafer Based Silicon PV			*78%*		*38%*
Polysilicon			**78%**		**38%**
Reduce SiO2 w/C-- produce MGS	0%	100.0%	78%		38%
Produce trichlorosilane (SiHCl3)	0%	100.0%	78%		38%
Fractional Distillation	0%	100.0%	78%		38%
H2 Reduction (Siemens Reactor)	0%	100.0%	78%		38%
Package Polysilicon	0%	100.0%	78%		38%
Wafer			**78%**		**38%**
Prep Silicon	0.0%	100.0%	78%		38%
DSS Cast Polycrystalline Ingot	0.3%	99.7%	78%	26%	38%
Slice into Bricks	0.6%	99.4%	78%		51%
Slice Bricks into Wafers	8.0%	92.0%	79%	43%	51%
Wafer Clean	0.6%	99.4%	86%		90%
Package Wafer	2.0%	98.0%	84%		90%
PV Cell			**86%**		**90%**
Incoming Inspection	2.0%	98.0%	86%		90%
Isotexture Etch	0.2%	99.8%	88%	10%	90%
Diffusion	0.6%	99.4%	88%		100%
HF Surface Etch	0.2%	99.8%	89%		100%
A/R Coating	1.6%	98.4%	89%		100%
Metal Line	1.0%	99.0%	90%		100%
Firing Furnace	1.5%	98.5%	91%		100%
Cell Test & Sort	2.0%	98.0%	92%		100%
Package Cells	2.0%	98.0%	94%		100%
PV Modules			**96%**		**100%**
Incoming Cell Inspection	1.00%	99.0%	96%		100%
Glass Washing	0.01%	100.0%	97%		100%
Tab & String Cells	1.50%	98.5%	97%		100%
Module Layup	0.00%	100.0%	99%		100%
Bussing and Inspection	1.00%	99.0%	99%		100%
Module Lamination	0.20%	99.8%	100%		100%
Module Curing	0.00%	100.0%	100%		100%
Module Trim & Taping	0.01%	100.0%	100%		100%
Frame Module	0.01%	100.0%	100%		100%
Module Termination		100.0%	100%		100%
Module Power Test	0.00%	100.0%	100%		100%
Module Safety Test	0.05%	100.0%	100%		100%
Package and Label Module		100.0%	100%		100%

<u>**Process materials**</u>

Step	(g/ cc)	Units	$/ Unit	Uts/ Mod.	$/Mod. (UnY'ld)	$/Mod. (Y'lded)	Deliv. Vol. units/ yr.	$/Unit Quotes at Units/Year Delivery Volume 1	100	1000	10000	1E+08	Conversions Value	Units
Cast Wafer Based Silicon PV					***$186.94***	***$265.72***								
Polysilicon	2.33					**$55.79**								
Wafer					**$12.02**	**$29.47**							11125	# wafers / charge
Prep Silicon													445	# wafers / brick
Slice Bricks into Wafers					$11.82	$29.20								
Silicon Carbide, ~ 10 micron		kg	63.2	0.161	$10.56	$26.08	5,373	$ 126.40	$ 79.00	$ 63.20	$ 63.20	$ 63.20	0.16	# kg/module
Glass support beam		$/ea	7.82	0.13	$1.10	$2.71	75,180	$ 8.15	$ 8.15	$ 8.15	$ 7.82	$ 7.34		
Brick Epoxy	0.93	kg	105.96	0.0015	$0.17	$0.42	51	$ 105.96	$ 105.96	$ 105.96	$ 101.72	$ 95.36	0.0015258	kg epoxy / module
Wafer Clean														
Package Wafer					$0.20	$0.26							26086957	Wafers per year (unyiel
Plastic Bag 12.7 x 17.8 cm		ea box	0.015	0.22	$0.00	$0.00	122,996	$ 0.03	$ 0.02	$ 0.02	$ 0.02	$ 0.02	272	# wafers/package
Styrofoam		ea box	0.62	0.22	$0.14	$0.19	122,996	$ 1.24	$ 0.81	$ 0.68	$ 0.62	$ 0.62		
Box 17.6 x 17.6 x 7cm		ea	0.23	0.22	$0.05	$0.07	122,996	$ 0.46	$ 0.30	$ 0.25	$ 0.23	$ 0.23		
PV Cell					**$42.27**	**$46.87**								
Metal Line					$41.99	$46.58								
Silver Paste (Front)		kg	620.7	0.032	$20.43	$22.66	15,261	$ 727.65	$ 660.00	$ 653.40	$ 620.73	$ 505.59		
Al Paste		kg	112.9	0.132	$15.48	$17.17	63,586	$ 120.00	$ 120.00	$ 118.80	$ 112.86	$ 91.93		
Silver Paste (Back)		kg	584.1	0.010	$6.09	$6.75	4,832	$ 590.00	$ 590.00	$ 584.10	$ 554.90	$ 451.97		
Package Cells					$0.27	$0.29								
Plastic Bag 12.7 x 17.8 cm		ea	0.015	0.30	$0.00	$0.00	151,535	$ 0.03	$ 0.02	$ 0.02	$ 0.02	$ 0.02	200	# cells/package
Styrofoam		ea	0.62	0.30	$0.19	$0.21	151,535	$ 1.24	$ 0.81	$ 0.68	$ 0.62	$ 0.62		
Tape		ea	0.015	0.30	$0.00	$0.00	151,535	$ 0.03	$ 0.02	$ 0.02	$ 0.02	$ 0.02		
Box 17.6 x 17.6 x 7cm		ea	0.23	0.30	$0.07	$0.08	151,535	$ 0.46	$ 0.30	$ 0.25	$ 0.23	$ 0.23		
PV Modules					**$132.65**	**$133.60**								

Process consumables

Step	Consumables	Lifetime	Consm. Cost	Units	Deliv. Vol.	$/Unit Cost at Units/Yr. Vol.				
	Description	days	$/Mod.		units / year	1	10	100	1000	10000
Cast Wafer Based Silicon PV			***$26.59***							
Polysilicon			**$0.00**							
Wafer			**$24.40**							
DSS Cast Polycrystalline Ingot	Coated Crucible	2.08	$8.88							
275 kg crucible	Crucible	2.08	$7.77	ea	5,081	$ 700.00	$ 700.00	$ 679.00	$ 665.00	$ 630.0
SiNx coating	Varnish	2.08	$1.11	ea	5,081	$ 100.00	$ 100.00	$ 97.00	$ 95.00	$ 90.(
Slice into Bricks	Saw Blade	1	$0.09	ea	1,825	$ 25.60	$ 21.76	$ 20.67	$ 20.67	$ 20.6
Slice Bricks into Wafers	Saw Wire, stainless steel	13.3	$6.55	800 km spool ea	274	$ 10,926	$ 10,926	$ 10,379	$ 10,379	$ 10,37
Wafer Clean										
Package Wafer										
PV Cell			**$0.12**							
Metal Line	Screenprint Tooling		$0.06							
Screens	Silk Screen	4	$0.05		1,043	$ 20.00	$ 20.00	$ 20.00	$ 20.00	$ 20.(
Doctor Blades	Doctor Blade	8	$0.01		522	$ 10.00	$ 10.00	$ 10.00	$ 10.00	$ 10.(
Package Cells	Flash Lamp	21	$0.04		35	$ 450.00	$ 450.00	$ 427.50	$ 427.50	$ 427.5
PV Modules			**$2.07**							
Incoming Cell Inspection	Flash Lamp	21	$0.04		35	$ 450.00	$ 450.00	$ 427.50	$ 427.50	$ 427.5
Tab & String Cells	IR Lamps	8.4	$0.10		174	$ 250.00	$ 250.00	$ 250.00	$ 250.00	$ 250.0
Module Lamination	Laminator Parts		$0.96							
	Diaphragm	13	$0.76		174	$ 2,000.00	$ 2,000.00	$ 1,900.00	$ 1,900.00	$ 1,900.C
	O-ring	13	$0.06		174	$ 150.00	$ 150.00	$ 142.50	$ 142.50	$ 142.5
	PTFE Release Sheet	13	$0.14		174	$ 375.00	$ 375.00	$ 356.25	$ 356.25	$ 356.2
Frame Module	Flash Lamp	336	$0.02		4	$ 1,700.00	$ 1,700.00	$ 1,615.00	$ 1,615.00	$ 1,615.C

Process depreciation

Step	Cycle Time	Batch Size	Up-time	Mach. F'tprint	# mach.	CapEx per step	Ann. Depr./ step	Deliv. Vol.	$/Unit Cap. Equip. Cst. ($000) at Units/Yr. Vol.				
units	min	# mod.	%	m^2	per factory	000K	$/Mod.	units / yr.	1	10	100	1000	10000
Cast Wafer Based Silicon PV							***$26.54***						
Polysilicon							**$0.00**						
Wafer							**$12.04**						
Prep Silicon	30	167.6	90%	10.00	0.3	$20	$0.01	0.30	20	19.5	19	18	17
DSS Cast Polycrystalline Ingot	3000	167.6	95%	16.8	28.5	$566	$5.93	29	580	566	551	522	493
Slice into Bricks	420	167.6	90%	13.20	4.2	$807	$1.46	4	806.6	786.435	766.27	725.94	685.61
Slice Bricks into Wafers	330	59.3	90%	15.00	9.3	$1,200	$4.34	9	1200	1170	1140	1080	1020
Wafer Clean	0.050	0.017	90%	9.00	4.6	$120	$0.22	5	120	117	114	108	102
Package Wafer	0.050	0.017	90%	5.00	4.7	$50	$0.09	5	50	48.75	47.5	45	42.5
PV Cell							**$11.85**						
Incoming Inspection	0.025	0.017	95%		2.2	$1,200	$1.30	2	1200	1170	1140	1080	1020
Isotexture Etch	0.030	0.017	95%	13.11	2.5	$756	$0.82	3	$756	737	718	680	643
Diffusion	0.038	0.017	95%	7.37	3.2	$1,200	$1.73	3	$1,200	1170	1140	1080	1020
HF Surface Etch	0.030	0.017	95%	7.94	2.5	$620	$0.67	3	$620	605	589	558	527
A/R Coating	0.040	0.017	90%	18.72	3.6	$2,300	$3.33	4	$2,300	2243	2185	2070	1955
Metal Line	0.046	0.017	95%	43.74	3.8	$1,400	$2.02	4	$1,400	1365	1330	1260	1190
Firing Furnace	0.043	0.017	95%	12.60	3.5	$800	$1.16	4	$800	780	760	720	680
Cell Test & Sort	0.025	0.017	95%	16.00	2.0	$750	$0.81	2	$750	731	713	675	638
Package Cells	0.025	0.017	95%	0.00	2.0	$0	$0.00	2	$0	0	0	0	0
PV Modules							**$2.66**						
Incoming Cell Inspection	0.03	0.017	95%	14.88	1.9	$750	$0.54	2	$750	731	713	675	638
Glass Washing	0.33	1	95%	9.55	0.4	$75	$0.03	0	$75	73	71	68	64
Tab & String Cells	0.05	0.017	95%	12.00	3.7	$675	$0.98	4	$675	658	641	608	574
Module Layup	2	1	95%	5.00	2.5	$8	$0.01	3	$8	7	7	7	6
Bussing and Inspection	3	1	95%	4.00	3.8	$5	$0.01	4	$5	5	5	5	4
Module Lamination	13	3	95%	17.60	5.4	$440	$0.95	5	$440	429	418	396	374
Module Curing	1	30	95%	1.00	0.0	$0	$0.00	0	$5	5	5	5	4
Module Trim & Taping	3	1	95%	1.00	3.7	$5	$0.01	4	$5	5	5	5	4
Frame Module	3	1	95%	0.41	3.7	$45	$0.07	4	$45	44	43	41	38
Module Termination	1.5	1	95%	1.00	1.9	$5	$0.00	2	$5	5	5	5	4
Module Power Test	0.33	1	95%	0.08	0.4	$150	$0.05	0	$150	146	143	135	128
Module Safety Test	1.5	1	95%	1.00	1.9	$15	$0.01	2	$15	15	14	14	13
Package and Label Module	3	1	95%	0	3.7	$0	$0.00	4	$0	0	0	0	0

Process auxiliary costs

Step	Aux. % of CapEx ($/Mod.)	Detailed Aux. Cost $/Module	Aux. Cost
Cast Wafer Based Silicon PV	***$3.38***	***$0.00***	***$3.38***
Polysilicon	**$0.00**	**$0.00**	**$0.00**
Wafer	**$1.53**	**$0.00**	**$1.53**
Prep Silicon	$0.00	$0.00	$0.00
DSS Cast Polycrystalline Ingot	$0.75	$0.00	$0.75
Slice into Bricks	$0.19	$0.00	$0.19
Slice Bricks into Wafers	$0.55	$0.00	$0.55
Wafer Clean	$0.03	$0.00	$0.03
Package Wafer	$0.01	$0.00	$0.01
PV Cell	**$1.51**	**$0.00**	**$1.51**
Incoming Inspection	$0.17	$0.00	$0.17
Isotexture Etch	$0.10	$0.00	$0.10
Diffusion	$0.22	$0.00	$0.22
HF Surface Etch	$0.09	$0.00	$0.09
A/R Coating	$0.42	$0.00	$0.42
Metal Line	$0.26	$0.00	$0.26
Firing Furnace	$0.15	$0.00	$0.15
Cell Test & Sort	$0.10	$0.00	$0.10
Package Cells	$0.00	$0.00	$0.00
PV Modules	**$0.34**	**$0.00**	**$0.34**
Incoming Cell Inspection	$0.07	$0.00	$0.07
Glass Washing	$0.0035	$0.00	$0.00
Tab & String Cells	$0.1242	$0.00	$0.12
Module Layup	$0.0010	$0.00	$0.00
Bussing and Inspection	$0.0009	$0.00	$0.00
Module Lamination	$0.1214	$0.00	$0.12
Module Curing	$0.0000	$0.00	$0.00
Module Trim & Taping	$0.0009	$0.00	$0.00
Frame Module	$0.0083	$0.00	$0.01
Module Termination	$0.0005	$0.00	$0.00
Module Power Test	$0.0069	$0.00	$0.01
Module Safety Test	$0.0014	$0.00	$0.00
Package and Label Module	$0.0000	$0.00	$0.00

Process floorspace requirements

Step	Mach. Ftprint	Aisles	Recv'ing	Ship.	Warehs.	Off.	Tot.	Bldg. or Rent	Bldg. Depr. or Rent
	m^2						000's m^2	000K	($/Mod.)
Cast Wafer Based Silicon PV	***1,374***	***1374***	***69***	***69***	***344***	***137***	***3***	***$4,713***	***$0.72***
Polysilicon	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**$0**	**$0.00**
Wafer	**755**	**755**	**38**	**38**	**189**	**76**	**2**	**$2,590**	**$0.40**
Prep Silicon	4	4.0	0.2	0.2	1.0	0.4	0	$14	$0.00
DSS Cast Polycrystalline Ingot	486	486.0	24.3	24.3	121.5	48.6	1	$1,667	$0.26
Slice into Bricks	59	59.0	3.0	3.0	14.8	5.9	0	$202	$0.03
Slice Bricks into Wafers	140	140.0	7.0	7.0	35.0	14.0	0	$480	$0.07
Wafer Clean	42	42.0	2.1	2.1	10.5	4.2	0	$144	$0.02
Package Wafer	24	24.0	1.2	1.2	6.0	2.4	0	$82	$0.01
PV Cell	**399**	**399**	**20**	**20**	**100**	**40**	**0.98**	**$1,369**	**$0**
Incoming Inspection	0	0.0	0.0	0.0	0.0	0.0	0	$0	$0.00
Isotexture Etch	36	36.0	1.8	1.8	9.0	3.6	0	$123	$0.02
Diffusion	26	26.0	1.3	1.3	6.5	2.6	0	$89	$0.01
HF Surface Etch	21	21.0	1.1	1.1	5.3	2.1	0	$72	$0.01
A/R Coating	68	68.0	3.4	3.4	17.0	6.8	0	$233	$0.04
Metal Line	169	169.0	8.5	8.5	42.3	16.9	0	$580	$0.09
Firing Furnace	46	46.0	2.3	2.3	11.5	4.6	0	$158	$0.02
Cell Test & Sort	33	33.0	1.7	1.7	8.3	3.3	0	$113	$0.02
Package Cells	0	0.0	0.0	0.0	0.0	0.0	0	$0	$0.00
PV Modules	**220**	**220**	**11**	**11**	**55**	**22**	**0.54**	**$755**	**$0.12**
Incoming Cell Inspection	30	30.0	1.5	1.5	7.5	3.0	0	$103	$0.02
Glass Washing	5	5.0	0.3	0.3	1.3	0.5	0	$17	$0.00
Tab & String Cells	44	44.0	2.2	2.2	11.0	4.4	0	$151	$0.02
Module Layup	13	13.0	0.7	0.7	3.3	1.3	0	$45	$0.01
Bussing and Inspection	16	16.0	0.8	0.8	4.0	1.6	0	$55	$0.01
Module Lamination	98	98.0	4.9	4.9	24.5	9.8	0	$336	$0.05
Module Curing	1	1.0	0.1	0.1	0.3	0.1	0	$3	$0.00
Module Trim & Taping	4	4.0	0.2	0.2	1.0	0.4	0	$14	$0.00
Frame Module	4	4.0	0.2	0.2	1.0	0.4	0	$14	$0.00
Module Termination	2	2.0	0.1	0.1	0.5	0.2	0	$7	$0.00
Module Power Test	1	1.0	0.1	0.1	0.3	0.1	0	$3	$0.00
Module Safety Test	2	2.0	0.1	0.1	0.5	0.2	0	$7	$0.00
Package and Label Module	0	0.0	0.0	0.0	0.0	0.0	0	$0	$0.00

Process utilities

Step	Utility % of Fact. Cost	$ / Mod. Water	$ / Mod. Elec.	$ / Mod. Compr. Air	Util. Cst $/Mod.	City Water Lt./Hr.	City Water $/Mod. (Y'lded)	Cooling Water Lt./Hr.	Cooling Water $/Mod. (Y'lded)	DI Water Lt./Hr.	DI Water $/Mod. (Y'lded)	Electricity kW	Electricity $/Mod. (Y'lded)	Compressed Air Lt./Hr.	Compressed Air $/Mod. (Y'lded)
Cast Wafer Based Silicon PV	*$7.63*	*$10.18*	*$8.59*	*$0.21*	*$18.97*	*493*	*$0.01*	*238793*	*$9.62*	*5435*	*$0.54*	*6241*	*$8.59*	*968944*	*$0.*
Polysilicon	**$0.00**	**$0.00**	**$0.00**	**$0.00**	**$0.00**	**0**	**$0.00**	**0**	**$0.00**	**0**	**$0.00**	**0**	**$0.00**	**0**	**$0.**
Wafer	**$1.07**	**$8.54**	**$5.88**	**$0.00**	**$14.43**	**435**	**$0.01**	**211741**	**$8.53**	**3**	**$0.00**	**4277**	**$5.88**	**0**	**$0.**
Prep Silicon	$0.00	$0.00	$0.00		$0.00					10	$0.0003	0.002	$0.000		
DSS Cast Polycrystalline Ingot	$0.00	$8.52	$3.92		$12.44			7800	$8.5247			105	$3.919		
Slice into Bricks	$0.00	$0.01	$0.08		$0.09			50	$0.0076			15	$0.078		
Slice Bricks into Wafers	$1.06	$0.01	$1.84		$1.84	27	$0.0062					160	$1.838		
Wafer Clean	$0.00	$0.01	$0.05		$0.06	50	$0.0056					9	$0.049		
Package Wafer	$0.01				$0.00										
PV Cell	**$1.70**	**$1.57**	**$1.88**	**$0.17**	**$3.63**	**58**	**$0.00**	**27052**	**$1.09**	**4824**	**$0.48**	**1367**	**$1.88**	**813522**	**$0.**
Incoming Inspection	$0.00				$0.00										
Isotexture Etch	$0.00	$0.24	$0.04	$0.06	$0.34	24	$0.0016			1000	$0.2413	12	$0.039	120000	$0.06
Diffusion	$0.00	$0.00	$0.67	$0.00	$0.67			10	$0.0012			160	$0.665	6600	$0.00
HF Surface Etch	$0.00	$0.24	$0.04	$0.06	$0.34					1000	$0.2393	12	$0.038	120000	$0.06
A/R Coating	$0.00	$0.93	$0.35	$0.00	$1.28			7200	$0.9275			80	$0.352	6000	$0.00
Metal Line	$1.69		$0.55	$0.01	$0.56							110	$0.549	10000	$0.00
Firing Furnace	$0.00	$0.16	$0.22	$0.03	$0.41			1200	$0.1613			47	$0.216	42540	$0.03
Cell Test & Sort	$0.00		$0.02	$0.00	$0.02							8	$0.021	9000	$0.00
Package Cells	$0.01				$0.00										
PV Modules	**$4.86**	**$0.06**	**$0.82**	**$0.03**	**$0.92**	**0**	**$0.00**	**0**	**$0.00**	**608**	**$0.06**	**598**	**$0.82**	**155422**	**$0.**
Incoming Cell Inspection	$0.00		$0.02	$0.00	$0.02							8	$0.020	9000	$0.00
Glass Washing	$0.00	$0.06	$0.01	$0.00	$0.07					1500	$0.0605	20	$0.011	10800	$0.00
Tab & String Cells	$0.07		$0.08	$0.02	$0.10							16	$0.076	30000	$0.02
Module Layup	$1.14				$0.00										
Bussing and Inspection	$1.35				$0.00										
Module Lamination	$0.00		$0.71		$0.71							100	$0.707		
Module Curing	$0.00				$0.00										
Module Trim & Taping	$0.06				$0.00										
Frame Module	$1.17		$0.00	$0.01	$0.01							1	$0.005	8400	$0.00
Module Termination	$0.76				$0.00										
Module Power Test	$0.00		$0.00	$0.00	$0.00							6	$0.003	1332	$0.00
Module Safety Test	$0.00				$0.00										
Package and Label Module	$0.31				$0.00										

Process utility and supply costs

Item	Units	$/Unit	$/Litr. or $/kWh	Deliv. Vol. units/yr.	$/Unit Quotes at Units/Year Delivery Volume									
					1	10	100	1000	10000	100000	1E+06	1E+07	1E+08	1E
Ammonia	Liter	$0.0036	0.0036	5,040,786	$0.0036	$0.0036	$0.0036	$0.0036	$0.00357	$0.0036	$0.0036	$0.0036	$0.0036	$0.0
Argon	Liter	$0.0013	0.0013	237,589,289	$0.0013	$0.0013	$0.0013	$0.0013	$0.0013	$0.0013	$0.0013	$0.0013	$0.0013	$0.0
City Water	Liter	$0.0013	0.0014	4,320,171	$0.0014	$0.0014	$0.0014	$0.0014	$0.0014	$0.0014	$0.0014	$0.0014	$0.0014	$0.0
Compressed Air	Liter	$0.0000	0.0000	8,487,949,296	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000	$0.0000	$0.0
Cooling Water	Liter	$0.0020	0.0020	2,091,825,762	$0.0020	$0.0020	$0.0020	$0.0020	$0.0020	$0.0020	$0.0020	$0.0020	$0.0020	$0.0
Detergent	Liter	$4.4667	4.4667	6	$4.4667	$4.4667	$4.4667	$4.4667	$4.47	$4.4667	$4.4667	$4.4667	$4.4667	$4.4
DI Water	Liter	$0.0049	0.0049	47,606,742	$0.0049	$0.0049	$0.0049	$0.0049	$0.00494	$0.0049	$0.0049	$0.0049	$0.0049	$0.0
Glycol	Liter	$4.3857	4.3857	2,217,937	$5.9120	$5.9120	$5.9120	$4.3857	$4.3857	$4.3857	$4.3857	$4.3857	$4.3857	$4.3
HCl 37%	Liter	$2.4600	2.4600	21,215	$2.4600	$2.4600	$2.4600	$2.4600	$2.46	$2.4600	$2.4600	$2.4600	$2.4600	$2.4
HF 49%	Liter	$8.7200	8.7200	74,167	$8.7200	$8.7200	$8.7200	$8.7200	$8.72	$8.7200	$8.7200	$8.7200	$8.7200	$8.7
HNO3 65%	Liter	$7.8000	7.8000	34,270	$7.8000	$7.8000	$7.8000	$7.8000	$7.80	$7.8000	$7.8000	$7.8000	$7.8000	$7.8
Hydrogen	Liter	$0.0000	0.0000	0	$0.5000	$0.5000	$0.5000	$0.5000	$0.50	$0.5000	$0.5000	$0.5000	$0.5000	$0.5
KOH 50%	Liter	$0.2200	0.2200	226,037	$0.2200	$0.2200	$0.2200	$0.2200	$0.22	$0.2200	$0.2200	$0.2200	$0.2200	$0.2
Nitrogen	Liter	$0.0003	0.0003	623,949,510	$0.0003	$0.0003	$0.0003	$0.0003	$0.00027	$0.0003	$0.0003	$0.0003	$0.0003	$0.0
Oxygen	Liter	$0.0004	0.0004	31,758,602	$0.0004	$0.0004	$0.0004	$0.0004	$0.00036	$0.0004	$0.0004	$0.0004	$0.0004	$0.0
POCl3	Liter	$0.0000	0.0000	0	$0.0000	$0.0000	$0.0000	$0.0000	$0	$0.0000	$0.0000	$0.0000	$0.0000	$0.0
Silane	Liter	$0.0035	0.0035	10,081,572	$0.0035	$0.0035	$0.0035	$0.0035	$0.00353	$0.0035	$0.0035	$0.0035	$0.0035	$0.0

Process maintenance

Step	% of CapEx	Parts/Labr. Est.	Maint.
	$/Mod.	$/Mod.	
Cast Wafer Based Silicon PV	***$7.43***	***$0.00***	***$7.43***
Polysilicon	**$0.00**	**$0.00**	**$0.00**
Reduce SiO2 w/C-- produce MGS			
Produce trichlorosilane (SiHCl3)			
Fractional Distillation			
H2 Reduction (Siemens Reactor)			
Package Polysilicon			
Wafer	**$3.37**	**$0.00**	**$3.37**
Prep Silicon	$0.00	$0.00	$0.00
DSS Cast Polycrystalline Ingot	$1.66	$0.00	$1.66
Slice into Bricks	$0.41	$0.00	$0.41
Slice Bricks into Wafers	$1.21	$0.00	$1.21
Wafer Clean	$0.06	$0.00	$0.06
Package Wafer	$0.03	$0.00	$0.03
PV Cell	**$3.32**	**$0.00**	**$3.32**
Incoming Inspection	$0.36	$0.00	$0.36
Isotexture Etch	$0.23	$0.00	$0.23
Diffusion	$0.49	$0.00	$0.49
HF Surface Etch	$0.19	$0.00	$0.19
A/R Coating	$0.93	$0.00	$0.93
Metal Line	$0.57	$0.00	$0.57
Firing Furnace	$0.32	$0.00	$0.32
Cell Test & Sort	$0.23	$0.00	$0.23
Package Cells	$0.00	$0.00	$0.00
PV Modules	**$0.74**	**$0.00**	**$0.74**
Incoming Cell Inspection	$0.15	$0.00	$0.15
Glass Washing	$0.01	$0.00	$0.01
Tab & String Cells	$0.27	$0.00	$0.27
Module Layup	$0.00	$0.00	$0.00
Bussing and Inspection	$0.00	$0.00	$0.00
Module Lamination	$0.27	$0.00	$0.27
Module Curing	$0.00	$0.00	$0.00
Module Trim & Taping	$0.00	$0.00	$0.00
Frame Module	$0.02	$0.00	$0.02
Module Termination	$0.00	$0.00	$0.00
Module Power Test	$0.02	$0.00	$0.02
Module Safety Test	$0.00	$0.00	$0.00
Package and Label Module	$0.00	$0.00	$0.00

Process factory overhead

Step	Ann. Cap. ($)	Wrk. Cap. ($/Mod.)	Equip. CapEx ($)	Aux. CapEx ($)	Bldg. CapEx ($)	Tot. Ann. Depr. ($)	Non-Ops. Cap.I ($/Mod.)
Cast Wafer Based Silicon PV		***$3.21***	***$80,770,846***	***$16,154,169***	***$4,712,820***	***$13,468,297***	***$7.64***
Polysilicon		**$0.00**	**$0**	**$0**	**$0**	**$0**	**$0.00**
Reduce SiO2 w/C-- produce MGS							
Produce trichlorosilane (SiHCl3)							
Fractional Distillation							
H2 Reduction (Siemens Reactor)							
Package Polysilicon							
Wafer		**$0.97**	**$36,632,750**	**$7,326,550**	**$2,589,650**	**$6,138,548**	**$3.50**
Prep Silicon	$178,879	$0.00	$22,000	$4,400	$13,720	$4,498	$0.00
DSS Cast Polycrystalline Ingot	$11,226,733	$0.26	$18,039,450	$3,607,890	$1,666,980	$3,048,985	$1.75
Slice into Bricks	$524,556	$0.01	$4,436,300	$887,260	$202,370	$735,974	$0.41
Slice Bricks into Wafers	$27,061,207	$0.62	$13,200,000	$2,640,000	$480,200	$2,181,728	$1.22
Wafer Clean	$1,464,032	$0.03	$660,000	$132,000	$144,060	$117,090	$0.07
Package Wafer	$1,556,255	$0.04	$275,000	$55,000	$82,320	$50,274	$0.03
PV Cell		**$0.71**	**$36,055,800**	**$7,211,160**	**$1,368,570**	**$5,963,183**	**$3.35**
Incoming Inspection	$273,301	$0.01	$3,960,000	$792,000	$0	$644,914	$0.36
Isotexture Etch	$1,935,076	$0.04	$2,494,800	$498,960	$123,480	$414,528	$0.23
Diffusion	$675,523	$0.02	$5,280,000	$1,056,000	$89,180	$865,831	$0.48
HF Surface Etch	$1,126,041	$0.03	$2,046,000	$409,200	$72,030	$338,008	$0.19
A/R Coating	$2,195,004	$0.05	$10,120,000	$2,024,000	$233,240	$1,663,664	$0.93
Metal Line	$21,922,480	$0.51	$6,160,000	$1,232,000	$579,670	$1,041,845	$0.60
Firing Furnace	$1,391,289	$0.03	$3,520,000	$704,000	$157,780	$583,776	$0.33
Cell Test & Sort	$500,032	$0.01	$2,475,000	$495,000	$113,190	$410,617	$0.23
Package Cells	$796,788	$0.02	$0	$0	$0	$0	$0.00
PV Modules		**$1.53**	**$8,082,296**	**$1,616,459**	**$754,600**	**$1,366,566**	**$0.79**
Incoming Cell Inspection	$160,185	$0.00	$1,650,000	$330,000	$102,900	$275,574	$0.16
Glass Washing	$103,079	$0.00	$82,500	$16,500	$17,150	$14,579	$0.01
Tab & String Cells	$1,333,913	$0.03	$2,970,000	$594,000	$150,920	$493,747	$0.28
Module Layup	$14,328,990	$0.33	$24,750	$4,950	$44,590	$7,003	$0.01
Bussing and Inspection	$17,184,531	$0.40	$22,000	$4,400	$54,880	$7,242	$0.01
Module Lamination	$1,203,715	$0.03	$2,904,000	$580,800	$336,140	$495,346	$0.29
Module Curing	$68,298	$0.00	$46	$9	$3,430	$236	$0.00
Module Trim & Taping	$1,851,711	$0.04	$22,000	$4,400	$13,720	$4,498	$0.00
Frame Module	$15,123,330	$0.35	$198,000	$39,600	$13,720	$33,160	$0.02
Module Termination	$9,699,436	$0.22	$11,000	$2,200	$6,860	$2,249	$0.00
Module Power Test	$98,888	$0.00	$165,000	$33,000	$3,430	$27,100	$0.02
Module Safety Test	$578,932	$0.01	$33,000	$6,600	$6,860	$5,832	$0.00
Package and Label Module	$4,743,932	$0.11	$0	$0	$0	$0	$0.00

Process corporate overhead

Step	$ / Module								
	R&D	Sales and Mktg.	Gen. & Admin.	Plant Exp'nsn	Insur.	Ship.	Wrnty.	Tax	Profit
Cast Wafer Based Silicon PV	*$5*	*$17*	*$44*	*$28*	*$4*	*$20*	*$9*	*$54*	*$102*
Polysilicon	0.46	0.93	4.65	11.16	0.46	1.86	0.00	11.16	6.51
Wafer	1.75	2.62	8.73	3.49	0.87	3.49	0.00	12.22	17.46
PV Cell	1.32	1.32	9.25	3.96	0.66	2.64	0.00	9.25	15.19
PV Modules	1.56	12.49	21.86	9.37	1.56	12.49	9.37	21.86	62.47

NOTE: The values of this model were updated with current values found online for 2010 addressing material costs, salaries, and utility expenses. Margins and shipping costs were found through corporate reportings of major solar module manufacturers. For further details, assumptions, and information, visit the Solar America Initiative model website hosted by the National Renewable Energy Laboratory at https://www.nrel.gov/analysis/sam/cost_data.html.

9 Appendix C: Detailed Cell/Module Benefits

Cell production impact

Cell Keeps Price

Facility Capacity	100	*MW*
Cell Size	156	*mm*
Efficiency w/o	15.80%	
Efficiency w/	16.32%	
Cell Capacity w/o	3.85	*W/cell*
Cell Capacity w/	3.97	*W/cell*

	2010 w/o coating		2010 w/ coating	
Capacity	100.000	*MW*	103.29	*MW*
Revenues	$174.64	*mil*	$180.38	*mil*
Cells	26.01	*mil*	26.01	*mil*
Price	$6.72	*per cell*	$6.94	*per cell*
Price/Wp	$1.75	*per Wp*	$1.75	*per Wp*

Added Revenues	$5.74	*mil*

	2012 w/o coating		2012 w/ coating	
Capacity	100.000	*MW*	103.29	*MW*
Revenues	$123.70	*mil*	$127.77	*mil*
Cells	26.01	*mil*	26.01	*mil*
Price	$4.76	*per cell*	$4.91	*per cell*
Price/Wp	$1.24	*per Wp*	$1.24	*per Wp*

Added Revenues	$4.07	*mil*

Rev. erosion w/o	29%	$50.94	*mil*
Rev. erosion w/	27%	$46.87	*mil*
savings		$4.07	*mil*

Assumptions:

- no price trend for photocell production, no change in price/Wp
- cell of 15.8% eff. at mkt. price of $1.75/Wp
- no change in physical cell production levels

Cell Takes Portion of Module Price Increase

Facility Capacity	100	*MW*
Cell Size	156	*mm*
Efficiency w/o	15.80%	
Efficiency w/	16.32%	
Cell Capacity w/o	3.85	*W/cell*
Cell Capacity w/	3.97	*W/cell*

	2010 w/o coating		2010 w/ coating	
Capacity	100.000	*MW*	103.29	*MW*
Revenues	$174.64	*mil*	$185.12	*mil*
Cells	26.01	*mil*	26.01	*mil*
Price	$6.72	*per cell*	$7.12	*per cell*
Price/Wp	$1.75	*per Wp*	$1.79	*per Wp*

Added Revenues	$10.48	*mil*

	2012 w/o coating		2012 w/ coating	
Capacity	100.000	*MW*	103.29	*MW*
Revenues	$123.70	*mil*	$127.77	*mil*
Cells	26.01	*mil*	26.01	*mil*
Price	$4.76	*per cell*	$5.04	*per cell*
Price/Wp	$1.24	*per Wp*	$1.27	*per Wp*

Added Revenues	$7.42	*mil*

Rev. erosion w/o	29%	$50.94	*mil*
Rev. erosion w/	25%	$43.52	*mil*
savings		$7.42	*mil*

Assumptions:

- photocell price trend follows that of module with Barclays model
- no change in physical cell production levels
- photocell changes in price/Wp

Module production impact

Fixed Model Module Production Costs Breakdown and Module Size Scaling of Costs

2010

Var. Costs	48.7%	of step	scale by	98%	->	47.9%	
Fix Costs	31.3%	of step	scale by	97%	->	30.3%	
unscaled	35.0%	of total un-Δed module price			scaled	34.2%	of total un-Δed module price

2012

Var. Costs	50.1%	of step	scale by	98%	->	49.3%	
Fix Costs	32.2%	of step	scale by	97%	->	31.1%	
unscaled	37.2%	of total un-Δed module price			scaled	36.4%	of total un-Δed module price

[$/Wp]

Module Producer Decision Tree			2010 Cell Price	2010 Prod. Costs	2010 Margin	2010 Mod. Price	2012 Cell Price	2012 Prod. Costs	2012 Margin	2012 Mod. Price
no change in cell price	*no change in size*	*no change in mod. price*	$1.75	$1.09	$0.27	$3.10	$1.24	$0.84	$0.18	$2.26
		change in mod. price	$1.75	$1.09	$0.35	$3.19	$1.24	$0.84	$0.24	$2.32
	const. power rating size change	*no change in mod. price*	$1.75	$1.06	$0.30	$3.10	$1.24	$0.82	$0.20	$2.26
		change in mod. price	$1.75	$1.06	$0.38	$3.19	$1.24	$0.82	$0.26	$2.32
change in cell price	*no change in size*	*no change in mod. price*	$1.79	$1.09	$0.23	$3.10	$1.27	$0.84	$0.15	$2.26
		change in mod. price	$1.79	$1.09	$0.31	$3.19	$1.27	$0.84	$0.21	$2.32
	const. power rating size change	*no change in mod. price*	$1.79	$1.06	$0.25	$3.10	$1.27	$0.82	$0.17	$2.26
		change in mod. price	$1.79	$1.06	$0.33	$3.19	$1.27	$0.82	$0.23	$2.32

NOTE: Production costs were taken from the NREL SAI production model described in Appendix B: Detailed Production Model. These costs were then scaled according to assumed economies with variable and fixed costs affected by the efficiency increase. It was assumed that a smaller module could be made with these more efficient cells keeping the same power rating. Variable costs would scale as the root of efficiency while fixed costs would scale linearly. Cell prices were taken similarly from NREL's SAI model. Cell price changes were scaled as a percent of the increase in price experienced by modules. This percent was taken from the portion of the final module price the cells would expect to take at current. Forecasted prices were taken from Barclay Capital's Solar Investor Guide released on May 14th, 2010. Margins were found from module price less production costs and cell price.

Module production impact continued

Module producer decision-tree formatted into a decision matrix.

2010

Profit Margin [$/Wp]

Size \ Price	no Δ: cell price Δ	no Δ: no cell price Δ	Δ: cell price Δ	Δ: no cell price Δ
no Δ	$0.226		$0.307	
		$0.272		$0.353
Δ	$0.250		$0.331	
		$0.296		$0.377

2012

Profit Margin [$/Wp]

Size \ Price	no Δ: cell price Δ	no Δ: no cell price Δ	Δ: cell price Δ	Δ: no cell price Δ
no Δ	$0.149		$0.208	
		$0.181		$0.240
Δ	$0.167		$0.227	
		$0.200		$0.259

Savings were determined by subtracting the expected profit margins of $0.272 and $0.181/Wp for 2010 and 2012 profit margins respectively.

2010

Profit Margin Savings [$/Wp]

Size \ Price	no Δ: cell price Δ	no Δ: no cell price Δ	Δ: cell price Δ	Δ: no cell price Δ
no Δ	($0.046)		$0.036	
		$0.000		$0.082
Δ	($0.022)		$0.060	
		$0.024		$0.106

2012

Profit Margin Savings [$/Wp]

Size \ Price	no Δ: cell price Δ	no Δ: no cell price Δ	Δ: cell price Δ	Δ: no cell price Δ
no Δ	($0.032)		$0.027	
		$0.000		$0.059
Δ	($0.014)		$0.045	
		$0.019		$0.078

10 Appendix D: Installation Assumptions

Installation base model

Installation Size	3.6	kW (DC)
Module Size	230	W
Total Cost	$25,815.35	
Cost/Wp (DC)	$7.17	
Direct Cost	$17,344.83	
Module	$11,443.04	
Module cost	$3.11	$/Wp (DC)
Module cost	$715.19	ea.
Module size	230	W
No. modules	16	
Battery	$0.00	
Battery cost		ea.
No. batteries		
Inverter	$2,189.79	
Inverter cost	$0.61	$/Wp (DC)
Inverter cost	$2,189.79	ea.
Inverter efficiency	90%	
Inverter Size	3,600	W (DC)
No. inverters	1	
Balance of System	$1,158.26	
Racking, wiring, mounting		
Module dependent	$710.26	
Fixed	$448.00	
Fixed pct. of std. cost	20%	
Installation	$1,472.00	
Install time/module	0.13	hr
No. modules	16	
Module install time	2.13	hr
Setup time	1	hr
Cleanup time	3	hr
Total install time	6.13	hr
No. workers	3	
Labor cost	$80.00	per hr
Indirect	$8,470.52	
Eng., Proc., Const.	$7,256.39	
Project, Land, Misc		
Sales Tax	$1,214.14	
Tax rate	7%	
applies to	100%	of direct cost

Market trends and relationships identified in this paper

Module Cost/W F(cell eff) — a0+a1*x+a2*x^2+a3*x^3+a4*x^4

	x	x^2	x^3	x^4
A0	**A1**	**A2**	**A3**	**A4**
554.3457	-117.94	9.37315	-0.32785	0.00427

Module Cost F(module size) — a+br^x

a	b	r
918.58	-918.3	0.992

Module Cost/W F(module size) — a-b*ln(x+c)

a	b	c
11.53249	1.48286	-1.25375

Inverter Cost/W F(cell eff) — a0+a1*x

	x
A0	**A1**
0.82	-0.023

Inverter Cost/W F(installation size) — a0+a1*x

	x
A0	**A1**
0.6083	-7E-06

Inverter Size F(cost/W) — a*x^b

a	b
1766.5	-1.197

BOS Fee F(installation size) — a*(x-x_c)*P+c

a	x_c	P	c
0.66	3800	1.01	2262

BOS Fee F(modules) — 0.2*a+b*x^c

a	b	c
2240	43.17749	1.01

Eng Fee F(installation size) — a*(x-x_c)*P+c

a	x_c	P	c
4.06	380	0.91	937

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