An Analysis of the Photovoltaic Value Chain for Reviewing Solar Energy Policy Options in Massachusetts

By

Ryan Dean

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the Requirement for the Degree of

Bachelor of Science

at the

Massachusetts Institute of Technology

May 2008

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
AUG 14 2008
LIBRARIES

© 2008 Ryan Dean
All Rights Reserved

The author hereby grants to MIT permission to reproduce and to distribute publicly paper and electronic copies of this thesis document in whole or in part in any medium now known or hereafter created.

Signature of Author ....
Department of Mechanical Engineering
May 9, 2008

Certified by ....
Richard K. Lester
Director of IPC, Professor of Nuclear Engineering
Thesis Supervisor

Accepted by ....
John H. Lienhard V.
Mechanical Engineering Undergraduate Officer
Chairman, Undergraduate Thesis Committee

ARCHIVES

An Analysis of the Photovoltaic Value
Chain for Reviewing Solar Energy
Policy Options in Massachusetts

by

Ryan Dean

Submitted to the Department of Mechanical Engineering
on May 9, 2008 in partial fulfillment of the
requirements for the Degree of Bachelor of Science in
Mechanical Engineering

ABSTRACT

We explore the photovoltaic value chain for 1st generation crystalline silicon, 2nd generation thin film and 3rd generation organic/ dye-sensitized PV in an effort to evaluate two levels of policy options intended to create new jobs and develop Massachusetts as a renewable energy hub. The primary option is whether to focus on bringing jobs in manufacturing, R&D or installation to the state. Once the state decides on the type of job or mix of jobs desired, then the state can explore which technology is most likely to accomplish this goal.

To evaluate each option we begin with an overview of solar industry in Massachusetts and then break down each generation into processing steps from manufacturing to installation. By defining a value chain for each PV generation, we are able understand which portion of the value chain may be important for developing a renewable energy hub. We find that the state's goals in developing a solar hub need to be more clearly defined before we can select the best policy option. Further research must also detail employment intensity at each value chain step. Once employment intensity and specific state goals are understood, each policy objectives can be reevaluated.

Thesis Supervisor: Richard K. Lester
Title: Professor of Nuclear Engineering, Director of IPC

Table of Contents

Introduction

The objective of any new energy source is to provide energy to customers at a price competitive with fossil fuels. Among alternative energy sources, photovoltaic (PV) technology has captured the imagination of energy enthusiast. Though solar PV technology has been available in terrestrial applications for approximately 30 years, costs today still remain above the fossil fuel level. Many countries around the world including Japan, Germany, the US and China, are now focusing on PV energy technologies for their environmental contributions, but also as a viable job creation tool for the economy. Advancements in production technology, materials, and design have fostered the growth of the photovoltaic industry across the world.

Today the three major "generations" of solar cells are crystal silicon, thin film, and organic/ dye-sensitized. Each generation aims to improve manufacturing efficiency or lower price over the previous generations. We describe the value chain for the three PV generations in order to set a framework for making policy decisions in Massachusetts. This value chain analysis provides a valuable reference for understanding what process steps it takes to go from cell production to installation and which Massachusetts companies participate in each portion of the value chain. With this information, policy makers will have a better idea of which companies and types of jobs are important in PV production.

In this thesis we explore two levels of policy options centered broadly upon the goal of developing Massachusetts as "a global center [of] alternative and renewable energy."[1] The first level focuses on distinguishing whether manufacturing, R&D or installation will develop the best mix of jobs for Massachusetts. The second level is

[1] Keller 2006

centered upon deciding which generation of PV best allows the state to meet its desired primary level goal. From a purely environmental perspective there is value added in ensuring the state is on the forefront of clean energy technology, but the state is also looking at the solar industry as a way to develop new jobs within the state. Depending on which portions of the value chain are located within the state, it is possible for there to be growth in both "knowledge economy" activities (i.e., those related to innovation) and also in activities able to provide a broad range of jobs.

Solar Energy Overview in Massachusetts

Governor Deval Patrick envisions a renewable energy industry in Massachusetts that brings an "economic bonanza for the commonwealth [and] at the same time that it improves the planets well being."[2] He hopes to develop jobs in the state as well as provide and economic boost to its economy. This has begun as Massachusetts has been ranked as one of the top 10 states in renewable energy employment, and top five of renewable energy firms per capita.[3] Yet, there is still work to be done in developing a broad range of companies to grow the Massachusetts solar cluster. In appendix A we list the PV companies located in Massachusetts. These companies will be discussed throughout the value chain analysis.

Massachusetts is home to many of the premiere research institutions in the world which strive to develop new PV technologies and ideas. Schools such as MIT and UMass Lowell are driving basic research which may some day be commercialized. Recent activity at MIT has brought new partnerships with the Chesonis Foundation,

---

[2] Chandler 2008
[3] Levy 2007

Fraunhofer, and Eni.[4][5][6] The MTC reports that the state has "a strong incubation infrastructure," in which over 2/3 of its renewable energy companies have revenue under $10 MM. This suggests that many Massachusetts companies are still in the start up phase of their development and are a long way from production or commercialization of products.[7]

Though Massachusetts may be known for its research and start up companies, their has recently been some success in brining manufacturing to the state. In 2007 Evergreen Solar began construction of its first US cell manufacturing facility in Devens, Massachusetts.[8] This manufacturing facility is expected to bring nearly 1,000 jobs to the state.[9] Still, developing manufacturing in the state continues to be an uphill battle as Schott Solar, Massachusetts's other major solar cell company, recently decided to build its new cell manufacturing facility in New Mexico.

General Value Chain

In this thesis we lay out a version of the PV value chain which will allow Massachusetts policy makers to think clearly about how the state's solar industry might grow. We have broken the value chain for each generation into three sections, figure 1. The orange boxes describe overarching tasks which people or process are assigned, the blue boxes describe the PV value chain from raw materials to installation, and the green

---

[4] MIT News Office, Chesonis 2008
[5] MIT News Office, Fraunhofer 2008
[6] MIT News Office, Eni 2008
[7] MTC 2007
[8] Evergreen Solar
[9] Chandler 2008

boxes illustrate outside industries, activities and institutions which support the value chain by contributing ideas or materials.

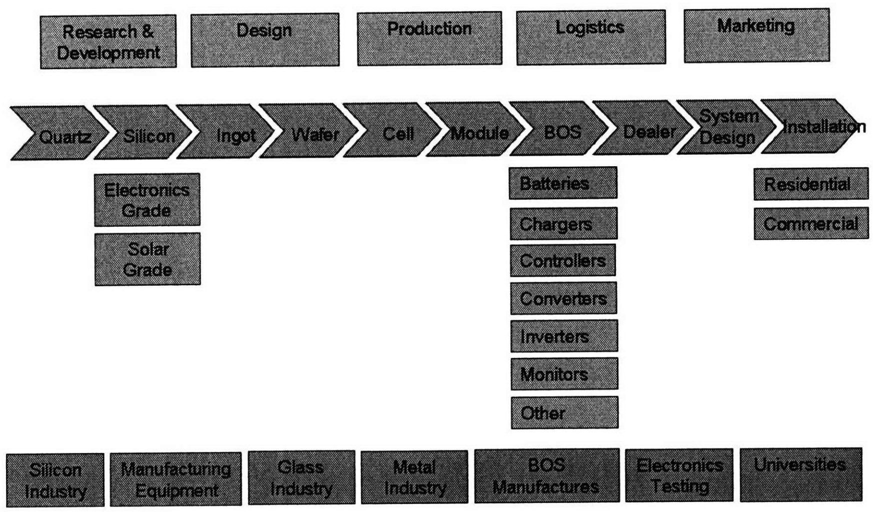

Figure1: 1st generation value chain

We begin by examining the orange boxes as a framework for grouping questions about coordination of processes and the required skills for each position. Research and development happens most commonly in the cell, wafer, module and balance of systems (BOS) steps of the value chain. In these steps, especially the cell stage, major strides have been made in the development of more efficient systems. Figure 2 below traces the efficiency gains since the early 1970s and reflects the fruits of R&D work.[10]

[10] Kazmerski 2006

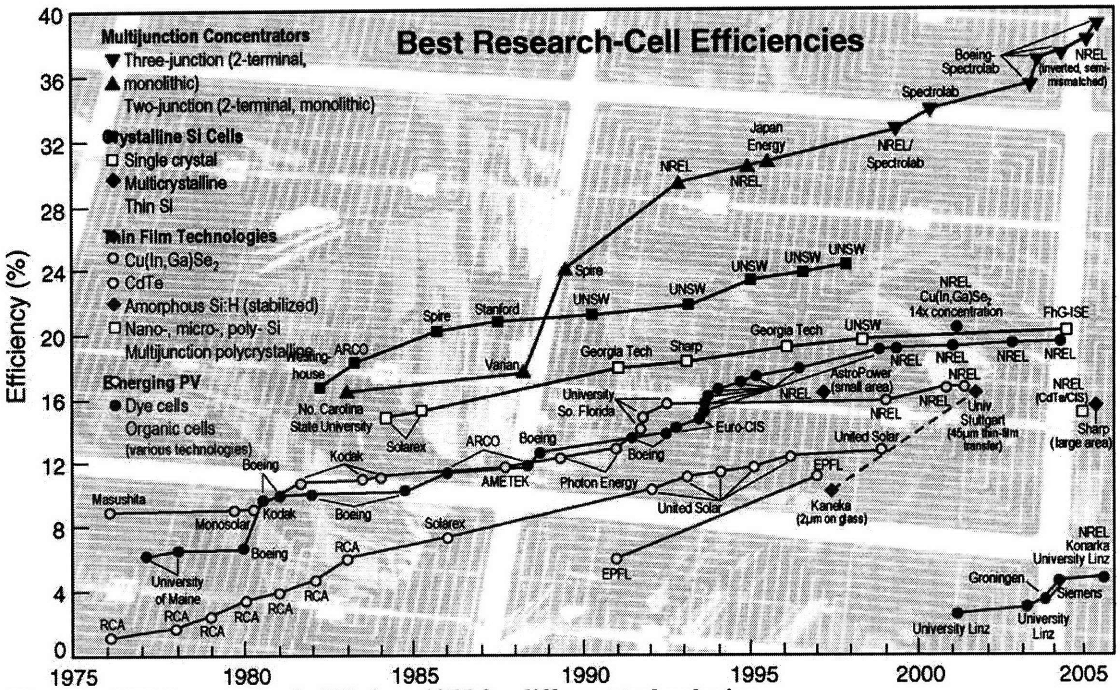

Figure 2: Efficiency gains in PV since 1975 for different technologies.

R&D involves highly skilled scientist and engineers pushing the limits of technology. In some cases this research is done at universities or national labs before the results are transferred to industry. In the U.S. grants and awards from public agencies, notably the National Renewable Energy Laboratory (NREL), DoE, NASA, and DoD, facilitate this progress.

Design takes on both a micro and a macro level focus throughout the value chain. Upstream design involves creating more effective manufacturing processes for cell and module production. This requires a strong understanding not only of research but also of production technologies. At the downstream end, individual systems must be designed to meet the power requirements for their intended application. Their design involves understanding power requirements for building and sizing the system appropriately. It also entails connecting the BOS components to the solar modules for optimal generation. One other important dimension of design is building-integrated PV (BIPV), in which architectural considerations are very important.

Production and *logistics* are heavily focused on physical manufacturing and coordination. This means ensuring that there are enough raw materials for production and that the distribution channels of the final product are clearly defined. This step relies heavily on the sales and marketing team because components are not necessarily produced in the area where they are marketed. For example, Sharp Solar manufactures PV modules in a Memphis, USA production facility and then sells panels through companies in Massachusetts.[11] This requires a complex network of dealers and installers which handle the modules. Marketing also happens directly at the dealer level with individual stores and websites promoting the use of PV installations.

All three PV generations have similar requirements for R&D, design, production, logistics and marketing. Newer generations like organic/dye-sensitized PV are more heavily focused on the R&D phase at present, but it is likely that as the technology matures and becomes more widely accepted the focus in each case will begin to mimic that of the more mature first generation silicon crystalline photovoltaics.

The orange boxes are described in the above section because they apply to each of the three PV generations. In the following sections, we will discuss the blue and green boxes of the value chain. We start with the crystalline silicon value chain laid out in Figure 1 and follow with discussions of thin film and organic PV.

---

[11] Sharp solar

1st Generation

First generation photovoltaics are crystalline silicon cells. This is the type of cell that is in most common use today and it accounted for over 90% of world cell production in 2006.[12] The production process is the most well defined for this type of cell since these cells have been in production for 30 years. Although crystal silicon cells are currently the most abundant source of solar power, they may not be the only long term PV solution.

Figure 1 illustrates the first-generation value chain. Each blue chevron describes either a physical object or step on the way to producing a solar panel. Understanding the underlying processes enables us to assess the importance of each step and its contribution to the final product. At each step there may be specific production machinery as well as intermediate products, and the introduction of new materials. By understanding in detail what is involved at each step, we can also better comment on the type of skills or level of automation required.

First generation solar modules start out as pure silicon which is extracted from quartz and purified as shown in figure 3. Solar panels require at least 99.999999% (6N) pure silicon, so the quartz must go through a carbothermic reduction to produce metallurgical grade silicon (MG-Si) which is approximately 96-99% pure. This MG-Si then goes through another purification step, the Siemens or fluid bed reactor (FBR) process, to produce useable solar silicon. As the solar market expands, companies may begin to produce solar silicon from MG-Si directly.[13]

[12] Ullal and Roedern 2007

[13] Flynn and Bradford 2006

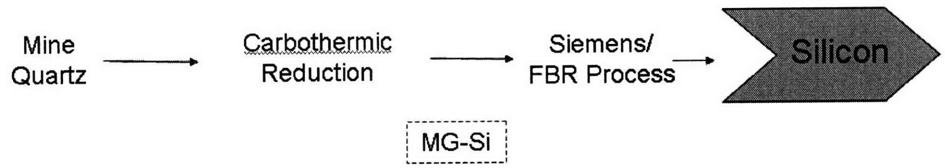

Figure3: Silicon purification process.

There are approximately 10 major producers of silicon world wide, but there is no production in Massachusetts.[14] (The world's largest producer of pure silicon, Hemlock, is based in Michigan.) The energy-intensive nature of production makes it unlikely Massachusetts will ever have silicon producing facilities as other areas around the world currently offer cheaper electricity.

Silicon is then solidified in order to form a wafer or sheet which can be used to produce solar cells. There are three major processes for producing wafers from silicon. The CZ float zone method is used to produce mono-si crystals, which have the highest efficiency, but are also the most expensive to produce. Directional solidification/ casting produces silicon ingots which have a multi-crystalline structure. This process is cheaper than the CZ float zone method, but the cells are less efficient than mono-crystal.[15] The third method, EFG / string ribbon, involves growing ribbons from a silicon melt. With this method the production rate is faster and less silicon is wasted than in traditional production methods.[16] EFG is used by Schott Solar and string ribbon is a propriety process of Evergreen Solar. Both companies are located in Massachusetts.

---

[14] REC
[15] Flynn and Bradford 2006
[16] SEBANE

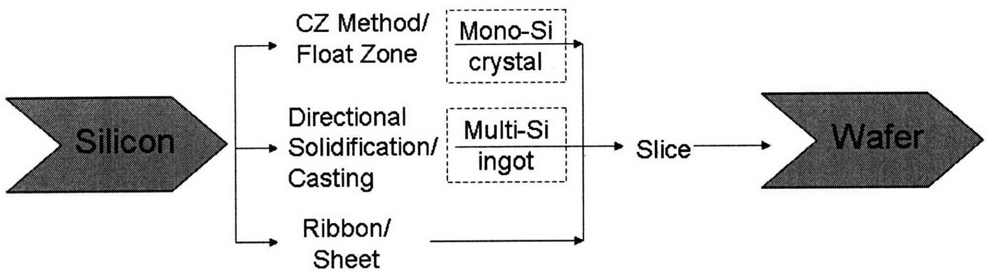

Figure 4: Three production methods for creating silicon wafer

There are approximately 50 ingot and wafer producers world wide.[17] Silicon and wafer manufacturing facilities need not be located close to the cell production site because transportation of materials at this stage is inexpensive. Still, because of a recent shortage of silicon, downstream companies have sought to form partnerships with silicon and wafer producers.[18] These partnerships guarantee a steady supply of silicon feedstock so cell manufacturing companies can set manufacturing capacity. Schott Solar and Evergreen Solar are the only two major wafer producers in the state.

Once a wafer or ribbon is produced the base for a solar panel has been created. The next steps involve turning this wafer into an electricity-producing cell. By taking advantage of the semiconducting properties of silicon, a cell can be created which produces electricity from incoming light photons.

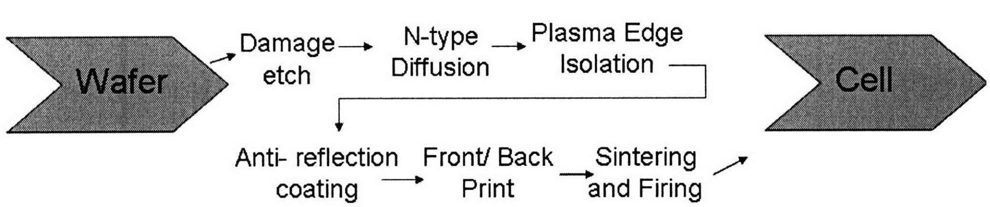

Figure 5: Process steps from wafer to cell creation.

[17] REC
[18] Solarbuzz.com

The wafer is first etched to remove the damage caused by sawing the ingot into wafers, except in the case of EFG or string ribbon growth where no sawing is involved. Next, phosphorus is diffused into the wafer through a process of heating up a phosphorus-based compound and letting it diffuse into the upper surface of the cell. Since the edge of the cell is now also phosphorus-doped, a process of plasma edge isolation is used to remove the N-type material on the outside of the cell. Anti-reflective coating is added to increase the amount of light absorbed by the cell. Finally, the front and back of the cells are printed with electronic connections to allow free electrons to move throughout the cell, and the whole unit is fired to finalize the contact printing.[19]

The solar cells are next strung together to make a module. First generation solar modules usually consist of at least 36 solar cells strung together in series to harness the energy each generates. The string of cells is laminated with a plastic material and backed with an aluminum frame and glass top. This final stage of assembly creates a solar module with an expected life span of more than 20 years.[21]

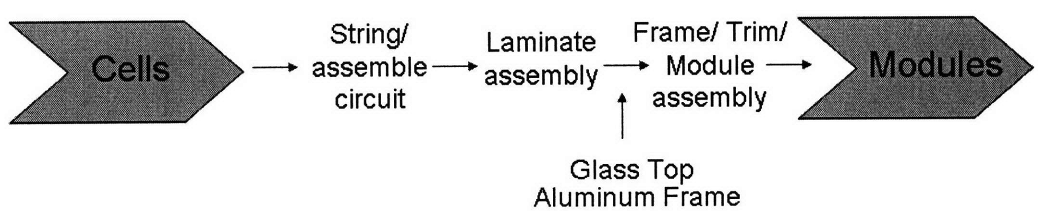

Figure 6: Cell to module process

Many of these processes are automated with the help of machines made by Spire and BTU International, each of which is Massachusetts based. These two companies manufacture what we refer to as "enabling technologies" – that is, the machines which

[19] Jester 2002
[21] REC

enable automated cell production. There are about 65 cell producers worldwide with Japan and Germany counting a majority of the companies.[22] Once again, Schott Solar and Evergreen Solar are the only major cell producers in Massachusetts.

Balance of system

Balance of system (BOS) components are required to regulate, store, and monitor the energy produced by the solar panels. The category can be defined more generally as any component of a photovoltaic system which is not included in the module. BOS includes cabling, controllers, load/grid interfacing, inverters, batteries and monitoring systems. Requirements are different for stand-alone versus grid-connected systems, but BOS components are necessary for both.[23] In some cases it is even possible to sell excess energy back to the power grid which can be done with the help of inverters and a monitoring system to manage excess power generation.

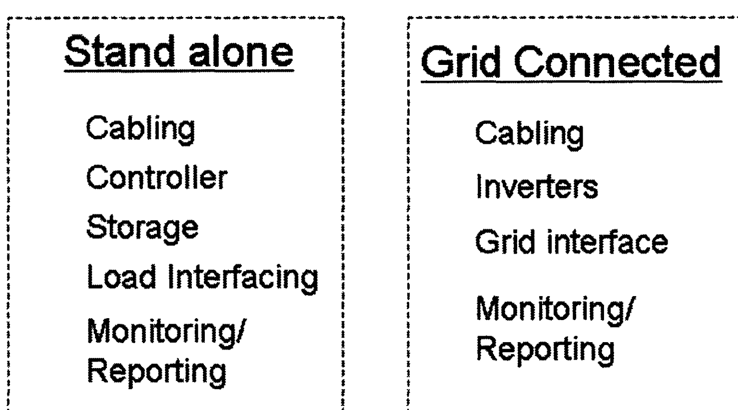

Figure 7: Stand alone vs. grid connected BOS components

[22] REC
[23] Cross

Massachusetts companies like Solectria, Beacon Power and Satcon make inverters for grid connected systems which are required to convert solar generated current from DC to AC. Rolls Battery makes batteries for stand alone systems which must store power for later usage. Irradiance, Heliotronics and FatSpaniel make monitoring and reporting systems for grid connected systems.

Applications/ Dealer/ Design and Installation

This group has by far the largest number of corporate participants of any part of the value chain. Firms usually serve as regional installers for large module manufactures. Companies tend to design and install systems for both commercial and residential installations. Dealers will sometimes install, but tend to focus on the sale of solar goods. They often sell a wide range of goods from solar modules to inverters and batteries. Installation time depends on the size of the system, but typically is 2-3 days for residential units. Installers have skill sets that are similar to those of construction workers or carpenters, but they must also be specially trained and certified in PV installation.

Research/ Consulting/ Non-profit

Research, consulting and non-profit organizations provide analysis of solar industry, but do no manufacturing or installation of physical products. They add to the knowledge economy and often employ experts from the industry. Consulting and research organizations collect data on solar industry growth, trends, installations and other area, then disseminate that information to a wide audience. Non-profits organize solar projects in developing areas and work to install PV in places without access to other energy systems. These companies contribute to the knowledge economy of the state and may be a good resource in attracting conferences or creating business centers of knowledge.

2nd Generation

Second generation PV refers to technologies employing thinner non-crystalline materials that often offer comparable performance to 1st generation cells at significantly reduced manufacturing costs. At the present nearly half of the cost of a first generation product comprises the materials used in cell production.[24]

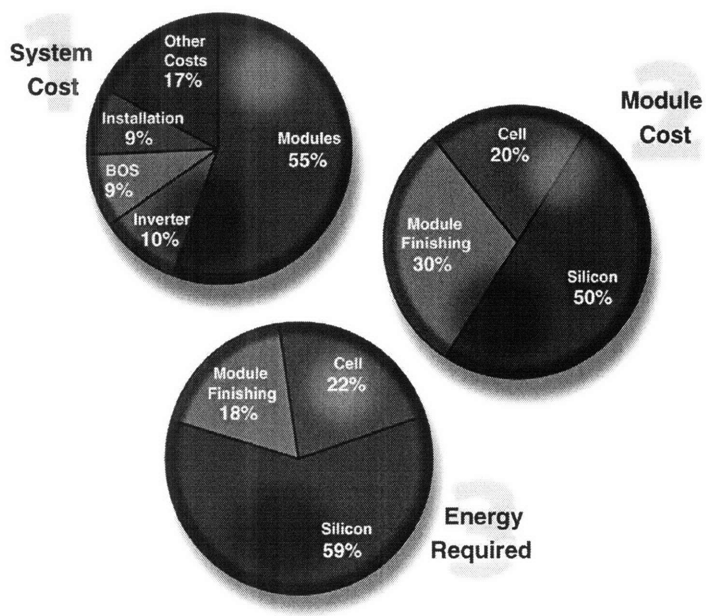

Figure 8: Typical cost breakdown for crystalline silicon solar module

These technologies currently have the potential for commercial and residential installations similar to those of first-generation technologies. Therefore the downstream

[24] Kazmerski 2006

portion of the first and second generation value chains look very similar and we will not discuss sales or installation for thin film products. The only difference is that flexible thin film technologies open up the possibility for portable PV power and building-integrated materials.

Thin film technology is less widespread than first generation PV, but can broadly be grouped into amorphous silicon (a-Si), CdTe, and CIGS/ CIS. In an effort to group each of the three major thin film technologies we categorized the upstream steps as mining, chemical processing and deposition because this broad categorization encompasses much of how each is produced. Notice also that the green boxes are very similar to the crystalline PV value chain except for the substitution of the chemicals industry for the silicon production.

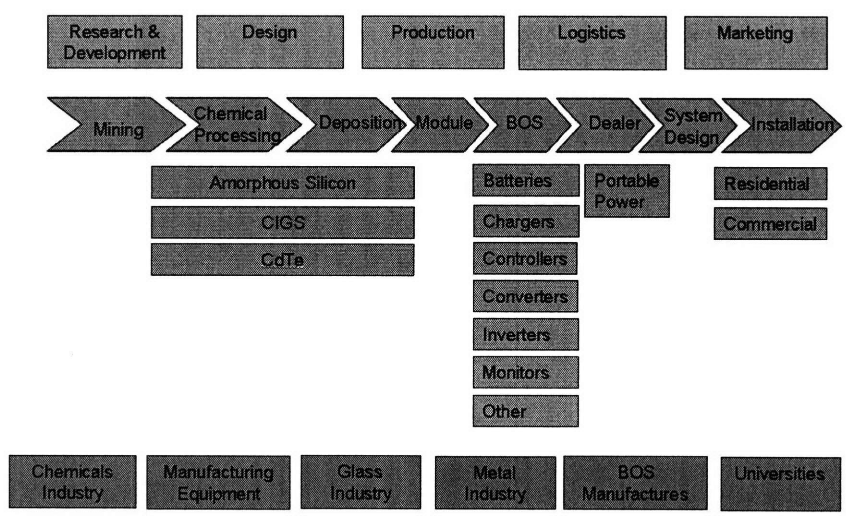

Figure 9: 2nd generation value chain

Amorphous Silicon

Amorphous silicon (a-Si) solar panels are formed by depositing different kinds of doped silicon onto a glass backing substrate. First, a transparent conductive oxide (TCO) is applied to a glass substrate which is followed by laser scribing to establish cell boundaries. Next. layers of p, i and n type silicon are deposited on the TCO. This "p-i-n" layer acts just as the N-type diffusion layer does in first generation technologies to allow for photons to excite hole-electron pairs. The p-i-n layer is then scribed again and contacts are applied to connect the newly formed cells.[25]

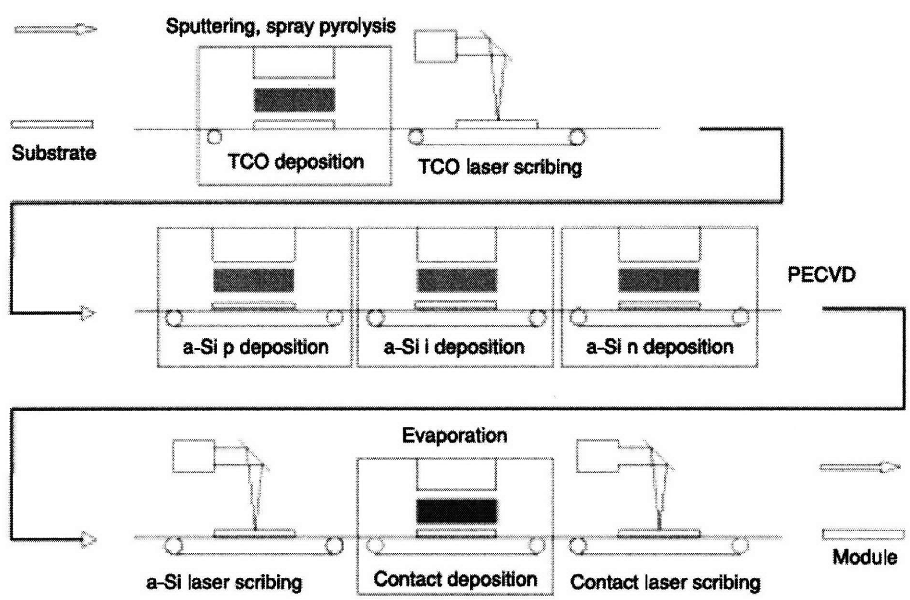

Fig. 3. Scheme of the basic steps for fabrication of a thin-film silicon photovoltaic module.

Figure 10: Deposition process for amorphous silicon

[25] Carabe and Gandia 2004

<u>CdTe</u>

CdTe is another type of thin film technology, and the process for a vertically integrated facility is located below. First, CdS is deposited on a glass substrate and laser patterned. This is followed by a CdTe layer and a $CdCl_2$ coating, which is patterned and thermally treated. Silver contacts are then added, followed by an epoxy resin to finish the cell.[26]

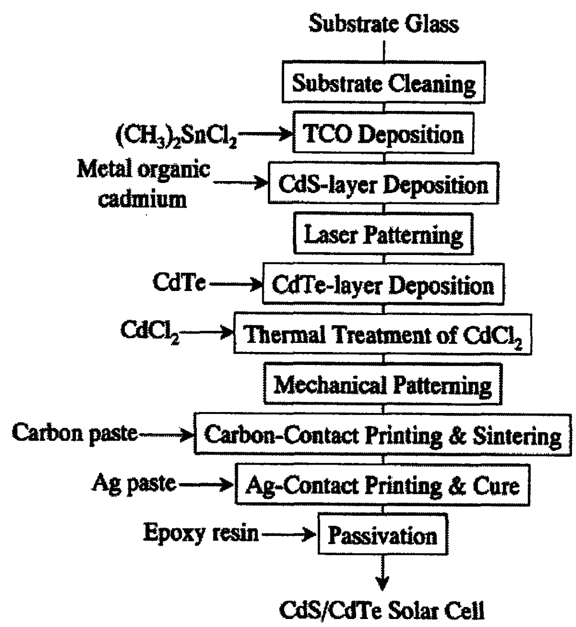

Figure 11: Vertically integrated CIGS plant

[26] Tuttle 2005

CIGS/CIS

The third form of thin film technology is CIGS/ CIS. Its production process is similar to the other second-generation technologies. Copper, Selenium, Indium and Gallium are sputtered onto rolled steel to form the base of the solar cell. This cell stack then gets the same metal contacts as in the other cases and is covered in plastic to form a module.[27]

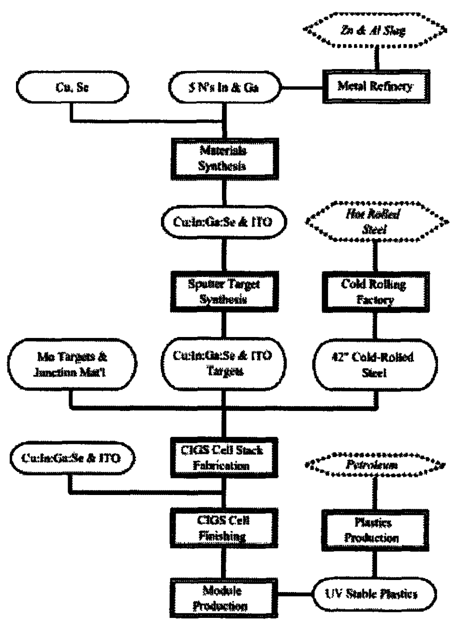

Figure 12: Vertically integrated CdTe plant

Although there are few second generation companies located in Massachusetts, there is still research at local universities aiding the development of this technology. It is unlikely that Massachusetts will develop into a major manufacturing sector for this generation of technology because centers for thin film have already developed in California, Colorado and other areas, but it is still possible for Massachusetts to make significant R&D contributions to thin film. Vanguard Solar, a recent start up, is an

---

[27] Kato et al 2001

example of thin film R&D knowledge in Massachusetts. The company has a proprietary technology, but plans to license rather than manufacture its own solar cells.[28]

3rd Generation

Third generation technologies rely on organic or dye sensitized materials to generate electricity. This technology is still in the developmental stages so we can not represent individual processing steps as we did for the first and second generations. Instead we focus on opportunities for downstream adoption of new technologies. Rather than only installing this technology in residential or commercial settings, 3rd generation PV has the opportunity to develop in areas including consumer electronics, building materials, and electronic fabrics.

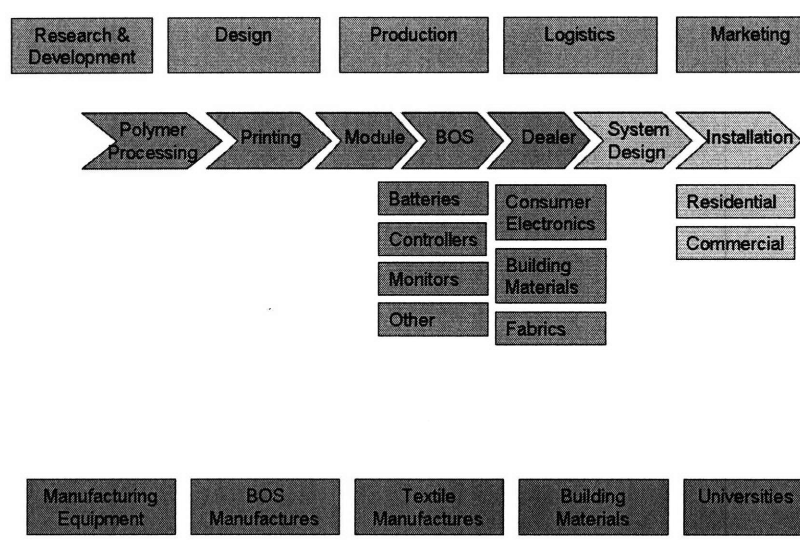

Figure 13: Third generation value chain

Notice that once again the upstream portion of the value chain has changed. The first two stages now include polymer processing and printing which generally represent

[28] Vangaurd Solar 2007

major steps in production. Printing will speed the manufacturing process and allow roll-to-roll processing (this is also available in some second generation technologies.)[29] A Massachusetts-based company called Konarka seems likely to be the first company in the US to successfully test this PV printing technology.

The potential downstream applications of this organic/ dye-sensitized PV area are limitless. It may one day be possible to wear a jacket with built in solar technology which charges your phone as it sits in your pocket, or to make a tent which folds out to become a portable electric generation system to power the subsystems on the inside. These possible applications open up the opportunity for expansion in many industries. Textile and building manufacturing may one day become part of this third generation value chain, just as the aluminum and glassmakers contribute to the more established technologies.

Policy Options

There are many paths Massachusetts can take as it moves forward in developing a solar industry, each of which will require different actions and have different consequences. Here we will explore two levels of policy options which align with the greater goal of developing Massachusetts as a clean energy hub. In the primary level, the state must decide whether to:

- bring in more cell and module manufacturing plants,
- work to strengthen the state as an R&D center, or
- introduce policy incentives to encourage local market development and home installations.

[29] Konarka

Bringing in cell and module manufacturing plants will replace jobs which have been lost in Massachusetts as companies look for less costly places to manufacture. Jobs would be created in skilled manufacturing sectors that involve work with semiconductor materials. Manufactured cells and modules would likely be shipped outside the state as supply would outpace demand. This goal is possible, but further research needs to be done on the cost of brining manufacturing to the state. As was discussed earlier, Massachusetts was successful in bringing in Evergreen, but unsuccessful with its loss of Schott Solar's facility to New Mexico.

Strengthening the state's R&D activity is a less tangible goal, but may fit well with the academic resources of the state. As globalization continues, local and regional economies are looking to strengthen their innovative capabilities. These capabilities foster the development of new companies and technologies. The latter can be licensed or sold after the developmental stage. A focus on R&D would likely create jobs for highly skilled researchers and scientists. These are extremely high value added jobs that would be hard to outsource to other areas. More consulting and research companies may follow to the area. While these types of jobs would not help the state's manufacturing economy, it is likely that strengthening research in the PV sector could benefit Massachusetts in new technologies.

Developing a large local market for PV in Massachusetts might turn out to be the largest driver of job creation. By creating incentives for homeowners and companies to install solar modules the state would be generating a demand for installers. It may be the case that this activity is so labor-intensive that developing a local market could bring with it enormous potential for job creation. This would simultaneously contribute to the goal of deploying sustainable energy in the state. As new legislation is passed and a carbon tax or other regulatory system is implemented, it may benefit the state to be a leader in deploying sustainable energy. Manufacturing companies may follow to the state because of the increase in deployment, as has occurred in California. Yet even without an influx of manufacturing companies, the increase in installers could create jobs for workers throughout the entire state.

Each of these three options alone would generate job growth, but further research needs to be conducted to understand the magnitude of job creation with each option. Even without data on the exact job creation in each option, it appears safe to say that some mix of the three options will be best for the state. It may turn out that investing heavily in local markets creates installation jobs while at the same time attracting manufacturing plants because there is a demand for modules. Another example would be the partnership between R&D and manufacturing. Remember that Vanguard Solar developed a proprietary thin film technology, but plans on licensing it to cell manufacturing companies rather than invest in plants itself. In this case R&D developments in the state may create more manufacturing jobs.

The secondary level policy option is to decide on which generation of technologies would allow the state to most easily accomplish its primary goals. We can now use our value chain analysis to discuss which generation is best suited for each primary option. Different maturity levels in each PV generation make it likely that certain generations would best suit each primary goal.

If the state were to decide that its most important objective was to create manufacturing jobs, it is likely that policy would be directed towards bringing manufacturing of 1st generation solar technologies to the state. The crystalline silicon technologies still make up 90% of the world market and account for a major portion of the 30% annual growth of the industry.[30] New plants like the Evergreen facility set to open in Devens could bring in as many as 1,000 new jobs in cell or module production.[31] Cells and modules would likely be shipped out of the region since New England would not be able to absorb the output of many major manufacturing facilities.

An R&D knowledge center focus would likely mean bringing more 2nd and 3rd generation technology to the state. Though there are still improvements in traditional crystalline silicon PV, major advances are being made in newer generations. Significant research is going on at universities throughout the state on new PV materials which continually contributes to the states knowledge economy. An example of this goal already being realized is how MIT has recently partnered with Fraunhofer to continue PV research in Massachusetts. We also see that Konarka will likely become the first company to successfully produce organic PV cells on a large scale using printing. If Massachusetts is able to promote Konarka as a successful 3rd generation PV company, it is possible that similar companies will also come to the state. This could help to stimulate a new center for PV innovation where cutting edge research is done in the state, but manufacturing takes place elsewhere.

Developing a local market currently means focusing on 1st and 2nd generation technology. Both crystalline silicon and thin film PV are in mass production and have been proven for residential and commercial installation. The value chain analysis shows that 1st and 2nd generation technologies differ significantly in the production process, but

---

[30] Ullal and Roedern 2007
[31] Chandler 2008

both produce end modules which are primarily used for building installation. There is little difference for installers as to which generation of PV is more prevalent in the state. Since these items will most likely be imported from other areas, the state does not even have to distinguish as to which technology is used when it offers installation incentives or rebates. The focus for this goal is therefore less on the technology and more on developing a local market for installers.

Conclusion

In this paper we have described the value chain for three generations of PV technology. This information was then used to identify which companies are located within the state. Finally, we have identified two levels of policy options which could meet the state's goal of becoming "a global center [of] alternative and renewable energy." Any of the three primary options could be a viable way of creating a renewable energy hub in Massachusetts, but each also emphasizes a slightly different policy objective.

To evaluate the effectiveness of each policy in job creation we need better employment data across the value chain. We have broken down the process from initial production to installation, but detailed data on the type and quantity of labor is now required for further discussion. Without better employment data we cannot complete our recommendation on which policy state officials should pursue.

If manufacturing jobs are most important to the state then the policy should likely emphasize bringing 1st generation cell and module manufacturers to the state, a process which has already begun with the Evergreen facility in Devens, MA. But if total job creation is the goal then it is not so clear that manufacturing jobs are the way to go. Data may show that since downstream installation activities are so labor-intensive encouraging the deployment of PV systems may be the most effective way to create local jobs.

In any case, there is a lot of fertile ground for further research in the economic development outcomes of shifting to renewable energy. For the purpose of this paper we have specifically examined PV in Massachusetts, but as clean energy regulation comes into affect, there will likely be an another opportunity to examine other renewable energy sources or focus on New England as a region rather than only Massachusetts.

Bibliography

Carabe, J and Gandia, J.J. "Thin Film Silicon Solar Cells." Opto-Electronics Review 2004

Chandler, David. "Governor Says Massachusetts Can Reap Benefits from Clean Energy." MIT news office. Cambridge, MA < http://web.mit.edu/newsoffice/2008/patrick-0423.html>. April 2008

Cross, Bruce M. "Developments in the 'Balance of Systems' and protection of PV installations. Energy Equipment testing service. IEE. London

Evergreen Solar. <Evergreensolar.com> 2001-2007

Flynn, Harry and Bradford, Travis. Polysilicon: Supply, Demand and Implications for the PV Industry. Prometheus Institute. 2006

Jager-Waldau, Arnulf. PV Status Report 2006: Research, Solar Cell Production and Market Implementation of Photovoltaics. European Commission, DG Joint Research Center. Ispra, Italy. 2006

Jester, Theresa L. Crystalline Silicon Manufacturing Progress. Progress in photovoltaics: research and applications. 99-106. 2002

Kato, K et al. "A life cycle analysis on thin-film CdS/CdTe PV modules" Solar Energy Materials and Solar cells 67. 2001

Kazmerski, Lawrence, L. "Solar photovoltaics at the tipping point: A 2005 technology overview." Journal of Electronic Spectroscopy and other phenomenon 150. pg 105-135. 2006

Keller, John. Massachusetts gubernatorial debate on CBS4. <http://www.govote.com/Archive/MA_Gov_Sept_2006_Energy_+_Oil.htm> September 2006

Konarka Technologies < http://konarka.com/> 2003-2008

Levey, David. L, Terkla, David. "Clean Energy in Massachusetts," MassBenchmarks. Vol. 9, Issue 1. 2006

MTC. Massachusetts clean energy census. Aug 2007

REC. "Frequently asked question."<http://recsolar.com /cm/Solar%20Learning%20Center/solar-energy-facts.html/>

SEBANE. "Evergreen Solar Announces Latest String Ribbon Technology Advance." <http://www.sebane.org/news_room/news_releases_viewer.asp?id=49>. January 22, 2004

Sharp Solar. <solar.sharpusa.com> 2008

Solarbuzz. "Solar Cell Manufacturing Plants." <http://solarbuzz.com/Plants.htm> 2007

Tuttle, J.R., Schuyler, T, Choi, E, and Freer, J. "Design considerations and implementation of very-large scale manufacturing of CIGS cells and related precuts" 20th European PV solar energy conference 2005

Ullal, H.S and Roedern, B.von. "Thin film CIGS and CdTe Photovoltaic technologies: Commercialization, Critical issues, and applications. 22nd European Solar Energy Conference. Milan, Italy 2007

Vanguard Solar. http://www.vanguardsolar.com/product.php#manufacturing> October 2007

Appendix A

Silicon	Wafer	Cell	Module	Manufacturing Technologies
Crystal Systems	Evergreen	Evergreen	Evergreen	Spire
	Schott	Schott	Schott	GT Solar
		Plastecs	Madico (backing)	BTU International
		Konarka	Crane Nonwovens (glass)	
		Vanguard	Konarka	
		Eikos		

Balance of system	Dealer	Applications
Satcon	Alternative energy store	SolarOne
Rolls Battery	Central New England solar store	
Irradiance	New England Solar Electric	
Heliotronics	Solar Marketing Inc.	
Solectria Renewable		
Unirac		
Beacon Power		
Tungstone Power		
Schaefer		
Battery Engineering		
Beta Dyne		

Design/ Installation

Berkshire photovoltaics
Solar design associates
Cotuit solar
Advanced energy systems development
TSC construction
SolarFlarir energy
ATC Energy management
Village power design
Clean energy design
Lotus Energy Consulting and Management
Pioneer Valley PhotoVoltaics Coop
All-Pro electric
Alternate energy
Borrego solar
Central New England solar store
Conservation service group
Environmental solar systems
Gloaria Spire
Harrisun systems
Kosmo solar
Kurkoski Solar Electric
Light Energy Solar
Lighthouse electrical contracting
New England Breeze
NextGen Energy Solutions
North Shore Solar and Windpower Company
S+H Construction
Solar Works
SolarWrights
South Coast Greenlight
Zapotec Energy

Consulting/ research/ non profit

Cadmus Group
Navigant Consulting
New Energy Options
Soluz
Conservation service group
Under the Sun
Enersol Associates