The Challenges of Organic Polymer Solar Cells

by

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B.Sc., Physics
B.Sc., Electrical Engineering
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Submitted to the Department of Materials Science and Engineering
in Partial Fulfillment of the Requirements for the Degree of

Master of Engineering in Materials Science and Engineering

at the

Massachusetts Institute of Technology

February 2011

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Abstract

The technical and commercial prospects of polymer solar cells were evaluated. Polymer solar cells are an attractive approach to fabricate and deploy roll-to-roll processed solar cells that are reasonably efficient (total PV system efficiency>10%), scalable and inexpensive to make and install (<100 $/m2). At a cost of less than 1$/Wp, PV systems will be able to generate electricity in most geographical locations at costs competitive to coal's electricity (at 5-6 cents/KWh) and will make electricity available to more people around the world (~20% of the world population is without electricity). In this chapter, we explore organic polymer solar cell technology.

The first chapter discusses the potential impact of solar cells on electricity markets and the developing world and its promise as a sustainable scalable low carbon energy technology. The second chapter discusses some of the complexity in designing polymer solar cells from new materials and the physics involved in some detail. I also discuss the need to develop new solution processed transparent conductors, cost effective encapsulation and long life flexible substrates. The third chapter discusses polymer solar cells cost estimates and how innovative designs for new modules could reduce installation costs. In the final chapter I discussed the prospects for commercialization of polymer solar cells in several niche markets and in grid electricity markets; the commiseration prospects are dim especially with the uncertainty in the potential improvement in polymer solar cell stability.

Thesis supervisor: Jeffrey C. Grossman
Title: Carl Richard Soderberg Associate Professor of Power Engineering

Acknowledgements

The thesis would not have been possible without the support of many people.

The greatest thanks go to my advisor Prof. Jeffrey Grossman who encouraged me to be an independent thinker and offered me guidance and support along the ways.

My deepest gratitude is for my family: my wife Renad , my son Khalid to my brothers Eyad and Ziyad and to my aunt Huda. My parents, Abeer and Khalid, who have been big believers in me all the time. And to them this thesis is dedicated.

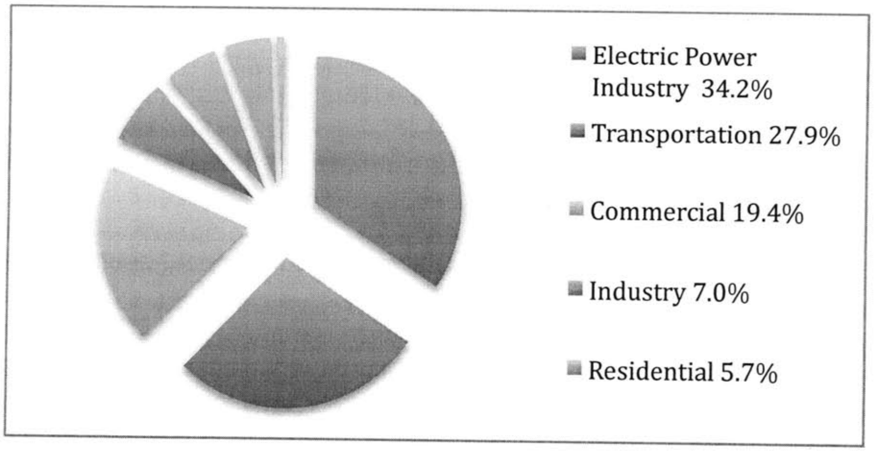
Table of Contents

Chapter 1: Introduction

Energy Challenge and Energy Need

The world's energy demand is expected to double within 40 years as the global population grows and rising living standards in developing countries such as India and China place a strain on available energy supplies. A 2004 United Nations study presented three scenarios; the conservative scenario estimates that the population to peak in 2050-2060 to a little bit over 9 billion people(*1*). Our current energy consumption is ~15 TW of power and could rise to about ~30TW by the year 2050.

New energy technologies are needed to meet population demand in a sustainable and environmental manner to enable human civilization to grow further and to hedge against environmental risks. Solar energy and other sustainable energy technologies are, in general, expected to be one of the biggest growth industries in the next 50 years, which makes it a strategic industry and a primary means to keeping the economy growing, creating new jobs, and creating real economic wealth.



Sources of US Green House Emissions as an example

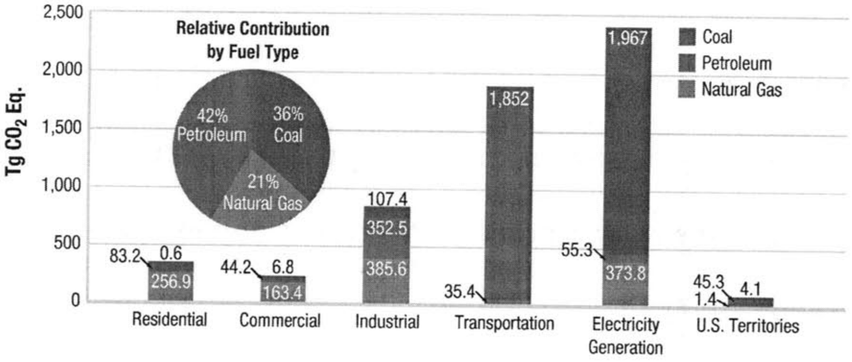


Figure 1.1: Sources of US Green House Emissions. Total emissions is 7150 teragrams of carbon dioxide equivalents (Tg CO2)
.Data from the US Climate Action Report 2010, US State Department; data represents 2007 emissions. Emissions include carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride

To hedge against the eminent risk of global warming that could have disruptive effects on biological diversity, weather, and world economies, most nations have put plans into effect to reduce global emissions; meeting sustainable world energy demands will prevent supply shortages and the resulting severe economic and social hardships.

Solar Energy

The sun is our planet's main energy source. The sun, in one hour, provides the earth with more energy than all human energy consumption combined. In just tow days, the sun provides the earth with the equivalent energy of all known oil reserves (three-trillion barrels of oil). The sun provides the earth's surface with 120,000 TW . Solar cells can be used to deliver part of our energy needs with much less carbon emissions. Developing economical solar energy technologies will enable sustainable and geopolitically stable electricity. Currently, the world's main energy source is based on the burning of fossil fuels, which are scarce, geopolitically unstable, and are the major source of carbon dioxide emissions, a greenhouse gas responsible for global warming as shown in Figure 1.1. Solar energy is more abundant than fossil fuels (mainly petroleum, coal, and natural gas), which collectively generate 86.4% of the world's primary energy consumption (US Energy Information Administration 2007).

Photovoltaics (PV) and Grid Electricity Markets

Photovoltiacs technology is a distributed power and modular technology. It can provide power to a residential scale system (1 kW-10kW), commercial system (100kW- 1MW), and utility scale system (10MW-1 GW) and can be deployed flexibly anywhere to support the grid quickly and efficiently. PV cells could satisfy all of our energy needs if they were combined with cost effective storage technology. There is an economic and environmental advantage to rooftop PV; for example, it will reduce electricity bills and electricity load peaks in many regions. PV can be effectively integrated with smart grids that monitor and optimize the bi-directional flow of electricity and are capable of integrating current energy storage technologies.

Integrating solar panels into electrical networks will facilated through smart grid networks. Advanced and cost-effective electrical storage technology will make solar power more reliable and more usable. Without storage technologies, solar energy could achieve a penetration rate up to 14% with minimal impact on the electric grid [DOE]. In some residential districts in Germany PV already supply about 5% of the electricity; If we extrapolate current PV industry growth, we could expect that by the year 2020, more than 1% of the world's electricity demands will be generated by photovoltaics (See Figure 1.2).

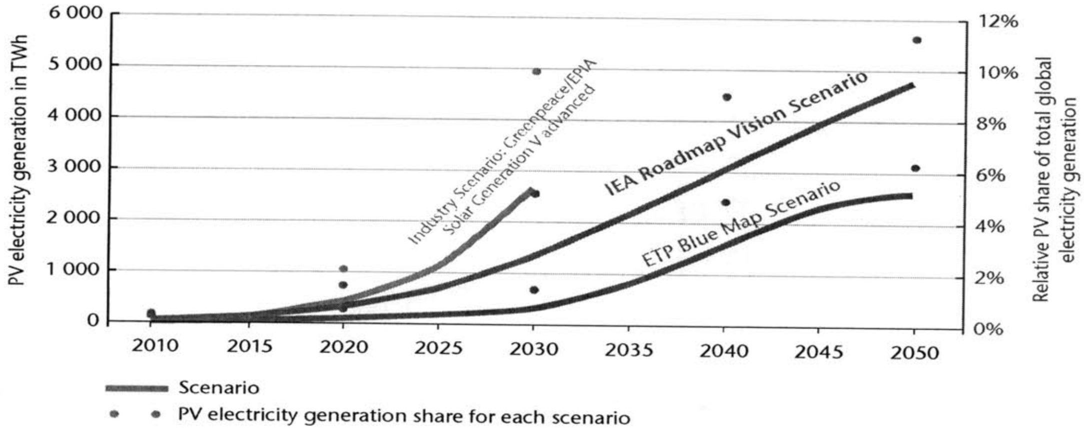


Figure 1.2 : Three possible scenarios for PV penetration of electrical grid markets. (IEA)

To reach the TW regime, the solar industry needs to sustain large volume production and be immune from material supply problems. Material supply limitations are evident in today's thinfilms solar technology, indium (e.g., CIGS), and telluride (e.g., CdTe).

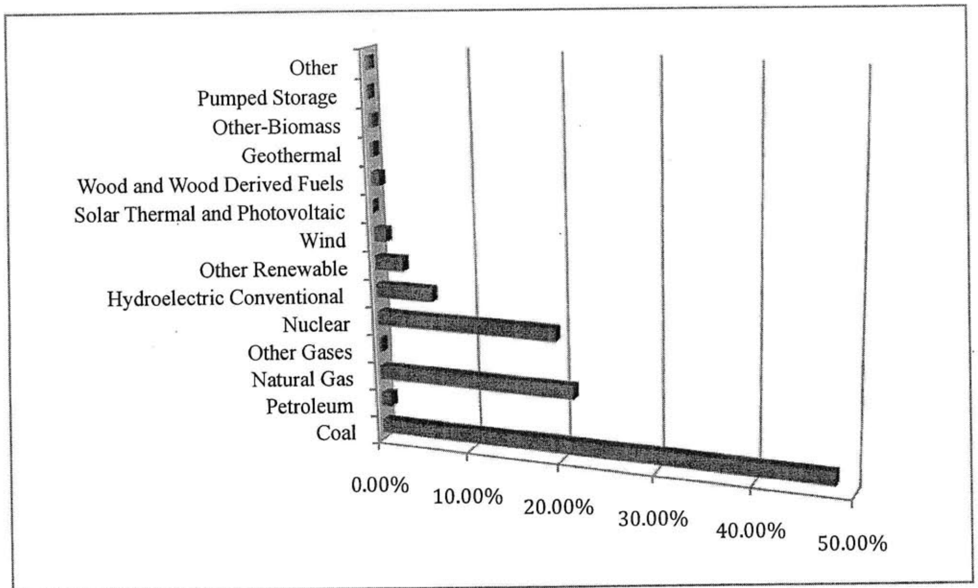
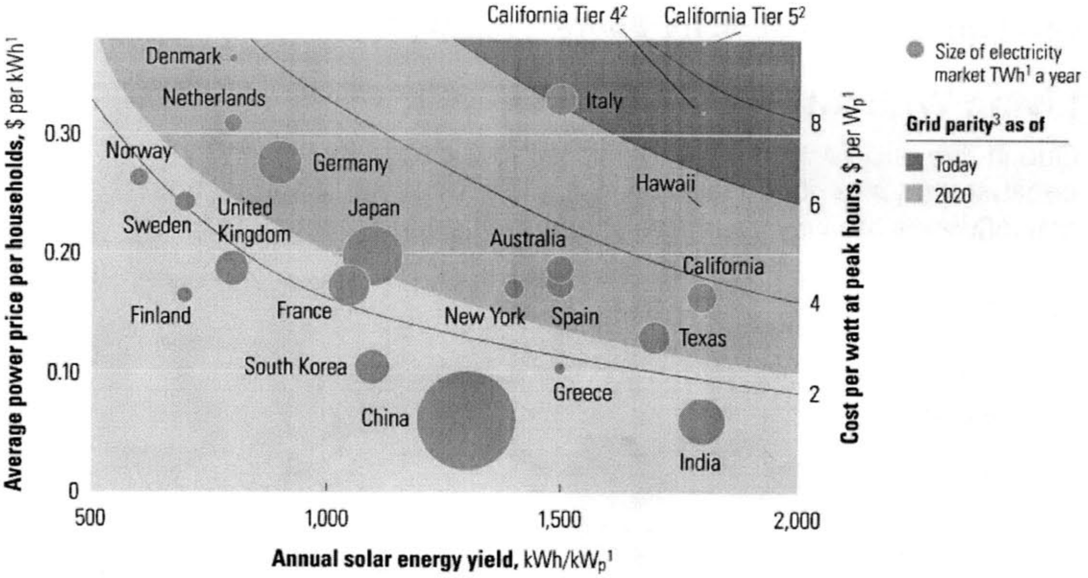


Figure 1.3: US Electrical Generation sources (DOE).

In the United States, about 69% of electricity generation is through fossil fuels, as shown in Figure 1.1. Solar photovoltaics provide less than 1/10 of 1% of electricity generation in the United States and the world. Photovoltaics have not become a source of electricity generation because it is too costly in comparison with other energy sources. Some photovoltaics are capable of producing electricity at competitive costs with peak retail electricity in some places like California and Italy (See figure 1.4). In the next few years, many photovoltaics technologies will be capable of producing electricity at competitive costs in several places.



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[1] kWh = kilowatt hour; kW_p = kilowatt peak; TWh = terawatt hour; W_p = watt peak; the annual solar yield is the amount of electricity generated by a south-facing 1 kW peak-rated module in 1 year, or the equivalent number of hours that the module operates at peak rating.

[2] Tier 4 and 5 are names of regulated forms of electricity generation and usage.

[3] Unsubsidized cost to end users of solar energy equals cost of conventional electricity.

Source: CIA country files; European Photovoltaic Policy Group; Eurostat; Pacific Gas & Electric (PG&E); Public Policy Institute of New York State; McKinsey Global Institute analysis

Figure 1.4: Electricity prices in different countries Vs PV electricity prices.

Developing World Need for Photovoltaics (PV)

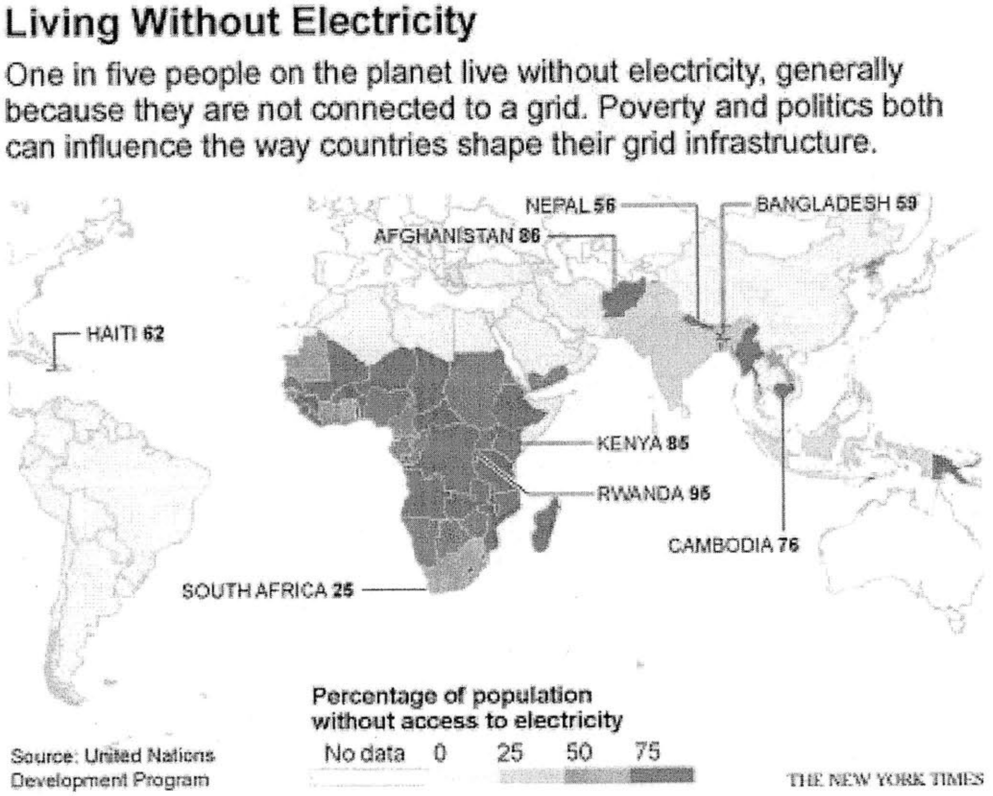

Figure 1.5: The map shows the percentage of population without access to electricity. Figure adopted from (*2*).

More than 20% of the world population does not have access to electricity, even supplies of rural electricity, depriving them of electric lighting, clean water, heating, and many other basic services (World Bank, 2010). PV technology can feasibly electrify remote rural areas where most of the people with no access to regular electricity live (IEA 2010).

Distributed power systems can instantly affect the lives of those who do not have access to electricity. Off-grid photovoltaic systems do not need complicated planning and excessive capital to build electricity grids infrastructure. Furthermore, distributed power systems such as off-grid solar panels can be deployed nearly instantly. For people in areas such as rural Africa, the ability to communicate electronically or to read and study at night can be enabled by using a portable solar cell (100-200 cm2) and an efficient lamp. Cooking and cooling food and drugs could become easier. The ability to find your way in the dark, trade, work, plan, and study at night could influence economic productivity. Electrical energy will be an important tool in raising economic productivity, improving health, and getting people out of poverty. **Large rural** electrification programs are expected to be carried out in China, India, and in parts of Africa. For example, China, the world's top producer of solar modulus, is planning a large rural electrification project that completely uses renewable energy, and solar electricity play a major role in this project (*3*).

Distributed power systems are suitable to un-electrified rural area as it reduces the capital needed to build the infrastructure. Independence, or at least partial independence, for the power station could improve the stability and resilience of power stations in situations of excessive demands, albeit it could affect the stability of the electrical grid if it was poorly managed. Furthermore, in unstable parts of the world, whether there are local or civil wars, having a distributed model to generate electricity such as solar PV could reduce dependence on central electricity generation utilities, which could be vulnerable under these circumstances.

Challenges of the Solar Spectrum

The solar spectrum is very broad-spectrum radiation, relatively dilute, intermittent. Nevertheless, a few square meters at reasonable efficiency (<1~0%) is capable of providing a important part of typical house daily electricity use in the developed world. More electricity could be generated on large fields. An area covered with 100x100 km2 of solar cells at an efficiency of 10% can generate 1 TW of peak power

The fact that solar insolation is low and consists of a broadband spectrum makes designing and building photovoltaic quantum converters to generate electricity from light photons challenging. The sun's periodicity and its relatively low maximum insolation, about 1Kw/m2, create a great challenge when designing materials with high quantum efficiency and a sufficiently low-cost installed system that is able to compete with conventional energy sources.

Furthermore, the sun insolation distribution varies greatly depending on the location and ranges from 1000 KWh/m2 to 3200 KWh/m2 in most geographical places. At an electricity price of 0.05 $/Kwh, this is equivalent to about 50-160 $/m2 generated each year. At 10% efficiency, this reduces to 5-16 $/m2 generated each year, (albeit at discounted energy prices for future years for a fair comparison to other sources).

To utilize this energy the PV system should be highly efficient (10% and preferably 20%) and inexpensive; the PV system typically consists of the solar module, connections, mounting system and need some installation labor to be installed on rooftops or in utility fields. The cheap solar cells paradigm assumes that 10-20% efficient solar module will be the best current approach to generate electricity from the sun.

Motivation for large scale cheap Flexible light weight solar cells

Historically, the affordability of energy has been dropping. This trend should continue to enable more energy to the 1.5 billion people without electricity. At one dollars per day, people will need to save all their money for about three years to buy a 1KW peak PV system at a cost of around 1$/Wp. Bringing the cost to about 0.25 $/Wp will shorten the period to months. Assuming that the power will be used by a group of people on essential technologies such as lighting, mobile phones , vaccine cooling, heating etc. this cost seems more viable. Zweibel (*4*)estimated the cost of plastic based organic solar cells to be viable to reach to 0.1 $/Wp at 8% efficiency for module only. Hence, it might be reasonable to assume a PV system with 0.25 $/Wp. The Gates foundation expects that bringing the cost of KWH to something close to say 1/4 of coal energy costs will be transformative and make energy widely accessible (*5*).

In the short term, photovoltaics are expected to supply 1% of the world's electricity by 2020Hence, there is a clear need and opportunity for large and quick production of solar modulus at low prices. The key property that makes organic photovoltaics so attractive is the potential of reel-to-reel processing of low cost substrates with standard coatings and printing processes. Polymer organic photovoltaics can potentially be a solution to processing low cost substrates at low temperature, in large volumes, and at a very low cost with standardized coating or printing processes. Furthermore, very lightweight and flexible materials are more suited for portable power applications and will open additional niche market opportunities if compared with thin film technologies such as CIGS or amorphous silicon. Organic photovoltaics manufactured on flexible substrates are potentially lighter, have a wider acceptance angle, and are better suited to working with diffuse light, low light intensity, and indoor lighting conditions.

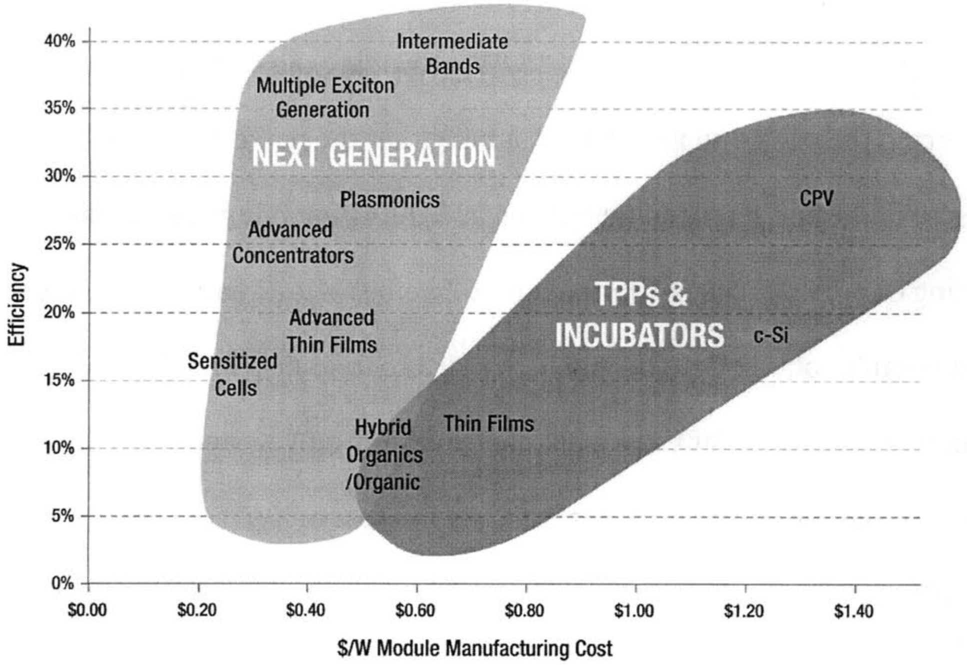

Figure 1.6: Space shows different technolgies and their economic paradigm in terms of module cost and efficiency.

Organic Solar Cells (OPV) Vs Competing Technologies

One main limiting factor of Polymer photovoltaics or organic photovoltaics (OPV), in general, is their lower efficiencies and shorter lifetimes, especially for polymer PV. Single junction solar cells are potentially able to create modules in the 10-15% range, while tandem solar cells are thought to enable the manufacturing of module with efficiencies up to 20%. These efficiencies are potentially not significant enough for polymer PV to impact the potential market, unless the module cost of polymer PV and its installation cost are significantly reduced. Hence, additional critical challenges for polymer modules are very cheap PV modules that are easier (inexpensive) to install than current solar modules. Furthermore, OPV can be deposited on a variety of substrates of different shapes—rigid, flexible, or substrates that can conform to many surfaces; other thin films, such as Copper indium gallium (di)selenide (CIGS), can be deposited similarly, but the supply of indium could limit scalability, and CIGS thin films over a large area have been proven difficult to achieve until know. New materials, such as thin materials, might be able to compete with OPV in this regard.

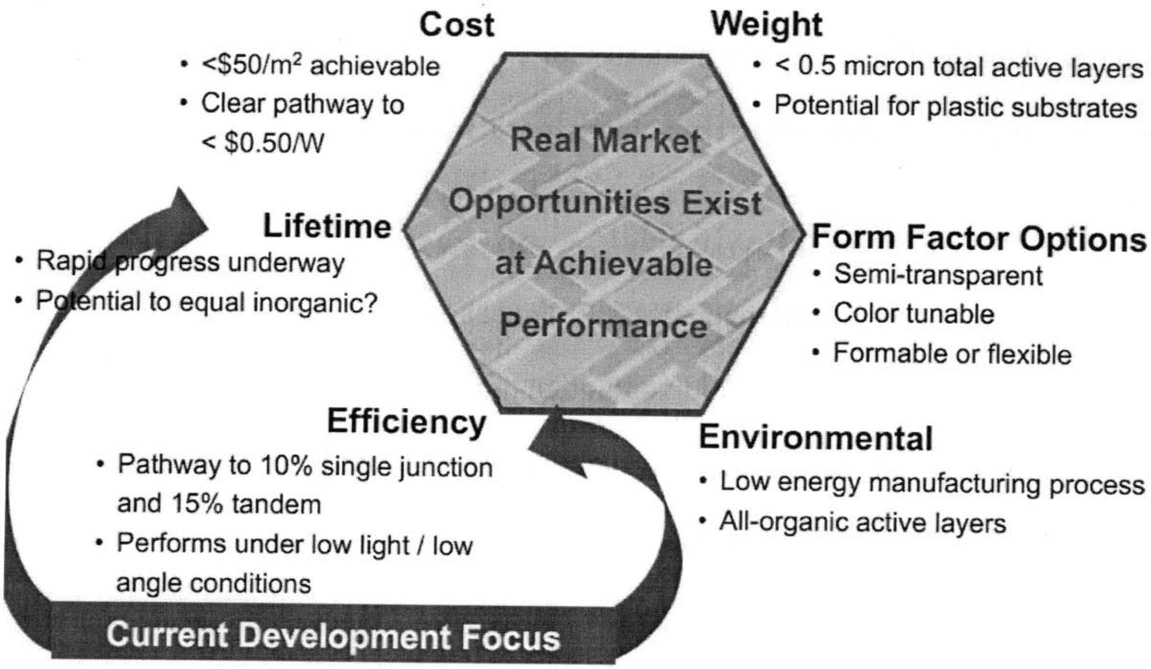

Figure 1.7: A solar PV company, Plextronics, value proposition for organic PV and current development focus. (Adopted from Plextronics)

Organic molecules and polymers strongly absorb light, which enables the use of more economically active materials (thin films ~ 100nm) and less active materials. Thin films of organic semiconductors can be deposited on and enable the deposition of flexible substrates. Furthermore, it is chemically tunable to be colorable or semitransparent, which opens up niche applications in building integrated PV where aesthetics play a crucial rule. A lifecycle analysis shows that the low energy manufacturing of polymer PV is potentially possible as energy intensive lab cells with low material efficiency have an energy payback time of about 2 years. The manufacturing of Polymer PV is also thought to avoid the use of many toxic materials that are used in silicon manufacturing, which could be more of a problem if solar PV is scaled up to 10 or 100 times.

Typically polymeric materials for polymer PV processing start from oil, but since the active materials required per unit are not significant (~1 g/m^2), there is no risk of material scarcity. The main risk for oil scarcity is its use in the transportation industry, not in the petrochemical industry.

Challenges for organic based solar cells

Polymer organic photovoltaics (PPV) needs to solve great challenges to overcome low efficiency, low lifetimes, and to improve the processing method. Developing better transparent electrodes, better encapsulation methods, and innovative installation methods are also needed to commercialize PPV into electrical energy markets.

Organic photovoltaics technology can be traced to 1986. Today, after more than 20 years, organic photovoltaics are just starting to be commercialized. The major commercialization hurdles are low module efficiency, short lifetime, and module cost.

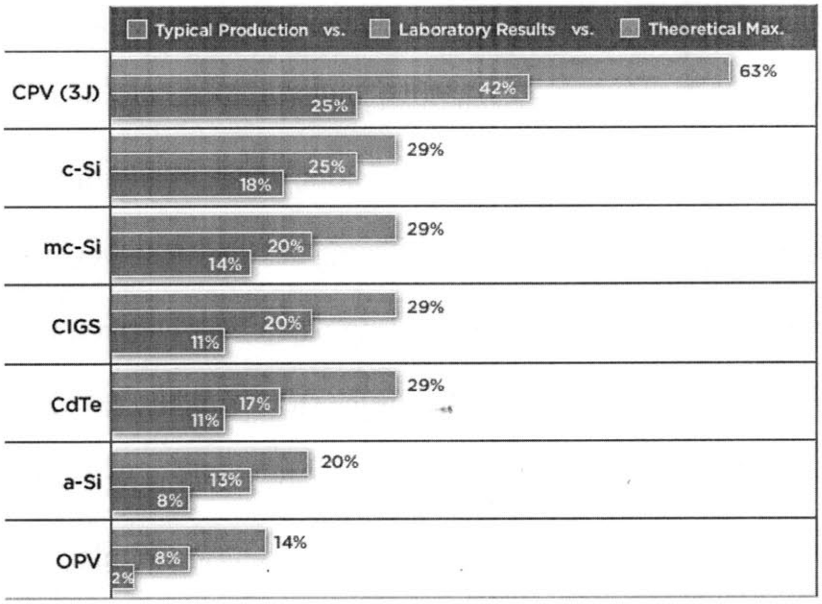

Figure 1.8: Successful Competing PV technologies are likely to complement each other in different applications. (DOE)

Polymer solar modules are solution processed, meaning that they easy to manufacture on a very large scale at a reasonable cost and speed. These cells can be manufactured by using already existing and underused roll-to-roll printing equipment. The chemical flexibility of polymers enables semitransparent and light tunable cells. They also have more environmental processing and recyclability and can potentially pay for themselves quicker than any other type of cell. However, polymer solar cells still lack reasonable efficiency, lifetimes, and to compete in the electrical utility market.

Cost of installed PV systems

There are three main components in PV installation costs: PV module costs, installation costs, and power electronics cost (indirect costs that are caused by regulations and permits are not considered here). OPV could play an important role in reducing the cost of these cost components. The module cost could be reduced by using inexpensive, abundant, scalable, and solution-processed organic materials. The reduction of installation costs could be driven by the ability to redesign the module to have controllable form-factors and different colors, which makes them easier to be integrated as building materials, or by designing flexible, light weight modules that are easier and quicker to install. The reduction in power electronics could be driven by increasing their lifetime and reliability or by the ability to integrate them as organic electronics or, independent of OPV, by integrating mass produced standardized electronics into monolithic modules or typical module designs. Furthermore, as in every PV technology, the entire cost breakdown can be reduced by increasing efficiency and lifetime to generate more energy over the lifetime of the solar cells, and by using less modules and less area.

Table 1: Possible cost reduction pathway toward 1 $/Wp for the cost of installed PV systems as enable by OPV. Regulation and permits cost are not shown here, but these costs could be reduced by creating solar friendly regulations.

Cost component $/Wp	Possible cost reduction pathway
Module	• Module efficiency (15%- 20%(max)) • Module lifetime (?) • Solution processed active materials • Solution processed electrodes • Inexpensive, abundant, and scalable active materials and transparent electrodes
Installation cost	• Module efficiency (up to 20%) • Module lifetime (?) • Flexible and light weight module

	• Building integrated module based on tunable colors and form-factors
Power electronics	• Increased module efficiency (up to 20%) • Module lifetime (?) • Increased electronics lifetime • Integrate Organic electronics • Standardize and mass produce • Redesign electronics to be cheaper

Overview of the Thesis

The purpose of this work is to evaluate polymer photovoltaics commercials prospects; in chapter two we discuss the technology limitations in efficiency and lifetime and how it could overcome them. In chapter three we discuss the cost of polymer modules and their installation. In chapter four we discuss the possible role of polymer PV in the electrical grid market and in niche markets such as BIPV , portable power sources.

Chapter 2: Polymer Solar Cells Technology and Challenges

Motivation

The sun provides the earth's surface with 120,000 TW. Our energy consumption could rise from an average ~15 TW of power to about ~30TW by the year 2050. Solar cells can be used to deliver part of our energy needs with low carbon emissions. However, for solar cells to make a significant contribution to our energy use, they need to be deployed over a large area. Covering 10 thousand square kilometers with 10% efficient solar cells will generate a peak power of 1TW. An attractive approach is to fabricate and deploy roll-to-roll processed solar cells that are reasonably efficient (total PV system efficiency>10%), scalable and inexpensive to make and install (<100 $/m2). At a cost of less than 1$/Wp, PV systems will be able to generate electricity in most geographical locations at costs competitive to coal's electricity (at 5-6 cents/KWh) and will make electricity available to more people around the world (~20% of the world population is without electricity). In this chapter, we explore organic polymer solar cell technology.

Single layer polymer solar cells can achieve practical module efficiencies of more than 10%, and tandem polymer solar cells can achieve practical efficiencies more than 20%. Furthermore, organic polymer solar cells can produced inexpensively at large scale in a roll-to-roll processing manner.

Introduction

Organic Semiconductors

Organic semiconductors include small molecules, oligomers (short polymers) and polymers. Examples of polymer organic semiconductors are conjugated polymers such as poly(3-hexylthiophene) (P3HT) and poly(p-phenylene vinylene) (PPV). When blended with fullerenes, these polymers make low efficiency photovoltaic material. In addition to organic semiconductors use in solar cells, they are evolving into flexible and more energy efficient LEDs, detectors, transistors and other electronic and spintronic devices.

Organic Photovoltaics (OPV)

Organic solar cells and panels have the potential to make solar to electricity conversion widely available and accessible to humankind. Organic solar cells can be made from inexpensive and abundant materials and can be manufactured into high throughput using scalable production with low cost processing and low energy input (*6*). The photovoltaic material can be made from inexpensive organic semiconductors that can be processed and recycled more economically than competing crystalline inorganic semiconductors. It is possible that organic solar panels can be completely solution processed. This includes solution-processed electrodes, the substrate and integrated organic diodes and organic power optimizer circuits. Furthermore, the flexibility of chemical tuning and the good solution rheology meet the demand of cheap solar cells.

Organic photovoltaics is an excitonic solar cell (*7*), which are characterized by bound excitons that are generated after excitation with light. The Excitons are quasiparticles that consist of a strongly bound state of electrons and holes. Organic based PV can be divided into three different types: dye synthesized solar cells, small molecule organic solar cells and polymer solar cells. They all share similar photovoltaic action physics whereby the photovoltaic action is modeled by donor-acceptor systems. The photoactive layer of organic solar cells consists of two materials: an electron donor material and an electron acceptor material. The donor typically does most of the light absorption; current acceptor materials absorb little light. The photo excitation of the donor material (conjugated polymer) generates photoinduced excitons, or bound electron-hole pairs, which can only be separated into negative and positive charge carriers at the donor-acceptor interface. The following discussion focuses on polymer photovoltaics but it is widely applicable to organic Photovoltaics in general.

Current Status of Organic Semiconductors Photovoltaics

The efficiencies of single junction polymer photovoltaic are increasing on a yearly basis and have reached over 8% on a single junction polymer solar cell with a small area lab cell ~1cm2 (Konarka 8.3% and Solarmer 8.1%) but with limited stability. The lifetime of commercial glass encapsulated modules ,from Konarka, have been limited to three or four years. Small molecules photovoltaic are much more stable than polymer based material, and tandem junction with similar efficiencies (Heliatek 8.3%, 2010) but longer lifetimes were also demonstrated on small area lab cells. Dye-sensitized solar cell (DSSC), which is a slightly older technology, were able to achieve higher efficiencies (over 13%), but they currently suffer from limited lifetime, and from the use a corrosive liquid electrolytes that makes their encapsulations difficult on a commercial scale. This chapter focuses on polymer photovoltaic solar cells.

The Basic Physics of Photovoltaics in Organic Semiconductors

Pi-Pi* Semiconducting Bandgaps

Organic semiconductors are made from conjugated organic materials, which have an alternating single bond (sigma bond) and double bonds (sigma and pi bond). The semiconductors' nature arises from the delocalized and weakly held pi electrons. The pi to pi* energy transition controls the electronic and optical properties of the materials. The band gap of current organic semiconductors ranges from 1.4 eV to 2.5 eV, which enables the fabrication of multijunction solar cells and offers low band gap materials that are close to optimal energy gaps relative to the solar spectrum (*8*). The narrow absorption bandwidth limits the efficiency of organic single layer solar cells to much less than the S-Q theoretical limit.

Narrow Absorption Bandwidths

Organic semiconductors are held by weak van der Walls forces, which make their processing relatively inexpensive but reduce their mobility. Nevertheless, they are still sufficient to make efficient solar cells. The weak intermolecular interactions and the strongly localized electronic wavefunctions lead to a narrow absorption bandwidth as opposed to the larger absorption bandwidth in inorganic semiconductors (*9*).

Nevertheless, this narrow spectrum absorption property could be seen as an advantage in some niche applications that require cells coloring, such as building integrated photovoltaics. Furthermore, this property could be overcome by using tandem (multijunction) cells to allow for a wider absorption of the light spectrum.

Light Distribution in Thinfilms

Light absorption in thin films of active materials is depends on light distribution in the device. The light distribution in functioning PV cells devices is determined by the incident light interference with reflected light in several layers of thin films with different complex refractive indexes. The impact of light distribution loss can be reduced by calculating and maximizing light distribution in the active layer, for example by using the transfer matrix formalism (TMF) (*10*).

Photon harvesting process in Donor-acceptor heterojunctions

Solar photons cannot be separated directly to generate electrons but must become absorbed into semiconductors of appropriate bandgap-generated electron-hole pairs, which can then be separated to generate electrical current. There are two approaches to harvesting photons and causing them to generate electrons from the sun spectrum-absorbing semiconductors: using inorganic (p-n) junctions or organic donor-acceptor (D-A) heterojunctions.

In organic donor-acceptor (D-A) heterojunctions, the nature of optical excitations is different from that of inorganic semiconductors. In inorganic semiconductors, the absorbed photons instantly generate free electrons and holes at room temperature. Organic semiconductors have a lower dielectric constant than inorganic semiconductors (~3 in contrast to ~12 in Si) and thus less electric field screening. Hence, the absorbed photons generate tightly bound singlet excitons.

Such excitons are called Frenkel excitons and have a small diffusion length of the order of (5-10 nm) (*11*), and their binding energies are in the order of (~.05 eV-1 eV) (*11*), which are several times more than the thermal energy at room temperature kT (~1/40 eV).

The absorbed photons generate a singlet exciton (tightly bound electron-hole pair) in the material, the donor or the acceptor. The singlet exciton, a neutral quasi particle, will diffuse into the junction. The energy level difference between the HUMO levels of the donor and acceptor will cause the exciton to dissociate into a negative polaron (an electron charge coupled with a cloud of phonons) in the acceptor side, and positive polaron in the donor side. The negative and positive carriers will stay bound at the interface. To separate them, an external electric field is needed. The external electric field arises from the metal junctions field and the PV field. The freed positive and negative charges will transport by hopping across the donor and acceptor material, respectively. From the point of view of the system chemistry, what happens is a photoinduced redox reaction, where electron and holes hop through a series of chemical reactions after the singlet exciton is dissociated at the donor-acceptor interface.

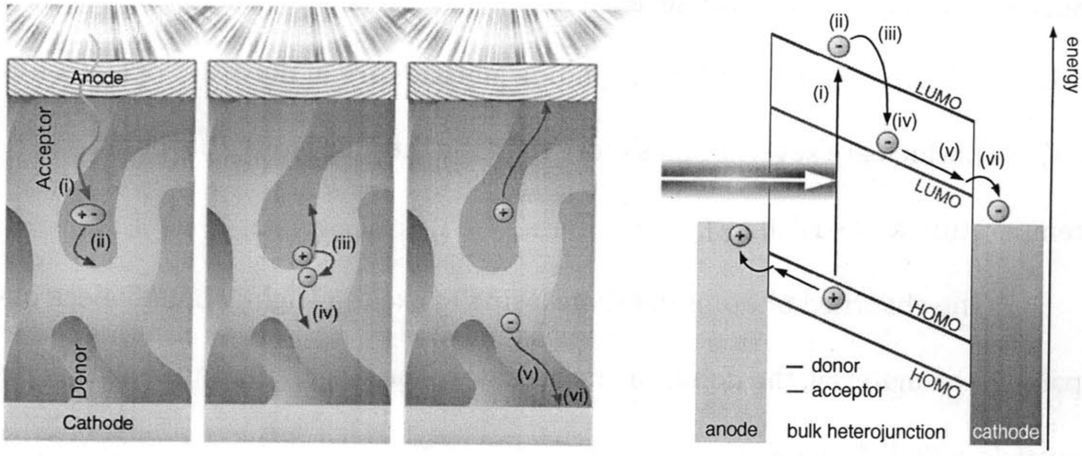

Figure 2.1: Show steps to generate a photocurrent from a photon in an organic solar cell. The effective bandgap is approximately equals to the LUMO(D)-HOMO(A) levels difference. (*12*)

The excitons in organic semiconductor bound energy are estimated to range from (0.1-0.4 eV), and they can dissociate at the heterojunction interface if there is a sufficient chemical gradient offset. Specifically, excitons separate into negative and positive charge carriers because of a sufficient difference between HOMO (Acceptors) and HOMO (donors) *excited* energy levels. The bound exciton energy will cause loss in the open circuit voltage by an equal amount.

It is worth noting that the dissociated charge carriers do not dissociate completely at the interface without the help of an external field. This behavior causes the photocurrent to be voltage dependent, limiting the FF and the Isc current of the solar cell as shown in Figure 1. The external field mentioned is due to the work function of the shottky metal junctions at the electrodes' interface in addition to the photovoltaic induced field.

Furthermore, it was observed that in some systems, singlet excitons dissociate into two triplet excitons that have larger diffusion lengths. Triplet excitons could separate at the donor-acceptor interface, similarly generating more electrons but with lower voltage.

Table 2.1: Different time and length scales in the photovoltaic process in polymer and organic PV. Materials thickness is limited by light absorption, exciton diffusion length, and charge carriers transport.

Process	Time	Length scale
Photoinduced electron transfer	~50-100s fs	-
Singlet exciton diffusion	~ ns	nm
Triplet exciton charge	~ us	um
Charge carriers transport	-	~ 100s nm

Efficiency Limits

The maximum practical conversion efficiency and lifetime is key for future commercialization and competition with Si base solar cells, because efficiency plays a key role in reducing the installation cost, the total PV system cost.

The maximum *theoretical efficiency* for a single bulk heterojunction organic solar cell is estimated to be ~20%. This is lower than the ~30% Shockley-Queisser (S-Q) limit for a single junction inorganic solar cell because of two main additional losses: exciton dissociation loss and polaron recombination and hopping (the charge carriers in OPV) related losses (*13*).

A single junction of classical photovoltaic materials, such as organic semiconductors, can be estimated with the Shockley-Queisser criteria (*14*), which assumes that only photons with energy greater than the energy gap are absorbed to generate an electron with a maximum potential E_g. Any excess photon energy is dissipated as heat. Using the detailed balance limit method of Shockley and

Queisser, a single inorganic junction is estimated to be about ~30% for a continued absorption band (*14, 15*).

However, the Shockley and Queisser assumptions of step-function absorptivity, infinite mobility and perfect internal fluorescence yield have not been achieved in silicon solar cells. A more practical efficiency limit for silicon estimates the highest efficiency to be about 29% for silicon with a band gap of 1.12eV (*16*). Polymer and organic photovoltaic efficiencies are limited further by the short absorption width of the active material.

Furthermore, the efficiency of organic polymer semiconductors is limited further by energy loss in the charge transfer and the polaron energy loss (*13*). This reduces the maximum theoretical efficiency for the 1.4 eV band gap polymer to about 20% (*13*).

There are additional "practical losses" that limit the cell efficiency further such as light reflection, electromagnetic field distribution, electrode shading, leakage and series resistance. For example, in real devices, the absorption of light in the active material cannot be 100%. Furthermore, there are additional losses introduced by the PV system because of the inverters, wiring, dirt, varying temperature responses and shading, which result in 20% or more loss in the PV system output.

Tandem Cells

Tandem or multijunction solar cells are made with two or more solar cells with different optimally aligned absorption bandgap with respect to the solar spectrum to allow higher efficiencies for the solar cells, more than 20%. Multijunction cells are usually connected in series. The photo-voltage of the different layers will add up but the cell will be limited by the minimum current; hence layers need to be optimized carefully in respect to the materials bandgaps, layers thickness and light distribution in the device. Another difficulty in tandem polymer cells processing is that different layers need to be solution processed on top of each other without affecting the device structure. A three contact parallel connection of photoactive layers has a current advantage over series connection, because it bypasses the minimum current limitations, however it is relatively harder to add additional contacts to establish a parallel connection.

Summary of Losses Mechanisms in the photon harvesting process

Table 2.2: summarizes losses mechanisms that limit conversion efficiency in an typical BH organic solar cell (*12*). Process numbers correspond to figure 2.1.

Process	Restrictive property	Potential solutions
i. Light absorption	• Narrow absorption width • Relatively high bandgap • Detailed balance thermodynamic limit for a single junction (<30%).	• Light trapping and management • Optical concepts • New materials with lower bandgap , including IR, and wider absorption width. • Multijunction cells • Use advance device concepts to beat S-Q limit.
i. Exciton dissociation (Ultrafast, ~ 100% efficient	• Short diffusion length (~1-10nm) • Voltage loss	• Increase exciton diffusion length using new materials with higher dielectric constant. • Improve Voc by Reducing voltage loss (limited to ~ 0.1eV). • Optimize morphology • Process improved device architecture to improve morphology

i. Polaron pair dissociation	- Polaron dissociation efficiency.	- New materials with higher dielectric constant - Optimize morphology by optimum phase separations - Optimize morphology Nanocrystalline domains of donor and acceptor.
. Charge transport and recombination	- Low charge mobility that limits BH device thickness. - High recombination	- New materials with higher charge mobility. - Reduce recombination using nanostructured materials phases
. Charge extraction	Low surface recombination	Use better device layouts such as blocking layers.

Polymer Photovoltaics Materials

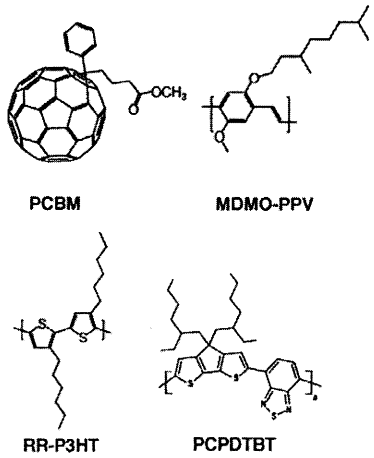

Figure 2.2: Example materials used in polymer photovoltaics. From left to right, Acceptor: PCBM: (6,6)-phenyl-C61-butyric acid methyl ester; Donor: MDMO-PPV: poly(2- methoxy-5-(3’,7’-dimethyloctyloxy)-1,4-phenylene-vinylene); RR-P3HT: regioregular poly(3-hexylthiophene); PCPDTBT: poly[2,6-(4,4-bis-(2-ethylhexyl)-4H-cyclopenta[2,1-b;3,4-b_]-dithiophene)-alt-4,7-(2,1,3- benzothiadiazole)].

Polymer solar cells consist donor-acceptor heterojunctions that are designed to harvest photons and separate the excitons generated from the solar spectrum efficiently. This includes absorbing light photons to generate excitons, dissociating and separating excitons, and transferring electrons to electrodes. This includes the PV active material layers, the substrate, the electrodes, and the encapsulations and barrier coating materials.

Photoactive materials (donors and acceptors)

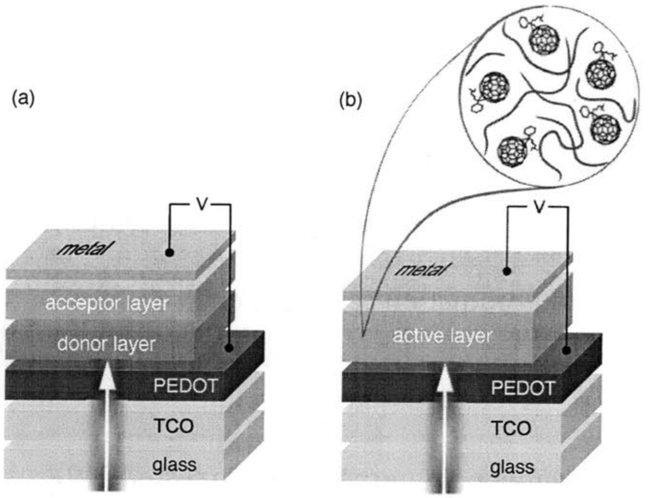

Figure 2.3: Two common device architecture are used to build polymer solar cells: (a) bilayer architecture (b) or (b) bulk heterojunction architecture (distributed planner layer). The active layer consist of (a) bilayer D-A heterojunction or (b) blend of D-A heterojunction. The front transparent contact in this figure is a transparent conductive oxide (TCO) such as indium tin oxide (ITO) is currently used. The PEDOT (poly(3,4-ethylendioxythiophen):polystyrolsulfonate) layer conducts positive carriers (holes) and block negative carriers (electrons) and helps in reducing local shunts. (Figure is adopted from (*12*))

The PV active materials in polymer solar cells consist primarily of solution processed donor-acceptor blinds. The electron donor material is electron-rich material, while the electron acceptor material is an electron-loving material. The light photons can be absorbed by the donor material to donate an electron or by the acceptor material to donate a hole. Bilayer architectures are not efficient in excitons' dissociation because the optical absorption of the polymer materials (~100nm) is much larger than the diffusion length of the photogenerated excitons(~10nm). This problem is resolved by the bulk heterojunction (BH) of donor-acceptor blinds form nanostructures comparable with the excitons' diffusion length and hence enable very efficient dissociation. It should be noted, though, bilayer architectures have less carrier recombination and better control over layers/interfaces properties than bulk heterojunctions (*17*).

Many systems have been proposed for donor-acceptor blinds. Examples are polymer–fullerene blends, polymer–polymer blends, and hybrid polymer–inorganic blends. In the next section, we will discuss the progress of conjugated polymer–fullerene blends, which started the bulk heterojunction cell architecture (*18*).

Conjugated polymer–fullerene blends

The majority of the common conjugated polymers have been tested (*19*). New polymers with a lower bandgap, lower dielectric constant, and greater purity with better-optimized morphologies are needed. Donor material use started with poly- phenylenevinylene materials, such as MEH-PPV and MDMO-PPV, and then was replaced by more stable and more efficient polymer poly-thiophenes (P3HT). P3HT has a limited absorption width of 300 nm with a relatively high band gap, limiting its photocurrent to about 20% of maximum (*12*). More efficient cells were achieved by using lower bandgap polymer donors, such as PBDTTT with an efficiency of 6.77% (*20*) and PCDTBT with an efficiency of about 6.1 % (*21*) and high quantum efficiency that approached 100% for a large part of the absorption band. New better-optimized polymer bandgaps and orbital energy offsets will be needed to reach efficiencies above 10%. Acceptors made from fullerene derivatives were used in all of the high efficiency cells (>4%). The development of new alternatives to fullerene derivatives has been investigated by several groups: conjugated polymers (*22*), CdSe nanorods (*23*), and titania nanocrystals (*24*), but these cells had lower efficiencies than fullerene derivatives.

Worldwide production of fullerenes is limited to research projects, as it does not have any commercialized uses yet. It is unknown whether scaling the production of fullerenes is possible at a large scale and low cost. Investigating mass production of fullerenes would reduce the ambiguity regarding mass production of fullerenes, if polymer solar cells become a tera-watt technology.

Conjugated polymers and other organic semiconductors have very short singlet exciton diffusion length of a few nanometers. Exciton diffusion lengths are usually hard to measure in conjugated polymers. For example, the exciton diffusion length of P3HT, despite being measured several times, is still in disagreement in the literature. Shaw et al estimated the singlet diffusion length to be around ~ 7 nm and more recently Cook et al estimated it be around 27 nm(*25*). The polymer processing methods and purity is expected to affect the exciton diffusion length. This problem could be reduced in the future, as material purity and processing become better understood.

Materials challenges

The properties of current materials limit the performance of solar cells. New materials with more optimized properties in relation to efficiency, stability, operational lifespan, and processing compatibility must be developed. Furthermore, there is a need to find optimized routes in order to mass manufacture the high-purity materials that maintain the optical and electronic properties at a low cost.

There is a need for chemists to develop innovative materials with a larger absorption spectrum and more optimized morphologies with increased ordered nanostructures. The use of new polymers with reduced efficiencies and a less optimized nanostructure morphology is responsible for many of the new record efficiencies in lab and module solar cells. For example, the low band gap alternating copolymer PCDTBT was used to make a 6.1% solar cell with a very high internal efficiency, PBDTTT with an efficiency of 6.77% (*20*), while Solarmer used PTB1 to achieve an efficiency of approximately 6.7 %. Later, before the end of 2010, Konarka and Solarmer increased their efficiencies of ~ 1cm2 lab cells to about 8.3% and 8.13%, respectively

Absorption of donors

The absorption spectrum of current donor materials such as P3HT has a small bandwidth and is limited to the optical regime. The development of low band polymers could extend absorption to the IR range of the solar spectrum (i.e., approximately 48% of the spectrum electromagnetic intensity). As indicated by the Shockley-Queisser estimation, it is necessary to have a lower band gap polymer in order to increase the maximum conversion efficiency.

Absorption of acceptors

Furthermore, current acceptor materials, such as Fullerenes derivatives, absorb little light; the synthesis of new absorbing acceptors will lead to cells with higher current. The acceptor absorption band should be complementary to the absorption spectrum. However, the exciton dissociation into holes and electrons must be allowed by a hole transfer from the electron-donor to the electron-acceptor. One approach with which to achieve that goal is to use nanoparticles whose conductivity and absorption spectrum can be tuned. The limitations have been in the transport of charges across the nanoparticles, which are surrounded by insulating legends.

Increasing the exciton diffusion length

It is possible to increase the exciton diffusion length and reduce the exciton binding energy by designing a material with a high dielectric constant. Lenes et al. lowered the binding energy of the excitons and bound charges in PPV derivatives by adjusting their side chain. As a result, the material permittivity was enhanced and the dielectric constant was roughly increased by a factor of 2. However, this cell had solar efficiencies that were less than 1%, despite an improved charge separation efficiency (*12*).

Increasing Voc by Reducing charge transfer loss

Photoinduced charge transfer consumes part of the photon's energy. This charge transfer loss causes additional Voc losses, in comparison to inorganic solar cells, which limits the efficiency of OPV. Some donor and acceptor material combinations are not optimal because their LUMO energy levels difference is larger than the exciton binding energy; as a result, excess kinetic energy dissipates after the exciton dissociation (*12*); LUMO differences between acceptor and donor materials determine the additional Voc loss and is ultimately limited by the minimum LUMO differences that are required to dissociate and separate the exciton , generated in the donor material, into charge carriers. Typically excitons bound energy are (0.1-0.3 eV). A value of 0.25 eV (*13*) is estimated by Dennler et al. to be a practical minimum LUMO difference that is required to dissociated the excitons although values as low as 0.1 eV were reported in functional heterojunction (*26*).

Better Control of Morphology

The morphology is key to high performance (*13*). Optimizing the morphology improves charges transport, maximizes the exciton dissociation at the interface and maximizes the collection of the dissociated electrons and holes to the electrodes. The larger percentage of electron collected, the higher the internal quantum efficiency (IQE). There is a need to understand how to control the morphology and how materials processing, annealing, drying, pressing, annealing free, additives affect the morphology(*27*).

Annealing can alter the morphology of the interpenetrating networks so that they have an optimized interfacial. For example, annealing P3HT-PCBM blends improves the charge generation and collection efficiency by optimizing the morphology of the donor-acceptor interpenetrating networks and enabling them to have large interfacial areas on continuous pathways to the electrodes;

Ma et al. have improved the power conversion efficiency of a P3HT-PCBM-based cell by approximately 67%, from 3% to 5% by the postproduction thermal annealing of P3HT-PCBM cells with the deposit of an Al electrode. Furthermore, high temperature annealing improves the crystalline nature of the phase of the networks. Therefore, it improves the charge transport to the electrode. This effectively lowers the series resistance of the active material and increases the fill factor. In addition, annealing influences the interfacial contact area between the metal electrode and the bulk heterojunction layer, while improving the layers' adhesion and charge transport across the bulk heterojunction-metal interface

(*28*).

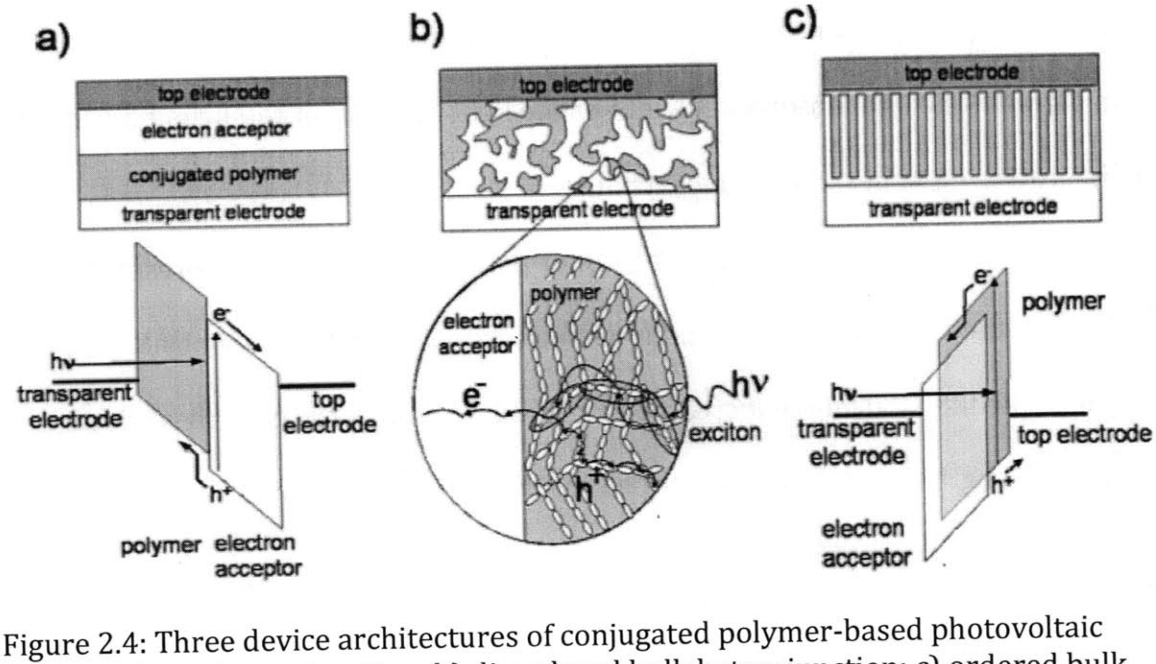

Figure 2.4: Three device architectures of conjugated polymer-based photovoltaic cells: a) bilayer heterojunction; b) disordered bulk heterojunction; c) ordered bulk heterojunction. Figure adopted from (*8*).

Ordered heterojunctions morphology

Increasing the order of heterojunction (see Figure 4) improves the charge transport and reduce recombination events and charge isolation (*11*). The width of each nanorod should be comparable to double the exciton diffusion length and the length of the nanorods should maximize light absorptions and charges transport. Ordered bulk heterojunction might be achieved by using a self-assembled block copolymer or through the application of nanoimprint lithography. For example block copolymers could be used to self assemble the material to self assemble the material to make ordered heterojunctions. Another approach is to pattern the template with the needed ordered bulk heterojunction but this might is not suitable for large-scale production as it need etching steps.

Enhancing Light absorption

Other material innovations that will increase the performance of the solar cell is concepts to enhance light absorption. Plasmonics and metallic nanoparticles can increase the light absorption width or the light absorption coefficient by either light scattering or near-field concentration.

Furthermore, using sensitizing donor polymers with a phosphorescent molecule, the exciton diffusion length will increase; as seen in a study by Rand et al., the exciton diffusion length increased from 4 nm to 9nm. Increasing the exciton diffusion length might enable larger phase segregation which, in turn, will improve the charge transport (*12*).

Increasing satiability and lifetime

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Tandem Solar Cells

Tandem or multijuction solar cells will be necessary for polymer photovoltaic materials to achieve the high efficiency that is necessary in order to compete in the electricity grid market. Assuming that polymer solar cells will be limited by installation and the balance of system costs, especially if they are manufactured on glass substrates, they will need to have an efficiency that exceeds 15% and is preferably higher than 20% to compete in the grid market assuming if the installation cost dominates the supposedly inexpensive module cost (See Market Challenge Chapter). Hence, multijunction solar cells might be necessary to commercialize polymer solar cells in electricity markets. Small molecule startups such as Heliatek are vapor depositing small molecules in tandem solar cells with efficiencies of up to 8.3% for solar cells, and approximately 5.7% for a solar cell covered with metal grids (*29*), with an extrapolated lifetime of more than 30 years. Heliatek double junction consists of small molecules called phthalocyanine as donors and C60 as an acceptor (*30*).

The most efficient polymer tandem solar cell made up to date is about 6.5% efficient (*31*). The optimization of the optical and electrical performance of tandem solar cells is more challenging because tandem solar cells are made from a larger number of layers. Gilot et al. (*32*) have made a proof of concept for trouble junction solar cells and Deibel et al. expects six-fold junctions to be realized (*12*). However, increases in device complexity coincide with rising costs, so a balance between efficiency and cost should be achieved.

Tandem solar cells require new materials at near optimal band gaps and new transparent electrodes and intermediate junctions to enable the fabrication of series connected and parallel connected tandem cells.

Advanced third Generation concepts

Applying advanced third generation concepts can enhance the absorption width. For example, up-conversion fluorescence was used by Baluschev et al. to transform a triplet-triplet from low energy photons into a singlet exciton (*33*). The down conversion of a singlet exciton into two triplet excitons with a much larger exciton diffusion length has been observed by Jadhav et al. in a small molecule and in conjugated polymers. However, the yield of both processes is still low.

Production of active materials

The commercialization of new materials such as fullerenes (discovered in the 1985) and conjugated polymers (discovered in the 1970s) is a complicated process. It takes an average of 20 years to commercialize new materials. It takes years before the processing methods of the materials come to maturity in terms of purity, uniformity, and cost, and it takes many years to optimize the materials' properties, the device's performance, and to enable related innovations.

The worldwide production of fullerenes is limited to research projects because they do not have any commercialized uses, so far. It is unknown whether or not scaling the production of fullerenes is possible at a large scale and inexpensive cost. Investigating the mass production of fullerenes will reduce ambiguity regarding such a process in the event that polymer solar cells become a Terawatt technology. A promising application and markets usually become available prior to mass production. However, mass manufacturing might be costly or difficult to achieve with the current technology. This realization brings uncertainty into the process of developing the technology itself. For example, carbon nanotubes have proven to be a challenge to mass-produce in a uniform manner for use in applications such as transistors and optoelectronics(*34*). It is a dilemma, as if fullerenes based polymer solar cells were commercialized on a large scale, more development in the production of fullerenes and conjugated polymers will be expected.

Other Materials Used in Organic Polymer Solar Cells

Electrodes

Electrodes are used to extract separated charges from the photovoltaic region. In typical solar cells, the top electrode is comprised of transparent-conductive oxides to allow for the absorption of light by the PV material. Currently, doped metal oxide films, such as tin-doped Indium oxide (ITO) and fluorine-doped tin oxide (FTO), which are widely used on flat screen electronic devices, are being used to function as an electrode to solar cells. ITO or FTO are not appropriate electrode technologies for a large-scale, flexible solar development. ITO is brittle and expensive to deposit in roll–to-roll manufacturing. ITO sputtering constitutes approximately 50% of the energy balance for processing lab based polymer solar cell. Furthermore, indium has a limited supply of materials and FTO (which does not suffer materials scarcity) cause shunts in the device.

It is worth noting that one of the main limitations of organic PV and thin film solar cells is the use of ITO as a front electrode. ITO over glass or over flexible PET substrate is the highest cost component in organic solar cells (over 50% in both cases with a flexible PET substrate having a lower cost). Furthermore, ITO has many limitations including being brittle, indium scarce, and involving a high processing cost. Metal fingers are sometimes used to replace ITO (*35*).

In addition, Current back electrodes used can limit the lifetime of an organic solar cell. The materials available to optimize the work function of electrodes are unstable in air. Using an inverted structure with a less optimal work function enhances the lifetime of an organic solar cell and makes it stable in air. Inverted structures can be fabricated and processed under an air environment, which is favorable for the manufacturing process, as the non-inverted structure will require processing under an N_2 environment, which is very costly. Higher work function electrodes in inverted cell usually are used as back electrodes. Metallic electrodes could be vacuums processes in a similar way to aluminum foils in the food packaging industry. However, printing them or solution processing them is more attractive for more cost efficient, faster and compatible to production of solution processed solar cells.

Limitations and replacement of current TCOs

Next-generation electrodes should be highly transparent, highly conductive, stable, abundant, inexpensive, lightweight and flexible materials that are compatible with large-scale manufacturing processes and compatible with large scale processing (*36*). Furthermore, it should allow the fabrication more efficient tandem cells (*37*) and should be used as frond and back contact electrodes to enable more efficient bifacial cells. Also, it should be adhesively compatible with different substrates whether glass, polymer or paper based substrates.

The development of more process-able and transparent electrode technology could significantly impact the efficiency and costs of a polymer solar module. In the literature there have been several proposal to replace ITO most notably by graphene, carbon nanotubes, metallic nanorods or conjugated polymers. Further work to increase balance their conductivity and their transparency are needed. A transparency of more than 90% and a sheet resistance of 10 Ohm/sq more is needed for polymer solar cells in monolithically integrated modules (*38*).

Charge selective layer

Charge selective layers can be deposited between the active materials and each of the electrodes to favor the transport of separated charge carriers (electrons or holes) to increase the photocurrent. PEDOT:PSS is widely used as a hole collector and electron blocker. A few alternatives have been reported, such as Plexcore and Polyprodot (*39*). Furthermore, semitransparent conducting metal oxides have proposed, such as V2O5, WO3, and MoO3. For electron conductors, metal oxides, such as ZnO and TiO2, have been explored (*39*).

Degradation

The degradation and instability of organic solar cells has several chemical and physical causes (*40*). In typical conjugated polymer-fullerene systems, this could be due to: 1) the photodegradation of conjugated polymers, 2) the degradation of conjugated polymers with increasing temperature, 3) the decrease in the mobility and conductivity of fullerene because of its oxidation, 4) the chemical change of electrodes or interface stability, for example, upon oxidation, and 5) physical changes in the morphology due to thermodynamic instability. Furthermore, the PEDOT:PSS layer is susceptible to degradation. In addition, electrodes degrade overtime. In particular, low work function electrodes such as Ca are unstable in air and oxidizes, but they are favorable to use to obtain higher efficiencies. (*41*)

The lifetime and degradation is key to commercialization of solar cell , especially in electricity grid market, as solar cells to bring down the relative cost of the PV system in $/Wp and to generate lifetime energy to bring the cost of electricity generated down. Degradation is one of the main limitations of polymer solar cells and the detailed mechanisms of degradation is still not understood. The polymer active material can be encapsulated to extend it life by filtering UV, H20 and 02. However, the polymer organic materials in intrinsically unstable and major breakthrough are required to extend their intrinsic lifetime. Small molecules have much longer lifetime, though still need high encapsulation. Heliatek, a small molecule start up, claim that their tandem small molecule solar cells can last for 30 years. Without major improvement in polymer solar cells lifetime their use will be limited to low lifetime niche markets. The commercialization prospects are explored in more details in chapter 4.

Air stable inverted solar cells

There are two basic types of organic solar cells architecture: inverted solar cells and normal solar cells. The energy levels of the electrodes in normal solar cells are more optimized than inverted solar cells; however, most normal solar cell architectures are unstable in air because the top contact electrode is made from a low work function metal. Low work function metals, such as Ca or LiF/Al, degrade easily in air through oxidation. All current commercialized solar cells such as the one from Konarka, Solarmer, are based on inverted solar cells. The best solar cell efficiencies with the heights fill factor are made from normal architecture organic solar cells. Inverted solar cells though can typically be optimized to have a thicker active material and a higher photocurrent.

In an inverted solar cell the layers and the charge transport in the solar cell are reversed, a high work function electrode such as silver will carry out i.e. hole instead of the transparent conductor. In inverted solar cells, the holes go through a cathode that has a higher work function than transparent conductive oxide (TCO). However, in normal solar cells, the holes go through the TCO. In this case, the TCO has a higher work function than the cathode, which has a relatively low work function.

Substrate

Several research groups and startups have demonstrated that possibility of flexible OPV. For example, the $170 million VC-funded startup Konraka has tried to commercialize (2-4%) a flexible module that has lifetime of about one to two years (the glass based module had a longer lifetime of three to four years). However, there remain many important questions about the lifetime of the modules and degradation in the organic active material, the durability of the substrates, and the expected resulting reduction in the installed PV system cost. In addition, there attempts to commercialize a-Si and CIGS on flexible substrates but their success has been limited because of low efficiency and degradation.

There are two basic types of flexible substrates: polymer based and metal foil based. Lightweight, flexible modules are thought to be an important way to re-engineer and fabricate new modules that have less installation cost in grid-connected power applications. Furthermore, it will enable new niche applications for solar PV.

Flexible substrates could allow for the design of new solar modules that are easier to install and lightweight. Furthermore, lightweight flexible substrates can have applications in new niche markets. Nevertheless, organic PV and particularly polymer PV glass-based modules have very short lifetimes, and the flexible modules have even shorter lifetimes, especially in outdoor conditions. If sufficient encapsulation is use in Flexible substrates, they are expected to similar lifetime for active materials as glass. However, flexible substrates need to provide long durability as glass substrates.

However it will be challenging to replace Glass. Glass is a proven technology for withstanding weathering effects and large variations in temperature over long periods of time that are needed for the solar module to generate enough electricity to pay back the installed PV system cost. Furthermore, depositing the active material on flexible substrates usually leads to reduced solar cell efficiency. This is partly because of the higher surface roughness of the flexible substrates and because of the inhomogeneity of the ultra-high barrier ITO coating (*42*). The lower efficiency of the flexible substrates is common across competing PV technologies, such as CIGS, DSSC, and a-Si. Efficiency in this case could be improved by using smoother substrates or by using smoothening thin film to improve the smoothness of the substrates. Furthermore, new transparent electrodes are needed to replace the energy intensive, inhomogeneous, and relatively brittle ITO electrodes.

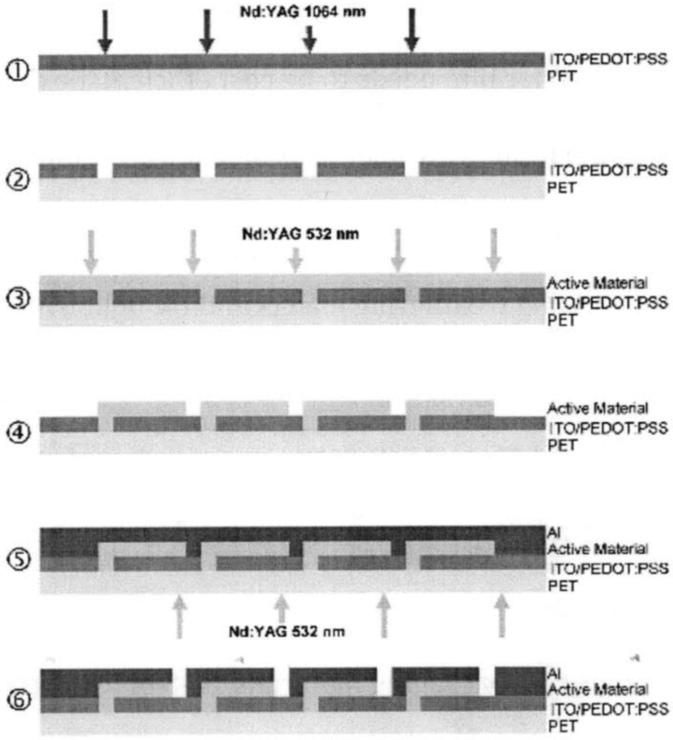


Figure 2.5: Nd-Yag patterning of polymer solar cell substrate to create a solar module.

The patterning of the flexible roll-to-roll module is not an obstacle as it can be done in ways similar to a-Si substrates. Researchers have suggested reliable patterning techniques for flexible solar panels, for example, using two frequencies of Nd-Yag laser to selectively pattern the substrate, active material, and electrodes of a monolithic OPV module in a manner similar to amorphous silicon. (*43*)

Flexible Encapsulations / thin-film permeation barrier

Flexible substrates could have a processing advantage in that they could be used in a continuous roll-to-roll manufacturing process to increase the production of solar cells in such a way as to bring costs down and meet large demands. However, they lack a transparent and highly weather resistant barrier, which is glass. Cost-effective, flexible, and transparent barriers need to be developed to last for a long time. Furthermore, barrier film needs to be cost efficient, flexible, electrically insulating, and compatible with solar cells and allow for high broadband solar spectrum transmission. It needs to last for more than the economic payback time of the PV system, withstanding weathering effects and UV light over this period.

The encapsulation ability to protect active materials from moisture and oxygen can be quantized by the following permeation rates. There are certainly some tradeoffs with using low-cost packaging, with a water permeation rate on the order of 0.1 g/m2/day, vs. high-cost packaging materials 1E-5 or 1E-6 g/m2/day and were on flexible substrates.

Encapsulation effects on degradation

It has been reported that the permeation rates of Oxygen transmission rate (OTR) < 1E-3 cm^3 m^{-2} day^{-1} atm and water vapor transmission rate (WVTR) < 1E-5 g . $m^{-2}day^{-1}$ are required to commercialize polymer PV, but studies in the literature using such high barrier films only brought the shelf life of organic materials in flexible substrates down to the shelf life of glass modules. Despite using ultra-high barriers, the organic active materials degraded. For example, Dennler et al. (19) , who is associated with Konarka, tested a flexible encapsulation of MDMO-PPV active materials with a ultra-high barrier and compared its shelf life performance to glass-based encapsulation and obtained similar performance. In this cell, it was noted that the Voc was stable while the Isc degraded and FF and efficiencies degraded even faster than Isc.

The processing method for the solar cells is partly responsible for the degradation. The cell swiftly degraded by 20% in the first 50 hours, indicating that residual oxygen and moisture should be removed or reduced during the fabrication step. No such fabrication method that we are aware of was tested in the literature to verify this conclusion. Second, the two component epoxy used in the device might have released byproducts that affected the cell lifetime. Third, the morphology of the bulk heterojunction could have changed although Dennler et al. thinks that no change in the morphology was achieved because the device was not heated to temperatures above the glass transition temperature of the active materials used (MDMO-PPV). However, other research groups hinted at the thermodynamic instability of the more optimal bulk heterojunction morphology. As Dennler et al. suggested, this result indicates that degradation is not due to flexible substrates and barriers. Other researchers reported that morphology of the active can sometimes be thermodynamically unstable and changes with time.

Proper encapsulation can bring the lifetime of a flexible solar cell down to the lifetime of the glass-based solar cell. The instability of organic active materials, such as P3HT:PCBM, is due to intrinsic properties. Greater stability is needed to successfully commercialize PPV. For example, a few years later, Dennler et al. used the more stable P3HT:PCBM and were able to extend the shelf life almost twice as much. The detailed degradation mechanisms of organic polymer semiconductors are not yet well understood, and more work is needed to find new ways to improve their stabilities.

Currently, judging from Konraka the lifetime of polymer glass modules is longer than that of polymers in flexible plastic substrates. However, it was demonstrated that the shelf life of OPV deposited in flexible substrates can approach that of glass ones with proper encapsulation(*44*).

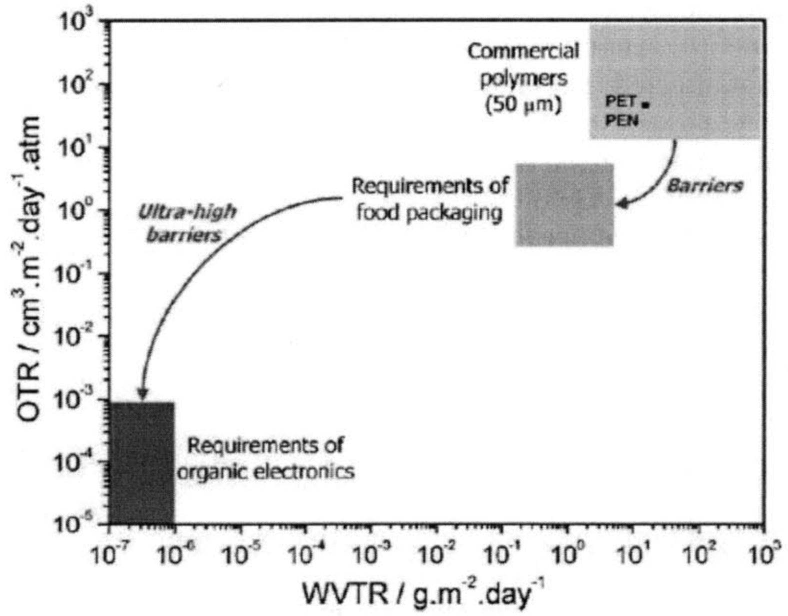


Figure 2.6: Shows the encapsulation requirements. Oxygen transmission rate (OTR) and water vapor transmission rate (WVTR)) for polymer solar cells and to organic electronics (exs. OLED) and commercial food packaging requirements. It should be noted that achieving these rates does not extend the lifetime of current solar cells beyond one or two years of operation (comparable to glass encapsulation lifetime). This is because polymer solar cells materials degrades for additional intrinsic and photoinduced reasons. (Figure adopted from (*44*))

Low cost permeation barrier technology is used in the pharmaceutical and food industry; however, organics photovoltaics (OPV) needs better barriers. One example of the barrier technology available in the market is the German-based

Evonik Industries, which developed a PMMA-based barrier film (http://international.pv-tech.org/product_reviews/evoniks_pmma_based_barrier_film_handles_flexible_thin_film_roll_to_roll_man). The transparency performance is comparable to that of glass in the optical region and a small part of the IR region only; although this is compatible with the current OPV absorption band, improving the transparency in the IR region is important for materials with higher efficiencies. Furthermore, it is unclear whether the barrier film has a favorable refraction index for better light trapping and distribution performance. Furthermore, this barrier film could be suitable for CIGS but not for OPV because its water vapor barrier is 10-3 g/(m2d). Another example is 3M, which developed the barrier "3M Ultra Barrier Solar Film" with moisture vapor transmission rates (MVTRs) below 5 * 10-4 g/m2/day and, #M claims, excellent durability and weatherablity for 25 years. However, barrier performance has yet to be proven in real-world conditions. It has not been shown to be higher than the economic payback period of the installed PV system as well as in the module.

Power electronics

The output of a solar cell (i.e., JV curve, Vmax, and Imax) changes with respect to the intensity of the incident radiation, as in partial shadowing, solar cell performance mismatch, hot spots, and thermal gradient.

To rectify these problems, a bypass diode and a maximum power point tracker are required. The bypass diode can disconnect the shaded solar panel from the PV system so that it does not affect the system performance. Shading can affect the system performance greatly, causing interruptions of electrical power, which can lead to formation of thermal gradient and hot spots dissipating heat and increasing the risks of material damage and module burn. It could also lead to a reduced lifetime of the module. Maximum power point tracker (MPPT) can boost the efficiency of the solar system by matching the varying impedance of the solar cells with its output, increasing the PV system energy yield. MPPT tracks the changes in the output of the solar cell and maximizes the DC power from the solar cells/panels. An additional advantage of MPPT is that it possibly could be cat as power and temperature mentoring device and as control and communication electronics.

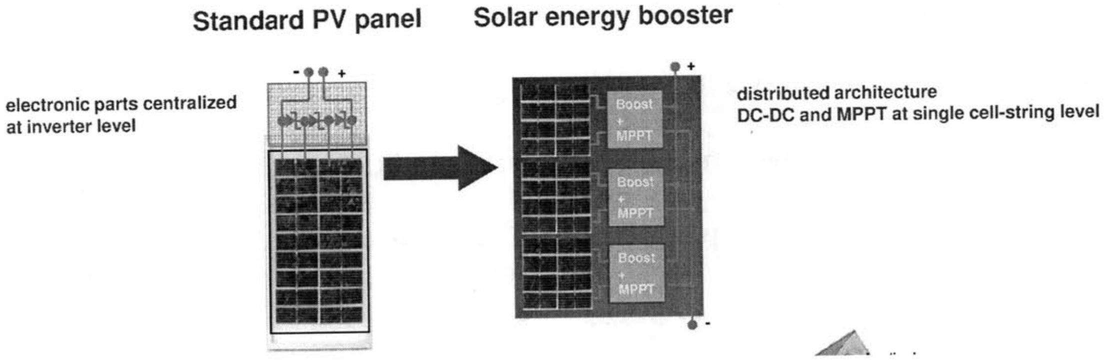


Figure 2.7: Centralized inverted based power electronics (left) and distributed module based power electronics (right) which could give a better energy yield, up to 25% in some situations. (Adopted form Avent em.avnet.com/ctf_shared/sta/df2df2usa/st_solar_diode_**mppt**.pdf)

A trade-off between the electronics cost and the gain in the energy yield, which varies from place to place, must be taken in considerations. The drop in electronics cost and the increasing efficiencies of silicon modules is driving some solar manufacturer to consider. SunTech estimates that up to 25% more energy can be attained with a power electronics system. This boost in PV system energy yields is comparable to the boost that comes from moving the panels around using a tracker. In the future, it could be possible to integrate power electronics into the manufacturing process of polymer PV (or small molecule PV) by making the electronics from organic semiconductors.

Polymer Solar Cells Characteristics

Current density-voltage (J-V)

The current density-voltage (J-V) characteristics are typically modeled on the generalized Shockley diode equations, which were originally derived for inorganic semiconductors. But the fitting parameters in this equation lack a physical interpretation associated with a physical process in organic semiconductor donor-acceptor heterojunctions systems. Furthermore, the Shockley diode equations break down at low temperatures.

Giebink et al. derived the current density-voltage (J-V) relation for donor-acceptor heterojunctions. This model was verified to predict the influence of temperature and light intensity and the maximum Voc for a given D-A material pair on dark current, open-circuit voltage (Voc), and short-circuit currents (Jsc).

The open circuit voltage

Open voltage (V_{oc}) can be controlled by varying the $HOMO_D$-$LUMO_A$ energy level offsets and the electrodes' work functions. The maximum possible Voc is limited by the $HOMO_D$-$LUMO_A$ energy levels offset (*45*). V_{oc} changes linearly with the energy level offset between the HOMO of the donor and the LUMO of the acceptor(*46*). Furthermore, within the maximum open circuit voltage, V_{oc} varies linearly with the work function difference between the two electrodes (*47*).

Thermal Coefficient

Under typical solar cell operating conditions ~(25–60°C), Katz et al. studided the temperature dependence of polymer-fullerene solar cells. Open-circuit voltage was found to decrease linearly with increasing temperature, while the short current and the fill factor increased monotonically with increasing temperature. The increase in the current and fill factor was more significant than the decrease in open circuit voltage, which caused the energy conversion efficiency to increase. Furthermore, maximum conversion efficiency was reached between 47-60 C (*48*). This result indicates that in most operating conditions, in moderate weather countries, organic solar cell performance will increase slightly in higher temperatures, unlike other types of solar cells such as Amorphous silicon, CdTe, CIGS, and c-Si. However, polymer solar cells have a lower tolerance to higher operating temperatures, depending on the polymer type and encapsulation.

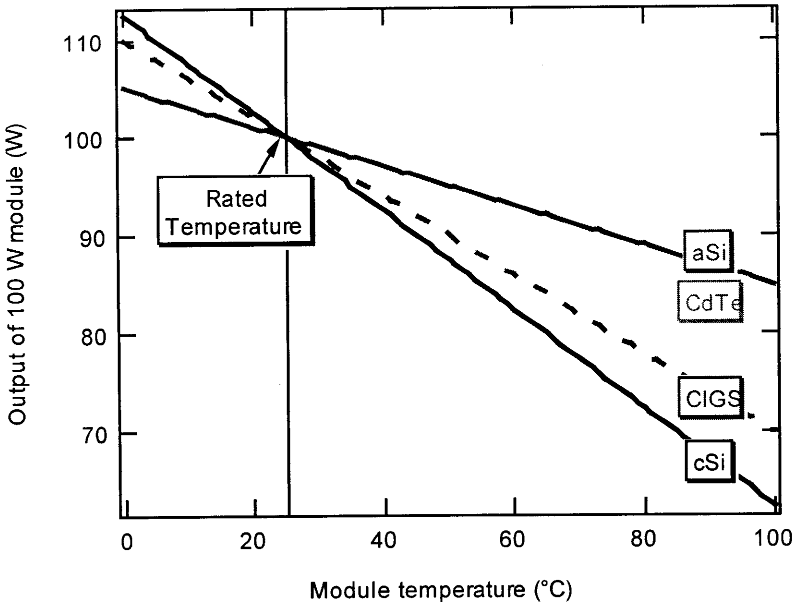


Figure 2.8: Temperature dependence of thermal coefficient for a-Si, CdTe, CIGS and c-Si. Sarah Kurtz, NREL [http://www.nrel.gov/docs/fy10osti/49176.pdf]

The temperature coefficient affects the actual energy yield in the field and can affect pricing and product choice is a small way ~10% .

Table 2.3: temperature coefficients for the main types of PV materials.

Solar Module	Temperature Coefficient effect on power outupt
Amorphous silicon*	-0.2%/°C (variable)
CdT*	-0.2 to -0.25%/°C
CIGS*	-0.4%/°C
Crystalline silicon*	0.4% to -0.5%/°C
Konarka Module 20 Series **	+0.05% / ºC

* Data from Sarah Kurtz, NREL [http://www.nrel.gov/docs/fy10osti/49176.pdf]
** Product specifications for 20 Series.
http://www.konarka.com/media/pdf/konarka_20series_10012010.pdf
(*48*)

Increased efficiency under low sun

This effect is thought to be because of reduced non-geminate recombination. For example sista et al. showed that the photoconversion efficiency of PSBTBT:PC70BM bulk heterojunction cell increases by 10% when the incident light intensity is reduced from 1 sun to 1half- sun because of the decrease in non-geminate recombination.(*49*)

Additional factors that increase polymer module energy generation

There are three main reasons to expect organic solar cells to be able to produce more energy yield than C-Si, CIGS, and a-Si and CdTe modules at similar efficiencies and degradation rate.

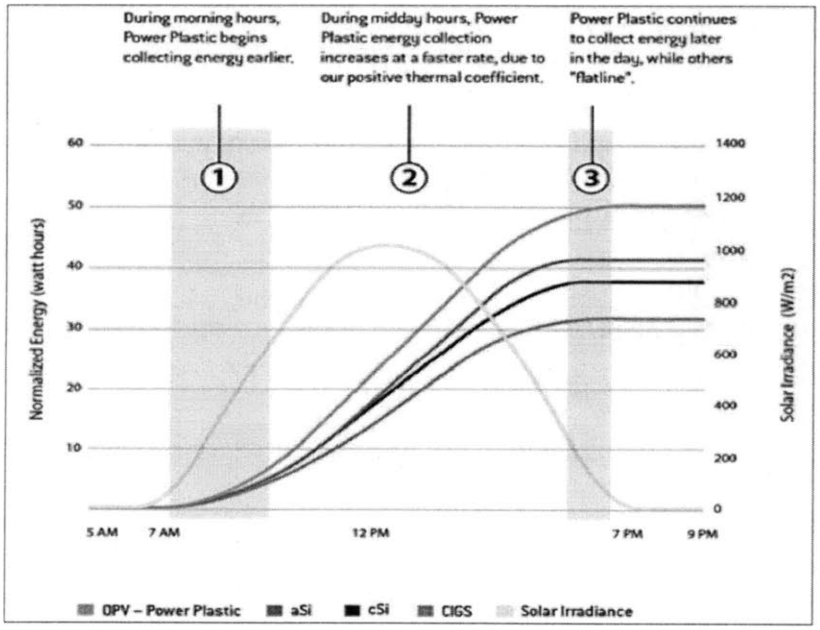


Figure 2.9 : The polymer PV company Konarka claims that the their energy yield is about ~55% higher than a typical c-Si module. The assumptions used for the effective module area was not available. [http://www.konarka.com/index.php/technology/our-technology/]

1. Organic PV has a positive thermal coefficient for the output power (=+0.05% / ºC) that is higher than amorphous silicon thermal coefficient (See Chapter two).
2. Increased efficiency at lower intensity, and a higher capacity factor because it works better than c-Si and inorganic thinfilms technologies in low lighting and diffuse light conditions. It has been experimentally shown that lab cells made form polymer solar cells, small molecule solar cells, and DSSC work better in low and diffuse light conditions as their efficiencies increase a little bit.
3. Polymer PV has a wider acceptance angle than C-Si. For example, according to Konrka, their organic module can collect solar rays up to 70° off axis.

Chapter 3: Cost Challenges

The promise of polymer photovoltaic was to use inexpensive materials and process them very cheaply to develop very cheap solar cells that cost less than 0.5 $/Wp for solar modules and less than 1$/Wp. The commercialization of polymer solar cells in the electricity markets (rooftops and ground utility installations) is determined by PV system cost. The PV system cost consists mainly from the module cost, the installation cost, and the power electronics cost. In this chapter, we discuss the challenges in reducing the module cost and the installation cost.

Reducing PV system Cost

The cost of installing PV systems is high relative to the amount of electricity generated by the current PV system over its lifetime. The three direct cost components of a PV system are the module cost, the power electronics cost, and the cost of installing the system. The latter consists of the balance of system (BOS) cost and labor cost. The cost of installation of PV systems has become a significant part of the total cost of solar electricity cost generation. Currently, the balance between system costs and installation costs constitutes about 50% of the total installed rooftop PV system cost (see Figure 3.1).

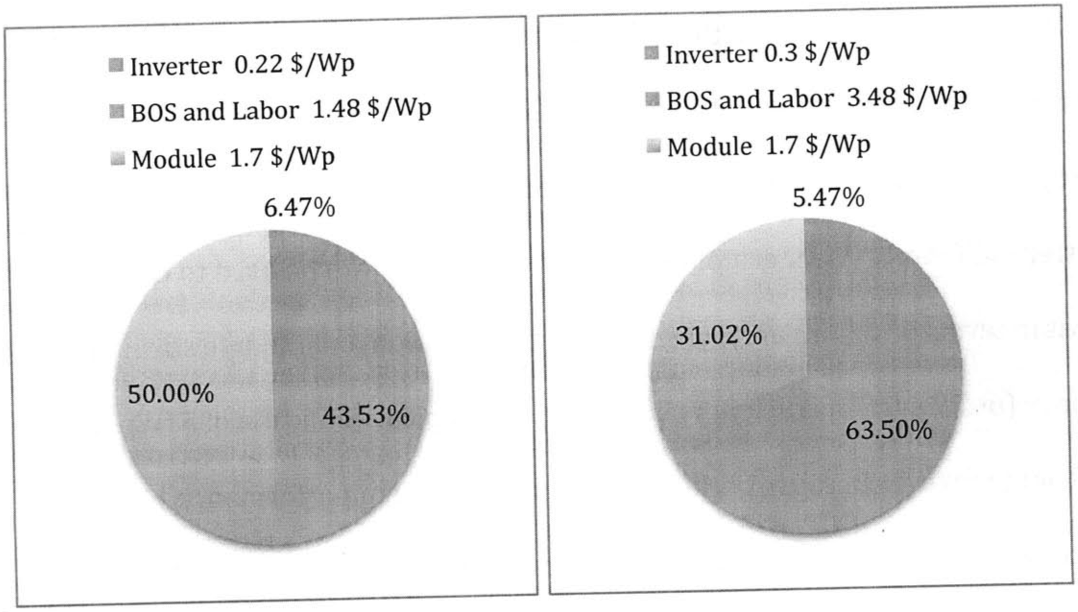


Figure 3.1: Cost breakdown for a utility c-Si PV system (left) and a typical residential rooftop PV system (right) in 2010. (Cost varies widely depending on the local market maturity, interest rates and other factors. These are the minimum estimates).

The balance of system components in installed PV systems mainly consists of the mounting or supporting structure for the module, wiring the module, and the power room (See Table 2). The installation labor is needed for the design and installation of the PV system. There are other indirect costs such permit costs, land, transportation, and marketing. Some of these costs scale with area, such as the number of modules and mounting, while all of the cost components amortize with the PV system energy output over the module lifetime; this mean that efficiency and lifetime are crucial ways to reduce the installation system costs. Both are lacking in current polymer PV technology. In the future, polymer PV technology will need face fierce competition from other more established technologies such as c-Si, CdTd, and CIGS, and possibly other material abundant solutions for processed PV.

One important measure that is helpful in comparing PV systems independent of location is the cost watt in dollar per watt peak, which is defined as the total cost of the system divided by the nominal peak power it generates at the beginning of the PV system's lifetime. One merit of this definition is that it can be used to estimate the cost in terms of $/unit area, given the peak insolation and module starting efficiency (or PV system efficiency). However, this typical definition of $/Wp is insufficient however because of the module and PV system performance degradation overtime. This is especially the case when calculating the cost of polymer PV in $/Wp. To reflect the lifetime and efficiency degradation, the average module efficiency over the device lifetime should be estimated and used instead of starting module efficiency.

The installation cost, which is a large part of the installed PV system cost, depends on whether the PV application is in residential rooftops, commercial rooftops, utility plants, buildings with integrated PV, or other niche markets like consumer electronics. For grid-connected markets, the highest installation cost is in residential roof markets, then on commercial roofs, and then in the utility cost. The installation cost in utility and commercial rooftops takes better advantage of scale and of task automation. The highest installation cost of PV systems is in space applications, and therefore the highest efficiency solar modules per unit weight are used in vital space applications. Table 1 shows a breakdown of installation costs for a commercial rooftop installation in Boston. Table 2 show a breakdown of lowest current installation costs in a utility system using strongly subsided c-Si modules.

Table 1: The cost breakdown for a 200kWp commercial PV installation in Boston. (Data form Borrego Solar),

Costs		Low	High	Low Estimate Percentage %
Module	$/Wp	1.7	2.0	44
Inverter	$/Wp	0.3	0.3	8
Rack	$/Wp	0.4	0.4	10
Labor	$/Wp	0.8	1.0	21
Project costs	$/Wp	0.4	0.5	10
Sales commission	0.0 %	0.1	0.1	2
Sales tax	0.1 %	0.2	0.3	6
Total PV system Cost		3.9	4.5	-

Table 2: Current cost breakdown for a typical utility PV system using c-Si module. The c-Si module cost estimates is skewed by strong subsides that chinease manufactures are able to receive. (Source- DOE – Solar White paper 2010)

Component Cost ($/W)	**2010 (Est.)**	**2017($1/WGoal)**
PV Module	$1.70	$0.50
Semiconductor	$0.54	
Raw Materials (Si feedstock, saw slurry, saw wire)	$0.36	
Utilities, Maintenance, Labor	$0.04	
Equipment,Tooling, Building, Cost of Capital	$0.06	
Manufacturer's Margin		
Cell	$0.45	
Raw Materials (eg. metallization, SiNx, dopants, chemicals)	$0.18	
Utilities, Maintainence, Labor	$0.04	
Equipment,Tooling, Building, Cost of Capital	$0.04	
Manufacturer's Margin	$0.20	
Module	$0.70	
Raw Materials (eg. Glass, EVA, metal frame, j-box)	$0.26	
Utilities, Maintainence, Labor	$0.01	
Equipment,Tooling, Building, Cost of Capital	$0.01	
Shipping	$0.08	
Manufacturer's Margin	$0.34	
Retail Margin	-	
Inverter	$0.22	$0.10
Magnetics	$0.03	
Manufacture	$0.05	
Board and Electronics (Capacitors)	$0.07	
Enclosure Power	$0.04	

Electronics	$0.03	
BOS/Installation	$1.48	$0.40
Mounting and Racking Hardware	$0.25	
Wiring	$0.14	
Other	$0.17	
Permits	$0.01	
System Design, Management, Marketing	$0.15	
Installer Overhead and Other	$0.19	
Installation Labor	$0.38	
Total	$3.40	$1.00

Module Cost

Polymer PV substrate uses less materials that typical silicon solar cells and their assembly is less complex. A typical silicon solar cell constitutes of glass, metal girds, EVA polymer, and frames while a flexible solar cell constitutes of an active layers and encapsulations only. A polymer glass solar module is comparable to a c-Si module but with out the silicon active layer, without the metal frames and with thinner polymer layers.

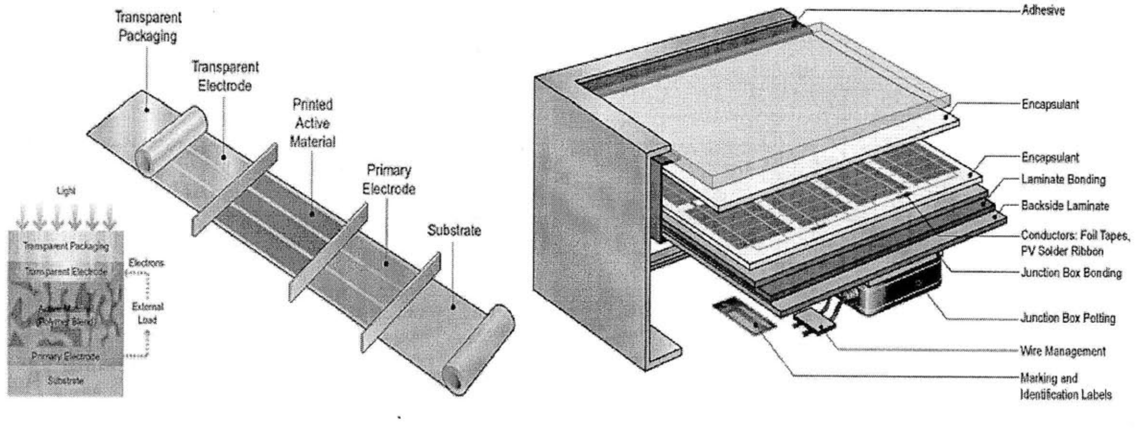


Figure 3.2: flexible polymer solar module (left, active material layer contain additional thins layers (~100nm) not shown here) consist of a fewer module. The weight and thickness is much less.

Solar module costs have dropped in the last few years to close to 1$/Wp by the end of 2010. Solar cell modules prices have been brought down to about 1.7 $/Wp (with module cost is about 10% less) by strongly subsided Chinese manufacturers; this was possible through zero-interest loans, free land and buildings and subsidized electricity, less environmental regulation, lower installation cost, and a potential depreciation in renminbi currency (by ~20%). These subsides are expected to continue as long as module prices are reduced further. The first solar, CdTe thinfilms company, manufactures panels at lower than 1 $/Wp and sells them for about. Other costs BOS and installations costs are highly dependent on location and application.

The actual production costs of polymer solar cells are unknown because it is still in development stage. Zweibel (*4*) estimated the cost for different thinfilms technologies with organic plastics modules estimated to have the lowest cost at 9 $/m2 at 8% efficiency (equivalent to 0.11 $/Wp) and 1 GWp production . A Danish research group from the Technical University of Denmark manufactured polymer modules using P3HT:PCBM with a minimum cost of around 5 euros/Wp despite using low production speed at a low manufacturing scale of 50kW/year. The cost breakdown for this experimental project is shown in figure and it shows that the PET coated substrates constitutes about 50% of the cost. Konarka solar panels are expected to be over 3 $/Wp, especially given their current low efficiency (~3.5%) and short lifetime (~2-4 years). However, theses costs in $/Wp do not take lifetime into account; to take life into account the average peak power of the module over the device lifetime should be estimated and used instead of the initial peak power of the module. The future cost will depends on many changing variables such as the module efficiency, lifetime, manufacturing speed and throughput and materials and processing costs. It worth noting that the materials cost as used by Konarka is relatively high (~1$/g) and will to reduced further at large manufacturing scale. Furth more, replacing the ITO with less costly solution-processed transparent conductors will simplify processing and increase production speed from a few meters/min to orders of magnitudes larger.

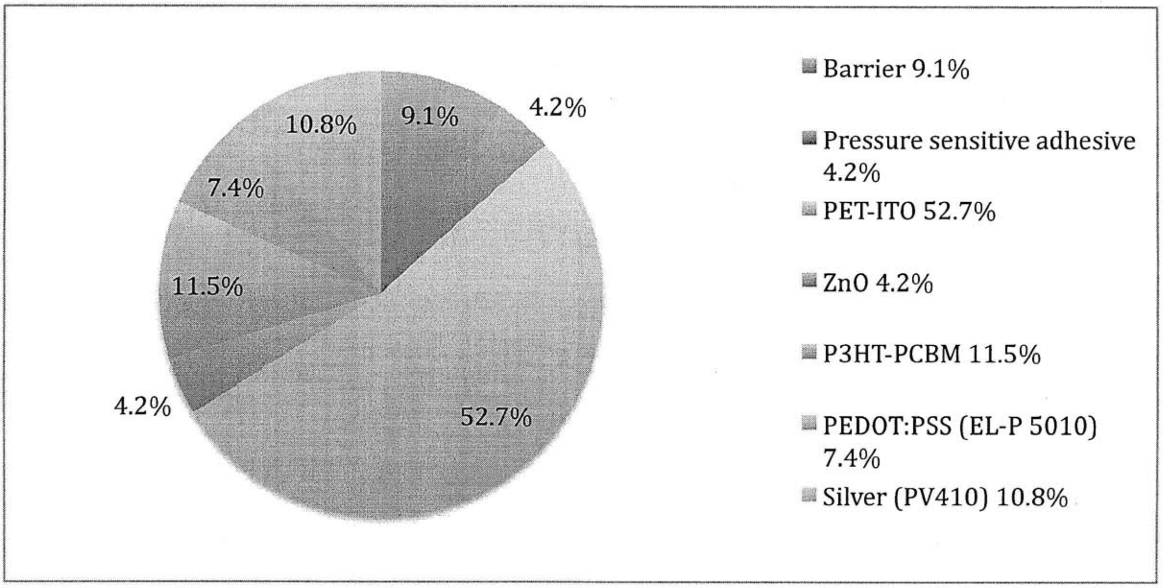


Figure 3.3: Material cost and Processing Cost breakdown as done by Krebs in a small scale production (*50*).

Installation Cost

Next, we will discuss how a polymer solar cell can impact the installation cost of PV systems, how the solar industry is trying to reduce costs, and whether lightweight flexible solar modules such as other small molecule organic solar cells, DSSC, CIGS, and other types of solar cells can reduce the installation cost by enabling new module designs that are easy to install to lower BOS costs and labor costs.

The cost of installing PV systems is being constantly reduced as the market matures, and policy, regulations, business models, and technology are directed to reducing installation costs. Here, we will focus on the technology factors affecting installation and limiting further reduction in installation costs.

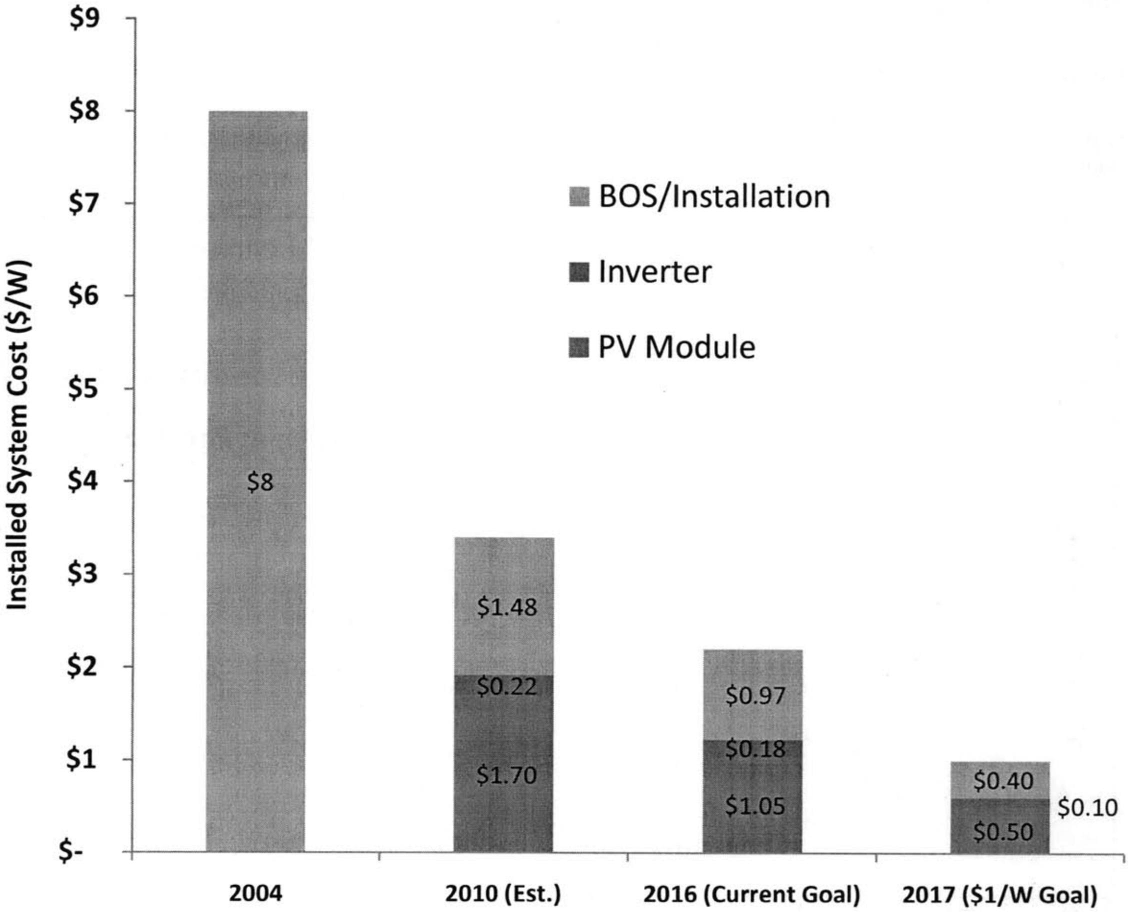


Figure 3.4: installed system cost in utility market. The cost is for Electricity generation only. (Adopted from DOE-White Paper 2010). In 2010, The average cost of installing PV systems of all types in the US is around 7.1 $/Wp with prices differing greatly from 5 $/Wp (ME) to 13 $/Wp (IA). (PV systems voluntarily samples at NREL Open PV project).

For PV to become competitive with coal in generating electricity at ~ 5c/kWh in most geographic locations and more affordable to poor developing nations, the cost of the installed PV system need to reach 1$/Wp. In recent years, there have been incremental drops in PV system costs driven by drops in module prices, inverter prices, BOS prices, and installation labor. But further innovations are needed to bring down the cost of modules, installation, and power electronics ; Figure 3.5 shows that the slope of the learning curve of PV system cost is likely to be reduced in the next few years because of lower reductions BOS costs. In the next section, we discuss the prospects of polymer PV technology in reducing module cost and installation cost, which includes the BOS and installation labor (See Table 2).

Figure 6: Shows that the drop in installed-PV-system cost does not differ much by high insulation. One reason for that could be market maturity among different states.

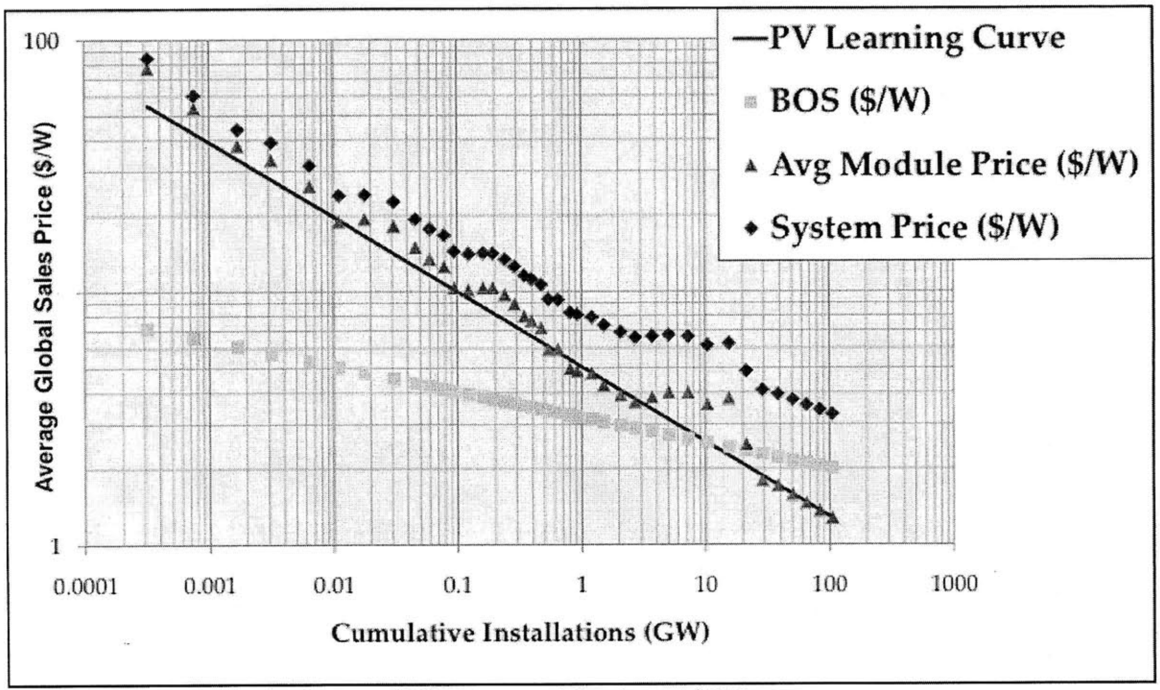


Figure 3.5: Learning curve for the cost of PV systems, module prices, and BOS cost.
Source Navigant Consultant – Adopted from DOE [http://www1.eere.energy.gov/solar/pdfs/dpw_chu.pdf]

Example on the Installation process of a glass-module Residential PV system

There are two stages for installing a PV system, the design stage and installation stage. The steps involved are long and require typically an engineer, module installer, and an electrician. If PV becomes more widespread, these functions could converge into a new job. The stages for installing a glass-module PV system on a typical rooftop are described in the next two paragraphs.

The design stage is becoming standardized and more efficient as software and IT tools are used to evaluate the projected system size and location, the predicted monthly reductions, the finance scheme, and aesthetics considerations. Still, local designers need to inspect the site and evaluate it. The installers need to ensure that the roof can structurally support the desired PV system and that the system could be oriented optimally toward the sun while avoiding any shade during along the day from neighboring structures or vent pipes. Furthermore, the system design should minimize all electrical losses due to wiring, inverters, fuses, and switches. Any materials used outdoors need to be sun- and weather-resistant for a long time. Furthermore, the design needs to meet all local utility interconnection requirements.

The installation stage usually takes a few hours for an experienced crew to finish. The time for installation varies and depends on the type of the mounting system, the connection system, the rooftop materials, etc. Innovations in mounting systems include Zepsolar's auto-grounding and drop-in mounting installing systems. The installer needs to recheck whether the roof can handle the weight of the PV system and, if necessary, supplement the roof structure. Roof penetration is typically required to install the racks to hold the PV modules in the optimal angle toward the sun. Any penetration needs to be sealed properly according to roofing industry standards. Some mounting systems reduce the number or even avoid roof penetration. Next, the installers need to install and wire the equipment carefully according to the manufacturer's specifications. The PV systems should be grounded correctly to reduce the threat of electrical shocks or surges. After that, the installers will need to check the PV system's operation and verify that it meets local utilities' interconnection requirements. Furthermore, inspection of the system performance and safety might be needed by the local authority or utility. In a 2001 report for the California Energy Commission, it was estimated that 10-20% of PV systems are installed incorrectly.

Reducing Module cost, Installation Cost and inverter cost

The levelized cost of electricity (LCOE) can be used to compare to the cost of electricity between different systems. The LCOE is the net present value (PV) of the total life cycle cost of the PV system divided by the quantity produced over the system's lifetime.

Total Energy production over lifetime

Efficiency, degradation rate, and lifetime determine the basic energy production over the system's lifetime. Other factors that affect performance in real environments include response to diffuse light, operating temperature, panel positioning, dirt accumulation, and shading.

The current low efficiency degradation rate of polymer PV does not generate sufficient energy to bring down the polymer module and cost of installation to competitive values.

To reach values around 0.5$/Wp for module cost and similar cost for BOS and installation, higher efficiencies and longer module lifetimes are needed. Furthermore, to bring the cost of polymer PV materials down, the production needs to scale up to reduce the cost of the novel active material and encapsulation. Scaling up production will be difficult if the module prices are too high to compete in electricity markets, but niche markets might offer an opportunity to scale up.

Effect of efficiency on cost

The effect of efficiency and lifetime is enormous because it affects the cost at the consumer end and at the manufacturing end. The lifetime effect on cost is important, but its significance decreases over time because of module performance degradation over time. Silicon solar modules that degrade at an average of 1.0-0.5% each year already last for a longtime of about 30 years. Polymer photovoltaic needs to increase its lifetime to comparable values to bring its module and PV system costs down to be competitive in electricity markets.

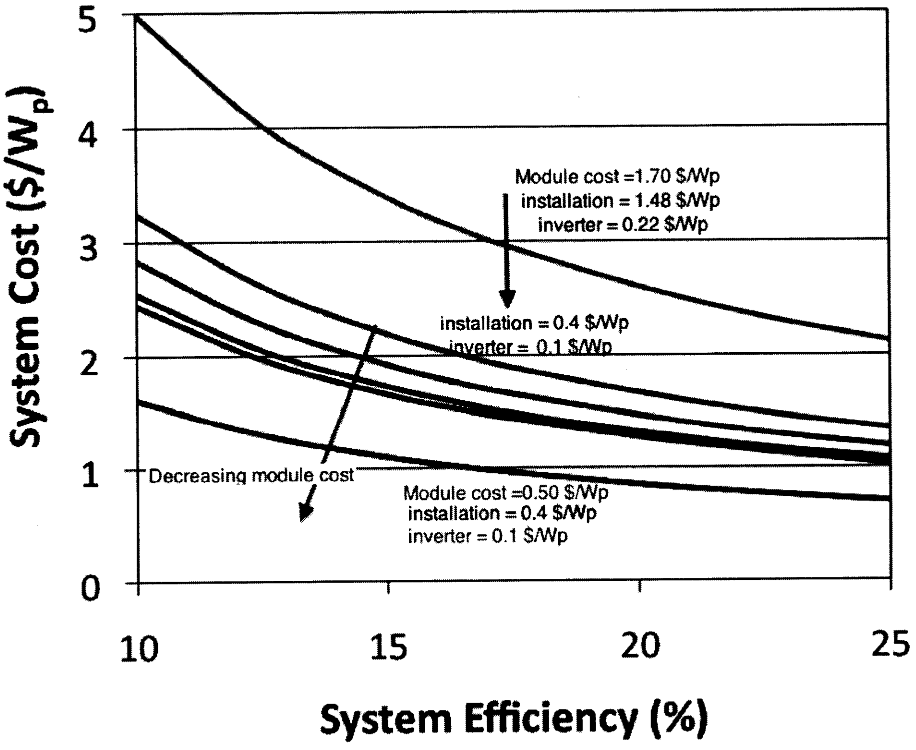


Figure 3.6: System cost in S/Wp vs. PV system efficiency. (Slide adopted from Prof. Tonio Buonassisi)

To compare the actual efficiency of solar modules, it is useful to incorporate the efficiency and degradation of the solar module into an average measure of efficiency over the lifetime of the module. In table 3, we compare a typical c-Si module to a typical polymer module. We will assume that both modules are glass-based and have similar installation and inverter costs.

Table 3: Comparison between the energy outputs of a typical c-Si (SunTech) with a typical polymer module (Konarka) in 2010.

Module type	Efficiency	Assumed Degradation	Average efficiency – up to ~80% of initial module lifetime	Average efficiency over 30 years	PV system cost
Typical c-Si (SunTech)	15.5 %	1%	14.0 % over 22 years	13.5 %	3.4 - 7 $/Wp
Polymer (Konarka)	3 %	10%	2.7 % over three years	1.1 %	?

Lifetime	c-Si average Efficiency over lifetime	Polymer average Efficiency over lifetime	Energy output ratio c-Si/Polymer
25.0	13.8	1.11	12.4
30.0	13.4	0.96	14.0

Table 3 compares the performance of a typical commercial c-Si with a typical commercial polymer module. The power generated from both PV systems will be proportional to their efficiency, degradation rate and lifetime. Table 3 shows that the c-Si PV system will generate 12.4X over 25 years (or 14X over 30 years) more energy; that is, an order of magnitude more energy is obtained using c-Si solar cells. Given that about 50% of the cost of the PV system will be in non-module costs, no matter how cheap the module made from organic polymer is, it will not be competitive with silicon solar cells as the installation and inverter costs will be about an order of magnitude higher in the case of polymer PV.

To investigate whether incremental improvement in the efficiency and lifetime of a PV system would make polymer PV more competitive, we assume that after 10 years the efficiency improved by 1% each year to a 18% lab cell that makes a 15% module (see Table 4). Furthermore, we assume the efficiency of c-Si will improve to 18% while maintaining its current lifetime. Table 4 shows that the PV system will be about 1.6X over 25 years or 1.7X over 30 years; that is, an order of magnitude more energy is obtained using silicon solar cells. If the inverter cost is 0.10 $/Wp and the installation costs are ~0.40 $/Wp , these costs will be about 0.80-0.85 $/Wp. This means that the polymer PV cost needs to be about 0.20–0.15 $/Wp to be competitive with Si modules. Such low module costs will be easier to achieve with flexible modules than with glass-based modules. Furthermore, flexible modules can have lower installation labor cost and possibly lower BOS costs.

Table 4: Comparison between the energy outputs of a typical c-Si (SunTech) with a typical polymer module (Konarka) after 10 years in 2020, raising the efficiency of the module by 1% each year.

Module type	Module Efficiency	Assumed Degradation	Average efficiency – up to ~80% of initial module lifetime	Average efficiency over 30 years
Typical c-Si	18 %	1 %	14.9 % over 23 years	15.6 %
Polymer (Konarka)	15 %	5 %	13.6 over 5 years	7.6 %

Lifetime	c-Si average Efficiency over lifetime	Polymer average Efficiency over lifetime	Energy output ratio c-Si/Polymer
25.0	13.8	8.7	1.6
30.0	13.4	7.9	1.7

We could assume that the polymer glass modules are replaced every few years, while paying additional costs for installation labor and replacement. This assumption was used by Dennler et al. (*13*) to examine at what efficiency and cost an organic PV is competitive with crystalline silicon and CdTe module performance in 2009. The study assumed a residential rooftop installation of 1 kWp and a 25-year lifetime for the PV system. The study assumed a module cost of 50 euros/m2 and a BOS cost of 70 euros/m2 and concluded that an efficiency of 7% and lifetime of 7 years will be needed to be competitive. This is equivalent to a low module cost of 0.71 $/Wp and an underestimated BOS of 1 $/Wp cost as residential rooftops for glass module is around 3 to 4 $/Wp in 2010.

According to the previous study by Dennler at al., to achieve a 10c/kWh in middle Europe, which has a relatively low insolation of around 1000 KWh/year/m2, the efficiency needs to be raised to 12% or the module cost needs to be reduced 5 times to 10 euros/m2 at 7% efficiency, equivalent to 0.1 $/Wp. A cost of 0.1 $/Wp is comparable to an estimate done by Zweibel for the minimum cost of organic PV albeit on cheaper flexible substrates. Efficiencies over 12% and low module costs of 50 euros/m2 are attainable by polymer PV. Moreover further reduction in BOS can be expected with new innovations in BOS and by using flexible substrates. However, it is unclear by how much the intrinsic stability of polymer photovolitcs can be improved.

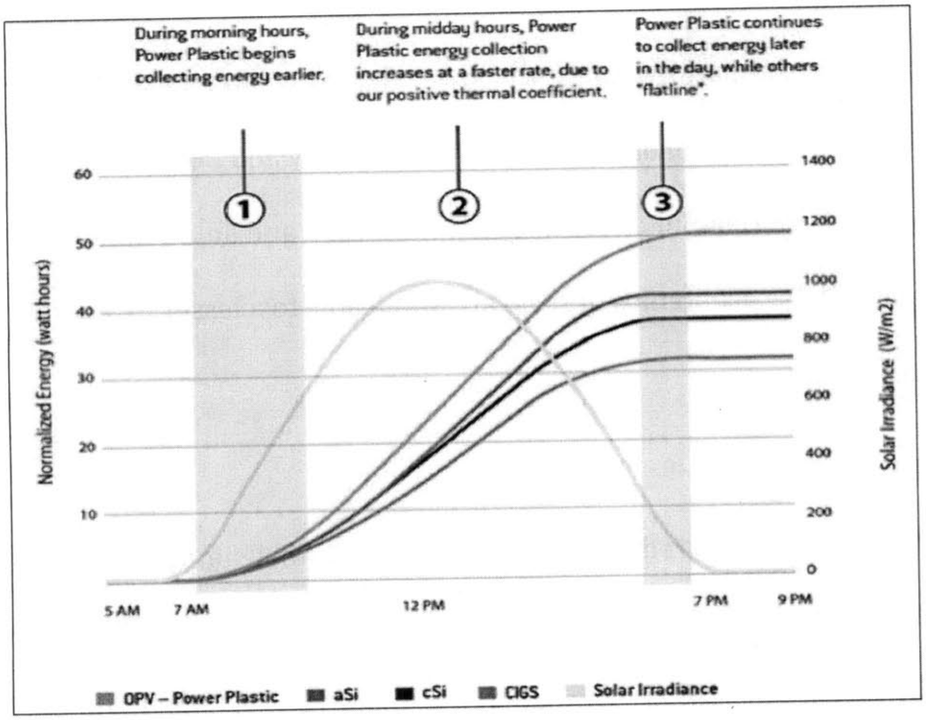
The lifetime performance is better in small molecule organic photovoltaic applications . Heliatek , a small molecular startup planning to start commercial production in 2012, expect their current double junction cells to be able to last for

30 years. Recently, they announced 8.3% efficiency for 1.1 cm2 lab solar cells and 7.2% for 70cm2 active area in a solar cell module (5.8% with metal grids).

Highly efficient and long-lifetime polymer PV will enable the fabrication of new module designs that are easy to install. For example fabricating polymer PV on flexible lightweight module could eliminate or minimize rooftop-penetration; it also could enable means to automated installation in large utility fields.

Additional factors that increase polymer module energy generation

There are three main reasons to expect organic solar cells to be able to produce more energy yield than C-Si, CIGS, and a-Si and CdTe modules at similar efficiencies and degradation rate.



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4. Organic PV has a positive thermal coefficient for the output power (=+0.05% / ºC) that is higher than amorphous silicon thermal coefficient (See Chapter two).
5. Increased efficiency at lower intensity, and a higher capacity factor because it works better than c-Si and inorganic thinfilms technologies in low lighting and diffuse light conditions. It has been experimentally shown that lab cells made form polymer solar cells, small molecule solar cells, and DSSC work better in low and diffuse light conditions as their efficiencies increase a little bit.
6. Polymer PV has a wider acceptance angle than C-Si. For example, according to Konrka, their organic module can collect solar rays up to 70° off axis.

Economies of scale

The installation cost in utility markets is lower than in rooftops market, albeit utility markets need additional cost for grid connectivity and possibly storage. Utility installations can use economics of scale for installation and automated installation methods. These economies of scale are applicable to a lesser extent in commercial installations.

Innovations in BOS

Installation costs could be reduced by module designs that simplify installations, automated installation, and other innovations that reduce the balance of system complexity and time. Other factors that are not directly related to the PV active material and PV systems such as interest rates, business models, market maturity, policies, and regulations are not sufficient to bring the cost down and are outside the scope of this chapter.

1. New module designs sticking, for example, by epoxying: reduced power optimization, heating concern for the module and the building
2. Reducing balance of system cost: use cheaper and lighter metal frames, and reduce connections by developing better connectors or by integrating power electronics into modules.
3. Rolling: Needs flexible cells, heating concern for the module and the building, low efficiency.
4. Building integrated PV, which needs to function as a construction material and be very reliable, and thus reduces installation costs. Additional costs will be incurred from wiring and safety precautions.
5. Reengineer the module. Solar modules made from polymer PV or solution-processed PV can bring the cost of installation down by enabling new module designs and using lightweight flexible substrates. There are other competing technologies to polymer PV that offer similar advantages such as small molecule PV, DSSC, solution-processed CIGS, and other solution-processed PV.

Table 4: Advantage of polymer PV and other types of solution-processed PV to reduce installation costs and other factors that push for more installations.

Market	Installation cost (Dependent on the rooftop, BOS type and the module type)	Possible innovations by polymer PV and solution processed PV to reduce installation cost
Residential Rooftop	~ 3.5 $/Wp	Penetration less installation by

Commercial Rooftop	~2.5 $/Wp	epoxing ,or stabling or solar shingles and BIPV
Utility	~1.5 $/Wp	Scaling up automation of installation techniques by light weight, flexible modules

Examples on how polymer based PV systems could reduces the installation cost

Replacing Glass Modules

Glass is used in the majority of solar panels. Glass is weather resistant and durable enough to last the minimum time needed for the solar cells to pay back economically and generate low cost electricity. However, glass is heavy and fragile, which add to shipping and handling costs. Furthermore, using flexible substrate might potentially help reduce installation costs. Using a lighter substrate will allow solar modules to be installed on roofs that cannot support module racks and heavy solar modules. Also, flexible solar panels could be integrated into the roof and provide additional aesthetics choices. One challenge for flexible modules is that they need to last for 20 years. Encapsulation and packaging of solar modules to last for the time required for the solar module to pay back is a challenge. Transparent films made from transparent materials such as plastic need to be developed to isolate the modules and preserve them for a long time under continuous outdoor exposure.

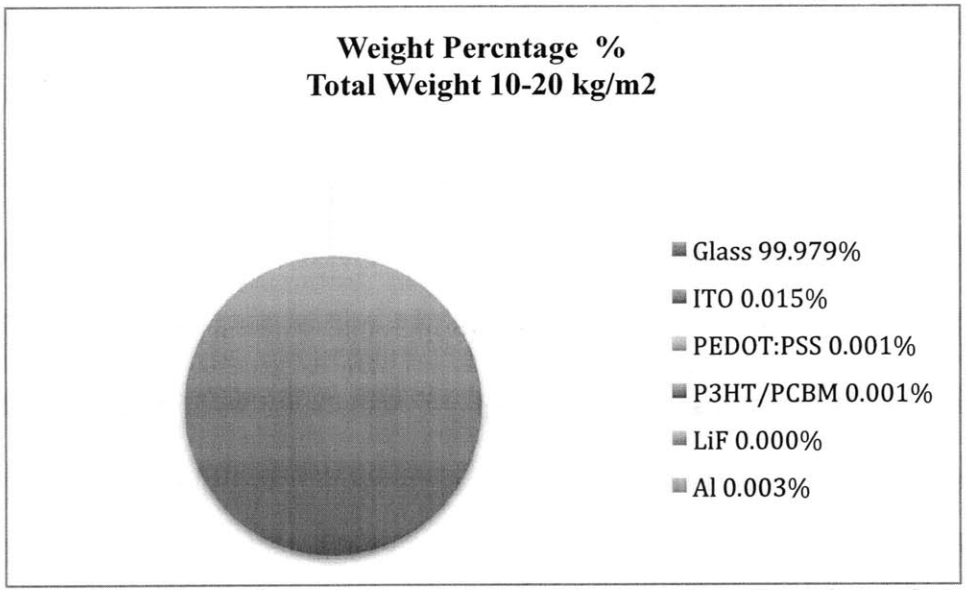


Figure 3.8.a: Materials needed to produce a polymer solar cell on glass substrate. Values refer to a solar cell area of 200 cm2 and assume a 10% material loss in production. Density and layer thickness are used to estimate the cell weight composition. (*51*)

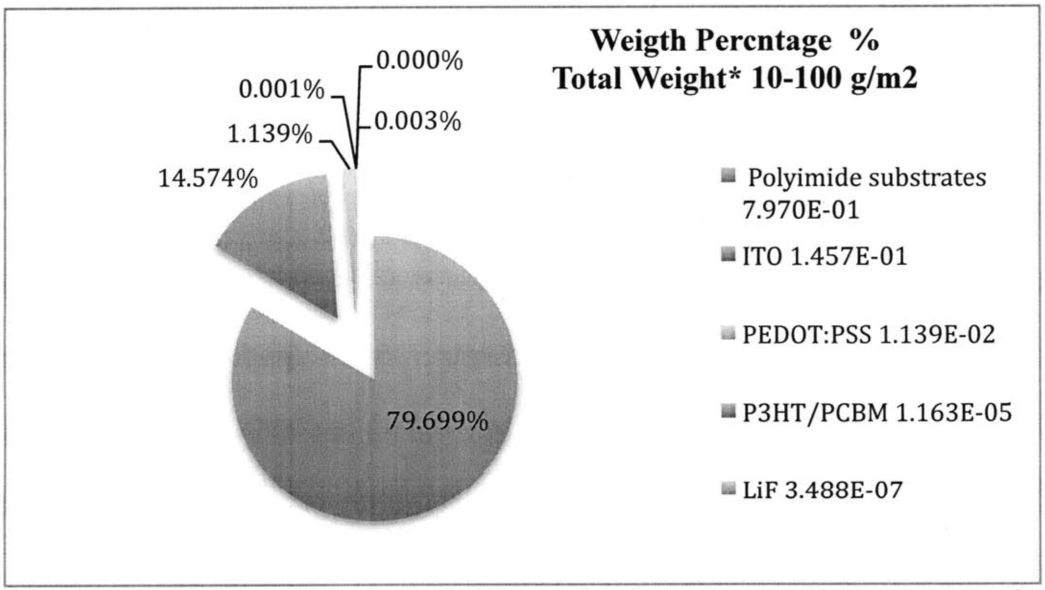


Figure 3.8.b: Flexible Polymer solar cell by gm/cm2 weight contribution. Polyimide substrate density is from (*52*), other Data is based on above figure.
*Encapsulation and epoxy are not accounted for in this figure. Konrka solar panels are around 1 kg/m2 while Solarmer solar cells are around 100 g/m2. (Weight data is estimated from the companies' websites).

Using glass-modules will not add any advantage for polymer PV systems over competing thin films and silicon technologies, except in their potential future use in niche market applications such as BIPV. BOS and installation costs are highly dependent on the module design and type. However, glass module could be used in BIPV markets in which polymer PV has several advantages such as color tenability and the light weight of the active material . Except in the BIPB market, polymer PV manufacturers will need to manufacture their solar modules on light weight, flexible substrates to bring installation costs down. Even if the balance of the system for glass-based modules becomes less than 0.5 $/Wp, polymer-based solar modules will probably have lower efficiencies and lifetimes. Therefore, using flexible substrates might give polymer solar modules more economic value.

DIY Solar

Light weight, inexpensive, easy-to-install rollable substrates might enable customers to install the panels themselves and eliminating the installation labor cost on rooftops (currently ~ 0.8-1.00 $/Wp in commercial rooftops) and possibly reducing balance of system cost which constitute nearly 50%-60% of current rooftop PV system costs.

Lightweight Flexible Solar Modules

Flexibility will open the door for niche applications, including lightweight portable PV panels or new undiscovered and unrealized markets. Flexibility is important in many niche markets, such as Building Integrated Photovoltaic's (BIPV) and portable PV applications. Lightweight modules have advantages in many niche applications, in portable power chargers, and in integration with consumer electronics. In space applications, where installation cost is very high, lightweight flexible modules could reduce the installation cost, but there are clearly other important characteristics that must be met. For example, it is very important for the module to be highly efficient in order to generate the maximum value of power. The module also needs to be radiation resistive, among other things.

The use of flexible modules might lead to simplification of the installation process on rooftops and in utility fields. For example, rollable, lightweight flexible substrate will take less time to install, while also removing the need for heavy costly racks and eliminating roof penetration through stabling or sticking the modules on the roof. In addition, flexible modules could enable automated installation in utility fields. Lightweight modules will facilitate the installation by the owner; it will also require less labor in a shorter amount of time--down from a few hours to less than an hour. This cost reduction is applicable to other types of PV active materials, especially solution processes, that could enable scalable and cost effective new module designs. Polymer PV needs to have the highest efficiency and longest life among these technologies to be commercially viable. Flexible substrate might be necessary for large production scales, possibly through roll-to-roll processing, which are required in order to meet the large energy demands in the coming years. However, it is not clear whether flexibility in itself is important for the main PV markets in residential, commercial, and utility areas.

Flexible solar modules need to account for many challenges. First, the encapsulation must last for a long time; this includes worst-case weather scenarios in a given geographic location, such as high wind or high temperature. The lifetime of the flexible installation should be sufficient to generate enough energy yield to bring the cost of the total PV system down. Second, the efficiency of the flexible module needs to be high enough to bring the cost of the PV system down to competitive values. Currently, commercial flexible modules in polymer PV and other PV techniques, such as CIGS, have lower efficiencies than glass-based modules. If there are large differences between the efficiency of glass modules and the flexible modules, the glass-based modules might be more attractive to install and mass produce, as is currently the case.

The rollable photovoltaic module would sacrifice optimal energy generation, as its orientation can be tilted or modified by a rack to generate the maximum power possible. This problem could be overcome in newly constructed houses that take the installation of a specific module type into account. Furthermore, the solar module orientation could cause trouble on some surfaces, at least on some roofs, as it would be easier for algae, water, or snow to accumulate. Another concern of rolling with no ventilation on roofs is that heating might reduce the efficiency of the solar panels. However, the actual performance of the flexible cells might not be lower due to increased heating or reduced cooling by ventilation, as in other PV technologies. Heating solar panels 40-60°C is expected to increase the efficiency of the solar panels, while operating at much higher temperatures could affect the stability of the polymer solar panels.

To gain some insights about the prospect of polymer PV on flexible substrates, we studied the difficulties with commercializing flexible amorphous silicon and CIGS, primarily because commercial and lab-based flexible substrates offer lower performance than glass. Development of high efficiency solar cells on flexible solar panels is more challenging than developing it on glass substrates because flexible substrates need to be compatible with the manufacturing process. One of the difficulties of depositing CIGS on flexible substrates is that the material's thermal stability that is needed to withstand processing at high temperatures to produce high quality CIGS films must typically be 450°C or higher. This could be an issue in organic photovoltaic, for example, if the annealing step were at a temperature that was too high to optimize the morphology of the active material. Furthermore, thermal expansion incompatibility between the substrate and the active material could cause cracks and de-lamination of the active layer from the substrate. In general, commercialized flexible thin films technology has suffered in a-Si and CIGS from lower efficiencies and lower module lifetime than materials deposited on glass substrates (which is still less economical than Si- or CdTe-based modules). To enable flexible modules, substrates and encapsulation used to make the module need to last long enough to pay back economically (20-25 years, depending on the module price, module efficiency, and solar insulation). The encapsulation should act as a transparent barrier that withstand high winds and weatherability and prevent H2O and O2 from diffusing.

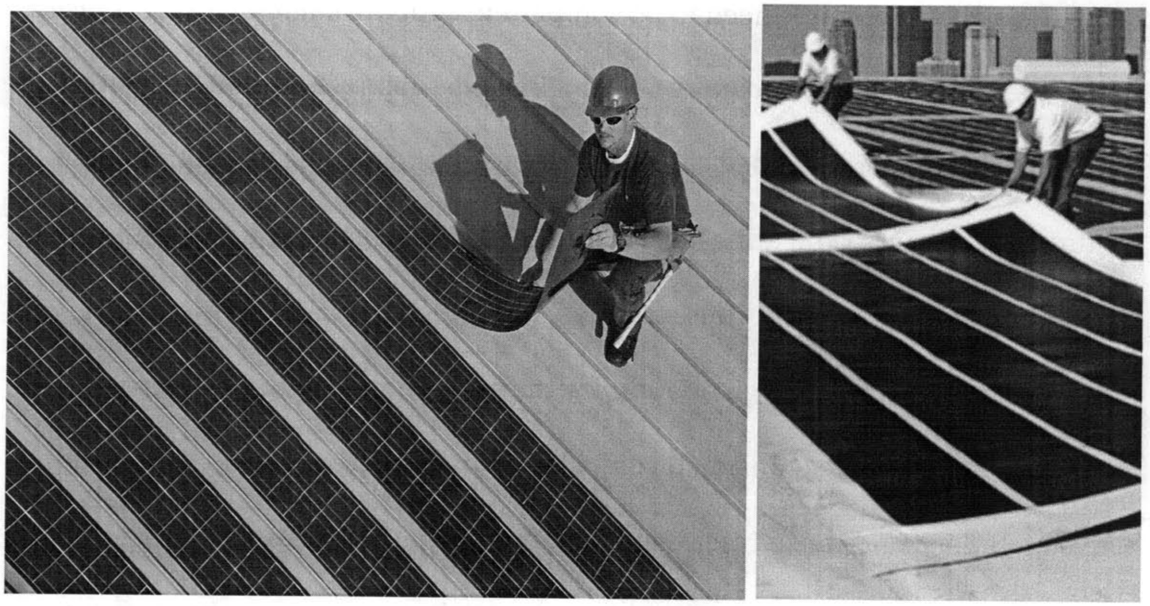


Figure 3.9: commercial roof installation of a-Si flexible solar cells rated at ~12% and manufactured by roll to roll electroplating SoloPower (left) and for Uni-Solar in 2004 (Right)..

Recently there have been advances in the lab to make highly efficient CIGS solar cells on flexible substrates. However, glass-based modules are still suffering relatively lower efficiency (<13%). Flexible modules suffer even lower efficiencies (< 10%). Nanosolar, which produces printed CIGS nano particles, commercialized only its tempered glass-based panels and not semi–flexible, metal-foil substrates, which was announced in September 2009 (www.nanosolar.com). MiaSole, which sells CIGS glass-based modules with 15.7% efficiency on rigid glass substrate, is planning to commercialize the flexible substrate market on rooftops, but they say that their first flexible rooftop product will be available in 2012 and is planned to be certified up to twenty-five years for all potential environments (*53*). A Swiss start-up, called FLISOM, achieved 17.6% over flexible polyimide, which was processed in a roll-to-roll manufacture of monolithically connected solar modules on polymer films. However, according to their Web site, they do not target the main PV markets, such as rooftops markets or utility markets, but rather target niche markets, such as Building-Integrated Photovoltaics (BIPV) on roofs and facades and mobile devices and vehicles. Nevertheless, upon contacting the company, they said they would develop applications for electricity markets.

Figure 3.10: Recent innovations from competing module technologies in the market place to cutting the installation cost. Polymer PV can potentially enable more innovations to reduce installation cost (BOS and installation labor cost).

Company	New idea for cutting the installation cost
Nanosolar	Use of penetration less mounts and large modules
Zep Solar	Use of fast mounting racks
SunPower	Automation of ground mounting an module installations

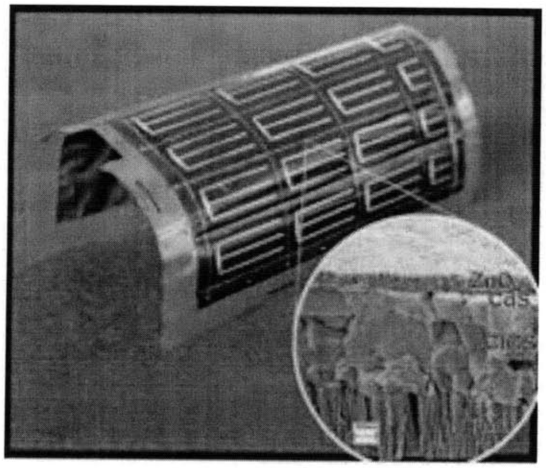


Figure 3.11: FLISOM flexible CIGS solar cell.

Table 5: Examples on Commercial flexible CIGS modules that shows that in general they currently have lower efficiencies than glass based modules. (All efficiencies are certified either by NREL or Fraunhofer institute).

Company	Module Efficiency	Substrate type	Production method
SoloPower SFX3	12.1 %	Flexible	roll to roll electroplating of CIGS
MiaSole	15.7 %	Rigid glass (18 Kg module)	Sputtering
MiaSole	? (unannounced)	Flexible	-

Company	Lab Cell Efficiency		
Lab Cell Swiss Federal Laboratories for Material Science and Technology (EMPA) with FLISOM	17.6% Polyimide	Flexible polyimide	roll-to-roll production of CIGS at 450 °C contacts by sputtering.
Lab Cell	18.1% glass	Rigid Glass	-
Nanosolar	15.3% (16.4% active-area efficiency)	Semi flexible metal-foil	coating/printing of CIGS

Although it is still unclear whether such flexible modules and transparent encapsulations would last for 20 or more, as more PV technologies develop higher efficiencies flexible solar panels, such as CIGS and organic photovoltaic, there is a rise of interest of encapsulation companies to develop such transparent encapsulation as required by PV modules. For example, 3M Renewable Energy Department is collaborating with CIGS manufacturers to develop a flexible front-side barrier that has high transparency, low moisture vapor transmission rate (MVTR), and that is weatherable and scratch resistant (*54*). 3M announced that it will start the commercial-scale production of an "ultra barrier solar film" with moisture vapor transmission rates (MVTR) below 5*10-4 g/m2/day and with excellent durability and weatherablity (*55*). The actual lifetime and weatherablity of these transparent encapsulations still need to be tested in the real operating environment, which will be clear in the next few years in the flexible CIGS solar modules. It worth noting that CIGS is venerable to moisture and MTVR rates on the order of 10-4 g/m2/day are needed for the stability of the active materials. While this MVTR is about on order of higher magnitude higher than the requirement of current polymer PV (to last for only a few years), it shows that such transparent encapsulation is possible at an economically efficient price.

Paper based substrates

The rise of paper-based electronics(*56, 57*) and devices indicate the possibility of using solar cells on paper substrates. Paper substrates share several advantages of flexible substrates such as form factor, and flexibility and the lightweight have several advantages over plastic substrates in that they offer better adhesivbility with more materials, especially organic based materials, higher conductivity, and can be equally encapsulated to increase their lifetime to the device operation lifetime (*58*).

Furthermore, there is interest to manufacture batteries(*59*), OLED, micro-fluidics(*60*) and other paper electronics. The lifetime of such applications could be comparable to the lifetime of current polymer photovoltiacs and could be an option to pursue and optimize.

Integrated Power Electronics

Organic power electronics might be integrated in the future to the fabrication of organic PV. Power electronics raise temperature and shade sensitive PV system performance by about 30% if attached to each module. Also, integrating the power electronics will simplify and save time through wiring and connections. However, numerous challenges are needed to meet in organic electronics. Inverters need to function at high temperatures and high switching rates. Furthermore, current inverters use discrete electrolyte capacitors, which need to be replaced by improving critics, deigns by lower integratable capacitance. MPPT also must include advanced logic circuits and microcontrollers.

Painting

Spraying or coating solution-based insulation, electrodes, active materials, and encapsulation might provide a means to deploy large-scale PV modules over a large area in select places. However, there are many challenges, which develop the materials needed to enable fabrication of the module without impurities affecting the optical or electrical PV module performance.

Three Dimensional Photovoltaic

The mechanical flexibility, flexible form-factor, potentially low planner module cost, high efficiency, and long lifetime of organic PV could enable the designs and fabrication of 3D modules on plastic or paper substrates. Three-dimensional PV modules clearly will use much more material per meter than a typical flat panel polymer while at best double the power generated per unit area (about 2.4 times the power generated from a two-dimensional flat module). However, these designs allow more power per unit area and have such a unique geometry that it could have niche applications. For example, in constrained areas, such as military applications. Additionally, compact and inflatable lightweight 3DPV could provide the highest power per footprint to soldiers in the field. Furthermore, the unique geometry of 3D PV could enable more applications, such as inflatable 3DPV modules, that float on the sea or in the air. For example, it can be used in supply boats or air balloons with energy. In addition, the three-dimensional structure of PV modules could be of aesthetic interests to BIPV in architectural applications. The lightweight and fixable form and potentially very low cost and efficiency of >10% could indicate that possibility. Large 3D modules will cause additional shading, causing, and therefore, is not suitable for utility installations and will regulatory challenges in typical cities, whether on rooftops or in lands. Furthermore, the 3D module designs will require structural and aerodynamic considerations, which will increase the module cost.

One of the first proposals to take 3D modules for photovoltaic seriously was by Myers et al. (*61*). A genetic algorithm that mimics evolutionary mechanisms and natural selection was used to improve the performance and material utilization per unit area of an open box structure. The researchers tried to minimize materials usage per unit area and self–shading, while generating a structure that maximizes the absorption of incident light, making it to act like a black box or as light macro-light trapping 3D structures as opposed to several 3D light-trapping materials based nanostructures such as fiber optics inspired Solar3D Inc., and microscale silicon rods immersed in a polymer (*62*). This approach could potentially eliminate or reduce the installation costs and the balance of system costs (BOS). The three-dimensional module does not need racks and accurate tilting toward the sun, nor does it need connections and wiring between the different solar cells "solar leaves"; the solar cells will already be connected. The BOS cost and the installation cost is half the cost of the installed PV system; the DOE future projections for PV technologies maintain this ratio, while reducing the module cost. However, while the installation cost and BOS cost can be eliminated, three-dimensional modules used more solar cells/unit area and hence generate less power from each solar cell. An estimated seven times the solar cell area is used as a flat panel and this was determined to of a superior performance to an open box structure. Therefore, the cost of module decreased significantly for three-dimensional modules could be competitive in more niche applications (for example, see previous paragraph).

Further Technical Improvement

There could be further technical improvement to 3D module design. For example, after evaluating the spectral light distribution density and the spectral light conversion efficiency density, the structure could be modified by using two or more complementary absorption spectrums for the solar cell. The trade-off between the 3D module cost and the manufacturing of more complicated 3D module structure will need to be evaluated.

Furthermore, it is possible to use nitrogen-inflated 3D modules to extend the lifetime of polymer PV or small molecules PV. There are several studies about the lifetime of polymer PV operating in air environment and not under nitrogen, to my knowledge, and for this reason this possibility could not be evaluated further.

Challenges

There are many challenges facing the construction and design of 3D PC. One challenge is to develop a very cheap module with flexible form-factor with a reasonably high efficiency. Properties, such as lightweight and materials flexibility, will be advantageous as well. Potential players are solutions processed that are fabricated on flexible substrates or (even glass substrates) and can act as a bifacial solar cell. Certainly, polymer PV and other organic PV such as, small molecule PV and DSSC are candidate for 3D module designs.

Another challenge is to build an actual PV3D and connect its solar leaves in the most optimized way. It is not clear how the solar leaves can be connected and whether they are best connected in series or in parallel to improve the system performance and design.

Getting the highest energy yield from a 3D structure is a challenge, too. Although the 3D PV module in the figure above was optimized for self-shading, the modules will still get self-shaded during the days that use a significant system performance problem. The self-shading of some of leaves could cause shading to part of the module, which could lead to further heating of the module, thus creating hot spots. Increased temperature and heating could burn or damage the active material or the encapsulation. The output of a solar cell (i.e., JV curve, Vmax, and Imax) changes with respect to the intensity of the incident radiation, as in partial shadowing, solar cell performance mismatch, hot spots, and thermal gradient. In addition, with respect to the cell operating temperature, this problem is even more significant in 3D architecture, where different leaves will have performances, because of different light incidence, and where leaves could self shade each other during the day.

To rectify these problems, a bypass diode and a maximum power point tracker are required. The bypass diode can disconnect the shaded solar panel from the PV system so that it does not affect the system performance. Shading can affect the system performance greatly, causing interruptions of electrical power, which can lead to formation of thermal gradient and hot spots dissipating heat and increasing the risks of material damage and module burn. It could also lead to a reduced lifetime of the module. Maximum power point tracker (MPPT) can boost the efficiency of the solar system by matching the varying impedance of the solar cells with its output, increasing the PV system energy yield. MPPT tracks the changes in the output of the solar cell and maximizes the DC power from the solar cells/panels. An additional advantage of MPPT is that it possibly could be cat as power and temperature mentoring device and as control and communication electronics.

A trade-off between the electronics cost and the gain in the energy yield, which varies from place to place, must be taken in considerations. The drop in electronics cost and the increasing efficiencies of silicon modules is driving some solar manufacturer to consider. SunTech estimates that up to 25% more energy can be attained with a power electronics system. This boost in PV system energy yields is comparable to the boost that comes from moving the panels around using a tracker. In the future, it could be possible to integrate power electronics into the manufacturing process of polymer PV (or small molecule PV) by making the electronics from organic semiconductors.

3D PV module has numerous challenges to overcome. Small installations have technical challenges to overcome. The large module can be used in the sea or in air, and in architectural applications and other niche portable power applications.

Chapter 4: Market Challenges

Commercialization Prospects

The prospects are dim for polymer PV commercialization in electricity markets unless the efficiency and lifespan of polymers can be improved. This is necessary so that polymers can compete with other technologies that offer an equally reduced cost of installation or a much longer lifespan.

Low efficiency, high degradation rate, and the impact of installation cost

If the non-module costs are higher than the module costs, then the non-module costs will dominate. If competing Si, and thin films technologies has double the efficiency or double the lifetime, their PV systems total costs will be lower than polymer PV systems costs not matter how inexpensive polymer PV solar modules are.

Furthermore, polymer solar cells have a problem with cell degradation at a rate that is not yet well understood. The research focus and progress on reducing this rate and increasing its lifespan is relatively low. Cost effective encapsulation does not stop current polymer materials from degrading and will not extend the encapsulated module lifetime beyond glass-based modules (less than 4 years). Without resolving this lifespan problem, polymer solar cells will be unable to compete in any market because alternative technologies with similar cost, transparency, flexibility, and form flexibility are available.

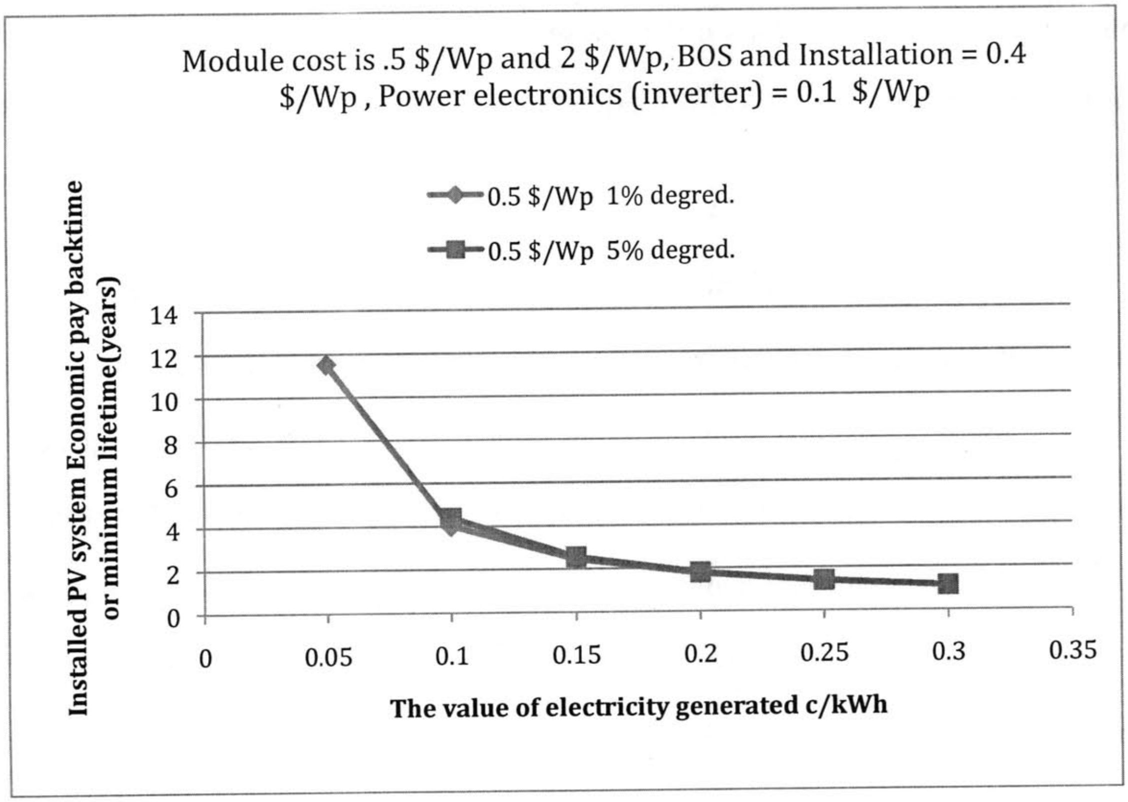


Figure 4.1: Simulations by the Solar Advisor Model (SAM) shows electricity prices vs. economic payback time, which is assumed as the minimum lifespan required.

Figure 4.1 shows the minimum lifespan required to generate a range of electricity prices using the low installation, inverter, and module costs of polymer solar cells. The use of polymer solar cells might generate electricity at $0.10/kWh at extremely low installation costs ($0.5/Wp) at about 5% degradation. Furthermore, it is hard to envision that the installation costs will be this low using a low efficiency and low lifespan system, but we made this assumption to make the point. Current commercial (Konarka) glass-based polymer solar cells work for only 3-4 years while flexible modules last 1-2 years, which is equivalent to a much higher degradation rate. In addition, many other competing technologies with higher efficiencies and longer lifespans could similarly utilize these low installation costs to generate electricity at lower costs. (See next section.)

Lifespan and degradation research statue

The study of lifespan and stability in organic photovoltaics is less active than the study of efficiency, although their impact on long-term performance is comparable. However, there is a rising interest in stability and degradation studies although no study has yet shown how a low-degradation polymer could be achieved. The study of the lifetime and degradation of these devices has been limited in part because the devices are made from multilayered thin films whose defective states are below the limit of detection by most optical detection tools (*63*). The polymer PV community should focus more of its attention toward polymers degradation.

The polymer module will not be commercialized if its degradation rate is too high. This is because alternatives are available, such as a-Si, solution processed CIGS, DSSC, and small molecule organic solar cells. All of these technologies have attractive characteristics, such as cost, module flexibility, and form flexibility. Furthermore, small molecules and DSSC share transparency and low light intensity compatibility.

In building integrated photovoltaics, a niche market for transparent technologies (including small molecules, DSSC, and polymer solar cells) could arise only if the cells could last for a long enough time to generate sufficient electricity to pay for the module and wiring, electronics, and safety costs. Small molecules are stable for a longer time (according to Heliatek, 30 years), while DSSC and polymer solar cells have stability problems. Increasing the materials stability to a range comparable to the building materials is essential; it is costly to replace building materials. Furthermore, it is reported that degradation changes the refractive index and generates oxides the material. This means that the colors could change and become distorted. Improving the lifetime, reliability, and stability of these colors is essential to compete in BIPV market.

BIPV

Three are some concerns about the ultimate scalability of thin films solar cells. However, a reasonable argument to make is that the materials cost in thin films are a very small (>1-2%) part of the total solar module cost, as the materials amount is minimal and the processing is inexpensive. This will give some hedge against rising scarce materials costs in CIGS (Indium) and CdTe (Telluride) solar cells in the 100 GW range. These rising materials costs will ultimately increase the amount of extractable reserves. Furthermore, with the progress made in more stable and equally inexpensive technologies, such as DSSC and small molecules, it is hard to see any commercialization for polymer PV without addressing its stability problem.

Portable Power

The key in portable power niche markets is that the device should refill within a day or two, and work in real time if low-power indoor conditions are typically 3-5%, unless close to a window or under a strong lamp, such as a 150w xenon lamp. The polymer solar cells module needs to maintain its lifetime over the lifetime of the devices (see Table 1) to be competitively efficient at competing using low solar cell costs and low installation costs. If polymer solar cells are commercialized only in this market, it will be hard for them to generate enough scale for portable power applications because the portable power market seems to be limited to outdoor applications.

One time use applications: active diagnostics microfluidics

At such low efficiencies and lifespan, polymer photovoltaics might be viable only in a market where there is a need for power on a one-time basis or for a very short time. The advantage of very cheap module cost sand solution processing could be important to succeeding against competitors; however, this market is yet developing and is not large enough to scale up and bring the cost of polymer solar cells down. Examples for such markets are deposable diagnostics tools that need brief power and paper-based diagnostics. It might be useful to have active paper diagnostics instead of passive devices.

The competition here would be with thin films batteries or other types of solar cells; accordingly, the cost and processing compatibility (i.e. installation cost) will be the dominating factor. Polymer solar cells need to scale up to be sufficiently cheap,

Table 4.1: Example of the portable power electronics niche market. The polymer solar cell module needs to be competitively efficient with low degradation in order to be commercializable in niche markets. The power generated needs to be stable, as high degradation will not be tolerated and will reduce competitivity.

Minimum power	Application
mW	Calculators,
mW	Very Low power electronics
mW	Microfludics
5W	Cellphone
5W	MP3 Player
5W	PDA
10W	12V Battery
10W	Handheld electronic devices (Moibles (iPhone),netbooks(IPad),video games)
20W	GPS
20W	Digital Camera
20W	Satellite phone
50-60W	Laptop
100 W	Electricity support in cars and boats etc.

Electricity Markets

CdTe modules are already produced at 12% efficiency and a possible cost reduction by more than 50% if the silicon wafer was made directly from the silicon melt bypassing the silicon crystal growth and the inefficient wire sewing steps. 1366. Furthermore, China strong subsides, cost reduction and raising innovations capabilities is expected to help bring the production cost further. The founder of sunTech, expects that c-Si will put innovations such as light trapping, plasmonics and, back point-contact, such innovations and other are expected to bring the efficiency to over than18.5% in 10 years. Furthermore, china produces more than 500 thousands of engineers each year. Furthermore, optimized inorganic multijuction solar cells can reach a theoretical efficiencies of 55%, and about 63% for three-junctions cells . They could found used in CPV where much of the cost is geared toward non-PV costs: the optics, cooling and mounting structure of the system.

Table 4.2: Competing flexible PV that could be installed without the cost of the rackes , metal frames or penetrations but probably will need installation labor for mounting, connecting, wiring, inverters .

Company	Module Efficiency	Substrate type	Production method
SoloPower SFX3	12.1 %	Flexible	roll to roll electroplating of CIGS
MiaSole	15.7 %	Rigid glass (18 Kg module)	Sputtering
MiaSole	? (unannounced)	Flexible	-

Company	Lab Cell Efficiency		
Lab Cell Swiss Federal Laboratories for Material Science and Technology (EMPA) with FLISOM	17.6% Polyimide	Flexible polyimide	roll-to-roll production of CIGS at 450 °C contacts by sputtering.
Lab Cell	18.1% glass	Rigid Glass	-
Nanosolar	15.3% (16.4% active-area efficiency)	Semi flexible metal-foil	coating/printing of CIGS

Future Competitors

There are new inorganic solutions, such as processed PV technologies, that are starting to be commercialized without stability problems while sharing most of the properties that allow them to compete in niche markets (except for the BIPV market where transparency is important; however, this is possible with DSSC and small molecule cells). Some examples include solution processed inorganic materials, such as copper-tin-zinc (~9.6%, IBM) based materials and CIGS (20% lab cell, 17.6% flexile substrate) among others. Furthermore, the very cheap solar cells are envisioned by inorganic solar cells, such as such as nanoparticles (including CuO, FeO, and CdSe). One of the limitations of using very cheap materials, such as CuO and FeO, is the challenge of achieving purity and phase uniformity (*64*). Some researchers (*64*), think that using nanoparticles can make the materials achieve uniform purity. In addition, very high efficiency materials could be made possible by multiple exciton generation concepts, intermediate bands, and plasmonics concepts.

Grid Electricity market opportunities for long lifespan and efficient lightweight flexible PV

In all of these markets, low cost and highly efficient flexible lightweight modules can play an important role, especially when solution processed. However, polymer PV performance could be inferior to its competitors (see pervious section) unless the lifespan and efficiencies of the solar modules are increased and the solar modules prices become scaled up and inexpensive.

Utility Scale

Automation already exists in large utility fields. For example, PV installation machines are used by SunTech to install posts in the ground and attach large solar modules. Using lightweight and flexible modules could enhance the automation of PV installations in large fields. For example, machines used in large-scale agriculture processes (reaping, binding, and threshing) can cover 200 acres a day (Solar DOE-White paper).

In this market, it is reasonable to assume very low installation costs (~$70/m2 or $0.6/Wp at 12%), as opposed to rooftop markets where this is very difficult to envision. With current methods, flexible solar cells installation costs are below ($1/Wp). This is unless installation becomes very simple and could be installed by customers. To generate electricity at $0.10/kWh, low installation costs of $70/m2 and low module costs of $50/Wp are required for solar cells with a minimum lifespan of seven years and efficiencies over than 12%.

Rooftops Market

Roofs protect the indoor building from the effects of weather and provide thermal insulation. Grid-tied PV systems installed on pitched roofs will be discussed as an example of rooftop installations. There are many types of roofing in residential housing (see Table 3). The durability of asphalt shingles is about 15 years to 30 years, depending on the quality of roofing. The lifetime for metal roofing can exceed 50 years. The various types of roofing materials as shown in Table 4.3 indicate the need for developing systems to install on different roof types, which is requirement dependent on having a flexible form factor such as polymer solar cells. Furthermore, there is an important aesthetic requirement of various shapes and tunable colors.

Table 4.3: shows the different types and market share of roofing materials in the US. The total roofing market in the western US was estimated to be around $3.6B. *

Roofing Type	Market share by	Market share by Roofing
Asphalt Shingle (Fiberglass and	47.7	54.2
Concrete Tile	13.8	10.4
Clay Tile	12.6	9.5
Metal architectural	5.9	6.7
Slate	4.7	3.6
Wood Shingle/Shake	4.7	3.6
Other	6.6	6.7
Metal structural roofing	1,9	2.2
Cementitious	1.1	1.2
Total	100	100

** Western Roofing Magazine, 2002.*

The three basic elements in a roof are materials, construction, and durability. The PV system module installation should preserve or enhance the aesthetics of the building and should not compromise the functionality of the roofing over its lifetime. Installation cost is dependent on the roofing material type, house layout, solar panel weight, installation, and wiring procedures. Furthermore, the mounting system may affect the module energy generation, reliability, and lifetime. In any installation, trade-offs are necessary in system and component selection.

The roofing material type affects the PV system installation costs. Depending on the roofing material, the installation time and costs will differ. For example, installing a typical PV system on metal roofing is easier than on shingled roofs because the wiring and the penetration, if existing, are easier on a metal roof (*65*). However, about half the residential roofs in the U.S. are made from fiberglass shingles, and innovative installation techniques are needed to bring the costs down

Furthermore, the module type and characteristics affect installation costs. The efficiency of the module plays an essential role since more efficient modules will use less area, take less installation time, and generate more energy. The weight of the module affects the installation costs. Flexible metal substrates are thought to be 10-20% less expensive to install than rigid silicon glass modules because they are lighter and easier to handle and transport. Figure 3.9 shows flexible installation of CIGS modules. (*66*); however, flexible solar cells are typically made from amorphous silicon or CIGS and are currently not suitable for residential roofs due to efficiencies less than 10%. PV modules could potentially be made from lighter, more flexible and solution-processed materials made from organic semiconductors (*67*). As was discussed before, these OPV including polymer solar cells suffer from low efficiency and short lifetimes. Developing solution-processed flexible and lightweight PV modules will allow for new means to reduce installation costs further.

Lightweight, flexible solar panels OPV systems that could potentially reduce installation cost even further will be discussed in the next subsection.

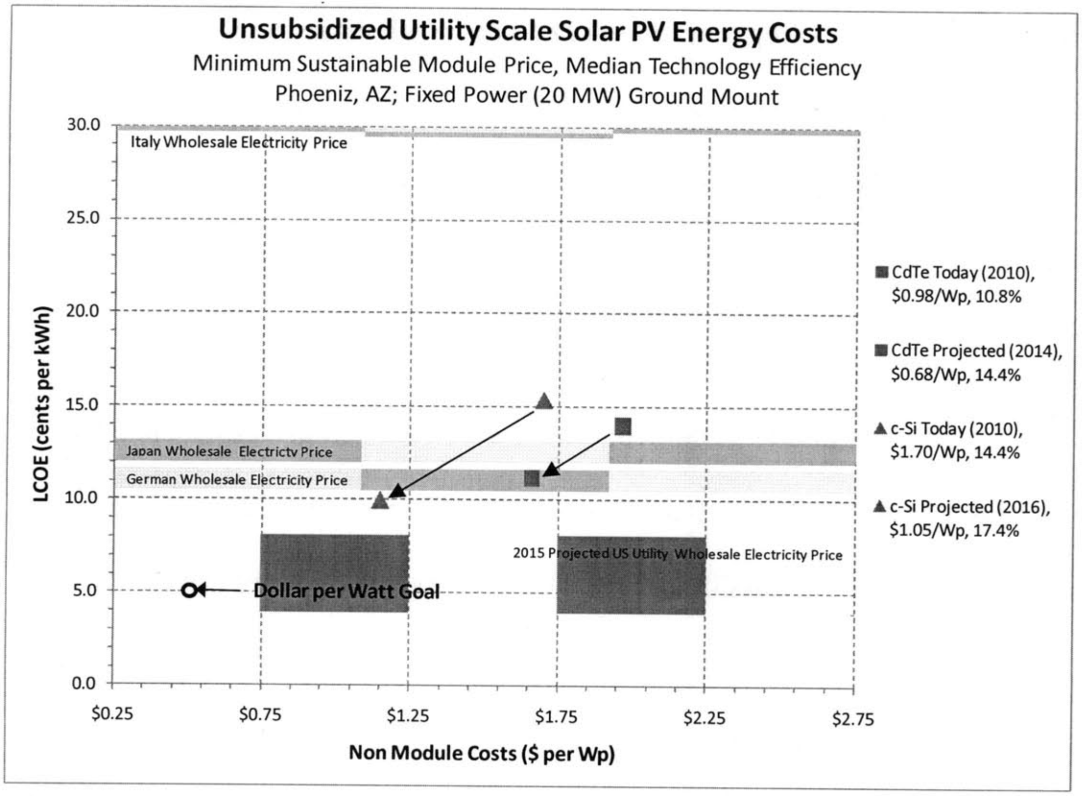


Figure 4.2: For a fixed module prices, current and projected electricity prices are compared for PV systems and wholes sale electricity rates for US, Germany, Japan and Italy. (*68*)

Integrating Module into new building construction

Integrating new PV into new construction is favorable because it will lead to lower installation costs, better PV performance, better aesthetics, and lower finance costs because the value of the system can be integrated into the mortgage. It is clear that if the architects planned for PV systems, the pitch and space will be optimized for PV system performance and installation costs.

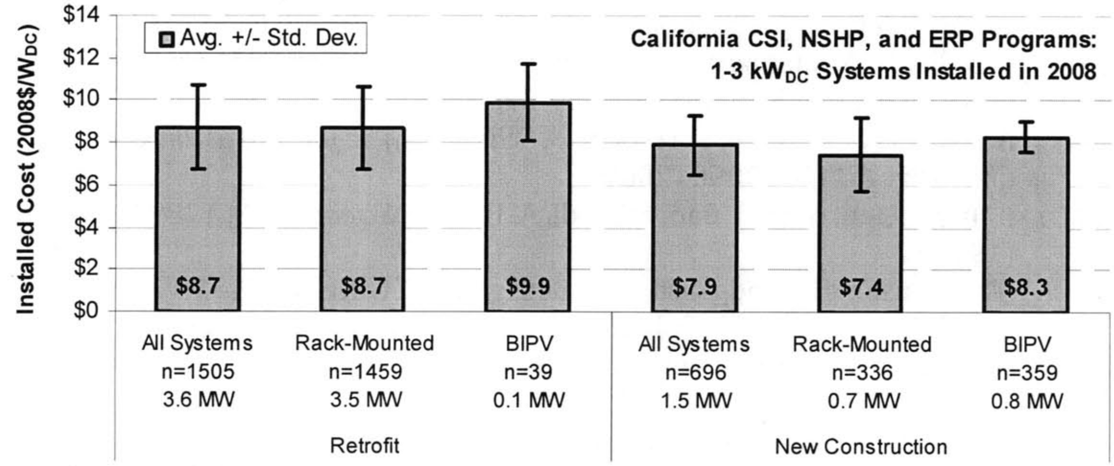
Roof lifetime: About half of roofs in the U.S. market are made from fiberglass shingles, which typically last from 15 to 30 years. This fact makes the case that a significant part of the roofing market will need to be rebuilt or newly reroofed., Internationally there has been increased confidence in residential PV systems, especially in developing markets. For example, the Kenyan government passed a law in 2010 that requires solar panels to be installed in all new homes.

Solar Shingles

Typical solar shingles suffer from low efficiency compared to normal PV panels. Solar shingles are made from flexible modules such as CIGS and amorphous silicon with efficiencies of less than 10%. This requires using more area and thus more modules, more wiring, and more connections. Furthermore, the market of solar shingles is limited by the fact that roofing needs to be available in various colors and shapes to provide aesthetics and varied options. It is a challenge for solar shingle manufacturers to scale up different types of solar roofing materials, given they have limited coloring options and limited forms that use current amorphous silicon or CIGS technologies. A modified approach to replacing low-efficiency solar shingles is to manufacture shingles that contain small high-efficiency multi-crystalline solar modules pre-attached to concrete or clay profiled tiles. Such a solar installation has all of the benefits of being installed at the same time as the rooftop with the efficiency and proven technology of monocrystalline or multicrystaline silicon solar cells [http://www.lumetasolar.com].

BIPV

Solar panels can be integrated into buildings in the facade, glazing, flat roofs, and pitched roofs. Pitched roofs, commonly covered in shingles, are the most widely used in the U.S. residential market. The module form factor and the flexibility of OPV (polymers, small molecule, and DSSC) provide an important competitive advantage in this niche market. BIPV systems have high weather resistance and very high reliability over long times as a building material; replacing a PV system because of a malfunction will be costly. OPVs' short lifetime is a significant barrier in their commercialization. Efficiency is also a significant barrier to their commercialization, since low efficiencies might not generate enough electricity over their lifetime to justify the additional costs of wiring, connections, power electronics, and other safety and insurance costs.



Note : The number of rack-mounted systems plus BIPV systems may not sum to the total number of systems, as some systems could not be identified as either rack-mounted or BIPV.

Figure 4.3: compare a sample PV system costs in 2008 between in residential retrofit , new construction and BIPV. (*68*)

Works Cited

1. United-Nations.
2. E. ROSENTHAL, *The New York Times,* (Dec 24 2010, 2010).
3. , (2010).
4. K. Zweibel, N. R. E. Laboratory, *The terawatt challenge for thin-film PV.* (National Renewable Energy Laboratory, 2005).
5. *Technology Review,* (September/October 2010).
6. R. García-Valverde, J. A. Cherni, A. Urbina, *Progress in Photovoltaics: Research and Applications* **18,** 535 (2010).
7. B. Gregg, *J. Phys. Chem. B* **107**, 4688 (2003).
8. K. Coakley, M. McGehee, *Chem. Mater* **16**, 4533 (2004).
9. C. G. a. M. D. McGehee, *National Academy of Engineering* **35**, (2005, 2005).
10. P. Peumans, A. Yakimov, S. Forrest, *Journal of Applied Physics* **93**, 3693 (2003).
11. A. Mayer, S. Scully, B. Hardin, M. Rowell, M. McGehee, *Materials today* **10**, 28 (2007).
12. C. Deibel, V. Dyakonov, *Reports on Progress in Physics* **73**, 096401 (2010).
13. G. Dennler, M. Scharber, C. Brabec, *Advanced Materials* **21**, 1323 (2009).
14. W. Shockley, H. Queisser, *Journal of Applied Physics* **32**, 510 (1961).
15. O. Miller, E. Yablonovitch. (Optical Society of America, 2010).
16. R. Swanson. (IEEE, 2005), pp. 889-894.
17. A. Ayzner, C. Tassone, S. Tolbert, B. Schwartz, *The Journal of Physical Chemistry C* **113**, 20050 (2009).
18. J. Hummelen, G. Yu, J. Gao, F. Wudl, A. Heeger, *Science* **270**, 1789ñ1791 (1995).
19. M. J¯rgensen, E. Bundgaard, R. d. Bettignies, F. C. Krebs, *The Polymer Solar Cell.* C. K. Frederik, Ed., Polymer Photovoltaics (SPIE Press, 2008).
20. H. Chen *et al., Nature Photonics* **3**, 649 (2009).
21. D. Moses, M. Leclerc, K. Lee, A. Heeger.
22. M. Granstrom *et al., Nature* **395**, 257 (1998).
23. W. U. Huynh, J. J. Dittmer, A. P. Alivisatos, *Science* **295**, 2425 (March 29, 2002, 2002).
24. A. C. Arango, S. A. Carter, P. J. Brock, *Applied Physics Letters* **74**, 1698 (1999).
25. S. Cook, H. Liyuan, A. Furube, R. Katoh, *The Journal of Physical Chemistry C* **114**, 10962 (2010).
26. X. Wang *et al., Applied physics letters* **85**, 5081 (2004).
27. G. Dennler *et al., Advanced Materials* **20**, 579 (2008).
28. W. Ma, C. Yang, X. Gong, K. Lee, A. Heeger, *Advanced Functional Materials* **15**, 1617 (2005).
29. C. Deibel, (2010).
30. Heliatek.
31. J. Kim *et al., Science* **317**, 222 (2007).
32. J. Gilot, M. Wienk, R. Janssen, *Applied Physics Letters* **90**, 143512 (2007).

33. S. Baluschev *et al.*, *Physical review letters* **97**, 143903 (2006).
34. R. V. Noorden, *Nature* **469**, 14 (5 January 2011, 2011).
35. F. Krebs, S. Gevorgyan, J. Alstrup, *Journal of Materials Chemistry* **19**, 5442 (2009).
36. A. Kumar, C. Zhou, *ACS nano* **4**, 11 (2010).
37. J. Wu *et al.*, *Applied Physics Letters* **92**, 263302 (2008).
38. M. Rowell, M. McGehee, *Energy Environ. Sci.*, (2010).
39. F. Krebs, T. Tromholt, M. J¯rgensen, *Nanoscale* **2**, 873 (2010).
40. Q. Song *et al.*, *Applied Physics Letters* **89**, 251118 (2009).
41. M. Jørgensen, K. Norrman, F. C. Krebs, *Solar Energy Materials and Solar Cells* **92**, 686 (2008).
42. C. Lungenschmied *et al.*, *Solar Energy Materials and Solar Cells* **91**, 379 (2007).
43. G. DENNLER, N. SARICIFTCI, *Proceedings of the IEEE* **93**, 1429 (2005).
44. G. Dennler *et al.*, *Thin Solid Films* **511**, 349 (2006).
45. B. Rand, D. Burk, S. Forrest, *Physical Review B* **75**, 115327 (2007).
46. M. C. Scharber *et al.*, *Advanced Materials* **18**, 789 (2006).
47. M. Lo *et al.*, *Applied Physics Letters* **96**, 113303 (2010).
48. E. Katz *et al.*, *Journal of Applied Physics* **90**, 5343 (2001).
49. S. Sista *et al.*, *Advanced Materials* **22**, 380 (2010).
50. F. Krebs, *Solar Energy Materials and Solar Cells* **93**, 1636 (2009).
51. A. L. Roes, E. A. Alsema, K. Blok, M. K. Patel, *Progress in Photovoltaics: Research and Applications* **17**, 372 (2009).
52. B. l. M. Basol, V. K. Kapur, C. R. Leidholm, A. Halani, K. Gledhill, *Solar Energy Materials and Solar Cells* **43**, 93 (1996).
53. PersonalCommunication-Benwilliams-MiaSole, (2010).
54. 3MPressRelease1, (2010).
55. 3MPressRelease2, (2010).
56. J. Rogers *et al.*, *Proceedings of the National Academy of Sciences of the United States of America* **98**, 4835 (2001).
57. A. Siegel *et al.*, *Advanced Functional Materials* **20**, 28 (2010).
58. H. Park, J. Rowehl, K. Kim, V. Bulovic, J. Kong, *Nanotechnology* **21**, 505204 (2010).
59. L. Hu, H. Wu, F. La Mantia, Y. Yang, Y. Cui, (2010).
60. A. Martinez, S. Phillips, G. Whitesides, *Proceedings of the National Academy of Sciences* **105**, 19606 (2008).
61. B. Myers, M. Bernardi, J. Grossman, *Applied Physics Letters* **96**, 071902 (2010).
62. M. D. Kelzenberg *et al.*, *Nat Mater* **9**, 239 (2010).
63. A. J. MoulÈ, *Current Opinion in Solid State and Materials Science* **14**, 123 (2010).
64. C. Wadia, A. Alivisatos, D. Kammen, *Environ. Sci. Technol* **43**, 2072 (2009).
65. F. C. f. S. E. S. Jan Kosny. (Cambridge 2010).
66. A. Payne, R. Duke, R. H. Williams, *Energy Policy* **29**, 787 (2001).
67. C. J. Brabec *et al.*, *Advanced Materials* **22**, 3839 (2010).

68. R. Wiser, G. Barbose, C. Peterman, "Tracking the sun: The installed cost of photovoltaics in the US From 1998-2007" (Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, CA (US), 2009).