Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 83 (2009) 1224–1231
SOLAR ENERGY
www.elsevier.com/locate/solener

Estimating the manufacturing cost of purely organic solar cells

Joseph Kalowekamo [1], Erin Baker *

220 Elab, University of Massachusetts, Amherst, MA 01003, USA

Received 22 September 2008; received in revised form 2 February 2009; accepted 5 February 2009
Available online 12 March 2009

Communicated by: Associate Editor Sam-Shajin Sun

Abstract

In this paper we estimate the manufacturing cost of purely organic solar cells. We find a very large range since the technology is still very young. We estimate that the manufacturing cost for purely organic solar cells will range between \$50 and \$140/m^2. Under the assumption of 5% efficiency, this leads to a module cost of between \$1.00 and \$2.83/W$_p$. Under the assumption of a 5-year lifetime, this leads to a levelized cost of electricity (LEC) of between 49¢ and 85¢/kWh. In order to achieve a more competitive COE of about 7¢/kWh, we would need to increase efficiency to 15% and lifetime to between 15–20 years.

Keywords: Cost; Purely organic solar cells; Photovoltaics

1. Introduction

In this paper we assess the potential of organic solar cells (OSC) to reduce the cost of photovoltaic (PV) electricity. We estimate materials, processing and overhead costs to estimate the manufacturing costs; we then fold in efficiency to estimate the module cost; and finally convert that into a levelized electricity cost (LEC). We find that there is a great deal of uncertainty about the capital costs of OSC, leading to manufacturing costs ranging from \$48.80 to \$138.90/m^2. Assuming efficiency of 5% and a 5-year lifetime leads to module costs between \$1.00 and \$2.83/W, and LEC between 49¢ and 85¢/kWh. But assuming 15% efficiency and 20-year lifetime leads to LEC between 7¢ and 13¢/kWh. We perform sensitivity analysis and find that the most sensitive parameters are substrate cost and cell efficiency. We discuss what technological characteristics could lead to a LEC on the order of 5¢/kWh, a cost that would make solar competitive with conventional sources of electricity generation such as coal.

1.1. Motivation

Silicon-based PV is still relatively expensive, and to this end, efforts have been made to develop potentially less expensive thin-film solar cells (TFSC) which may have purely inorganic materials, such as amorphous silicon, cadmium telluride, and copper–indium–diselenide or contain organic materials as an essential part of the device (Dai et al., 2004). In principle, these TFSC have the potential to reduce material cost and lower manufacturing costs through simplified design and processing techniques that are not available to crystalline inorganic semiconductors.

The production of organic-based PV using industrial screen printing has demonstrated the possibility of producing in the order of 1000–100,000 m^2 on a process line per day while production of the same solar cell area based on silicon typically takes 1 year (Krebs et al., 2007). Given that the materials costs are low enough, the cost reduction due to printing techniques can be enormous for organic

* Corresponding author. Tel.: +1 413 545 0670.
E-mail addresses: jkalowek@gmail.com (J. Kalowekamo), edbaker@ecs.umass.edu (E. Baker).
[1] Principal Energy Officer, Department of Energy, Renewable and Alternative Energy Division, P/Bag 309, Lilongwe 3, Malawi. Tel.: +1 265 1 770688.

0038-092X/\$ - see front matter
doi:10.1016/j.solener.2009.02.003

semiconductor processing. However, it is observed that the average performance of printed solar cells is slightly below the average performance of discrete processed, spin coated solar cells, but the differences are small. With further emphasis on the improvement of processing techniques, especially with respect to the quality criteria for smooth, homogeneous layer structures with reasonable resolutions, printing techniques will certainly soon match the performance of discrete processing techniques (Brabec, 2004). However, there are still some shortcomings of organic-based PV that need to be addressed before they are commercialized and these include efficiency, lifetime and stability. The first organic PV device was fabricated in 1986 with 1% conversion efficiency (Tang, 1986) and since then, numerous efforts have been made to improve efficiency to a commercializable value, estimated at 10%. In 2005, 5% conversion efficiency (Kim et al., 2009) and operational lifetime of 20,000 h (Bundgaard and Krebs, 2007) were obtained. However, there is still room for improvement in these properties. Organic solar cells have to fulfil all requirements simultaneously i.e. lifetime, efficiency and costs otherwise they will be limited to a niche market (Brabec, 2004).

While extensive research work is being carried out on other properties such as efficiency, lifetime, stability and even processability of organic solar cells, in this paper we make an effort to estimate the manufacturing cost of these cells. We focus on purely organic solar cells which are based on low cost, purely organic semiconductors such as polymers, dyes, pigments and liquid crystals. These cells belong to the class of PV known as excitonic solar cells, which are characterized by strongly bound electron–hole pairs (excitons) that are formed after excitation with light.

2. Methods and results: Estimating module cost

2.1. Overview of method

We start by estimating the manufacturing cost of OSC per square meter. We use bottom-up cost estimation for the materials, overhead, and labor costs. We were unable to get any reliable data on capital costs for individual processes, thus we use simple top-down estimation instead. Throughout the paper we will refer to cost estimates for dye-sensitized solar cells (DSSC). These partially organic cells have many similarities to OSC, which will simplify the cost estimation because Smestad (1994) and Meyer (1996) presented detailed estimates for the manufacturing costs of DSSC. Fig. 1 shows the basic layered device architecture for DSSC and OSC.

We calculate the module cost in $\$/W_p$ by dividing the manufacturing cost per square meter by the output of the same area, in this case 1000 W_p/m^2 times efficiency. We report costs in $\$/W_p$ because it includes efficiency, cell and module yield, and it enables the estimate to be comparable with other PV technologies. We estimate an average

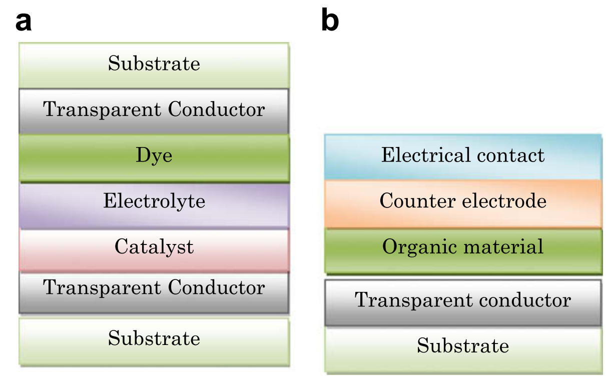

Fig. 1. Basic layered device architectures (a) DSSC (b) OSC.

LEC in \$/kWh in order to compare solar power with other sources of electricity generation such as coal.

2.2. Manufacturing cost model

In the next three subsections we estimate the materials, process and overhead costs.

2.2.1. Materials costs

Table 1 summarizes our results, listing the materials for each component of DSSC and OSC, along with cost estimates. According to Halme (2002), there are a number of alternative semiconductor materials that can be used in OSC which are broadly categorized into conducting polymers, dyes, pigments, and liquid crystals. In this paper, we estimate the cost of carbon-60 (C_{60}), copper and tin phthalocyanines (CuPc and SnPc), which are pigments and conducting polymers, respectively. We have chosen these materials because their combination has resulted in the best OSC device so far, achieving 5% laboratory efficiency. Basing our assumptions on similar work done by Haynes et al. (1994), we assume the total amount of the semiconductor materials in a micron-thickness across an area of 1 m^2 is 1 cm^3, and that there are about 1 g/cm^3 of semiconductor material. Haynes et al. (1994) reports that thicknesses for thin films range from 1 to 10 microns depending on design. We assume a thickness of 1 micron because we expect OSC to be the thinnest of all cell designs. Therefore, the amount of semiconductor material required is 1 g/m^2. We assume 75% material utilization due to wastage, therefore 1.3 g/m^2 of semiconductor material is required. According to Peumans (2006), CuPc costs \$1.00/g. Based on prices from Aldrich catalog, we estimate the cost of SnPc and C_{60} at \$0.50/g and \$1.00/g, respectively. Using these figures, we estimate the semiconductor materials cost for OSC at $1.3\ g/m^2 * \{\$1.00/g + \$0.50/g + \$1.00/g\} = \$3.30/m^2$. We take this to be the minimum estimate, and assume the maximum would be \$5.00/m^2 based on the average cost of semiconductor materials for TFSC technologies.

Meyer (1996) estimated electrical interconnections and electrical contacts combined for DSSC at \$5.00/m^2, which

Table 1
Comparison of materials costs estimates for DSSC and OSC.

Cost Component	DSSC			OSC		
	Type used	Cost ($/m^2)		Type used	Cost estimate ($/m^2)	
		Low	High		Low	High
Semiconductor	TiO_2	0.04*	6.84#	C_{60}, CuPc & SnPc	3.30	5.00
Electrical contacts and interconnects	–	2.90*	6.84#	Aluminum, silver paint	3.40	5.00
Substrate[a]	PET glass	29.00	43.50*,#	Flexible Plastic, ITO	7.90	13.68
Protective cover	Glass cover	2.90*	45.58#	Flexible encapsulant	2.90	4.40
Sealant	Surlyn	2.90*	4.35#	Surlyn	2.90	4.40
Packaging material	N/A	N/A	N/A	–	2.00	3.00
Specialty chemicals	N/A	N/A	N/A	4 TBP	1.00	2.00
Other (absorbing dye; catalyst; electrolyte)	Ruthenium; platinum; tri-iodide	10.30*	14.50#	N/A	N/A	N/A
Total		45.14	121.61		23.40	37.48

* Smestad (1994), adjusted to 2008 values.
\# Meyer (1996) adjusted to 2008 values.
[a] There are two substrates in DSSC devices hence the estimates are for the 2 substrates and not just one. For this reason, we base our estimate on $10/m2, which is the cost of one substrate.

is equivalent to $6.80/m^2 in 2008.[2] Assuming monolithic design, we expect the cost of electrical contacts in OSC to be lower than that of DSSC because of the thinner cells. The thickness of OSC is typically half that of DSSC and the other TFSC such as CdTe, hence relatively less of the materials are used. For this reason, we estimate the cost for electrical contacts and electrical interconnections for OSC to be 50% of $6.84/m^2 = $3.42/m^2.

We are assuming OSC will use ultra-thin flexible transparent plastic substrate coated with ITO. Based on price data posted on the internet by manufacturers/suppliers, we have calculated an average cost for flexible plastic substrate at $5.00/m^2. From Aldrich catalog, ITO costs $2.40/g. Based on manufacturing cost information for TFSC as reported by Haynes et al. (1994), we assume 1 g of ITO is used per m^2 hence we estimate ITO cost at $2.40/g $*$ 1 g/m^2 = $2.40/m^2. Based on Keshner and Arya (2004), we estimate that coating the flexible plastic substrate with ITO will cost $0.50/m^2. Using these figures, we finally estimate the ITO-coated flexible plastic substrate at $5.00/m^2 + $2.40/m^2 + $0.50/m^2 = $7.90/m^2; with a cost range from $7.90 to $13.68/m^2. We have based the maximum cost on the current cost of TCO-coated glass substrate for a sandwiched-type DSSC.

For the cost of the protective cover and the sealant, we simply use the estimated cost for DSSC, which ranges from $2.90 to $4.40/m^2. However, it should be noted that OSC is all-solid device as such, it may require much less severe encapsulation than DSSC. We assume that the cost of packaging material will be higher for OSC than for other TFSC for two reasons: (1) organic materials are sensitive to oxygen and water vapor in outdoor environment and (2) because of the ultra-thin structure i.e. the thinner the cell the higher the packaging cost. We estimate that the packaging cost will range from a low of $2.00/m^2 (as estimated by Zweibel (2005) for inorganic TFSC) to $3.00/m^2, a 50% increase in the cost.

We expect OSC to have instability problems due to degradation of polymer materials, and as a solution to this, we expect use of specialty chemicals. We assume the cost of this to be the same or even higher than that of inorganic thin films. Zweibel (2005) estimated specialty chemicals cost for inorganic thin films at $1.00/m^2, and based on this, we estimate this cost at $1.00/m^2, with a range from $1.00 to $2.00/m^2.

We present a summary of the estimated materials costs for OSC, and compare this with estimated costs for DSSC in Table 1.

We find that active materials for OSC constitute about 27–29% of the total materials cost compared to 7–11% for DSSC. The flexible plastic substrate for OSC constitutes the largest portion of the materials cost i.e. 34–36%, however, it is less expensive than glass substrate for DSSC, which constitutes 36–64% of the total materials cost. The total materials cost for OSC is lower than that of DSSC, perhaps significantly lower depending on which estimates are used. We note that the difference is primarily driven by the substrate cost.

2.2.2. Processes: Capital and labor

OSC has many of the same process steps as DSSC. In fact, all processes in OSC have a parallel process in DSSC; there are a number of processes required for DSSC, however, that are not required for OSC. Table 2 lists the processes that are common to both, and those that are only carried out for DSSC.

Ideally, we would like to estimate the process cost for each process step separately in order to estimate capital cost. However, we have not been able to find any publicly available data. Therefore, we have taken two top-down approaches: the first approach takes the average start-up

[2] From CPI, $5 in 1996 has a buying power of $7.25 in 2008, thus increasing the figure by a factor of 1.36875.For consistency, all the 1996 figures in this paper have been multiplied by a factor of 1.36875, while 1994 figures have been multiplied by a factor of 1.45.

Table 2
Common and uncommon processes in DSSC and OSC.

Common processes in DSSC and OSC	Processes in DSSC only
Substrate preparation	Dye sensitization
Screen-printing of semiconductor material	Drying and firing
Sintering	Hole drilling and sealing
Sandwiching of electrodes	Electrolyte filling, and
Encapsulation and sealing	Framing
Electrical interconnection	–

capital equipment cost for an OSC manufacturing company, and backs out the per panel cost. The other approach uses published estimates for the capital cost of DSSC.

Based on publicly available data on the internet, the average start-up capital equipment cost for an OSC manufacturing company is \$20 million. This is in agreement with the report by Haynes et al. (1994) that the capital equipment costs for thin-film manufacturing plants, which are being built or are planned, fall in the range of \$14.5 to \$43.5 M for 10 MW of annual production capacity at 6.5% efficiency. We assume a plant lifetime of 7 years; and a discount rate of 10% per year. We have based these assumptions on a similar work done by Little and Nowlan (1997) for thin films.

Based on 10 MW annual production capacity, 6.5% efficiency and output per unit area of 1000 W_p/m^2, we calculate the first-year module production of our hypothetical firm as $10\ MW_p/(1000\ W_p/m^2 * 6.5\%) = {\sim}150{,}000\ m^2$. Amortizing the capital cost over 7 years; at 10% annual interest; and using an annuity formula,[3] initial capital investment of \$14.5 M–\$43.5 M is equivalent to \$2.98 M–\$8.94 M/year. Therefore, our capital equipment cost estimate per square meter is \$2.98 M/150,000 m^2 to \$8.94 M/150,000 m^2 or between \$19.86 and \$59.57/m^2.

This estimate is significantly higher than the estimated process costs of DSSC i.e. between \$7.25 and \$11.60/m^2 and that projected for CdTe i.e. \$10.0/m^2. As pointed out, OSC requires fewer steps than DSSC and therefore should require a lower capital investment. We will take an extreme assumption for our lower estimate: since OSC only requires 5 of the 11 steps required for DSSC, we assume that the capital cost of OSC is 5/11 that of DSSC. Therefore our lower bound estimate for capital costs is $5/11 * 7.25 = \$3.3/m^2$. Hence our capital equipment cost range is \$3.30–\$59.60/m^2. Note that our low number implies a capital investment of only \$2.4 M for a 10 MW plant.

We also calculate the direct labor cost associated with processes cost. Based on Haynes et al. (1994) and Kapur and Basol (1990) for TFSC and CIS, respectively, we assume a semi-automated 10 MW factory, with three shifts per day, will require 10 operators/shift; thus 30 full time operators. Assuming 8 h/shift, 350 days/year and a wage rate of \$17.0/h, then the direct labor cost is estimated at 30 people * 8 h/day * 350 days/year * \$17.00/h = \$1,428,000/year. Using the yearly production output, the direct labor cost per square meter is (\$1,428,000/year)/150,000 m^2/year = \$10.00/m^2. Smestad (1994) estimated labor cost for DSSC at a very low \$0.44 to \$0.73/m^2; while Meyer (1996) estimated it at \$18.00/m^2. First Solar estimated labor cost for CdTe, which includes plant labor and operations management at \$12.00/m^2. We consider our \$10.00 estimate to be the maximum labor cost for OSC, and assume the minimum cost to be \$6.00/m^2. Our estimate for the lower end of the range, \$6.00, is based on long term goals for TFSC technologies, assuming full automation, as projected by Zweibel (1999). Thus our cost range is \$6.00–\$10.00/m^2. The summary of the processes cost is presented in Table 3 below.

[3] Annual worth, A/P, i, $n = [i * (1+i)\text{^}n * P]/(1+i)\text{^}n - 1$ where $P = \$10$ M or \$30 M; $i = 10\%$; and $n = 7$ years.

2.2.3. Overhead costs

Table 4 shows our estimates for overhead costs for OSC (including facilities, utilities, maintenance of equipment, miscellaneous, and customer warranty costs) and compares them to estimates for DSSC. We assume that facilities costs will be the same. We assume that utilities will be lower for OSC since they are manufactured at room temperature and require very little water. Our simplifying assumptions about maintenance, customer warranty, and any miscellaneous costs are in the table.

2.2.4. Result and sensitivity analysis

In summary, we estimate that the total manufacturing cost, with 95% cell yield will range between \$48.80 and

Table 3
Summary of processes cost for manufacturing of OSC.

Cost component	Cost (\$/m^2)	
	Low	High
Capital equipment	3.30	59.60
Labor	6.00	10.00
Total	9.30	69.60

Table 4
Summary of Overhead costs estimates for OSC and DSSC.

No	Cost component	DSSC		OSC	
		Cost (\$/m^2)		Cost estimate (\$/m^2)	
		Low	High	Low	High
1.	Facilities (e.g. rent)	7.25	10.15	7.25	10.15
2.	Utilities (electricity, water)	7.25	10.15	2.18	4.35
3.	Maintenance of equipment (4% of capital cost)	–	–	0.13	1.25
4.	Miscellaneous (5% of total manufacturing cost)	–	–	2.11	4.73
5.	Customer warranty (5% of total manufacturing cost)	–	–	2.11	4.73
Total		14.50	20.30	13.78	25.21

Note: Where there is a dash we assume this cost was not considered in the estimate.

Table 5
Summary of total manufacturing cost for OSC.

Cost category	Low estimate ($\$/m^2$)	High estimate ($\$/m^2$)
Materials	23.40	37.48
Capital	3.30	59.60
Labor	6.00	10.00
Overhead	13.78	25.21
Total manufacturing cost	46.48	132.29
Cell Yield (95%)		
Total manufacturing cost with cell yield[a]	48.80	138.90
Module efficiency (5%)		
Module yield (98%)		
Module Cost ($\$/W_p$)[b]	1.00	2.83

[a] = \$46.48 *1.05 and \$132.9 * 1.05.
[b] = (\$48.8/m^2 * 1.02)/(1000 W_p * 5%) and (\$138.9/m^2 * 1.02)/(1000 W_p * 5%).

\$138.90/m^2 as shown in Table 5. When we fold in efficiency and module yield, which we have assumed to be 5 and 98%, respectively, module cost is estimated to range between \$1.00 and \$2.83/W_p calculated as follows: Module cost (\$/Wp) = (manufacturing cost) $*$ 1.02/(output/unit area), where output per unit area is 1000 W_p/m^2 $*$ 5% module efficiency.

If we take the low end cost estimates shown in Table 5, materials constitute the largest part of the total module manufacturing cost followed by overhead and processes costs. But taking the high end cost estimates, processes costs constitute the largest part of the total direct module manufacturing cost followed by materials and overhead costs.

We perform sensitivity analysis on the impact of variations in the substrate cost, wage rate, machine lifetime, interest rate and cell yield; taking as a baseline our low estimate for manufacturing cost of about \$50/m^2. Substrate cost significantly affects manufacturing cost as shown in Fig. 2 followed by cell yield and wage rate. The effect of machine life and interest rate on manufacturing cost is very minimal.

We also perform sensitivity analysis on the impact of substrate cost, wage rate, machine life, cell yield and cell efficiency on *module cost*, using a central figure of \$1/Wp. As shown in Fig. 3, module manufacturing cost is very sensitive to cell efficiency. It is also sensitive to cell yield, substrate cost and wage rate, and is relatively insensitive to machine lifetime and interest rate. There is only a small increase in module manufacturing cost if interest rate and machine lifetime are increased by 50%.

2.3. Module cost and total module manufacturing cost

In Fig. 4, we analyze the effect of manufacturing cost, at different efficiencies, on the module cost. There is a linear relationship between module cost in $\$/W_p$ and module manufacturing cost per square meter as a function of efficiency. Module cost decreases with an increase in efficiency combined with a decrease in module manufacturing cost. Using the baseline manufacturing cost of between \$48.80 and \$138.90/m^2, we find that if efficiency increases to 15% the module cost decreases correspondingly from the baseline cost of between \$1.0 and \$2.83/W_p to between \$0.33 and \$0.94/W_p. On the other hand, these lower module costs can be achieved if the efficiency is held constant at 5% and module manufacturing cost reduces to between \$16.18 and \$46.08/m^2. Therefore, cell efficiency and total module manufacturing cost per square meter have a significant impact on module cost.

PV market penetration by OSC will depend on cost competitiveness with the other TFSC and crystalline silicon technologies. In Table 6, we compare the estimates for OSC with the projected estimates for other TFSC and

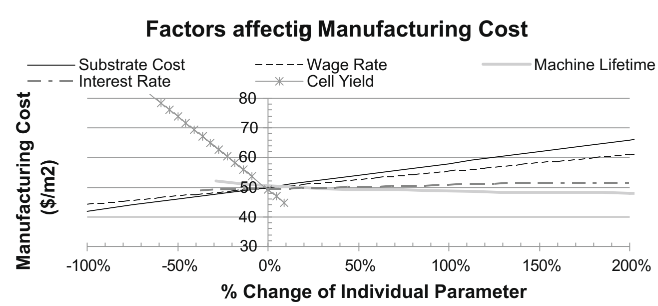

Fig. 3. Sensitivity analysis on percent variation of substrate cost, wage rate, machine life, and cell yield and cell efficiency.

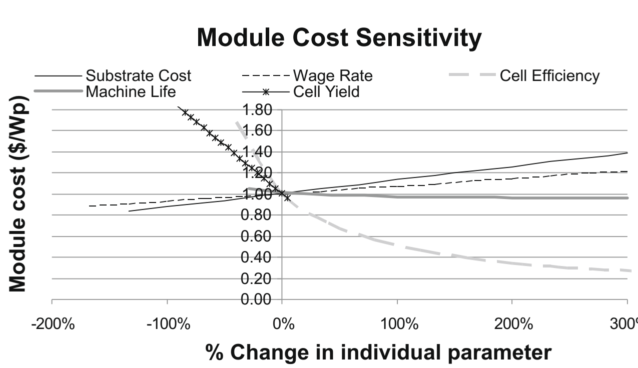

Fig. 2. Sensitivity analysis on substrate cost, wage rate, machine lifetime, interest rate, and cell yield.

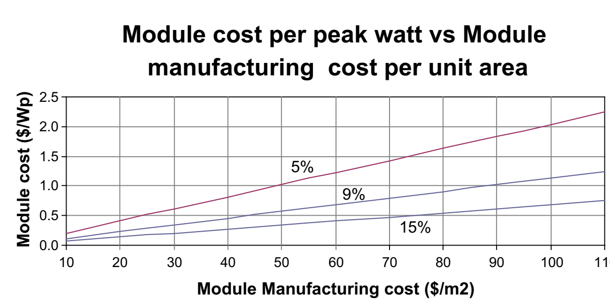

Fig. 4. The relationship between module cost and total module manufacturing cost per unit area (\$/m^2) at different cell efficiency levels.

Table 6
Comparison of the cost estimates for OSC to projected cost estimates for other thin films and mc-Si.

Tech.	Materials			Process Costs ($/m²)	Overhead Costs ($/m²)	Module Manuf. Costs[a] ($/m²)	Module Cost[b] ($/Wp)
	Active ($/m²)	Inactive ($/m²)	Total (%)				
OSC	6.7–10.0	16.70–27.48	(27–48)	9.30–69.60	13.78–25.21	48.80–138.80	1.0–2.83
DSSC(1)*	10.3–16.0	5.22–5.51	(22–23)	7.69–10.88	11.6	36.55–46.19	0.75–0.94
DSSC(2)#	23.54	97.59	(80)	18.07	1.23–10.95	157.66	3.22
CdTe†	6.84	58.86	(53)	30.11	27.38	129.33	1.65
mc-Si‡	150.57	57.49	(57)	95.81	23.27	343.50	2.34

* Estimates by Smestad (1994).
\# Estimates by Meyer (1996).
† Estimates by Zweibel (1999).
‡ Estimates by Little and Nowlan (1997).
a Takes into account 95% cell yield.
b Representative efficiencies used : 5% for OSC, DSSC (1) and DSSC (2); 8% for CdTe; and 15% for mc-Si; 98% module yield for all.

mc-Si modules based on previous studies by Smestad (1994) and Meyer (1996) for DSSC, Zweibel (1999, 2000) for CdTe and Little and Nowlan (1997) for mc-Si.

We have a very large range in our estimated costs for OSC. The low end estimate is second lowest to DSSC (1); the high end estimate is second highest to DSSC (2). Note that DSSC (1) is the least cost while DSSC (2) is the high cost technology. This wide range reflects the uncertainty in estimating a process that has not even been perfected in the laboratory, let alone transferred to industry.

3. Levelized energy cost

We have estimated the LEC for an OSC PV system. The LEC includes balance of systems cost (BOS), as well as the amount of sunlight and the lifetime of the modules. We define BOS as costs common to all PV technologies, and include land, support structures, wiring, power conditioning, installation, and transportation. The total system cost is therefore the sum of module and BOS costs. We use a BOS cost of $75/m^2$, based on the projected long term goal for traditional silicon-based solar cells (BES, 2005). Adding this value to our baseline cost range of between $48.80/m^2$ and $138.90/m^2$ and dividing by output gives an installed capital cost (ICC) of between $2.48 and $4.28 per peak watt of power output.

To convert to LEC, we must amortize the capital cost of an installed watt of PV over the lifetime of the PV module, and divide by the energy produced in a year. We use a Capital Recovery Factor (CRF) based on a 10% discount rate and a 5-year lifetime.[4] To find the energy produced in a year by 1 W of installed PV, we use a capacity factor (CF) of 15.5%. This takes into account that PV cells only operate at a fraction of peak power when averaged over the course of a year, due to the diurnal cycle, seasonal variation in sun angle, and cloud cover. To arrive at this capacity factor we used an average location in U.S. i.e. Kansas City with 1700 kWh/m^2-year and assumed that total system output (in AC) is about 20% less than peak power rating (in DC) due operating temperature, resistance and power conditioning. Thus, our capacity factor equals $15.5\% = (1700 * 0.8)/8760$, assuming 8760 h in a year. Finally, assuming Operating and Maintenance costs (O&M) of $0.001/kWh, we estimate the LEC to be between 49¢ and 85¢/kWh, based on the following formula by Zweibel (2005)

$$LEC = (ICC * 1000 * CRF)/(CF * 8760) + O\&M$$

These costs are far from being competitive. We recalculate assuming that R&D into OSC will increase the efficiency and lifetime to an optimistic 15% efficiency and a 20-year lifetime.[5] Given these parameters the LEC would range between 7¢ and 13¢/kWh. From the literature, production costs of electricity in the U.S. by source in 2002 were as follows: 1¢–4¢/kWh for coal, 2¢–5¢/kWh for gas, 6¢–8¢/kWh for oil, 5¢–7¢/kWh for wind and 6¢–7¢/kWh for nuclear (http://nsl.caltech.edu). We contrast these costs, alongside the estimated LEC for OSC in bar graphs shown in Fig. 5.

The bar graphs in Fig. 5 show that the LEC for OSC at 15% efficiency and 20 years lifetime is higher than those of conventional electricity. However, the low end cost for OSC is the same as the high end cost for wind and nuclear. This generally means that OSC cannot economically compete with conventional sources of electricity. However, at this energy cost, OSC are inexpensive as compared to other PV technologies whose average LEC is 25¢–50¢/kWh. In fact, OSC are reducing the cost of PV electricity by fourfold.

Fig. 6 shows how the LEC is impacted by lifetime, efficiency, and manufacturing cost. We have plotted the LEC against lifetime for two different efficiencies and two different manufacturing costs. The impact of lifetime on LEC is most important when the lifetime is short; at longer life-

4 $CRF = \{i * ((i+1)^n\}/\{(i+1)^n - 1\}$.

5 Expert elicitations have indicated that the probability of achieving 15% and 30 years is 37% given $10 million/year for 10 years of federal funding (Baker et al., in press).

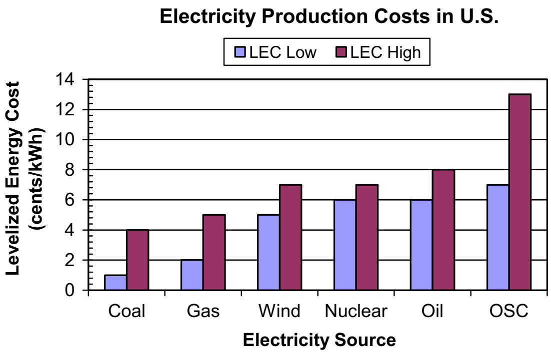

Fig. 5. Production costs of electricity in U.S. based on 2002 averages and that of OSC based on our estimates.

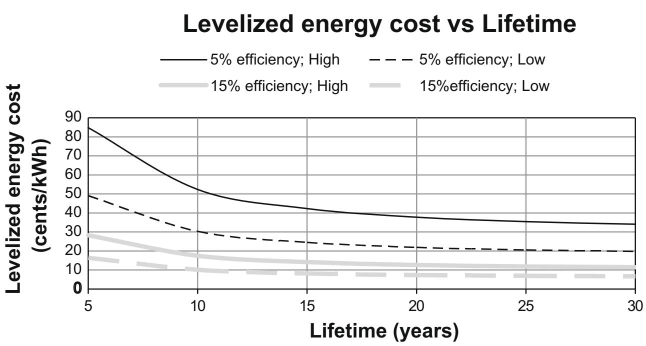

Fig. 6. LEC for OSC as a function of cell lifetime and efficiency based on the baseline low and high end overall module manufacturing cost estimate.

times it flattens out. Manufacturing cost is much more important when efficiency is low, with a maximum spread of \$0.36/kWh between the high and low estimate of manufacturing cost; compare this to a maximum spread of \$0.11 when efficiency is high.

4. Conclusions

We estimate that manufacturing costs for OSC will be between \$48.8 and \$138.9/m^2, resulting in a module cost between \$1.0 and \$2.83/W_p if we consider 5% module efficiency, 98% module yield and 1000 W_p power output per square meter. In this cost range, OSC compete economically with the TFSC technologies and traditional silicon-based PV technologies. However, assuming an efficiency of 5% and a lifetime of 5 years, this results in LEC between \$0.49 and \$0.85/kWh, a cost which is far from competitive in the general electricity market. If the industry can achieve efficiencies of about 15% and lifetimes of 20 years, we estimate that the LEC would range between \$0.07 and \$0.13/kWh.

The most important factor in the manufacturing cost is the substrate cost. In fact, the major benefit from OSC appears to be much lower substrate costs. If these costs could get even lower than our estimates it would be a great advantage to OSC. If, on the other hand, we are over-estimating the cost savings that can be achieved, OSC may lose some of their competiveness with other TFSC. The cell yield – the percentage of cells that are successfully manufactured – has the potential to derail OSC if it is not able to be held at a consistently high value. The single most important factor to the module cost and the LEC is the cell efficiency. At current efficiencies of 5%, OSC is nowhere near competitive with non-solar electricity. If higher efficiencies can be achieved, OSC starts looking much more attractive. Finally, the lifetime of the cells appears to present a hurdle – there is great improvement in LEC if cells last 10 or more years. Extending the lifetime from 20 to 30, say, has much less impact.

This is a preliminary estimate of OSC costs. It shows that OSC has the potential to reduce the cost of PV electricity by fourfold. However, much work remains to be done on understanding the particular processes for producing OSC, and the capital and labor costs associated with them.

Acknowledgement

This study was made possible with financial support from the Fulbright Scholarship awarded to Joseph Kalowekamo through the US Department of State from 2005–2007.

References

Baker, E., Chon, H., Keisler, J., in press. Advanced solar R&D: combining economic analysis with expert elicitations to inform climate policy. Energy Economics.

Basic Research Needs for Solar Energy Utilization, 2005. Report of the Basic Energy Sciences Workshop on Solar Energy Utilization. April 18–21 2005. US Department of Energy.

Brabec, C.J., 2004. Organic photovoltaics: technology and market. Solar Energy Materials and Solar Cells 83, 273–292.

Bundgaard, E., Krebs, F.C., 2007. Low band gap polymers for organic photovoltaics. Solar Energy Materials and Solar Cells 91, 954–985.

Dai, S. et al., 2004. Dye-sensitized solar cells, from cell to module. Solar Energy Materials and Solar Cells 84, 125–133.

Halme, J., 2002. Dye-sensitized nanostructured and organic photovoltaic cells: technical review and preliminary tests. Master's Thesis. Helsinki University of Technology, Finland.

Haynes, K.K., Baumann, A.E., Hill, R., 1994. Life Cycle Analysis of PV Modules Based on CdTe. Proceedings of the 12th EC PV Solar Energy Conference, Amsterdam, Netherlands.

Kapur, V.K., Basol, B.M., 1990. Key issues and cost estimation for the fabrication of $CuInSe_2$ (CIS) PV modules by the two-stage process. Proceedings of a 21st IEEE Specialists Conference, Kissimmee, Florida.

Keshner, M., Arya, R., 2004. Study of Potential Cost Reductions Resulting from Super-Large-Scale Manufacturing of PV Modules: Final Report. NREL Report No. SR-520-36844.

Kim, S.Y. et al., 2009. Network structure organic photovoltaic devices prepared by electrochemical copolymerization. Solar Energy Materials and Solar Cells 93, 129–135.

Krebs, F.C. et al., 2007. Large area plastic solar cell modules. Materials Science and Engineering B 138, 106–111.

Little, R.G., Nowlan, M.J., 1997. Crystalline Silicon Photovoltaics: the hurdle for thin films. Progress in Photovoltaic Research and Applications 5, 309–315.

Meyer, T., 1996. Solid state nanocrystalline titanium oxide photovoltaic cells, Thèse N° 1542, École Polytechnique Fédérale de Lausanne.
Peumans, P. 2006. Solar Cells Based on Organic Pigments: Device Architectures and Processing. In: SPIE Optics and Photonics Meeting, San Diego, CA.
Smestad, G., 1994. Testing of dye-sensitized TiO_2 solar cells I & II. Solar Energy Materials and Solar Cells 32, 259–272.
Tang, C.W., 1986. Two-layer organic photovoltaic cell. Applied Physics Letters 48, 183–185.
Zweibel, K., 1999. Issues in thin film pv manufacturing cost reduction. Solar Energy Materials and Solar Cells 59, 1–18.
Zweibel, K., 2000. Thin film PV manufacturing: materials costs and their optimization. Solar Energy Materials and Solar Cells 63, 375–386.
Zweibel, K., 2005. The Terawatt Challenge for Thin Film PV. Technical Report NREL/TP-520-38350.