Email enoch1680@mediaone.net
http://www.heliotronics.com
Tel: (781) 749-9593
Fax: (781) 749-3406

1083 Main St. Hingham, MA 02043

An Experience Curve Based Model for the Projection of PV Module Costs and Its Policy Implications

By Clayton Handleman
Heliotronics, Inc.
1083 Main St. Hingham, MA 02043
Ph 781 749 9593 Fax 781 749 3406
email chandleman@Heliotronics.com

The perennial question, asked of our industry, is "when will grid connected photovoltaics (PV) be cost effective"? PV modules are the most costly system component and therefore, understanding their cost behavior goes a long way towards providing an answer to this question. A commonly used industry rule of thumb is that each year module prices drop approximately 5%. This suggests that cost reduction is dependent on time and justifies wait and see policies. Heliotronics, however, has found that using a learning curve based model provides a much better fit to the industry production and cost data. In other words, PV modules cost reduction is dependent on the total cumulative production to date rather than time. In a relatively stable market, average wholesale PV module costs will drop 17% for every doubling of *cumulative*[1] production, *irrespective* of how long it takes for that doubling to occur. If sales growth is rapid and sustained, the annual cost reduction can be substantially higher than 5%. If sales growth is slow then annual cost reductions will be less than 5%. This subtle difference in framing has important implications for how we approach policy makers and how our industry presents itself to the general public. In particular, a time-based model suggests that policy makers wait until PV is cost competitive before committing public resources to it. Why should they spend their constituent's money on PV now when, at today's prices, they can have no significant impact on either cost or energy? However, the learning curve model sends a very different message. The more we install the cheaper it gets. If we install it sooner, the cost drops faster, if we wait, it will take longer for prices to drop. It creates for them the possibility of being enrolled as proactive participants in solving a world environmental and resource problem.

In this paper we present data to illustrate the excellent performance of the learning curve model. Using the model, we show the relationship between annual cost reduction and sales growth. Then based upon these tools provide a set of projection curves that enable decision makers to create policy that enables them to "dial in" PV break-even.

---

[1] It is important to make a distinction between cumulative production and annual production. Annual production is the sum total of all modules produced in a year. Cumulative production is the sum total of all modules produced since they first went into production.

Email enoch1680@mediaone.net
http://www.heliotronics.com
Tel: (781) 749-9593
Fax: (781) 749-3406

1083 Main St. Hingham, MA 02043

The key aspect of the model is that it uses, for the independent variable, total cumulative production rather than time. This is commonly done for manufactured products and it is striking how well PV cost and production data correlates to this type of model.

Figure 1 below shows the average wholesale price of PV modules as a function of cumulative production. Several aspects of the plot are noteworthy,

1) There is a remarkably consistent slope trend overall,
2) There is a major dip off trend,
3) There is a major rise above trend,
4) After the first transient, the plot reverts nicely back onto its original trend line.
5) After the second transient, the slope matches its previous value.

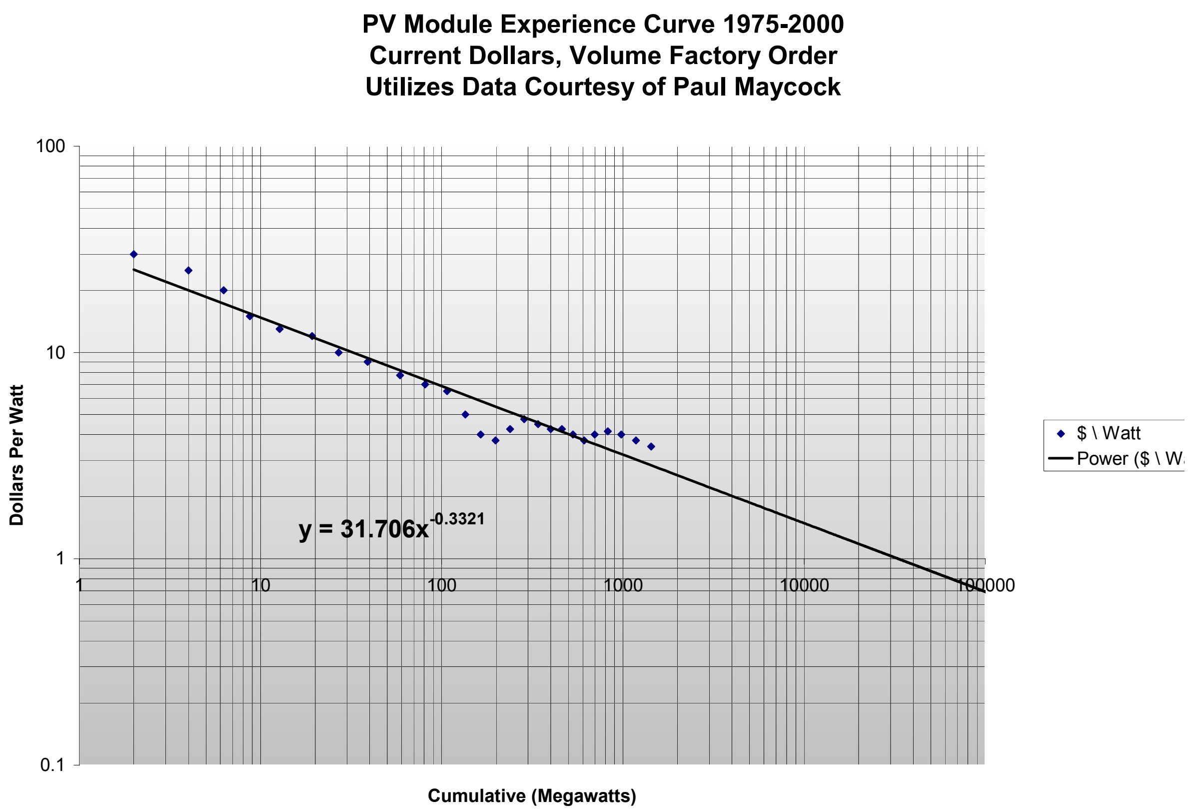

Figure 1 Log Log plot showing a log linear relationship between dollars per Watt ($/W) and cumulative megawatts.

The first of the two transient events corresponds approximately to 1985, the year in which tax credits for residential PV expired. This caused the industry's annual growth to

Email enoch1680@mediaone.net
http://www.heliotronics.com
Tel: (781) 749-9593
Fax: (781) 749-3406

1083 Main St. Hingham, MA 02043

slow from a staggering 45% to about 12%[2], see figure 1. In that year about 26MW of PV was sold. Production had been ramping and suddenly the bottom dropped out. Manufacturers were forced to sell at a loss and module prices dropped dramatically from $6.50 / Watt in 1985 to $3.75 / Watt in 1988. The beginning of this dip can be seen in figure 2 at about 100MW and ends at about 300MW. After the transient event, the experience curve returns to the trend line. The conclusion is that manufacturing costs continued to follow the trend while market forces altered the margins that companies could charge.

The second transient begins at about 600MW. This point corresponds to 1995. In 1994, the Japanese began to phase in a large PV industry stimulus program, in 1995 the Germans phased in a PV stimulus program. Combined these programs have taken the industry from roughly 15% annual growth in production to about 30% annual growth. This demand spike caused an uptick in module prices. Interestingly, while shifted up somewhat, the slope of the trend line resumed parallel to its earlier slope. During this period, demand has tended to exceed projections. While manufactures have been increasing production rapidly there is still a backlog. This has maintained market pressure preventing a return to the nonshifted cost curve. The shifted parallel nature of the trend is explained by the fact that demand pressure has allowed manufacturers to charge higher margins. The parallel slope indicates that manufacturing costs have continued to decline in the same way as before the demand peak arose. This is consistent with the fact that the industry is currently capacity constrained. With manufacturers adding capacity rapidly, it is anticipated that supply will catch demand and the curve will return to its earlier trend line. It would be highly desirable to generate the learning curve based upon the average manufacturing *production cost*. Unfortunately this data set was unavailable to us. This would be less impacted by the market fluctuations. However, when the explanations for the market transients are taken into account, our curve's fit to the data is very impressive.

[2] We plotted annual production growth rates vs time. We observed three regions where obvious changes had occurred. Those regions were segregated and in each region an average annual growth rate was calculated. We refer to the regions at the Energy Crisis Region, the Reagan Region and the Green region.

Email enoch1680@mediaone.net
http://www.heliotronics.com
Tel: (781) 749-9593
Fax: (781) 749-3406

1083 Main St. Hingham, MA 02043

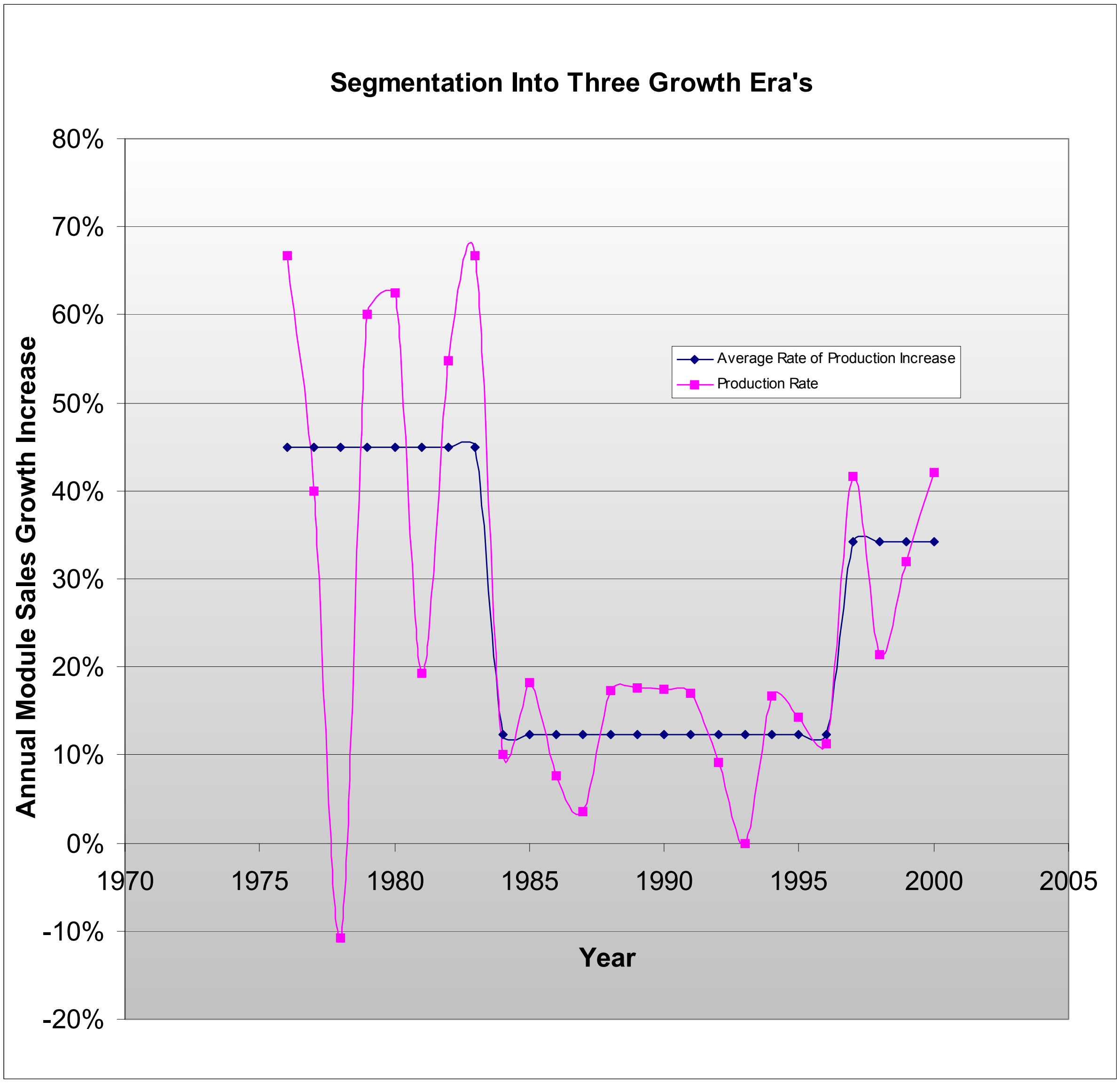

Figure 2, We have broken the industry development into three eras, the Energy Crisis Era (ECE), the Energy Glut Era (EGA) and the Green Era (GE). This plot shows the average during each of the eras as well as the dramatic short term fluctuations.

So where did the 5% rule come from anyway? While we have been unable to locate documentation for the 5% rule, we have been able to develop a plausible explanation. According to Renewable Energy World[3] the average annual growth rate for off grid applications is 15%. Using that number and our model, we calculate that module prices drop 4.6% annually. Referring to figure 2 we see that this is relevant between 1985 and

[3] Grid-Tied markets for photovoltaics – a new souce emerges, Bill Rever, BP Solar, Renewable Energy World July/August 2001.

Email enoch1680@mediaone.net
http://www.heliotronics.com
Tel: (781) 749-9593
Fax: (781) 749-3406

1083 Main St. Hingham, MA 02043

1995. Before that time and after, growth is much faster and therefore the module prices drop much faster.

We have entered a new phase of industry growth. With annual production growing at about 30% per year since 1995, the learning curve model predicts a trend of 8% annual reduction in module prices. Compounding this over the long term yields substantial benefits. For example, in 10 years at 5% the model predicts modules will cost 60% of what they did. At 8% it is down to 43% of what they cost today. In 21 years its 34% vs 17%! Figure 3 shows the annual percent decrease in module prices as a function of annual production growth. This is derived using the 17% learning curve model. It is useful in projecting annual price decreases for a constant industry growth rate.

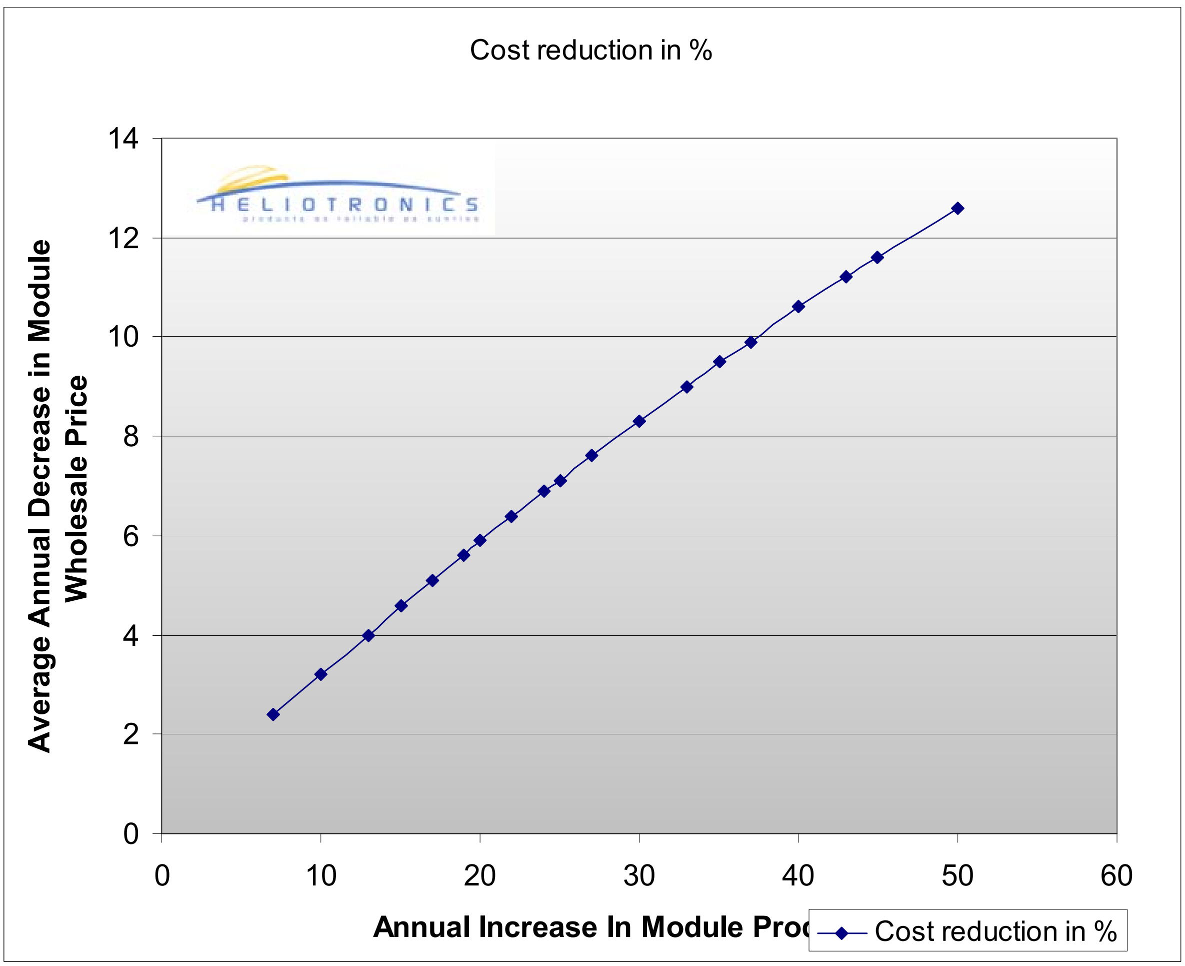

Figure 3, Rate of module cost reduction as a function of production growth.

Email enoch1680@mediaone.net
http://www.heliotronics.com
Tel: (781) 749-9593
Fax: (781) 749-3406

1083 Main St. Hingham, MA 02043

Using figure 3, we have put together a set of curves, figure 4, that projects breakeven under a variety of growth scenarios. If the market grows at a sustained rate these should provide an excellent prediction of average PV module wholesale prices. Many in the industry think that PV will be cost competitive with conventional sources when module prices reach $1.25 per Watt[4]. We show that cross over and the cross over for $1.00 per Watt. Using the more conservative figure of f$1.00 per Watt and assuming that the industry maintains a 30% growth rate, this model predicts breakeven in 2012.

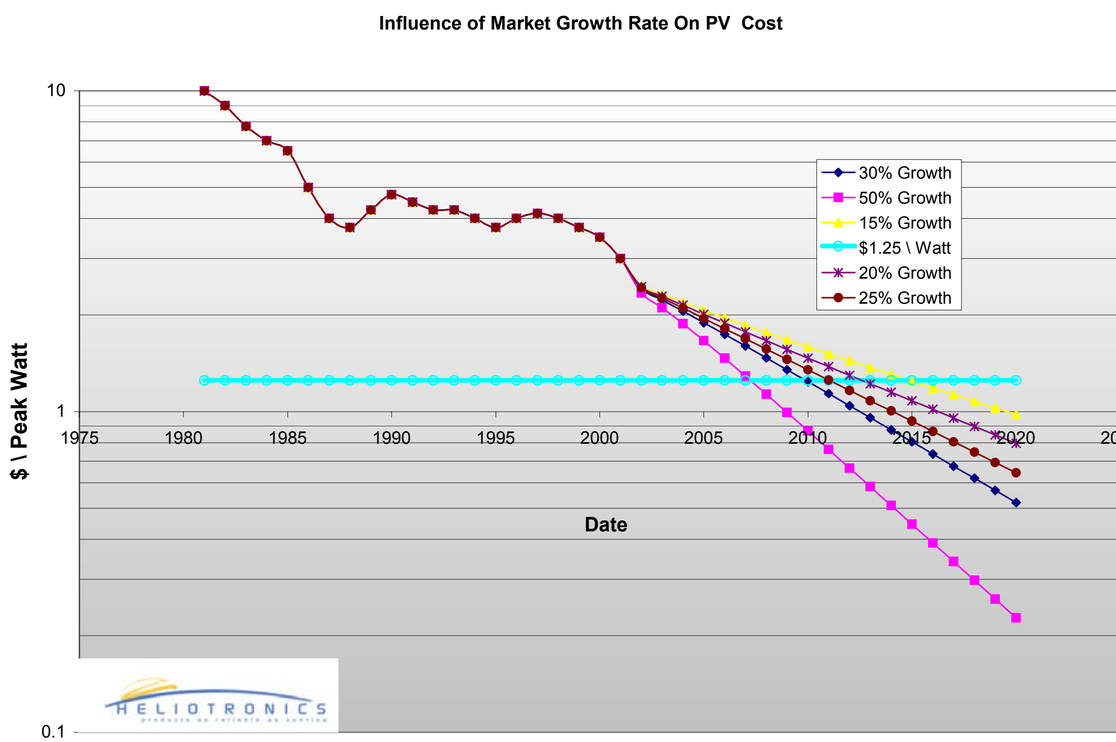

Figure 4 PV breakeven analysis. The irregular part of the curve represents average annual wholesale costs to date. The straight sections are cost projections for constant growth rates indicated in the legend.

Using a learning curve model we get an excellent fit to the data[5]. Where it doesn't fit, there are explanations in terms of market transients that likely caused wholesale prices to

[4] The argument goes that economies of scale will lead other costs such as installation, costs and balance of systems cost, to track the reductions in module costs. Also barriers such as nonuniform interconnection standards are expected to be reduced substantially. As such, module price projectiosn provides a good 1st order tool for breakeven analysis.

[5] In general, learning curves have been found to be useful and effective ways to understand costs of manufactured goods. However, when technologies shift, a different learning curve may result. There are some who think that the transition to thin film modules represents such a shift. The good news is that that will need to be a "better" learning curve than the current crystalline/polycrystalline curve or else there will not be a

Email enoch1680@mediaone.net
http://www.heliotronics.com
Tel: (781) 749-9593
Fax: (781) 749-3406

1083 Main St. Hingham, MA 02043

stop tracking production costs. We believe that the primary weakness of the model is that we don't know at what growth rate it breaks down. For example it predicts that at 500% growth, PV modules would cost $0.76 / Watt in 2003. Even with an enormous inflow of capital, common sense dictates that this could not occur, if for no other reason, the industry could not ramp production that fast. However, since we see good agreement at up to 45% growth rate there is a good range of conditions for which it appears to be valid.

While most in the industry understand intuitively that increased production leads to cost reductions, the data points to a very predictable pattern. The data correlates extremely well to cumulative production and poorly to time. In other words, 5% per year cost reduction was a fairly good rule of thumb when the industry's annual growth was close to 15%. It is off the mark when the industry growth rate is 30% annually. This distinction allows us to arm ourselves with a powerful perspective. That is that we can be proactive, we can tell the public and our elected officials that *they* can accelerate cost reduction by stimulating demand.

---

substantial movement, by the market, onto the new curve. It is likely that the model used in this paper represents a worst case. New technologies could accelerate cost reduction.

Email enoch1680@mediaone.net
http://www.heliotronics.com
Tel: (781) 749-9593
Fax: (781) 749-3406

1083 Main St. Hingham, MA 02043

The author thanks Paul Maycock for his ongoing compilation of data on the PV industry and his enthusiastic support of those who attempt to extract further value from the data. The primary data for this paper was provided by Paul in a December 29, 2000 fax. Additional information was obtained from conversations with Paul and from his annual industry summary printed in his newsletter Photovoltaic News.