Cost Reduction in Crystalline Silicon Solar Modules

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Abstract
A firm level dataset of the solar module industry is used to examine the factors that have contributed to the reduction in the unit production cost of crystalline silicon solar modules during 2005-2012.

Introduction
The production cost of crystalline silicon solar modules has decreased rapidly over the last few decades. Figure 1 plots the industry average module price over the years.

Figure 1
The module price has declined by a factor of over 100 during 1975-2012.

The decreases in production cost have often been attributed to the presence of learning externalities and economies of scale in the industry. In industries where there are learning externalities, firms accumulate experience as they produce their output, leading to lower production costs in the future. In industries with economies of scale, technical features of the production process are such that unit production cost is lower at higher production levels. Economies of scale are often thought to exist at the plant level, where bigger plant sizes allow for better optimization of production tools. It is important to know the extent of learning externalities and economies of scale in the solar industry because whether subsidies to the purchase or production of solar modules are welfare enhancing depend on the extent of learning externalities or economies of scale in the industry (see Benthem, Gillingham, and Sweeney (2008)). The learning process in the solar industry is usually captured using the equation $c = aY^{-b}$, where $c$ is the cost per watt of solar modules, and $Y$ is the total cumulated industry output. A simple regression of the form $\ln(p) = constant - b \ln(Y)$, where price per watt $p$ is used to proxy for cost per watt, gives a high $R^2$ of 0.91 and an estimate of -0.21 for the parameter $b$. The tight long-run fit of the learning curve has led to its use as a tool to predict the future cost of solar panels. Nemet (2006) is skeptical of the view that learning has been an important driver of cost reduction, and uses data during 1975-2002 to show that increases in plant size has been the most important driver of reduction in cost per watt.

Previous studies, including Nemet (2006), have used industry level data to examine the sources of cost reduction, and have used price as a proxy for cost. Industry level data is used because company level data is hard to come by in the solar industry. Prior to 2000, most of solar modules were manufactured by big oil corporations (BP and Shell) or diversified conglomerates in Japan (Sharp, Kyocera, Sanyo and Mitsubishi). These companies do not publish production costs for their solar module divisions, making it difficult to perform any firm level analysis on drivers of cost reduction. The early 2000s saw the emergence of many pure play solar companies as significant players in the solar market, many of whom listed as public companies on U.S stock exchanges. Since these companies are required to disclose their annual production costs in their filings at the Securities and...
Exchange Commission (SEC), a fair amount of firm level cost data has become available since then. The firm level data obtained from reports of these pure play solar companies are used to analyze the contribution of different factors towards reduction in production cost.

Data

Data was collected on 15 leading solar companies for the period 2005-2012. The annual Cost of Goods Sold (COGS) reported by these companies was divided by their annual shipments (in watts) to obtain their unit production cost for each year. The cumulated shipments of these companies was used as a proxy for learning.

Data was also collected on a number of variables which could affect the production cost. The light-to-electricity conversion efficiency of solar modules has increased over the years, and annual values for efficiencies of panels manufactured by the companies were calculated using data available from the Photon magazine. The price of polysilicon, the principal raw material used in the production of crystalline silicon solar modules, has changed over the years. Since purchase price of polysilicon for each company was not available, an industry average price of polysilicon was used. The quantity of polysilicon needed to produce a watt of solar modules has also decreased, and annual values of polysilicon usage were obtained from annual reports of the companies and other online articles. The average plant size of each company for every year was obtained from their annual reports.

Regression Equation

The following regression equation was estimated using the firm level data,

\[ \ln(c_{jt}) = b_0 + b_1 t + b_2 \ln(E_{jt}) + b_3 \ln(y_{jt}) + b_4 \ln(X_{jt}) + b_5 \ln(u_{jt}) + b_6 \ln(v_{jt}) + b_7 \ln(I_{jt}) + b_8 D_c \]

where \( c_{jt} \) is the unit production cost of company \( j \) in year \( t \), \( E_{jt} \) is the conversion efficiency, \( y_{jt} \) is the average plant size (in megawatts), \( X_{jt} \) is the cumulated production, \( u_{jt} \) is the polysilicon usage in grams/watt, \( v_{jt} \) is the industry average price of polysilicon, \( I_t \) is the total industry capital expenditures and \( D_c \) is a dummy variable that is set to 1 if firm \( j \) is from China and 0 if the firm is from another country. Pillai (2014) derives the equation above as the outcome of decisions made by solar module firms attempting to minimize their cost of production.

Results

The regression equation was estimated with various combinations of the right hand side variables. If only time, or cumulated firm output (which proxies learning) or plant size is included in the regression, the coefficient on each is statistically significant at the 1% level. However, when the full equation is estimated, the coefficients on these three variables are not significant even at the 10% level. The coefficients on the remaining variables all turn out to be statistically significant. The estimated coefficients imply that 1% reduction in polysilicon cost is associated with a 0.9% reduction in unit cost, a 1% reduction in polysilicon usage is associated with a 0.52% reduction in cost, a 1% increase in efficiency is associated with a 1% reduction in cost, and a 1% increase in industry investment is associated with a 0.26 % reduction in cost. The coefficient on the China dummy indicates that production cost of firms from China is 22.4% lower than firms from other countries. If annual firm output is used as a proxy for scale of production (instead of plant size), or if cumulated industry output is used a proxy for learning (instead of cumulated firm output), the results are very similar.

Conclusion

While proxies for learning (like cumulated firm or industry output) and for economies of scale (like plant size or current output) are highly correlated with the unit production cost of solar modules, they do not have any statistically significant explanatory power on production cost once other factors are taken into account. Decrease in the price of polysilicon, decrease in polysilicon usage, increases in conversion efficiency, increasing presence of lower cost firms from China and increases in industry investment were the important drivers of cost reduction in crystalline silicon solar modules during the period 2005-2012.

References

