Source of Cost Reduction in Solar Photovoltaics

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Abstract

The price of solar panels has fallen rapidly over the last few decades. Using an extensive dataset of prices, costs, output, sales and technical characteristics of firms in the solar industry during 2005-2011, this paper investigates the factors that have contributed to the decline in costs and prices. While previous studies have attributed learning-by-doing and static scale economics as the main drivers of cost reduction, we find that these do not have any significant effect on cost once four other factors are taken into account, namely, (i) reduction in the cost of a principal raw material, (ii) increasing presence of solar panel manufacturers from China, (iii) technological innovations, and (iv) increase in investment at the industry level. Together, these suggest that innovations in the upstream industries that supply the solar panel industry with raw materials and capital equipment have been an important driver of technological progress in the solar panel industry.

Keywords: Photovoltaics, Technological Change,

JEL: L19, L13, O30

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1. Introduction

The solar industry has expanded rapidly in the last few years. Annual production of solar panels has increased by a factor of fifteen during the period 2005-2011, growing at an average annual rate of 58% during the period.[1] Generation of electricity through solar panels is more costly than generation through conventional sources like coal or natural gas. The rapid expansion of the industry in the face of this cost disadvantage has occurred because of generous subsidies in many countries, including Germany, Italy, Spain, U.S, France, Japan, China and India.[2] These government subsidies have often been advocated on the grounds that support to the solar industry will lead to expansion of solar electricity generation and reduction in price of solar panels, which will eventually displace polluting generation sources like coal and natural gas. The underlying assumption behind this reasoning is that increases in output in the industry will reduce the cost of producing the panels, an assumption which has mostly been justified on the grounds that there are learning externalities and static economies of scale in the industry (see Algoso et al. (2005)). The increase in production in the last few decades has in fact been accompanied by reduction in the price of solar panels, a fact that has been often used to vindicate the presence of learning externalities and static economies of scale in the industry. In contrast to many earlier studies that attributed learning and static scale economies as being the important sources of reduction in the price of solar panels, this paper finds that (i) reduction in the cost of a principal raw material, (ii) increasing presence of solar panel manufacturers from China, (iii) technological innovations, and (iv) increase in investment at the industry level, were the principal drivers

[1] The growth rate was calculated based on annual production data published in Mehta (2011).

[2] Frondel et al. (2010) estimate the cost of subsidies to solar generation systems during 2000-2010 in Germany to be over 53 billion euros. The California state government has allocated 2.16 billion dollars for subsidies to solar during 2007-2016 (see CPUC (2009)). In 2012, Italy spend over $8.8 billion on subsidies to solar electricity (see http://www.pv-magazine.com/news/details/beitrag/a-look-at-italys-latest-conto-energia-100008223/#axzz2IioZQ4nZ)

of the reduction in cost and price of solar panels during 2005-2011.

There have been numerous studies, across many industries, documenting the decreases in unit production cost occurring alongside increases in variables used to proxy learning. These include Wright (1936) in the aircraft industry, Rapping (1965) in the ship building industry, Epple et al. (1996) in the truck manufacturing industry, and Lieberman (1984) in the chemical industry. Different variables have been used to proxy for learning, with cumulated output and cumulated investment being the two popular ones. For example, Sheshinski (1967) found that cumulated output and cumulated investment gave better results than calendar time in explaining improvements to productivity (which is inversely related to unit production cost) in many manufacturing industries. Lieberman (1984) uses different proxies for learning and finds that cumulated industry output and cumulated industry investment together provide the best explanation for reduction in unit production costs in the chemical industry.

Earlier critiques of the learning studies pointed out that while cumulated output has been found to have explanatory power in cost reduction, the sources by which learning occurs has not been made clear in many studies. This has led many researchers to look for other explanatory factors like R&D, engineering effort, and managerial policies which might be correlated with cumulated firm or industry output. These attempts have had mixed results, with Adler and Clark (1991), Mishina (1992), Jarmin (1994) and Lieberman (1984) finding that other variables only augment the effect of learning or have no effect at all. Other studies, find that the explanatory power of learning variables decrease when other factors are properly accounted for. Revisiting Rapping (1965) study on learning in the ship building industry, Thompson (2001) finds that capital deepening played an important role in productivity improvement in the U.S shipping industry, and halves the estimated size of the learning effect. Sinclair et al. (2000) find that cost reductions in a big chemical company which appear to be the result of learning were in fact the result of R&D and related activities undertaken by the company.

In the solar panel industry, most studies have used cumulated industry output as a proxy for learning. These studies assume that unit production cost is related to cumulated industry output through the relationship, $c(Y) = aY^{-b}$, where c is the unit production cost and Y is the cumulated output. The reduction in unit production cost with cumulated output is usually stated in terms of the learning rate, which is the percentage reduction in cost that occurs when cumulated output doubles. Williams and Terzian (1993) estimate that solar panel prices on the global market followed a learning rate of 18% between 1976 and 1992. IEA (2000) and Van der Zwaan and Rabl (2004) both find a learning rate of around 20%. Similarly, van Sark (2008) estimate learning rates ranging from 0.70-0.84. In contrast to the studies that emphasize learning effects, Nemet (2006) argues that expansion in plant size was the main driver of cost reductions in solar panels during 1975-2002.

Figure 1 shows the learning curve plotted using the average cost (and price) and cumulative output for the set of firms in the dataset used for the current study.

There is a clear break in the curve at 2008, with industry average price decreasing at a much faster rate with cumulated output during 2008-2011 than during 2005-2008. Similar to the earlier studies on solar industry, this paper finds that a simple regression of unit cost of production against variables used to proxy for learning, cumulated firm output or cumulated industry output, gives a highly significant learning coefficient. The unit production cost is also highly correlated with with proxies of static scale economies, current production or average plant size. In contrast to the earlier studies, this paper finds that the effect of any proxies for learning and static scale economies become statistically insignificant once four other factors which affect the cost of production are taken into account.

First, changes in the price of polysilicon, the principal raw material used in production of solar panels, have significant impact on the cost of solar panels. Second, firms based in China have significantly lower production costs than other firms. Third, technical improvements have played a role in the reduction in cost of solar panels. The industry has focussed on two well know technological pathways to reduce costs, through improvements in *conversion efficiency*, and through new techniques that reduce the usage of polysilicon in manufactur-

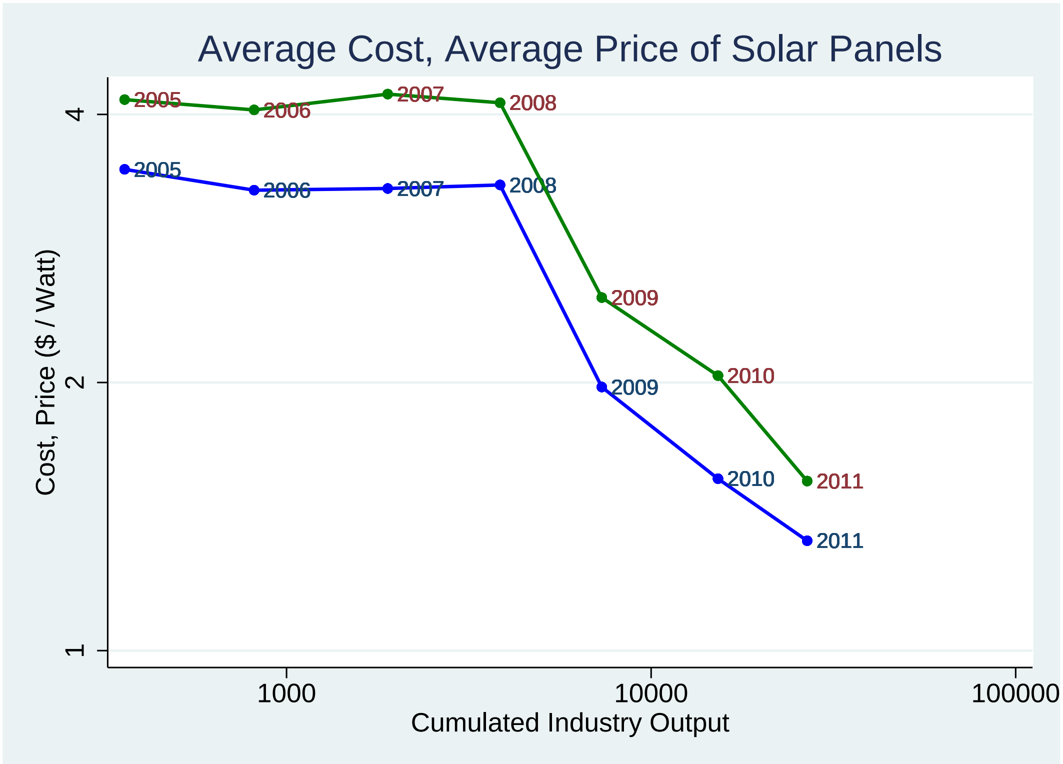

Figure 1: Learning curve for Solar Panels (2005-2011)

ing. These two are measurable parameters, and advertised by firms to signal the technical improvements that they have achieved. Data collected on these two variables show that technological improvements in these parameters have significant impact on production costs. Finally, increases in level of current industry investment also reduces cost of production of solar panels. The fact that it is the current industry investment, and not cumulative industry investment, which affects cost suggests that it is not learning associated with capital investment that is driving cost reductions. The most likely explanation is that the increased production of capital equipment reduced the cost of production of capital equipment because of economies of scale in the manufacture of capital equipment.

These four factors account for the spurious learning effect seen as correlation between cumulated output and production cost, and the spurious economies of scale seen as correlation between current output and production cost. The decrease in polysilicon price occurred during the same time that the industry was rapidly expanding in response to generous subsidies by many countries. The period also coincided with the rapid entry and expansion of many low cost firms from China, thus causing a spurious correlation between firm output (or plant size) and production cost. Similarly, increases in industry investment would clearly be correlated with increase in production. When these other factors are taken into account, proxies of learning and static economies of scale become statistically insignificant.

Many studies, including Lieberman (1984), use unit price as a proxy for unit cost for identifying learning effects, because of the non-availability of cost data. This is especially true in solar industry, where all existing studies have used data on module prices, and not costs. A novel aspect of the current paper is the use of both unit cost and price data. The sources of the data are described in section 4. The results are the same whether one uses unit cost or unit price with one notable difference. Improvements in conversion efficiency does not have any effect on price, while it reduces costs. The reason for this difference is examined in section 5.4. The next section provides an overview of the industry and sets the background for the model developed in section 3.

2. Overview of the Solar Panel Industry

The ability of some materials to convert sunlight to electricity, the photovoltaic effect, was first observed by Alexandre-Edmond Becquerel in 1839. Since then there have been much progress in the manufacture of solar cells that use such photovoltaic materials to produce electricity from sunlight. While solar cells can be made using a number of materials that show the photovoltaic effect, the most popular technology for making commercial solar cells is the crystalline silicon technology. Crystalline silicon solar cells commanded nearly 85% of the solar market in 2011. This paper focuses on sources of cost reduction in crystalline silicon solar cells.

The production of crystalline silicon solar cells begins with the manufacture of the high purity polysilicon, the base material from which solar cells are made. While silicon is cheap, found abundantly as sand, the conversion of silicon to high purity polysilicon is a sophisticated chemical process, and until recently most of it was undertaken by a handful of leading chemical companies. The polysilicon resulting from the purification process is in the form of large ingots. These ingots are then sliced into thin wafers and the wafers are then injected (or *doped*) with new materials to make the solar cell. Many such solar cells are strung together to make a solar module (also called a solar panel), the ones that are seen as square panels on rooftops. There are thus four basic steps in making a solar panel - manufacture of polysilicon, slicing polysilicon to wafers, conversion to solar cells, and stringing cells together to make solar modules. While some solar panel makers just specialize in the last step, other are backward integrated and manufacture cells, wafers and sometimes even polysilicon.

Solar modules are rated in terms of the electric power that they can generate, stated in watts. The clear focus of technological improvements in the solar industry has been to reduce the cost of making a watt of solar modules. Figure 1 shows that the cost and price of solar panels have decreased over the period 2005-2011. A cursory examination of the industry shows that many factors have contributed to this decline.

First, the price of polysilicon has changed significantly during 2005-2011. Figure 2 shows the price of polysilicon during 2005-2011. The price of polysilicon spiked up during 2005-2008, as the supply of polysilicon could not keep up with the increase in demand triggered by the new solar subsidies offered by many countries during 2005-2008. Construction of polysilicon plants takes over two years on average. The period 2005-2008 saw rapid expansion of capacity by incumbents as well as entry of new firms, and resulted in subsequent decline in polysilicon price. Note that the spike in polysilicon price during 2005-2008 coincides with the horizontal section of the learning curve in Figure 1 during 2005-2008, when cost and price of solar panels held steady despite the increase in output.

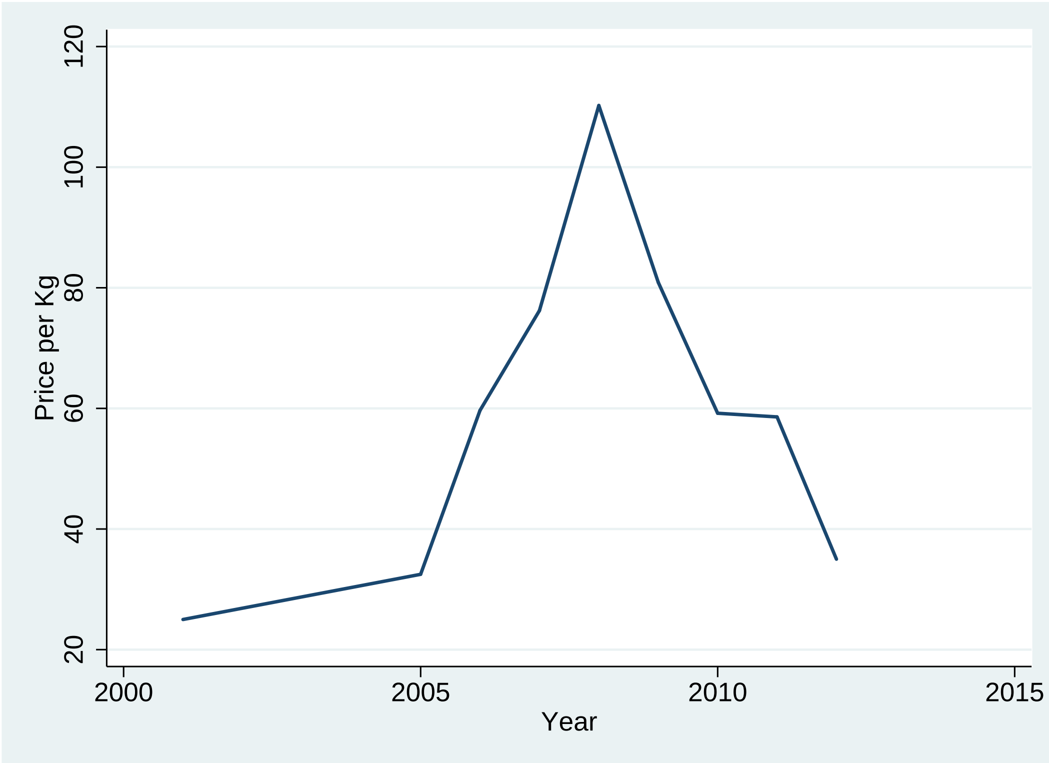

Figure 2: Average price of Polysilicon (2005-2011)

Notes: The price of polysilicon is the average of the selling price for four leading polysilicon manufacturers - Wacker, REC, GCL and Daqo. The selling price for each polysilicon manufacturer was obtained by dividing the annual revenue from polysilicon sales by the annual shipments. The prices obtained were quite close to the ones mentioned in Winegarner (2011).

Technological innovations in the industry during the last few years has also been an important driver of the cost reductions seen in Figure 1. There are two main technological pathways which firms have followed to reduce the cost per watt. First, firms undertake R&D and engineering efforts to reduce the amount of polysilicon needed to make a watt of solar modules. They do so using a number of different approaches, for example by reducing the thickness of wafers used and by reducing the wastage of polysilicon during the process of slicing wafers into cells (called in the industry as the *kerf loss*). The quantity of polysilicon required to make one watt of solar panels has decreased over the years (see Figure 3).

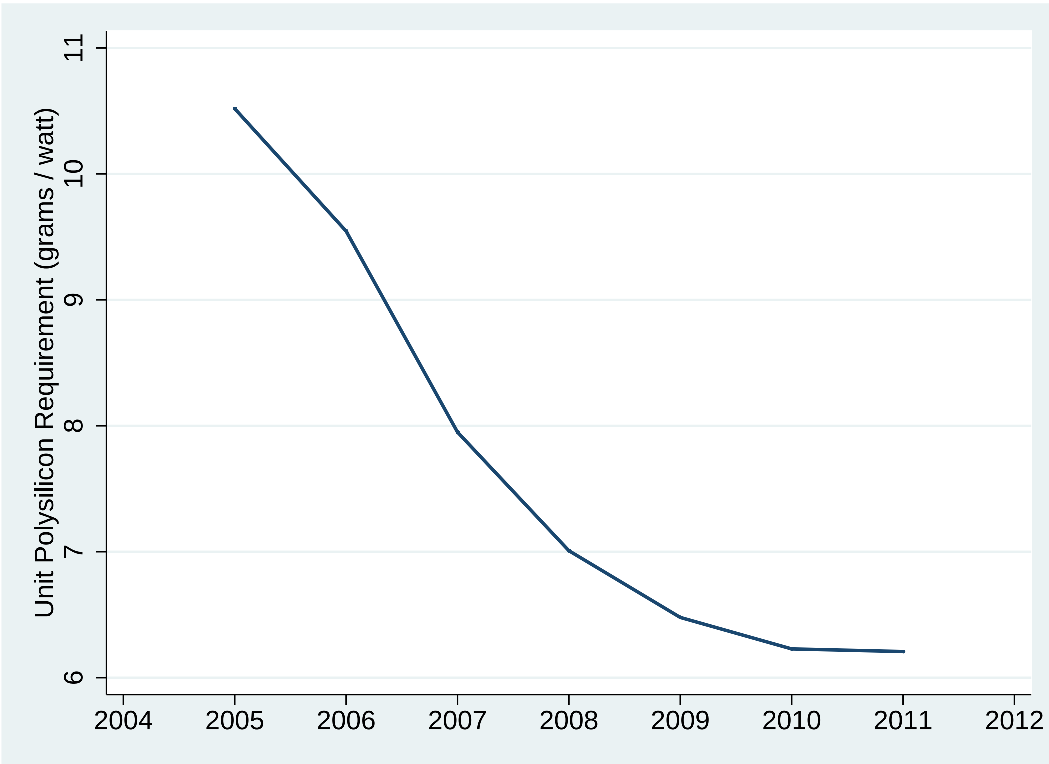

Figure 3: Average Unit Polysilicon Requirement (2005-2011)

Notes: The average of the unit polysilicon requirements of the firms in the dataset (see section 4) was used in the above figure. The unit polysilicon requirements of each firms was obtained from their annual reports or from articles in industry magazines.

Second, firms develop new methods that can increase the *conversion efficiency* of solar cells, often referred to as simply efficiency in the industry. Efficiency measures the ability of the solar panel to convert a given amount of light to electrical energy. For example, if a solar panel has an efficiency of 15%, it means that it can convert 15% of the light energy that falls on it to electrical energy. Everything else remaining the same, higher conversion efficiencies result in lower cost per watt. The average conversion efficiency in the industry has increased over the time period considered in this study (see Figure 4).

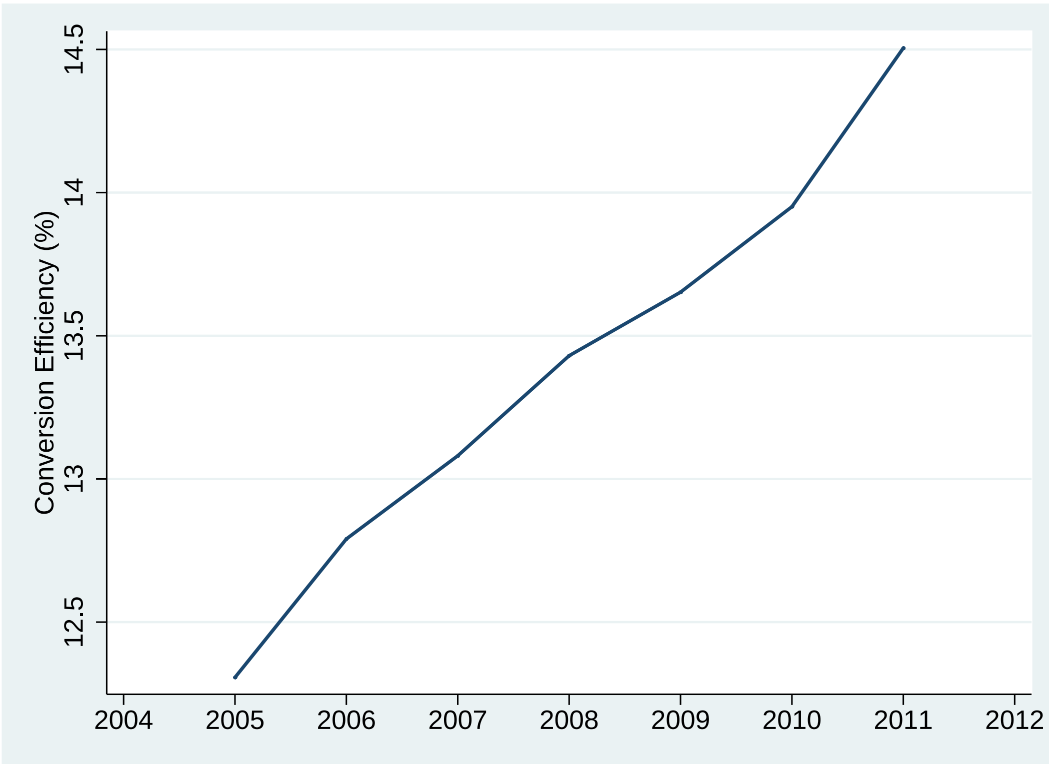

Figure 4: Average Efficiency of Solar Modules (2005-2011)

Notes: The module efficiency of each firm was obtained from their annual reports or from articles in industry magazines.

Reductions in price of polysilicon, decrease in unit polysilicon requirements and increases in efficiency of solar cells have been perhaps the more prominent aspects of this industry during the period of the study. An equally important facet has been the change in the international composition of production, especially the increasing presence of firms from China in the production of solar panels. The production cost (and selling prices) of solar panels is substantially lower for firms from China compared to firms from other parts of the world (see Figure 5), a fact that has drawn a lot of attention in recent policy debates. While this paper does not investigate the reasons for the lower production cost in China, note that both the unit production costs and selling prices are lower for firms from China.

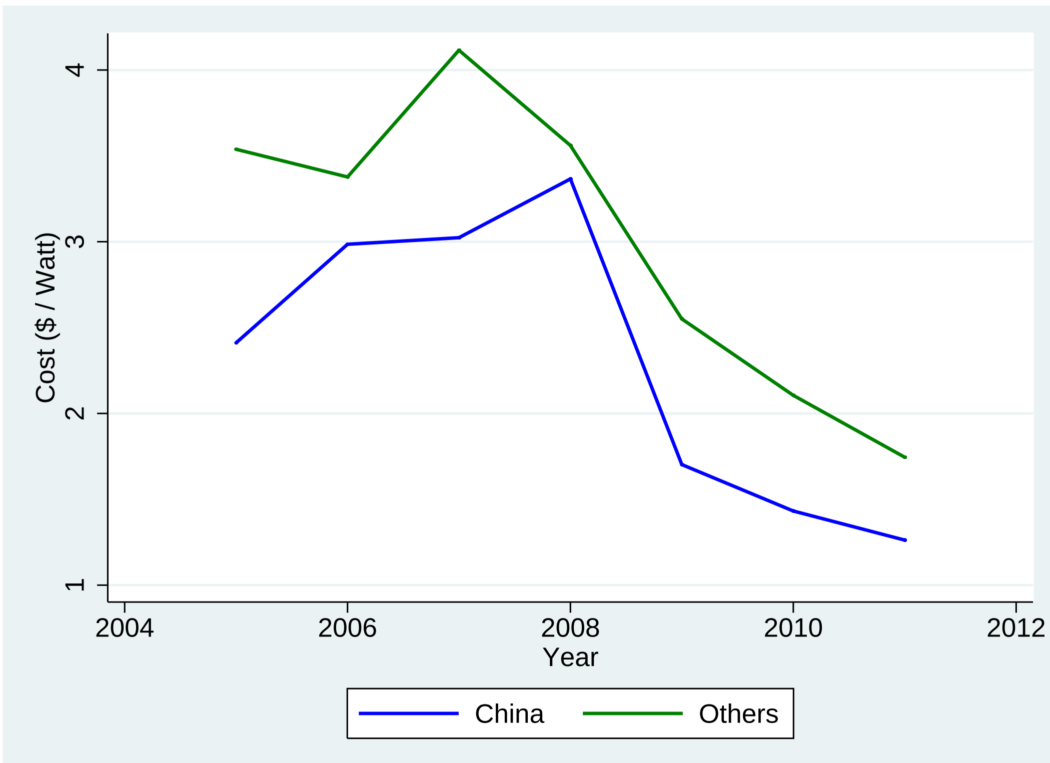

Figure 5: Average Cost of Solar Panels from China and from other Countries

Finally, the expansion of the industry during the period of the study has been accompanied by changes in the upstream capital equipment industry that supplies the solar panel industry with the machinery required to manufacture solar panels. There has been entry of new firms, expansion of existing firms as well as technological improvements in capital equipment. Many industry reports argues that these changes have led to reductions in the cost of capital equipment required to produce a unit of output.

The features of the solar technology and industry outlined above are used in the next section to develop a model of production used in the regression analysis.

3. Model

Solar panel manufacturing firm j produces panels according to the production function,

$$y_{jt} = e^{\lambda t} X_{jt}^{\theta} A_{jt}^{\delta} M_{jt}^{\alpha} K_{jt}^{\beta} \eta_{jt} \tag{1}$$

where X_{jt} is an index of cumulated experience of firm -j in time t, A_{jt} is an index of observable technical parameters that are known to influence the productivity of the firm (efficiency and unit polysilicon requirement), M_{jt} is the quantity of polysilicon input used, K_{jt} is the capital used in production and η_{jt} is the error term. The factor $e^{\lambda t}$ captures the effect of any variable that changes over time and is not captured through the other variables , X, A, K or M. Labor has been left out of the production function, primarily because many studies of the industry have found that payments to labor have been a minor component of cost of production during the period of the study, especially compared to expenditures on purchase of polysilicon and capital equipment (see Goodrich et al. (2011)).

Firms choose M_{jt} and K_{jt} to minimize the cost of production,

$$C_{jt} = v_t M_{jt} + r_t K_{jt} \tag{2}$$

where v_t is the price of polysilicon and r_t is the rental rate of capital equipment, which is the same across all solar panel manufacturers. Cost minimization leads to the following average cost function,

$$\bar{c_{jt}} = \left(e^{\lambda t}\right)^{-\frac{1}{\alpha+\beta}} y_{jt}^{\frac{1-\alpha-\beta}{\alpha+\beta}} \left(X_{jt}\right)^{-\frac{\theta}{\alpha+\beta}} \left(A_{jt}\right)^{-\frac{\delta}{\alpha+\beta}} v_t^{\frac{\alpha}{\alpha+\beta}} r_t^{\frac{\beta}{\alpha+\beta}} \eta_{jt}{}^{-\frac{1}{\alpha+\beta}} \tag{3}$$

It is assumed that there is an inverse relationship between price of capital equipment and volume of equipment purchases, and the assumption is incorporated into the model with the following equation,

$$r_t = i_t^{-\theta} \tag{4}$$

where $i_t = \sum_{j=0}^{N} i_{jt}$ is the total capital expenditures of all firms in the industry. Substituting equation (4) and taking logs gives the equation used in the regressions,

$$\ln(\bar{c}_{jt}) = b_0 + b_1 t + b_2 \ln(y_{jt}) + b_3 \ln(X_{jt}) + b_4 \ln(A_{jt}) + b_5 \ln(v_t) + b_6 \ln(i_t) + \epsilon_{jt} \tag{5}$$

The only addition made in the regression equation used in section 5 is the expansion of the term A_{jt} to include the technological parameters (efficiency and unit polysilicon requirement) separately.

4. Data

The dataset covers the period 2005-2011 and includes a total of 15 firms engaged in the manufacture of solar panels. Not all the firms are included every year, but data is available for all subsequent years once a firm is in the dataset, except for one firm which exited the industry in 2010 (see Table 1). The firms in the dataset accounted for only a portion of the total global solar panel panel production (13% in 2005 and 45% in 2011). The dataset includes most of the top producers of crystalline silicon solar panels in 2011, except for three Japanese conglomerates who do not publish data separately for their solar divisions.[3] The companies in the dataset are Suntech Power, Yingli Green Energy, Trina Solar, Canadian Solar, Hanwha Solarone, LDK Solar, ReneSola, Sunpower Corporation, Evergreen Solar, Solarworld AG, Aleo Solar, Solar Fabrik, Centrosolar and Renewable Energy Corporation. The percentage of solar panels in the dataset that were produced by firms from China increased steadily from 27% in 2005 to 79% in 2011.

[3]The three Japanese firms excluded from this study are Sharp, Kyocera and Sanyo.

Table 1: Data Summary

Year	Firms	Global Shipments (Million Watts)	Shipments in Dataset (Million Watts)
2005	8	1786	225
2006	11	2521	455
2007	12	3746	1080
2008	12	7056	1958
2009	13	10,660	3471
2010	15	20,800	7930
2011	14	26,255	11,884

For each company, annual data was collected on cost of goods sold (COGS), revenue, shipments and capital expenditures. For the U.S companies, the data was collected from their annual 10-K statements. All the companies in the dataset that are based in China are registered in U.S stock exchanges, and hence file an annual 20-F statement with the U.S Securities and Exchange Commission. The format for the 20-F statement is similar to 10-K statement, providing comparability between the data used for companies based in U.S and China. The cost of goods sold (COGS) for the companies in the dataset filing 10-K and 20-F includes the cost of materials, direct labor cost, utilities and depreciation of capital, and excludes the expenses on R&D, marketing and general administration. Hence the COGS reported by these companies are a good measure of their variable cost of production. For the companies based in Europe, the data was obtained from their annual reports. While some of the European companies report the cost of goods sold, a few report only the earnings before income and taxes (EBIT). Subtracting the sum of EBIT and reported expenses on R&D, marketing and general administration from the annual revenues, gives a measure of the variable cost of production that is comparable to the COGS reported by companies registered on U.S stock exchanges. All companies report their annual shipment of solar panels in watts.

The use of cost data derived from annual reports of companies has sometimes been criticized in the literature. But there a number of reasons to believe that concerns raised are less severe for the cost data that is used in this study. First, all the companies considered in the analysis are pure solar companies, so the variable costs they report in annual statements are those associated with solar production alone.[4] Second, many of the companies state in their annual reports that a substantial fraction of the COGS that they report are material costs, which are usually correctly reflected in annual reports. Third, the unit cost of production is the most closely watched metric in the industry, and market analysts routinely publish estimates of the units costs for different companies using their own methods. It is quite likely that the close scrutiny by industry observers put a heavy burden on the firms to report their costs truthfully. Fourth, the availability of price data, which is much less susceptible to the problems affecting cost data, provides a means to check on the results obtained using cost data.

The average variable cost of producing solar panels for each firm,($\bar{c}_{jt}$), was obtained by dividing COGS by annual shipments. The average price of solar panel was obtained by dividing revenue by shipments. The prices and costs were converted to base 2011 using the U.S. Consumer Price Index.[5] Data was collected on the size of plants (in watts) owned by each company, and an average plant size was variable was constructed for each year for each company. Annual data on the two technological parameters, efficiency and unit polysilicon requirement, for each company were obtained from their annual reports and from articles in industry magazines, especially Photon International and PV News.

The annual price of polysilicon was constructed from annual reports of leading polysilicon companies. The annual revenues of major polysilicon companies were divided by the annual

[4]One additional complication is that some of the companies are vertically integrated and manufacture wafers and solar cells in addition to solar panels. All companies considered here report the revenue and COGS for the panel (modules) sales separately from the revenue and COGS of other segments.

[5]Using undeflated values resulted in almost identical results, except for a slight increase in the rate of decrease in cost (price) over time.

shipments to obtain the average selling price of each companies. A quantity weighted average of these prices was taken the price of polysilicon.

5. Results

The results of the regression analysis are reported in Table 2. The dependent variable is the average variable cost.

5.1. Learning Curve and Static Economies of Scale

The first column of Table 2 shows the effect of regressing the average production cost on time (t). Time is significant at the 1% level, with the coefficient indicating a 18% average annual reduction in cost over the time period. The second column estimates a learning curve with the cumulative firm output as a proxy for learning. The firm cumulative output is significant at the 1% level, with doubling of output reducing the average cost by around 15%. If cumulative industry output is used instead of cumulative firm output, the learning rate learning rate decreases slightly to 13%. Learning rates obtained using cumulative industry output in other studies mentioned in section 1 are higher than the 15% found in this study, possibly because other studies considered older time periods, mostly during 1980-2000. The third column estimate the static economies of scale, using current firm output as a proxy. As indicated, current output is significant at the 1% with doubling of current output leading to a 15% reduction in costs. Using average plant size of each firm as a proxy for economies of scale, gives similar results, with doubling of average plant size corresponding to a 16% reduction in costs.

However proxies for learning (cumulative industry or cumulative firm output) and economies of scale (current output or average plant size) become insignificant in the regression when the list of explanatory variables are expanded to include the price of polysilicon and a dummy variable to indicate whether or not the firm is based in China. As can be seen from column (4), these two variables are significant at the 1% level, while cumulative output and current

Table 2: Estimates of average cost function parameters. Dependent variable - Average Variable Cost.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
t	-0.18***			-0.16***	-0.11***	0.003	-0.12***	-0.03	
	(-0.016)			(0.02)	(0.02)	(0.04)	(0.02)	(0.09)	
Y_{jt}		-0.21***		0.10	0.06	0.03	0.03	0.04	
		(0.02)		(0.07)	(0.07)	(0.06)	(0.07)	(0.07)	
y_{jt}			-0.24***	-0.11	-0.05	-0.01	-0.01	-0.01	
			(0.02)	(0.08)	(0.08)	(0.07)	(0.08)	(0.07)	
$china$				-0.23***	-0.25***	-0.28***	-0.27***	-0.28***	-0.26***
				(0.06)	(0.06)	(0.05)	(-0.06)	(0.05)	(0.04)
r_t				0.57***	0.70***	1.10***	0.69***	1.08***	1.05***
				(0.09)	(0.08)	(0.14)	(0.08)	(0.16)	(0.08)
u_t					0.48***	0.46***	0.43***	0.46***	0.46***
					(0.11)	(0.10)	(0.11)	(0.10)	(0.10)
e_{j0}					0.66**	0.70**	0.63**	0.70**	0.60
					(0.33)	(0.31)	(0.33)	(0.31)	(0.29)
e_{jt}					-1.01**	-1.17***	-1.02**	-1.16***	-0.98***
					(0.45)	(0.43)	(0.45)	(0.43)	(0.37)
i_t						-0.28***		-0.32**	-0.25
						(0.09)		(0.13)	(0.03)
i_{jt}							-0.02		
							(0.02)		
I_t								0.08	
								0.19	
R^2	0.59	0.47	0.53	0.82	0.86	0.88	0.87	0.88	0.88
Obs	87	85	85	85	83	83	82	83	83

Notes: Standard errors are given in brackets. Three stars indicate that the variable is significant at the 1% level, two stars at the 5 % level, and 1 % at the 10% level.

output become insignificant. Surprisingly, time remains significant in the regression, indicating the influence of some factor not captured through cumulative or current output. These possible additional factors are explored next.

5.2. Technological Innovations

It is possible that in the regression in column (4), time is capturing the impact of improvements in technological characteristics which are not correlated with current or cumulative output. These technological improvements could be the result of R&D and engineering efforts undertaken by firms. Fortunately, as mentioned in section 2, there are two measurable technological parameters in the solar panel industry that have been the main targets of R&D efforts to reduce cost - conversion efficiency and unit polysilicon requirement. Although all the firms included in this study use the same basic technology, they often include additional processing steps based on proprietary knowledge to increase the conversion efficiency of solar cells. Additional processing steps usually result in higher costs, so firms with higher efficiency solar panels usually have higher production costs as well.[6] Hence, one would expect a higher efficiency to be associated with higher costs in a cross-section of firms, while higher efficiency would be associated with lower costs for a given firm over time. These two effects can be captured with two variables, the efficiency of the firm in the first year of the study, and the efficiency of the firm in the current year.

Column (5) of Table 2 shows the regression results when these three technological parameters are included. Unit polysilicon requirement is significant at the 1% level while the efficiency parameters are significant at the 5% level. As expected, the coefficient on initial efficiency is positive, capturing the cross-sectional impact of differences in efficiency on cost. The coefficient on current efficiency is negative, indicating that increases in efficiency have led to reduced costs, once the differences in initial efficiency are controlled for.

However, even after the technological variables are added in, time still remains significant

[6]Increasing efficiency has been a primary focus of R&D at all firms during the period of the study, and many have released new products based on technological improvements that increase efficiency. For example, the leading module company Suntech released a new family of high-efficiency solar modules codenamed Pluto, purporting higher efficiency than its current products. The leader in efficiency has been Sunpower whose Maxeon product line has the highest efficiency of all commercial solar cells.

in the regression.

5.3. Investment

To explore whether the explanatory power of time in column (6) of Table 4 is due to factors related to changes in investment over time, a number of measures related to investment where constructed. The annual capital expenditures undertaken by each firm where obtained from their annual reports, and used as a measure of firm level investment. Firm level capital expenditures were added up across firms to obtain a measure of total annual industry investment. The annual capital expenditures were added up over years to obtain cumulative investment at the firm and industry level.

Column (7) shows the results when current industry investment is added in the regression. Not only is current industry investment significant at the 1% level, but the inclusion of current industry investment makes time insignificant in the regression. Firm level investment however, does not have any effect on costs, and time remains significant when firm level investment is included. To check whether the effect of industry investment is because of any learning associated with capital equipment, cumulated industry investment was added to the regression along with current industry investment. Column (9) show the result, cumulated industry investment is insignificant while current industry investment remains significant, suggesting that it is not learning associated with investment that is leading to lower production costs.

5.4. Using Price instead of Costs

A number of authors have raised objections to the use of accounting cost data in economic studies. Schmalensee (2012) however argues that cost data when used judicially can be useful in economic studies. As a check on the results with cost as the dependent variable, the regression analysis was repeated with average price as the dependent variable. The regression results are shown in Table 3.

The results are essentially the same as in the regression with cost as the dependent variable, with one notable exception. The technological parameters, initial efficiency and current efficiency are not significant in the price regression, while they are significant in the cost regression. The reason for this difference is that consumers value efficiency per se, and improvements in efficiency increases the price that consumers are willing to pay. This is because higher efficiency solar panels require less physical area to achieve the same electric power when compared to low efficiency panels. This decrease in physical area required is valuable to consumers, especially in the case of residences where rooftop area is limited. Further, lower area means that less of accessorial materials like mounting structures are needed to fix the solar panels, thus reducing the overall cost of the system. Hence, on hand increases in efficiency reduces the production cost of solar panels and on the other hand increases in efficiency raises the price that consumers are willing to pay. These opposing effects result in efficiency being insignificant in the price regressions.

6. Discussion

Although the production costs of solar panels have fallen over the last few decades, further declines are necessary for solar electricity generation to achieve cost parity with conventional generation sources. A report by the U.S Department of Energy, for example, sets a target solar panel price of $0.54 per watt, well below the average price of $1.55/watt in 2011, for solar to achieve cost parity with other sources (see DOE (2012)). This section analyzes the results of the regressions and examines the prospects of further declines in solar panel costs in the light of the results.

As the results indicate, polysilicon price has a significant impact on production cost of solar panels. During the period of the study, polysilicon price first rose and then declined to the levels close to what it was at the beginning of the time period covered in this study. This reduction in prices was preceded by the expansion of production capacity by incumbents and entry of new firms. The resulting increase in competitive pressure has lead to decreasing

Table 3: Regression results. Dependent variable - Average Price

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
t	-0.19***			-0.18***	-0.14***	-0.04	-0.15***	-0.17*	
	(-0.02)			(0.02)	(0.02)	(0.04)	(0.02)	(0.09)	
Y_{it}		-0.20***		0.13	0.11	0.09	0.10	0.09	
		(0.03)		(0.07)	(0.07)	(0.07)	(0.07)	(0.06)	
y_{it}			-0.24***	-0.11	-0.11	-0.08	-0.09	-0.06	
			(0.03)	(0.07)	(0.08)	(0.07)	(0.09)	(0.06)	
$china$				-0.23***	-0.20***	-0.23***	-0.21***	-0.25***	-0.29***
				(0.05)	(0.06)	(0.06)	(-0.06)	(0.05)	(0.05)
r_t				0.58***	0.64***	1.00***	0.64***	0.91***	1.12***
				(0.08)	(0.09)	(0.15)	(0.09)	(0.16)	(0.10)
u_t					0.31***	0.29***	0.29**	0.31***	0.33***
					(0.11)	(0.11)	(0.12)	(0.10)	(0.13)
e_{j0}					0.28	0.32	0.27	0.31	
					(0.35)	(0.34)	(0.35)	(0.33)	)
e_{jt}					-0.05	-0.19	-0.05	-0.15	
					(0.48)	(0.46)	(0.48)	(0.46)	
i_t						-0.25***		-0.40***	-0.34***
						(0.09)		(0.13)	(0.04)
i_{jt}							-0.01		
							(0.01)		
I_t								0.31	
								0.20	
R^2	0.55	0.46	0.52	0.79	0.85	0.86	0.85	0.86	0.81
Obs	85	84	84	84	84	84	84	83	85

gross margins for polysilicon firms. Analyst's reports indicate that many firms are operating at zero gross profits, and a few firms have exited the industry (see Prior and Campbell (2011)). Exit of firms and letting up of competitive pressure might make further declines in polysilicon prices difficult. But there has also been new technological developments in polysilicon manufacturing, with many firms turning to the development of cheaper chemical processes in the manufacturing.[7] Even so, Pillai and McLaughlin (2012) use a model of competition in the solar industry to show that even a 75% decline in the price of polysilicon cannot, by itself, enable cost parity of solar generation with conventional generation sources.

The increasing presence of manufacturers from China whose production costs are less than other firms has been another reason for the decline in the average industry cost. It is to be noted that the costs (and prices) of firms from China are lower even after accounting for differences in technological factors like conversion efficiency and unit polysilicon requirement. The coefficient -0.26 on the dummy for China indicates that production cost of firms from China are 23% lower than that of firms from other countries.

The results indicate that a 1% increase in efficiency leads to almost 1% reduction in average cost and a 1% reduction in unit polysilicon requirement leads to a 0.46% reduction in cost, everything else remaining the same. Further improvements in the the two technological parameters, unit polysilicon requirement and efficiency, have been the focus of R&D efforts at many leading solar companies. Gabor and Mehta (2012) outlines a set of nine technological innovations that firms are currently pursuing which might lead to higher efficiencies and lower unit polysilicon requirements.

The regression results show that a 1% increase in investment in the industry is associated with a 0.25% reduction in the average production cost. The decrease could be the result

[7] For decades, all polysilicon has been manufactured using the so called Siemen's process. In the last decade, new processes called FBR and UMG processing have been developed which are supposedly cheaper than the traditional Siemen's processes.

of economies of scale in the production of capital equipment. It could also be that the bigger size of the market increases the incentive for capital equipment firms to do R&D to reduce the cost of equipment that they sell to solar panel firms. Further investigation of the upstream capital equipment market is necessary to provide more insight into the causes of the decline in equipment prices.

7. Conclusion

The reduction in average production cost and price of solar panels during 2005-2011 have been driven by reduction in cost of polysilcon, improvements in technology, increasing market penetration of lower cost firms from China, and increases in industry investment. Learning externalities and static economies of scale do have any significant explanatory power over solar panel cost (or price), once the other factors are taken into account. These results suggest that government policies aimed at reducing the cost of solar panels, necessary to achieve cost parity of solar electricity generation with conventional sources, should target technological advancements not only in the solar panel industry but also in the upstream industries manufacturing polysilicon and capital equipment.

References

Adler, P.S., Clark, K.B., 1991. Behind the learning curve: A sketch of the learning process. Management Science 37, 267–281.

Algoso, D., Braun, M., Chiaro, B.D., 2005. Bringing solar to scale: California's Opportunity to Create a Thriving, Self-Sustaining Residenital Solar Market. Technical Report. California Research and Policy Center.

CPUC, 2009. About the California Solar Initiative. Technical Report. California Public Utilities Commission.

DOE, 2012. Sunshot Vision Study. Technical Report. Department of Energy.

Epple, D., Argote, L., Murphy, K., 1996. An empirical investigation of the microstructure of knowledge acquisition and transfer through learning by doing. Operations Research 44, 77–86.

Frondel, M., Ritter, N., Schmidt, C.M., Vance, C., 2010. Economic impacts from the promotion of renewable energy technologies: The german experience. Energy Policy 38, 4048–4056.

Gabor, A.M., Mehta, S., 2012. Innovations in Crystalline Silicon PV 2013: Markets, Strategies and Leaders in Nine Technology Areas. Technical Report. Greentech Media.

Goodrich, A., James, T., Woodhouse, M., Noufi, R., Margolis, R., 2011. Solar PV Manufacturing. Technical Report. NREL.

IEA, 2000. Experience Curves for Energy Technology Policy. Technical Report. International Energy Agency.

Jarmin, R.S., 1994. Learning by doing and competition in the early rayon industry. RAND Journal of Economics 25, 441–454.

Lieberman, M.B., 1984. The learning curve and pricing in the chemical processing industries. RAND Journal of Economics 15, 213–228.

Mehta, S., 2011. 27th annual data collection results. PV News , 3–8.

Mishina, K., 1992. Learning by new experiences. Mimeo .

Nemet, G.F., 2006. Beyond the learning curve: factors influencing cost reductions in photovoltaics. Energy Policy 34, 3218–3232.

Pillai, U., McLaughlin, J., 2012. Polysilicon price declines and solar grid parity. Working Paper .

Prior, B., Campbell, C., 2011. Polysilicon 2012-2016: Supply, Demand and Implications for the Global PV Industry. Technical Report. Greentech Media.

Rapping, L., 1965. Learning and world war II production functions. Review of Economics and Statistics 48, 81–86.

van Sark, W.G., 2008. Introducing errors in progress ratios in determined from experience curves. Technological Forecasting & Social Change 75, 405–415.

Schmalensee, R., 2012. On a level with dentists? Reflections on the evolution of industrial organization. Review of Industrial Organization 41, 157–179.

Sheshinski, E., 1967. Test of the learning by doing hypothesis. Review of Economics and Statistics 49, 568–578.

Sinclair, G., Klepper, S., Cohen, W., 2000. What's experience got to do with it? Sources of cost reduction in a large specialty chemicals producer. Management Science 46, 28–45.

Thompson, P., 2001. How much did the liberty shipbuilders learn? New evidence for an old case study. Journal of Political Economy 109, 103–137.

Williams, R.H., Terzian, G., 1993. A benefit/cost analysis of accelerated development of photovoltaic technology. Technical Report.

Winegarner, R.M., 2011. Polysilicon (supply and demand). `http://www.sageconceptsonline.com/docs/report2.pdf`.

Wright, T.P., 1936. Factors affecting the cost of airplanes. Journal of Aeuronautical Sciences 3, 122–128.

Van der Zwaan, B., Rabl, A., 2004. The learning potential of photovoltaics: Implications for energy policy. Energy Policy 32, 1545–1554.