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Drivers of cost reduction in solar photovoltaics☆

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ABSTRACT

Using a new dataset of costs, output, sales, technical characteristics, and capital expenditures of firms in the solar industry during 2005–2012, this paper investigates the factors that have contributed to the decline in the cost of producing solar panels. While previous studies have attributed learning-by-doing and economies of scale as important drivers of cost reduction, 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. These findings suggest that the upstream industries that supply the solar panel industry with raw materials and capital equipment have been important contributors to the reduction in the production cost of solar panels.

1. Introduction

The solar photovoltaic industry has expanded rapidly in the last few years. Annual production of solar panels has increased by a factor of sixteen during the period 2005–2012, growing at an average annual rate of 56% during the period.[1] Generation of electricity through solar panels was more costly than generation through conventional sources like coal or natural gas for the period 2005–2012 (see Woodhouse et al. (2011), Tidball et al. (2010) and Prior (2011)). The rapid expansion of the industry in the face of this cost disadvantage has occurred because of generous subsidies in many countries.[2] These government subsidies have often been advocated on the grounds that support to the solar industry will lead to the expansion of solar electricity generation and reduction in production cost and price of solar 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 Benthem et al. (2008), Algoso et al. (2005), and Shrimali and Baker (2011)).

There have been numerous studies, across many industries, documenting decreases in unit production cost occurring alongside increases in variables used to proxy learning.[3] Different variables have been used to proxy for learning, with cumulated output and cumulated investment being the two popular ones.[4] Critiques of the learning studies have pointed out that learning curves do not explain the process by which cost reduction occurs, which has led many researchers to look for explanatory factors which might be correlated with cumulated firm or industry output.[5]

In the solar panel industry, most studies have used cumulated industry output as a proxy for learning, assuming a relationship of the form $c(Y) = aY^{-b}$, where c is the unit production cost and Y is the cumulated output. The reduction in unit production cost with increases in cumulated output is usually stated in terms of the learning rate, which is the

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[1] The annual production data were taken from the dataset compiled by Earth Policy Institute, available at http://www.earth-policy.org/data_center/C23.

[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 spent 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). A number of studies examine the impact of subsidies to renewable energy products on adoption of these products—see Hughes and Podolefsky (2013) and Chandra et al. (2010).

[3] 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.

[4] 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. Dimensions of learning can vary across industries, see Argote (2013) for a good description of learning in different industries.

[5] These attempts have had mixed results, with Adler and Clark (1991), Mishina (1999), Jarmin (1994), and Lieberman (1984) finding that other variables only augment the effect of learning or have no effect at all. Revisiting Rapping's (1965) study on learning in the ship building industry, Thompson (2001) finds that properly accounting for capital deepening halves the size of the learning effect estimated in Rapping (1965). 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.

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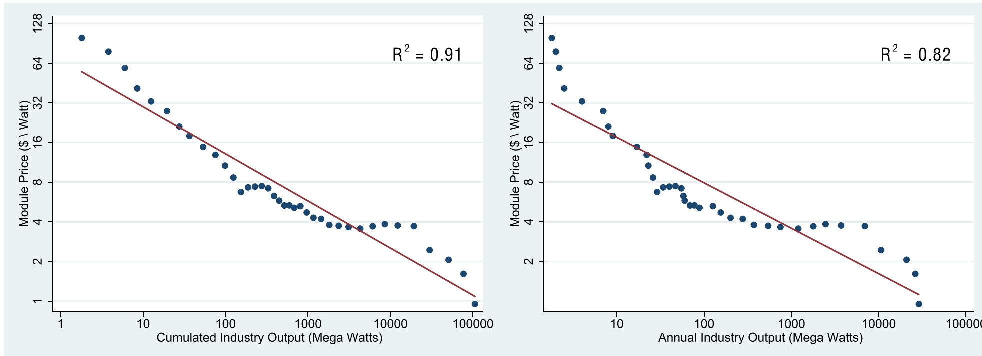

(a) (b)

Fig. 1. *Notes:* The graph on the left, plotting module price against cumulated industry output, is often referred to as the learning curve. The slope of the regression line corresponds to a price decline of 21.5% for every doubling of cumulated output. The graph on the right shows the module price against annual industry output. The slope of the regression line corresponds to a price decline of 21% for every doubling of current output.

percentage reduction in cost that occurs when cumulated output doubles.[6] Since cost data are usually unavailable, price is usually used to proxy cost. The left graph in Fig. 1 plots the price against cumulated industry output for 1970–2012, which indicate a learning rate of 21.5%.[7] Similarly, the right graph in Fig. 1 indicates that price also shows a log-linear relationship with current industry output, with the negative slope often perceived as indicating the presence of economies of scale in production.[8]

However, this paper finds that cumulated industry output (or other proxies for learning like cumulated firm output, cumulated firm investment, or cumulated industry investment) and current industry output (or other proxies for economies of scale like current firm output or plant size) do not have a statistically significant effect on production cost once other relevant factors are taken into account. The next section examines these factors in detail.

2. Overview of the solar panel industry

The ability of some materials to convert sunlight to electricity, the photovoltaic effect, was first observed in the mid nineteenth century. Since then, there has been much progress in the manufacture of solar cells that use such photovoltaic materials to produce electricity from sunlight. The most popular technology for making commercial solar cells is the crystalline silicon technology, which accounted for over 90% of the industry output in 2012. This paper focuses on sources of cost reduction in crystalline silicon solar panels.

The production of crystalline silicon solar panels begins with the manufacture of the high-purity polysilicon, which is then subjected to many chemical processes to make a solar cell, the basic electricity-producing unit. Many solar cells are strung together to make a solar panel (also called a solar module), which are the square panels seen on rooftops. The focus of this paper is on firms that manufacture solar panels, though most of the firms in the dataset used in this study are vertically integrated and also manufacture solar cells. Solar panels are rated in terms of the electric power that they can generate, stated in watts, and firm and industry output are quantified in terms of watts produced. Fig. 2 shows the reductions in price per watt and cost per watt for the period 2005–2012.[9]

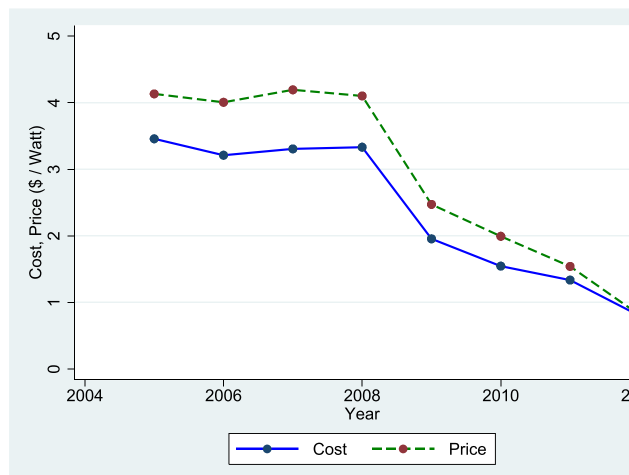

Fig. 2. Reduction in price and cost of solar panels (2005–2012). *Notes:* The cost per watt and price per watt are the averages of these variables for the fifteen firms in the dataset. See Section 4 for details.

A cursory examination of the firm level data used in this paper suggests a number of reasons that could have contributed to the decline in cost per watt seen in Fig. 2. Four factors that have commonly been considered as important drivers of cost reduction show up in the data (see Fig. 3).[10] First, all firms in the dataset show increases in the light-to-electricity *conversion efficiency* of their solar panels, often referred to as just efficiency in the industry (Fig. 3a). Efficiency measures the ability of the solar panel to convert a given amount of light to electricity, and everything else remaining the same, higher conversion efficiencies result in lower cost per watt.[11] Second, the price of polysilicon, the main raw material used in the manufacture of solar panels, has changed significantly during 2005–2012 (Fig. 3b). Third, all firms have reduced the amount of polysilicon needed to make a watt of solar panels (Fig. 3c). Fourth, the average size of manufacturing plants of each firm has also increased over time (Fig. 3d). Nemet (2006) argues that increase in plant size was the main driver of cost reduction in solar panels during 1975–2002.

The data also point to two other factors that have not been considered before in the literature. The international composition of solar

[6] Suppose $c = aY^{-b}$, and cost changes from c_0 to c' when output doubles. Then when output doubles, cost reduces by a factor $\frac{c'}{c_0} = 2^{-b}$. Hence the percentage reduction in cost (learning rate) is $LR = \left(1-\frac{c}{c_0}\right) * 100 = \left(1-2^{-b}\right) * 100$.

[7] 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%.

[8] The data for Fig. 1 were taken from the dataset compiled by Earth Policy Institute.

[9] The industry average gross margins for the years 2005–2012 were 17%, 20%, 21%, 19%, 21%, 22%, 11%, and 2%, respectively.

[10] Nemet (2006) and Swanson (2006) discuss these four factors.

[11] 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.