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# A Model of Competition in the Solar Panel Industry <sup>☆</sup>

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## Abstract

We develop a model of competition in the solar panel industry. Solar firms manufacture panels that are differentiated both vertically and horizontally, and compete by setting quantities. The equilibrium of the model is consistent with a set of stylized facts that we document, including variation in prices, markups and market shares across firms. We calibrate the model using a new dataset data on prices, costs and shipments of leading solar companies, as well as solar sales in four leading markets. The calibrated model is applied to evaluate the impact of a decline in the price of polysilicon, a key raw material used in the manufacture of solar panels, on the equilibrium price of solar panels.

*Keywords:* Photovoltaics, Competition, Polysilicon

*JEL:* L19, L13, O30

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## 1. Introduction

The electricity generation sector is the leading contributor of greenhouse gas emissions. Most plans to stabilize greenhouse gas emissions view solar photovoltaics as an electricity generation technology with potential to replace a sizeable section of fossil fuel generation (see Nakicenovic and Riahi (2002); Baker and Solak (2011); Lewis and Nocera (2006)). At

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present however, electricity from solar photovoltaics constitute a very small fraction of the world electricity production. The cost of generating electricity from solar PV systems have fallen over time. A major factor behind this decline has been the continual decrease in the price of solar panels (also called solar modules), the principal component in PV systems. These declines have brought the price of solar generated electricity closer to the price of electricity generated from conventional sources, but a gap still remains.

There has been an extensive examination in the literature of factors that have contributed to the decline in solar module prices. Most of the existing studies are based on learning curves, which extrapolate past observations about the relationship between the price of solar modules and the volume of production (for example, see Swanson (2006) and Schaeffer (2004)). There have been other studies, for example Nemet (2006) and Bruton (2002), which look at the contribution of various factors like plant size and module efficiency in reducing the price of solar modules. Learning curve models and models like Nemet (2006) are suited to explain how different factors affect the cost of production. The use of these models in predicting changes in price depend entirely on the assumption that changes in cost will translate into identical changes in price. If the solar module industry was perfectly competitive with modules being sold at a price equal to its marginal cost, then any reduction in cost would result in the same reduction in price. The solar module industry, however, is not a perfectly competitive industry. As documented in section 2, there are differences in prices, markups and market shares of different firms in the industry, all indicative of deviation from the assumption of perfect competition. Under imperfect competition, the effect on price of a change in cost would depend on how firms respond to the change in cost. The use of price instead of cost in learning curve models and in Nemet (2006) provide a useful simplification, but ignoring the role of competition among firms in determining equilibrium prices is not without consequence. For example, Nemet (2006) finds that changes in factors that affect cost can only explain a part of the change in the price of solar modules in some of the years considered in his study. He argues that there was an increase in the extent of

competition in the industry in those years, which might partially account for the residual variation in price over and above the variation in cost. A contribution of this paper is to develop a model that explicitly incorporates competition among firms in the industry and can be used to evaluate how changes in costs affect the selling price of solar modules.

In section 2 we lay down three empirical observations that capture the salient features of competition in the industry. In section 3, we develop a model that is consistent with these observations. The model derives a demand function for solar modules, taking into account the behavior of electric utility companies, power producers and solar module manufacturers. Electric utility companies, who deliver electricity to consumers (either directly or through local distribution companies), purchase electricity from solar power producers, who can be individual households, businesses or commercial power producing companies. These solar power producers in turn demand solar modules from module manufacturers. The solar modules made by different firms are differentiated both vertically and horizontally. The module firms compete by setting quantities and we derive a set of equations that can be used to compute the equilibrium prices, markups and market shares in this Cournot model.

The model can be extended to incorporate other features of the solar industry, and section 4 describes some of the possible extensions. The inclusion of non-module (or balance-of-system) costs does not affect the equilibrium strategies of the module firms but increases the price of solar generated electricity. The effect of differences in *insolation* (the intensity of incident sunlight) can be easily incorporated in the model. Finally, the model can be extended to consider the impact of changes in usage of different factors of production on price of solar modules. These extensions can be used to investigate the impact of decline in balance-of-system costs, the impact of differences in insolation, and the impact of technological improvements like reduction in raw material requirements or plant automation on the equilibrium price of solar modules and of electricity generated from solar modules. The data necessary to calibrate the basic model described in section 3 can be obtained from publicly available sources, as described in section 5.

In section 6, we put the calibrated model to use for one application. The price of polysilicon, a key raw material used in the manufacture of solar modules, has declined in the last few years and analysts expect further reductions in the price of polysilicon. We use the model to evaluate the impact of decline in polysilicon price on the price of solar modules. Alternative simulations are performed to evaluate the impact of decline in polysilicon price if competition among firms intensify because of standardization of modules, or if solar generated electricity becomes more differentiated from electricity generated from other sources.

We begin by giving a brief description of the solar module industry in the next section.

## 2. The Solar Module Industry

The solar module industry consists of a number of firms located in many countries. The output of the firms is usually measured in watts of solar modules.<sup>1</sup> In 2011, the solar module industry shipped around 28,000 megawatts of solar modules.<sup>2</sup> Contrary to the casual observation that solar modules are standardized homogenous products, solar modules sold by different companies differ in many ways. The most significant of these differences is in the *efficiency* with which they convert sunlight to electricity. The more efficient the solar modules are, the smaller is the size of the module required to produce a unit of electricity. Small module size (or fewer modules) translate to lower expenses on the accessories required to mount the module on a rooftop or ground. Thus higher efficiency is valued in a quantifiable way, and we capture this by treating solar modules as being vertically differentiated with regard to efficiency. Even after adjusting for the efficiency of the modules, there is a dispersion in the price charged per watt by different firms in the industry (see Figure 1).

In addition to efficiency, the modules sold by different companies differ in other technical

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<sup>1</sup>Ideally, a solar module rated at 1 watt when exposed to sunlight for 1 hour would generate 1 watt-hour of electricity. In practice however, the amount of electricity generated depends on the intensity of sunlight, the angle at which the modules are mounted, etc.

<sup>2</sup>A megawatt is a million watts.

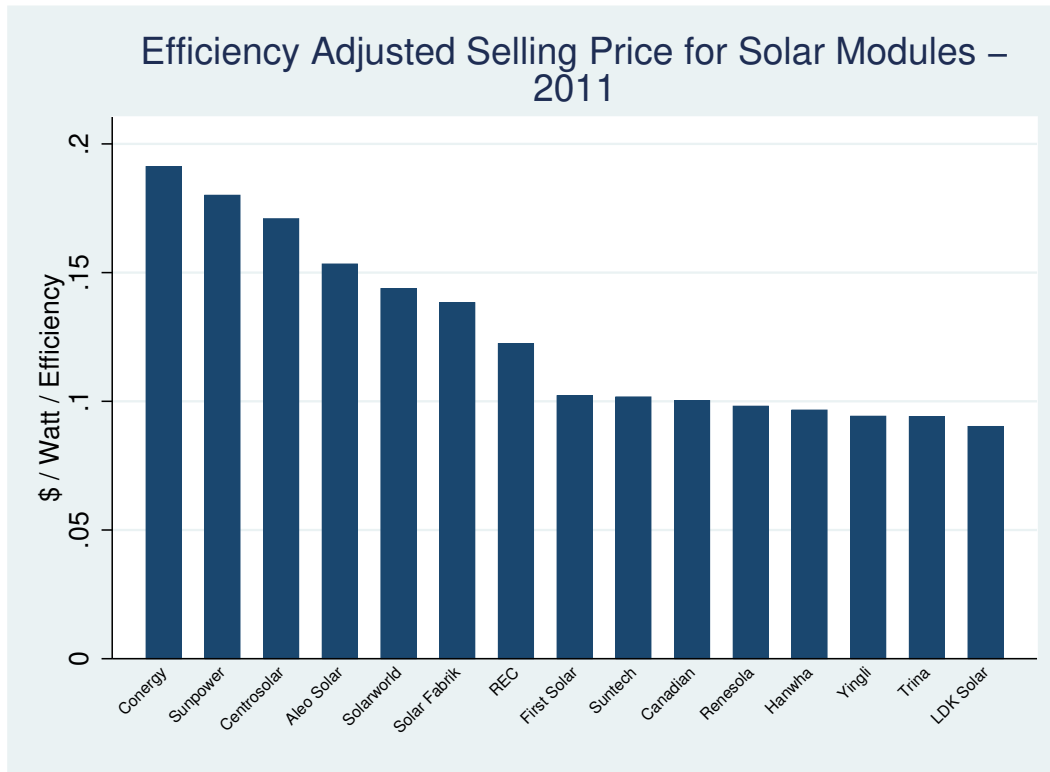


Figure 1: Efficiency Adjusted Price of Solar Modules in 2011.

*Notes:* The prices were calculated by dividing the annual revenues of the companies by their annual shipments. The variable on the y-axis is price divided by efficiency of the modules. See section 5 for the sources of data.

attributes as well in commercial attributes, like the offered warranty period. Further, firms also differ in their access to distribution and marketing channels, which are important in the sales of solar modules. These differences in product characteristics, together with the dispersion in efficiency-adjusted prices seen in Figure 1, suggest that a differentiated goods model with firms engaging in monopolistic competition would be appropriate for the industry. However, in contrast to the popular Dixit and Stiglitz (1977) monopolistic competition

model, there is also a dispersion in the markups charged by the firms in the industry. Figure 2 plots the markups (gross margins) of companies against their market shares. As can be seen from the figure, bigger firms tend to have bigger markups as would be implied by a Cournot model, although there are deviations from a simple linear relationship. The observations above can be summarized in three stylized facts,

1. There is a dispersion in efficiency adjusted prices across firms.
2. There is a dispersion in markups across firms.
3. Larger firms tend to have bigger markups.

The next section develops a model of the solar module industry that is consistent with the three observations above.

### **3. The Model**

Our model is a modification of the model developed in Smith and Venables (1988) and Atkeson and Burstein (2008). We develop the model in a number of steps, and begin by deriving the demand for solar modules in the next section.

#### *3.1. Demand*

The electricity industry consists of three vertically connected segments. At the very top are the electric utility companies who sell electricity to final consumers. At the next rung are the power producers (including solar power producers) who own power plants and generate electricity which they sell to the electric utility companies. At the bottom rung are the equipment companies, like solar module companies, who manufacture the equipment used by power producers to generate electricity. Demand for solar electricity, and hence solar modules, is essentially driven by government policies, which differ across countries. In many European countries (Germany, Italy, Spain, France and Czechoslovakia), the government requires electric utility companies to buy electricity generated by solar power producers at a

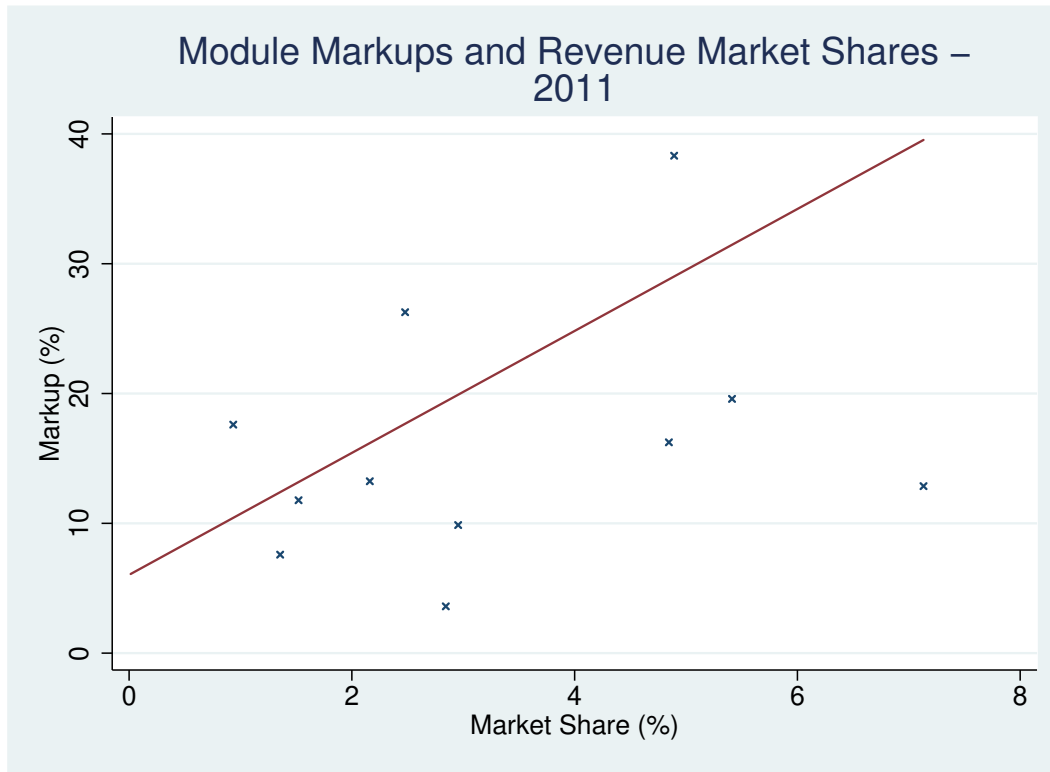


Figure 2: Bigger firms tend to have higher markups.

*Notes:* Each point in the graph corresponds to a firm. The market shares were obtained by dividing the annual revenue of the firm by an estimate of the total sales of solar modules. The estimate of total sales was obtained by multiplying the average price of firms in the dataset by the total shipment of solar modules in 2011.

guaranteed price. In many U.S states on the other hand, the demand for solar modules stem from Renewable Portfolio Standard (RPS) mandates, which require electric utility companies to obtain a portion of the total electricity that they sell from renewable sources. We abstract from the differences in policies and assume that for an electric utility company, the effect of these policies is to make solar generated electricity an imperfect substitute for electricity



generated from other sources.<sup>3</sup> Electric utility companies choose the quantities of electricity to procure from solar producers and other producers so as to minimize their total cost of production, i.e they solve the problem,

$$\begin{aligned} \min_{Q_s, Q_c} & P_s Q_s + P_c Q_c \\ \text{s.t.} & \left( Q_s^{\frac{\eta-1}{\eta}} + Q_c^{\frac{\eta-1}{\eta}} \right)^{\frac{\eta}{\eta-1}} = Q. \end{aligned}$$

where  $Q_s$  is the quantity of electricity that the utility purchases from solar power producers,  $Q_c$  is the quantity they purchase from non-solar sources,  $Q$  is the total quantity of electricity that the utility has to produce,  $P_s$  is the price of solar generated electricity,  $P_c$  is the price of electricity generated from conventional sources, and  $\eta$  is the elasticity of substitution between solar electricity and electricity generated from other sources. The solution for the problem gives the demand for solar electricity as,

$$Q_s = Q \left( \frac{P_s}{P} \right)^{-\eta}, \quad (1)$$

where  $P$  is the aggregate price index for electricity given by  $P = (P_s^{1-\eta} + P_c^{1-\eta})^{\frac{1}{1-\eta}}$ . Hence, if the price of solar electricity relative to the aggregate price index for electricity ( $\frac{P_s}{P}$ ) decreases, the utility shifts away from conventional electricity and increases its procurement of solar electricity.

The solar power producers, the second rung in the electricity industry, can be individual households who have solar panels on top of their houses, or companies who collect solar electricity from many households and sell to utilities (often called *aggregators* in the industry), or solar power plants. We model this as a competitive segment and firms earn zero

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<sup>3</sup>In addition to differences in regulatory policies, production variability is another important difference between solar generation and generation from conventional sources. There is variability in the generation of electricity from solar because of unpredictable changes in the environment, like the onset of clouds. Such unforeseeable variability does not exist for generation through coal or natural gas.

profits in this segment. Each solar power producer buys solar modules, which we model as a differentiated good, and uses these modules to generate electricity. As mentioned in section 2, firms are vertically differentiated by the conversion efficiency of the modules that they sell. To accommodate this, we consider the the efficiency adjusted units of solar modules used by a power producer. In addition to this vertical differentiation with regard to efficiency, solar modules are also horizontally differentiated. We capture this using the production function for the solar power producer,

$$Q_s = \left( \sum_{j=1}^N (e_j q_j)^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} \quad (2)$$

where  $q_j$  is the quantity of modules from module producer  $j$ ,  $e_j$  is the efficiency of modules from producer  $j$ , and  $\rho$  is the elasticity of substitution between the different types of modules. We make the reasonable assumption that  $\rho > \eta > 1$ , i.e the elasticity of substitution between solar electricity and electricity generated from other sources is less than the elasticity of substitution between different types of modules. Competitive solar power producers solve the problem,

$$\begin{aligned} \max_{q_j} P_s Q_s - \sum_{j=0}^N p_j q_j \\ \text{s.t. } Q_s = \left( \sum_{j=1}^N (e_j q_j)^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} \end{aligned}$$

This gives the demand for firm- $j$ 's modules as

$$q_j e_j = Q_s \left( \frac{p_j / e_j}{P_m} \right)^{-\rho} = Q \left( \frac{P_s}{P} \right)^{-\eta} \left( \frac{p_j / e_j}{P_m} \right)^{-\rho}. \quad (3)$$

where  $P_m$  is the efficiency adjusted aggregate price index for modules, given by,

$$P_m = \left( \sum_{i=1}^N \left( \frac{p_i}{e_i} \right)^{1-\rho} \right)^{\frac{1}{1-\rho}} \quad (4)$$

Hence the demand for solar modules for firm- $j$  depends both on how expensive the firm's solar module is relative to that sold by other firms,  $\left(\frac{p_j/e_j}{P_m}\right)$ , and how expensive solar electricity is relative to electricity from other generation sources  $\left(\frac{P_s}{P}\right)$ . Since solar power producers are perfectly competitive, they make zero profit, and hence the price of solar electricity is given by,

$$P_s = P_m \quad (5)$$

Hence the demand equation (3) can be written as

$$q_j e_j = Q \left(\frac{P_s}{P}\right)^{-\eta} \left(\frac{p_j/e_j}{P_s}\right)^{-\rho}. \quad (6)$$

Having derived the demand facing each module producer, we move on to the optimal pricing decisions made by the module producers given the demand function above that they face.

### 3.2. Equilibrium

We assume that the solar module firms engage in Cournot competition. Each solar firm takes  $P$ , the price index for electricity as given when making its quantity and price decisions. But the firm considers the effect of its decisions on the solar module price index,  $P_m$ , and the price of solar electricity,  $P_s$ . We assume that module firms have a constant marginal cost of production, and denote module firm- $j$ 's marginal cost by  $c_j$ <sup>4</sup>. Firm- $j$  solves the problem,

$$\begin{aligned} \max_{q_j} \quad & p_j q_j - c_j q_j \\ \text{s.t.} \quad & q_j e_j = Q \left(\frac{P_s}{P}\right)^{-\eta} \left(\frac{p_j/e_j}{P_s}\right)^{-\rho}, \\ & P_s = \left(\sum_{i=1}^N (p_i/e_i)^{1-\rho}\right)^{\frac{1}{1-\rho}} \end{aligned}$$

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<sup>4</sup>It is possible that the marginal cost would decrease with increases in production (see Nemet (2006)), but we ignore that for purposes of tractability.

Solving the above problem gives the result that equilibrium price exceeds cost by a factor given by,

$$\frac{p_j}{c_j} = \frac{1}{1 - \frac{s_j}{\eta} - \frac{1 - s_j}{\rho}}, \quad (7)$$

where  $s_j = \frac{p_j q_j}{\sum_i p_i q_i}$  is the market share of firm- $j$ . Equation (7) can be rewritten to obtain the markup (gross margin) as,

$$\frac{p_j - c_j}{p_j} = \frac{s_j}{\eta} + \frac{1 - s_j}{\rho} \quad (8)$$

Further, using equation (3), the market share can be written as

$$s_j = \frac{p_j q_j}{\sum_{i=1}^N p_i q_i} = \frac{p_j \frac{1}{e_j} Q_s \left( \frac{p_j/e_j}{P_s} \right)^{-\rho}}{\sum_{i=1}^N p_i \frac{1}{e_i} Q_s \left( \frac{p_i/e_i}{P_s} \right)^{-\rho}} = \frac{(p_j/e_j)^{1-\rho}}{\sum_{i=1}^N (p_i/e_i)^{1-\rho}} \quad (9)$$

The model is consistent with the observations about competition in the industry summarized in Section 2. Since  $\rho > 1$ , equation (9) implies that bigger firms (larger market share  $s_j$ ) charge a lower efficiency-adjusted price ( $p/e$ ). Given this, and the assumption that  $\rho > \eta$ , equation (7) implies that firms with higher efficiency-adjusted marginal cost ( $c/e$ ) charge a higher efficiency adjusted-price ( $p/e$ ).<sup>5</sup> Thus firms charge different efficiency-adjusted prices, consistent with Figure 1 and stylized fact 1. Equation (8) implies that firms charge different markups, consistent with stylized fact 2. Since  $\rho > \eta$ , equation (8) also implies that bigger firms charging higher markups, consistent with Figure 2 and stylized fact 3.

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<sup>5</sup>This is most easily seen by considering equation (7) for two firms, say firm 1 and firm 2. Equation (7) implies that

$$\frac{p_1/e_1}{p_2/e_2} = \frac{\frac{\rho-1}{\rho} - s_1 \left( \frac{1}{\rho} - \frac{1}{\eta} \right)}{\frac{\rho-1}{\rho} - s_2 \left( \frac{1}{\rho} - \frac{1}{\eta} \right)} = \frac{c_1/e_1}{c_2/e_2}.$$

Hence if  $c_1/e_1 > c_2/e_2$ , it must be that  $p_1/e_1 > p_2/e_2$ . If  $p_1/e_1 < p_2/e_2$ , then equation (9) implies that  $s_1 > s_2$ , and hence the left hand side of equation above will be less than one and right hand side greater than one.

Equation (7) makes clear that price can vary from cost. The factor by which price is greater than cost depends on the market share of the firm, and the elasticities  $\eta$  and  $\rho$ . For bigger firms, the price/cost factor is larger. As  $\eta$  increases, price/cost factor decreases because the differentiation between solar generated electricity and electricity from other sources decreases, and they become more direct competitors. As  $\rho$  increases, the price/cost factor decreases because the differentiation among the different module firms decreases and they become more direct competitors.

It is straightforward to compute the equilibrium of the model, if the unit costs  $\{c_j\}$ , efficiencies  $\{e_j\}$ , and elasticities  $\eta$  and  $\rho$  are known. Substituting equation (9) in equation (8) gives a system  $N$  non-linear equations in  $N$  unknowns prices, and hence can be solved to obtain the equilibrium prices  $\{p_j\}$ . The above model provides a tool to evaluate how module prices change in response to changes in the cost of production of modules. In many cases one is interested not only in the price of modules, but also in the price of a fully installed solar generation system, as well as in the price of the electricity generated from such systems. In section 4 we outline how the above model can be extended to accommodate this. With additional data one can use the extension of the model to evaluate the impact of cost changes on the price of a fully installed solar system and on the price of solar generated electricity.

#### 4. Extensions of the Model

The basic model of competition in the solar panel industry described in section 3 can be extended to incorporate other features of the industry.

##### 4.1. Balance of System Costs and Insolation

The solar modules considered in the model above form the core of a solar photovoltaic electricity generation system. In addition to the cost of the module itself, the cost of a solar generation system also includes the cost of electrical components necessary to connect the system with the electrical grid and the cost of mounting structures necessary to fix the

modules on a rooftop or on the ground. There are also non-hardware “soft-costs” - the cost of getting a permit to install the system, the cost of labor necessary to install the system, etc. As module costs are declining, the other costs, which are often collectively labeled the balance-of-system costs, are becoming an important fraction of the total cost of the system (see Feldman et al. (2012) and Aboudi (2012)). The balance-of-system costs can be added to the model in a simple manner, by assuming that cost of the total solar system is a factor  $k$  times the module cost, i.e the total cost is now  $k \sum_{i=1}^N p_j q_j$ .

Further, in addition to the characteristics of the solar module, the amount of electricity that can be generated from a solar module also depends on the amount of sunlight that is incident on the module. This parameter is referred to in the industry as *insolation*. This can be incorporated into the model by modifying the production function in equation (2) to,

$$Q_s = h \left( \sum_{j=1}^N (e_j q_j)^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}} \quad (10)$$

where the insolation factor  $h$  converts the rated power into the actual amount of electricity produced.

It is to be noted that the balance-of-system cost factor  $k$  and insolation  $h$  can vary across markets. The balance-of-system costs depend on the labor cost, permitting policies in place and so on. For example, Seel et al. (2012) report that the balance-of-system cost in Germany was lower than in the U.S in 2010. Similarly, the insolation factor would also vary across markets, with sunny countries like Spain or India having higher  $h$  than countries like Denmark or Germany. One could apply the above model to a specific region where the insolation and balance-of-system cost factor remains the same across different solar power producers, under the assumption that each module producer treats every region as a different market. Under this assumption, the problem of the solar power producer in market- $i$  becomes

$$\max_{q_j} P_s Q_s - k^i \sum_{j=0}^N p_j q_j$$

$$s.t \quad Q_s = h^i \left( \sum_{j=1}^N (e_j q_j)^{\frac{\rho-1}{\rho}} \right)^{\frac{\rho}{\rho-1}}$$

The demand function for each module and the price index for modules remain the same as in the basic model (as given in equations (3) and (4) respectively). The equilibrium prices and markups also remain the same as before, as given in equations (7) and (8) respectively. But the price of solar generated electricity becomes  $P_s^i = \frac{k^i}{h^i} P_m$ . Thus the price of solar generated electricity will be lower in regions with lower balance of system costs and higher insolation. With data on  $k^i$  and  $h^i$ , one could use this extension of the basic model to evaluate the impact of a decrease in balance-of-system costs on the price of solar generated electricity.

#### 4.2. *Technological Improvements*

Many technological improvements have contributed to the decline in module prices. Improvements in efficiency has been an important contributor to the decline in module prices, and the model described in section 3 can be used to simulate the impact of increases in efficiency on module prices. Another important facet of technological progress has been in the reduction of the quantity of inputs needed to produce a watt of modules. The quantity of polysilicon needed to produce 1 watt of solar modules has decreased over the years (see Swanson (2006) and Nemet (2006)). Such technological improvements can be incorporated into the model by considering a Leontief production function for the production of solar modules,

$$q_j = \text{Min}(aM_j, bL_j)$$

where  $M_j$  is quantity of polysilicon used,  $L_j$  is the amount of labor used,  $a$  is the unit polysilicon requirement and  $b$  is the unit labor requirement. Module firm- $j$ 's profit maximization

problem now becomes,

$$\begin{aligned}
& \max_{M_j, L_j} p_j q_j - w L_j - v M_j \\
& s.t \quad q_j = \text{Min}(a M_j, b L_j), \\
& s.t \quad q_j e_j = Q \left( \frac{P_s}{P} \right)^{-\eta} \left( \frac{p_j / e_j}{P_s} \right)^{-\rho}, \\
& P_s = \left( \sum_{i=1}^N (p_i / e_i)^{1-\rho} \right)^{\frac{1}{1-\rho}}
\end{aligned}$$

where  $v$  is the price of polysilicon and  $w$  is the labor wage rate. The solution to the problem remains the same as the ones described in section 3, with  $c_j$  being replaced by  $\frac{w}{b} + \frac{v}{a}$ . The model can then be simulated to understand the impact of a decrease in unit polysilicon requirement (a decrease in  $a$ ), or the effect of a decrease in price of polysilicon (a decrease in  $v$ ).

In section 6, we describe how we can calibrate the model and simulate it to calculate the impact of a decrease in  $v$ , the price of polysilicon. In the next section we describe the sources of the data that we use to estimate the model parameters necessary to calibrate the model.

## 5. Data and Calibration

In the simulations to evaluate the impact of a decline in polysilicon price on module price, we model the solar module industry as being comprised of 15 companies. These include the companies which were in the top 10 in terms of shipments in 2011 (Suntech, First Solar, Yingli, Trina, Canadian Solar, Sharp, Hanwha Solarone, Jinko, Solarworld and LDK Solar) and 5 other leading module manufacturers (Sunpower, REC, JA Solar, Kyocera and Aleo Solar). Together these companies accounted for over 60% of the global shipments in solar modules in 2011, and companies not in the list contributed less than 2 % each to the total industry shipments. Among the 15 companies, 14 companies make solar modules using polysilicon as the raw material. However the lowest cost firm, First Solar, uses a technology



different from the rest, and does not use polysilicon in its production process.<sup>6</sup> We leave the cost of First Solar at its 2011 level in our simulation.

The variable production costs of 12 of the above companies were obtained from their annual reports. For each company, annual data was collected on cost of goods sold (COGS), revenues and shipments. 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, some report only the earnings before interest 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 are 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 whose cost data is used in the analysis are pure solar companies, so the variable costs they report in annual statements are those associated with solar production alone. Second, many of the companies state in their annual reports that a substantial fraction of the COGS that they

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<sup>6</sup>First Solar produces solar modules using Cadmium Telluride.

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 of companies using their own methods. It is quite likely that the close scrutiny by industry observers puts a heavy burden on the firms to report their costs truthfully.

The average variable cost of producing solar panels for each firm was obtained by dividing COGS by annual shipments. For the 3 companies for whom cost data was not available (Sharp, Kyocera, and Jinko), we used equation (8) to obtain the unit costs of the companies, given their prices and market shares. The prices for these companies were obtained from the Photon Magazine or from their annual reports. To provide an illustration of the accuracy of the model in backing out costs from prices, we plot in Figure 3 the costs backed out by the model against the actual costs of the companies for which we have cost data.

We now turn to the two demand parameters whose values are needed to simulate the model, the elasticity of substitution between solar and non-solar electricity,  $\eta$ , and the elasticity of substitution between solar modules,  $\rho$ . A high  $\eta$  would imply that solar electricity is less differentiated from electricity generated from other sources. We estimate the demand elasticity from the data on module price and quantity sold in four markets - Germany, Italy, Spain and France. The data on annual solar installations in these countries is taken from IEA (2010) and is available for Germany from 1990-2010 and for the other three countries from 1995-2010. The quantity sold in each of these markets is likely to be influenced by the subsidy policies of the governments, which we include in the regression. We perform two regressions to estimate  $\eta$ . In the first regression, we do not use any instruments for price. In the second regression, we instrument the price of solar modules with the total market share of firms from China in the worldwide shipments of solar modules. The entry of firms from China prompted a decline in prices, either because of low cost of production of firms in China or because of production subsidies offered in China. Hence the increasing penetration of Chinese firms in the solar market represent a supply side shock not correlated to demand

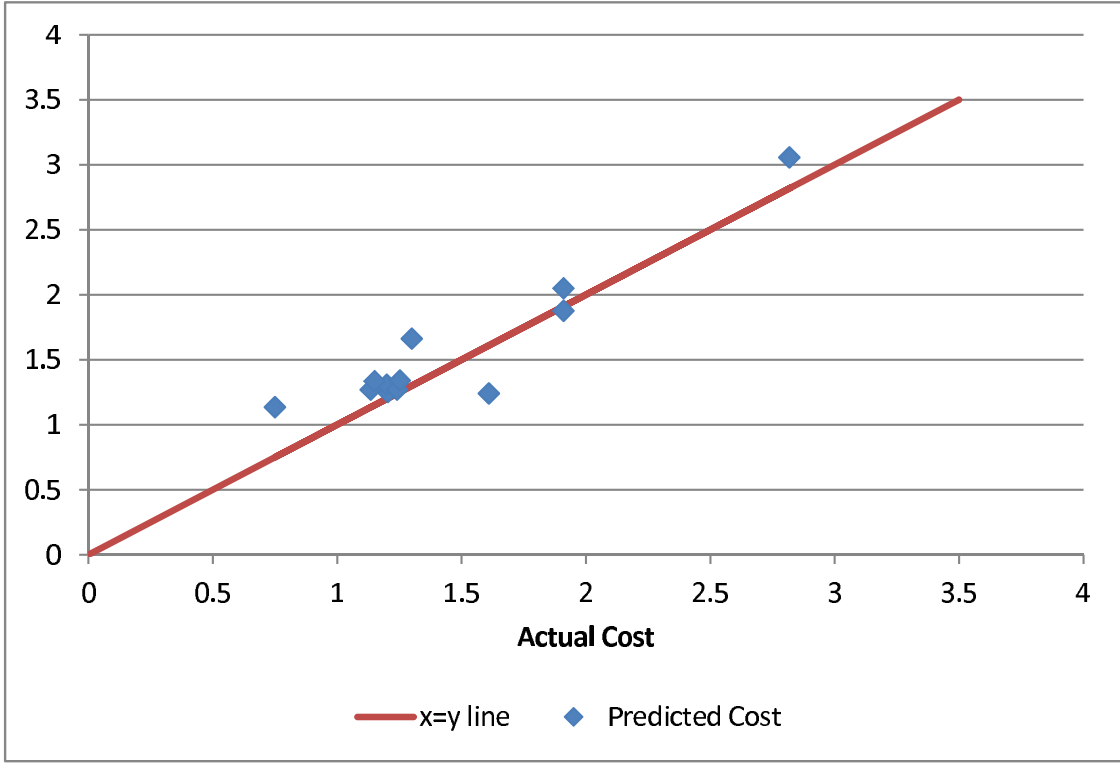


Figure 3: Predicted versus actual costs.

*Notes:* Each point in the graph corresponds to a firm. The y-axis shows the costs backed out by the model from the data on prices, and x-axis shows the actual cost. The vertical distance of each point from the the x = y line is the deviation of the cost backed out by the model from the actual cost.

and hence is an appropriate instrument.<sup>7</sup> The regression equation is,

$$\ln(q_{it}) = \beta_0 + \beta_1 s_{it} + \beta_2 \ln(r_t) + \eta \ln(p_t) + \epsilon_{it} \quad (11)$$

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<sup>7</sup>While there is a possibility that the Chinese firms might have anticipated the changes in government subsidies, it should be noted that there was always considerable uncertainty regarding the continuity of the subsidies in many countries.

Table 1: Estimates of Demand Elasticity ( $\eta$ )

	I	II
Demand Elasticity ( $\eta$ )	-5.34*** (0.45)	-6.13*** (0.52)
$\beta_1$	0.07*** (0.006)	0.07*** (0.006)
$\beta_0$	-0.006 (1.42)	1.52 (1.43)
Observations	52	52
$R^2$	0.903	0.898

where  $q_{it}$  is the quantity (watts) of solar modules sold in country  $i$  in year  $t$ ,  $s_{it}$  is the subsidy (feed-in-tariff) offered in country  $i$  in period  $t$ ,  $r_t$  is price of polysilicon in year  $t$ , and  $p_t$  is the price per unit in year  $t$ . The regression results are given in Table 1.

Next, we move on to the value of  $\rho$ . A high  $\rho$  would mean that the modules are less differentiated products, and in fact  $\rho \rightarrow \infty$  would imply that the modules of different companies are perfect substitutes.<sup>8</sup> As can be seen from equation (8), the value of  $\rho$  determines the markup (gross margin) of a small firm with almost zero market share. From the annual reports, we note that the fixed operating costs in the industry (including Selling, General and Administrative Expense and R&D expense) is on average 10% of the revenues of the firms. Since a firm that cannot cover its fixed cost will exit the industry, a value of  $\rho = 10$  (which provides just enough profits to cover the fixed operating costs), seems appropriate. The value  $\rho = 10$  is also the one used by Atkeson and Burstein (2008).

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<sup>8</sup>In fact, for the case of  $\rho \rightarrow \infty$ , the model collapses to the standard homogeneous good Cournot model.

## 6. Impact of Polysilicon Price Decline

One of the factors that has contributed to the decline in module prices over the last few decades is the decline in the price of polysilicon, the principal raw material used in building crystalline silicon solar cells. The average price of solar modules has declined by a factor of close to over 50 in the period 1975-2010, and the cost of the polysilicon needed to make one watt of solar modules has decreased by a factor of 20 over the same period (see Figure 4).

Following a sharp increase during 2004-2008, the price of polysilicon almost halved during 2008-2010. Yu et al. (2012) examine the reasons for the changes in polysilicon price during 2004-2009 and conclude that demand shocks played an essential role in the fluctuations, as also did changes in cost of producing polysilicon.<sup>9</sup> Generous subsidy schemes for solar generated electricity implemented in many European countries led to a surge in the demand for polysilicon. The rising polysilicon prices lead to an expansion in capacity by existing polysilicon firms and the entry of many new firms into the industry.<sup>10</sup> Total worldwide polysilicon capacity increased from around 50,000 metric tons in 2005 to around 300,000 metric tons in 2010 (see Prior and Campbell (2012)). Based on investment plans announced by polysilicon suppliers, Winegarner (2011) anticipates polysilicon capacity to increase to over 500,000 metric tons in 2015. These increases have been accompanied by improvements in the production technology, as polysilicon firms found ways to reduce the

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<sup>9</sup>Yu et al. (2012) consider oil and natural gas shocks as the main source of changes in the production cost. In addition to demand and production cost shocks, they also find that fluctuations in exchange rates had a significant impact on polysilicon price. Note that the price of solar modules held steady despite the spike in polysilicon price. This was possibly because of the increasing market penetration of lower cost firms from China during the same period.

<sup>10</sup>Hemlock, the leading polysilicon supplier increased its capacity from 7700 to 36,000 metric tons from 2005 to 2010. Wacker, the second largest established polysilicon supplier, increased its capacity from 5500 to 24,000 metric tons. New firms GCL-Poly and OCI entered the market in 2007-2008 and quickly build their capacities to 21,000 and 27,000 metric tons in 2010.

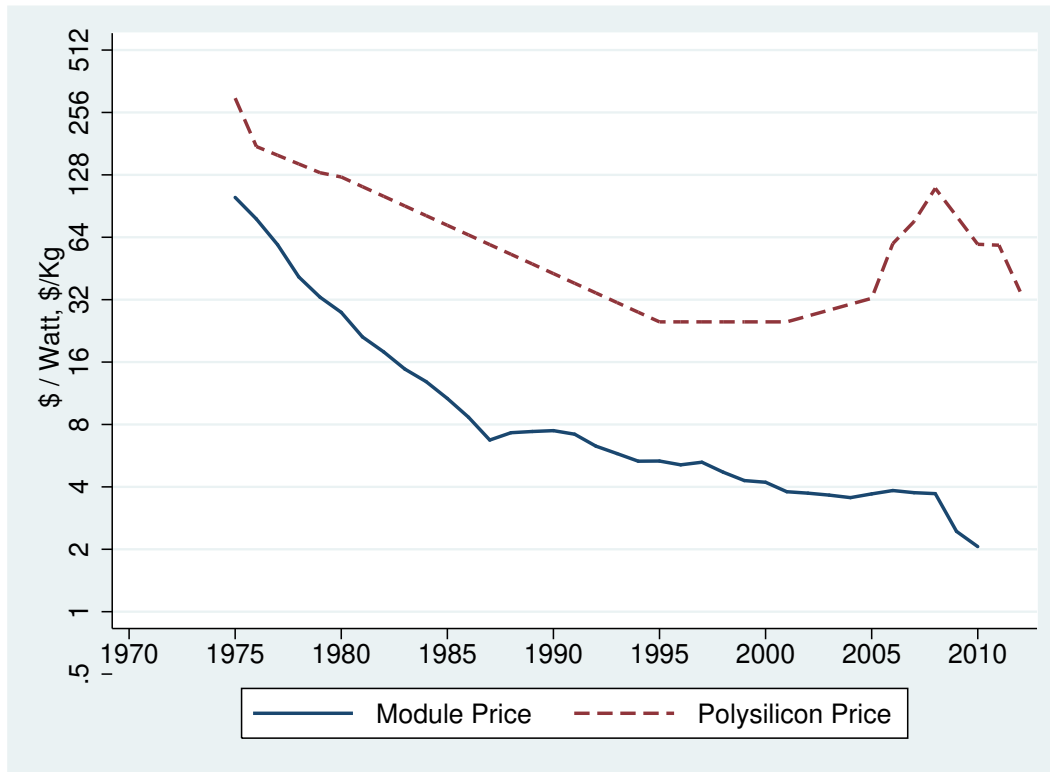


Figure 4: Decline in Solar Module Price and Cost of Polysilicon Used in Solar Modules.

*Notes:* The prices of solar modules for 1975-2006 were taken from Maycock (2002) and from the dataset at Earth Policy Institute. The price of solar modules during 2007-2010 was taken as the quantity weighted average of price of leading solar module companies. The data for polysilicon price and unit polysilicon requirement was taken from Nemet (2006) for 1975-2002 and from Winegarner (2011) and company annual reports for the years 2003-2010.

cost of production. The addition of new capacity and intensifying competition among new and established polysilicon manufacturers, as well as the development of new cost reducing innovations in the manufacture of polysilicon, have led many industry observers to forecast a continued decline in the price of polysilicon and consequent decline in module prices (see

Fessler (2012) and Prior and Campbell (2012)).

We use a variation of the model described in section 4.2 to simulate the impact of the forecasted polysilicon price drop on the price of solar modules. To focus on the impact of polysilicon price declines, we consider a variation of the model with polysilicon as one input and all other inputs lumped together as the second input. With the Leontief production function described in section 4.2, this results in the unit cost of firm- $j$  being,

$$c_j = \frac{v}{a} + z_j \quad (12)$$

where  $v$  is the price of polysilicon,  $a$  is the quantity of polysilicon needed to produce one watt of solar modules, and  $z_j$  is the non-polysilicon cost of firm- $j$ . The price of polysilicon in 2011 was constructed from annual reports of leading polysilicon companies. The annual revenues of four polysilicon companies (Wacker, REC, GCL-Poly and Daqo) were divided by the annual shipments to obtain the average selling price of each company. A quantity weighted average of these prices was taken as the price of polysilicon, which was found to be \$59 per Kg. The data on  $a$  was obtained for a few of the solar module companies mentioned in section 5 from their annual reports, and the average value obtained was 5.6 grams per watt. The variable  $z_j$  includes the costs of all other factors of production (labor, capital, utilities and other raw materials) and was calculated from the data on  $c_j$ ,  $v$  and  $a$ , i.e  $z_j = c_j - \frac{v}{a}$ .

In the simulations, the values of  $a$  and  $z_j$  were left at their 2011 values and the price of polysilicon was reduced from the 2011 value of \$59/Kg to \$15/Kg, which is almost a 75% reduction in the price. The simulations were done for three value of  $\eta$ ,  $\eta = 5.5$  which we consider as a baseline case based on the estimates in section 5, a low value  $\eta = 2$  and a high value  $\eta = 10$ . Two values of  $\rho$  were also considered ( $\rho = 10$ , which is used in Atkeson and Burstein (2008) and a value of  $\rho = 20$ ). Note that a higher value of  $\rho$  means that products are less differentiated, and firms have less market power. The results are shown in Table 2, with the last column showing the quantity weighted average module price.

A 75% reduction in the price if polysilicon (from \$59 per Kg to \$15 per Kg) causes

Table 2: Impact of polysilicon price decline on average module price

$\eta$	$\rho$	Polysilicon price ( $v$ )	Module Price
5.5	10	59	1.21
		15	1.04
5.5	20	59	1.10
		15	0.99
2	10	59	1.31
		15	1.10
2	20	59	1.23
		15	1.06
10	10	59	1.17
		15	1.02
10	20	59	1.06
		15	0.96

a reduction in module price of between 8.6% and 16%, depending on the values of  $\eta$  and  $\rho$ . Note that the module price is lower with higher values of  $\eta$  because the markups of the module companies decrease as demand for solar electricity becomes more elastic (i.e. solar generated electricity becomes less differentiated from electricity generated from other sources.) Similarly, module price is lower with higher values of  $\rho$  because the modules of different companies become less differentiated leading to a decrease in markups. In all cases listed in Table 2, the resulting module prices are still considerably higher than target values given in many studies at which large-scale adoption of solar would occur. For example, a recent study by the U.S Department of Energy (DOE (2012)) sets a target module price of U.S \$0.54 per watt to achieve large-scale residential adoption of solar in the U.S.<sup>11</sup> The results in Table 2 raises the question of size of reduction in non-polysilicon costs that will

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<sup>11</sup>DOE (2012) estimates that a module price of \$0.54 per watt is required to achieve a total system price of \$ 1.5 per watt, a price which DOE argues will make solar energy competitive with other generation sources in the U.S. This target, and other similar ones, are based on many assumptions but provide a benchmark to compare the results of the simulation.



result in equilibrium module prices near the targets given in DOE (2012). To explore this, we simulate the model with a reduction in non-polysilicon cost, alongside the reduction in polysilicon price to \$15 per Kg. We assume that the non-polysilicon cost of all firms decline by the same factor, and consider 3 scenarios in which the non-polysilicon cost declines by 25%, 50% and 75%. Table 3 shows the results of the simulation.

Table 3: Impact of decline in polysilicon and other costs on average module price

$\eta$	$\rho$	Reduction in non-polysilicon Cost	Module Price
5.5	10	25%	0.80
		50%	0.56
		75%	0.30
5.5	20	25%	0.76
		50%	0.53
		75%	0.28
2	10	25%	0.85
		50%	0.59
		75%	0.33
2	20	25%	0.81
		50%	0.54
		75%	0.31
10	10	25%	0.79
		50%	0.55
		75%	0.29
10	20	25%	0.74
		50%	0.51
		75%	0.26

If we take the module price set by DOE (2012) of \$0.54 per watt as a target, we see from Table 3 that a 75% reduction in non-polysilicon cost achieves the target under all values of  $\eta$  and  $\rho$  considered, while a 25% reduction in non-polysilicon cost will not suffice under any of the values of  $\eta$  and  $\rho$  considered. A 50% reduction in non-polysilicon cost will achieve the target under the assumption of the high value for  $\rho$ . The simulations above provide a first attempt at using a rigorous model to examine the impacts on equilibrium price. A useful extension of the model would be to break up the non-polysilicon cost,  $z_j$ ,

into various components like labor, capital and others and examine the effects of reduction in these component costs on equilibrium module price.

## **7. Conclusion**

We developed a model of competition in the solar module industry that is consistent with three observed facts. Firms charge different prices, they differ in their price-cost markups and larger firms tend to have higher markups. The model was calibrated using data collected from a number of sources and the calibrated model was used to evaluate the impact of a decline in polysilicon price on the equilibrium price of modules. A 75% decrease in the price of polysilicon leads to a 8.6% to 16% reduction in the average price of modules. The decline in polysilicon price by itself does not lead to module prices that are considered necessary in many studies to lead to large scale adoption of solar. The polysilicon price reductions have to be coupled with substantial reduction of over 50% in non-polysilicon costs to achieve such targets. Simple extensions of the basic model can incorporate other aspects of the industry, like balance of system costs. Such extended models can be used to evaluate the impact of changes in the industry on the equilibrium price of electricity generated from solar panels, in addition to the price of modules.

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