The role of the supply chain for innovation

The example of Photovoltaic Solar Cells

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Abstract

We examine incentives for innovation from learning-by-doing for photovoltaic cell producers. Industry structure and insights from interviews are reflected in a two-period and two-stage model. Equipment suppliers decide on the price level for innovative manufacturing devices. Cell producers invest in new production lines and chose the share of innovative production equipment. Policy instruments that increase confidence in future market size increase innovation, while unexpected current demand reduces innovation. Competing innovative manufacturing equipment suppliers can explore and select multiple innovative ideas, but fail to appropriate the full innovation benefits. This can be compensated with public support for innovation in the production process.

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1 Introduction

High oil prices and concerns about climate change have heightened interest in alternative energy technologies. They can serve a large share of energy demand, if costs decrease and performance improves. ([Stern(2006)], [IPCC(2007)], [Edenhofer et al.(2006)Edenhofer, Lessmann, Kemfert, Grubb, and Köhler]). Can government policy accelerate this process of innovation? While publicly financed research and development plays an important role, this paper analyses the role that demand-pull policies, sometimes referred to as "strategic deployment", play in inducing innovation. ([Popp(2006)], [Clarke et al.(2006)Clarke, Weyant, and Birky], [Neuhoff(2005)], [Goulder(2004)]).

Strategic deployment subsidizes electricity produced from alternative energy technologies and thus increases the size of the market for these technologies. One important motivation are the expected benefits from learning by doing; companies improve performance and cost of the technology as they gain experience through additional production volumes ([Arrow(1962)], [Rosenberg(1969)]). Indeed, correlations between manufacturing volumes and cost reductions have been observed across a large variety of technologies ([Wright(1936)], [Dutton and Thomas(1984)], [Argote and Epple(1990)]), but other factors also play a role in cost reductions ([Hall and Howell(1985)]). In this study we explore the cost-reducing mechanisms at work as growth and market structure affect the incentives for innovation.

Our analysis is based on a case study for photo-voltaic cells (PV), semi-conductor devices that directly convert sunlight into electricity. Since the 1950s, PV has been used in space applications, then increasingly in off-grid applications. Since 1997 the majority of demand has been created by strategic deployment programs. Along with growing market size, costs have fallen by a factor of 100 since the 1950s ([Nemet(2006)]). If PV is to provide a large share of energy demand, costs of producing cells have to decrease substantially to about a third of today's level.

To understand the role that industry structure plays in the process of innovation, we conducted a survey with extended interviews. Insights from these interviews led us to develop a two period model that reflects innovation along the supply chain in the PV cell production. In both periods, cell producers invest in new production lines and also produce up to their available production capacity. They buy the individual components of the production line from equipment suppliers. We employ the dimensions depth and breadth to distinguish two types of process innovation. Cell producers decide on the breadth of innovation: the fraction of the expenditure on a new production line that is spent on innovative manufacturing equipment, rather than on established equipment. This innovation in technology creates direct costs and also results in production delays with forgone sales in the period when it is first applied. Subsequently innovation offers the benefits of lower production costs in period two, both for the initial investment and for all new production lines that apply the new technology ([Utterback and Abernathy(1975)]).

Three insights emerge from the model: (i) We first explore the impacts of market growth on innovation. A larger market in period two creates more benefits from low cost production, and induces cell producers to explore more innovative technologies in period one (increased breadth of innovation). We confirm that expected future demand growth accelerates innovation. Policies that can create market confidence in such future growth are desirable. In contrast, we find that unexpected future demand growth cannot have such an effect. Even worse, an unexpected demand increase today can be detrimental to innovation. It creates scarcity and higher prices for PV cells; cell producers benefit from the higher prices, and reduce the level of innovation applied in new production lines to avoid delays in the production start.

(ii) We then explore the role of the supply chain for innovation. In our stylized model, we assume that innovation is either pursued by cell producers or by equipment suppliers. The innovator retains ownership of the innovation, at least temporary, via patents, secrecy, or tacit knowledge. This allows the innovator to benefit from new production lines built in period two using the innovative approach.

If equipment suppliers innovate, then the equipment supplier with the best innovation will sell to all cell producers in period two. Thus the best available technology for any production step will be applied. In contrast, if cell producers innovate, then this selection for the best solution does not occur for every production step. Hence the competition among innovative equipment suppliers can accelerate PV production cost reductions.

This result suggests that technology policy should allow for competing equipment suppliers. They bring in expertise from other sectors and allow for selection of best technology from various options. It cannot be expected that these equipment suppliers bear the learning cost until the technology is cost effective, because then they would not price technologies at cost, thus preventing the market mechanism from selecting the best technology. It also creates uncertainty as to who will eventually receive the benefit from the new technology. Our interviews suggest that both equipment suppliers and cell producers are leading some of the innovation, a healthy mix that future policy might wish to continue to maintain.

(iii) The model illustrates a third effect arising from competing innovative equipment suppliers. The most successful equipment supplier cannot price its technology so as to capture the cost improvement relative to conventional technology in period two, but has to compete against the second best innovator and lower its price. It will receive fewer benefits in period two, and hence offer less of a discount in period one to the cell producer that is prepared to explore the innovation in a new production line. As a result, cell producers use less of the innovative technology and the breadth of innovation falls. Comparing the simulated market outcome against the social optimum shows that the cell producers invest too small a share of new production lines in innovative components. Technology policy could try to compensate for this, e.g. by providing subsidies for the use of innovative components where new production lines are built.

To an extent, these results support the earlier work on "demand pull" innovation, which focused on the role that increases in expected future demand play in creating incentives for innovators ([Schmookler(1962)], [Rosenberg(1969)], [Mowery(1983)]). We model the near term costs, due to delay and disruption, when integrating new process technology. The result points to the trade-off firms face between exploring new technical possibilities and fully exploiting existing processes [Benner and Tushman(2003)]. The possibility that integrating new technology produced by equipment suppliers is complicated and difficult suggests the need for coordination of innovation across these production steps. Our finding about the impact of competition in the supply chain is consistent with earlier work. However the access that equipment suppliers have to technology outside the PV industry has not been emphasized in the context of industry structure and innovation, although the results do support the notion that inter-sectoral flows of knowledge can be important.

The paper is structured as follows. We first provide a description of the industry, the types of firms that participate, and the manufacturing processes at its core. We then develop the model in three steps reflecting the three sets of policy insights that they offer. Finally we conclude with a discussion of the implications for improving the design of public policy.

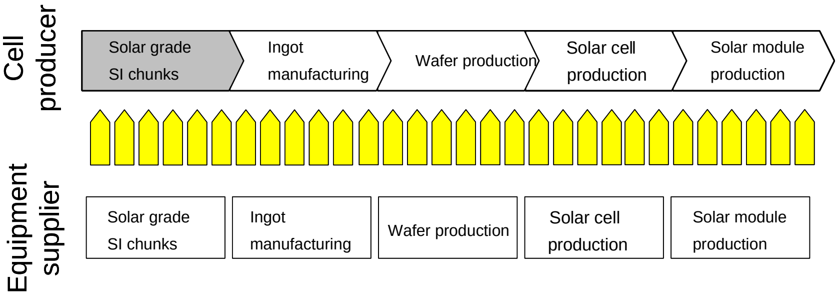

Figure 1: PV cell production process

2 Description of the industry

The production of PV cells consists of several production steps. The horizontal line of Figure 1 shows the processes of cleaning the silicon, growing the crystalls. The crystals are cut into wavers. The wavers receive Chemical and electronic structure and are connected electrically to become solar cells. Finally many solar cells are linked and put into solar modules.

As much of the PV cell production is automated, the design, innovation, and adoption of manufacturing equipment is an important component of costs and performance in photovoltaics.

We first assessed the level of horizontal integration of industry across various stages of the PV cell production. Figure 2 illustrates for surveyed cell and module producers, during which stages of the production they are active (dark boxes). While integration across the cell production is standard, the recent shortage of clean silicon induced a trend of expanding the integration towards silicon preparation - either with long-term contracts or ownership arrangements.

Cell producers by manufacturing equipment across the production line from equipment suppliers. Figure 3 lists for 111 equipment suppliers, for how many steps of the cell production they provide equipment (width of the bars).[1] In contrast to the cell producers that usually cover most of the cell production steps, the equipment suppliers are focused on individual steps. 82 of the covered companies only provide equipment for one production step, 18 for two, 7 for three, 4 for four, and only one company provides equipment for all five production steps. This result was confirmed in our industry survey; while some equipment suppliers provide turn key solutions, most equipment suppliers offer manufacturing equipment

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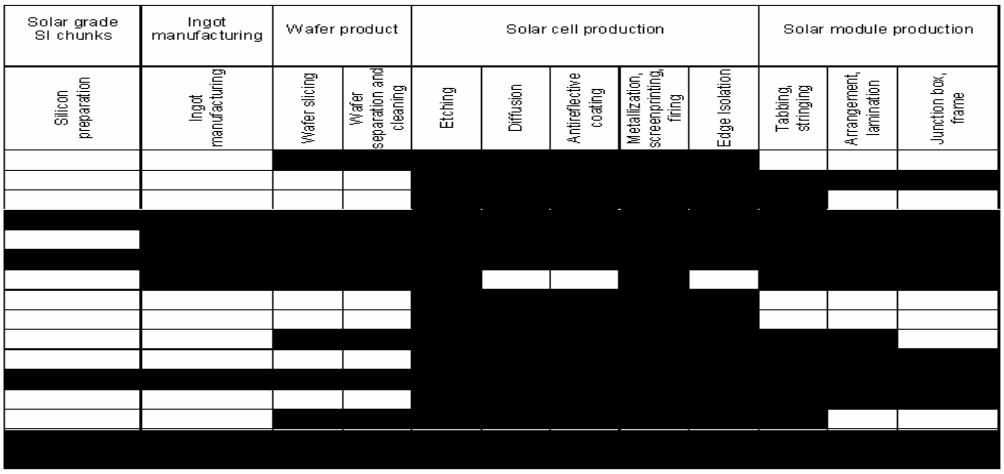
[1] http://www.enf.cn/database/equipment-ingot-turnkey.html



Solar grade SI chunks	Ingot manufacturing	Wafer product		Solar cell production					Solar module production		
Silicon preparation	Ingot manufacturing	Wafer slicing	Wafer separation and cleaning	Etching	Diffusion	Antireflective coating	Metallization, screenprinting, firing	Edge Isolation	Tabbing, stringing	Arrangement, lamination	Junction box, frame
		■	■	■	■	■	■	■			
				■	■	■	■	■	■	■	■
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Figure 2: Cell producers actvity along production chain, based on survey (dark=active).

only for individual production steps. As there is neither a dominant producer nor equipment supplier at any production step, in our model we will assume competition across the value chain.

One interesting dimension of the innovation introduced to the PV production is the appearance of equipment suppliers that already have a large presence in other industrial sectors. Growing market potential creates the opportunity for these companies to transfer their expertise and research capabilities to related challenges in the PV cell production.We are interested in understanding where innovation of PV cell production resides. Do manufacturing equipment suppliers or cell producers initiate, pursue and retain the ability to direct innovation? In our interviews with 17 cell producers and 10 equipment suppliers we asked both groups to name three recent innovations in the cell production. We asked who initiated the idea for the improvement? (Figure 4)

Equipment suppliers think most innovations are initiated by equipment suppliers, while cell producers think that the majority of innovations are initiated by cell producers. Overall this response is in line with many other answers from the survey. Suggesting that some ownership of the innovations resides with cell producers, while other aspects are directed by equipment suppliers.

Based on this understanding of industry structure and innovative activity, we now model the incentives for innovation of these actors.

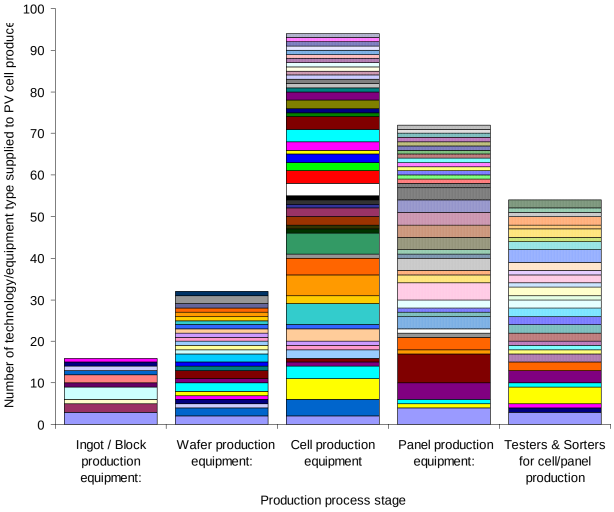
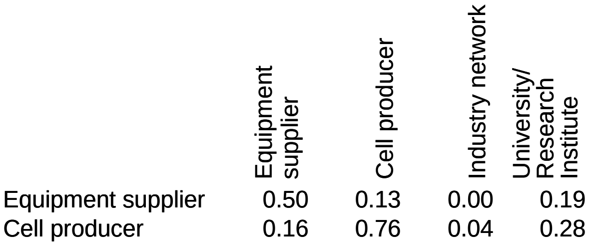


Figure 3: Multitued of technology companies supplying the PV production process



	Equipment supplier	Cell producer	Industry network	University/ Research Institute
Equipment supplier	0.50	0.13	0.00	0.19
Cell producer	0.16	0.76	0.04	0.28

Figure 4: Survey result: Who initiated the improvement?

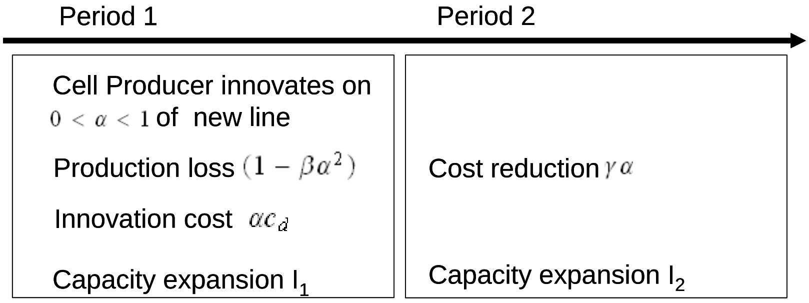


Figure 5:

3 Model of innovation in PV cell production

In this section we establish a simple framework for looking for evidence of learning-by-doing. We then focus on the adoption of new machinery in the cell production, in order to evaluate innovation in the PV cell production.

We model two periods, where a period captures a couple of years. These periods correspond to the life-cycle of PV products and to the frequency of decision-making about new manufacturing lines. Cell producers can expand their production capacity in both periods t by I_t. This additional capacity is available for production within the same period. In other words capacity in period t is directly a function of I_t. Because the usable lifetime of equipment is short, we do not attribute any future value to invested capacity or ownership of new technology post period two.

In period $t = 1$, cell producers decide on which fraction α the line will apply the advanced technology on their new production lines (i.e. the fraction of production line where new machinery is deployed). We will refer to α as the breadth of innovation.

Cell producers incur adjustment costs in the form of higher production downtime or lower product quality during the first period they apply a new production technology. In the model, production in period 1 is reduced to $\left(1-\beta\alpha^2\right)$ of full capacity. The downtime costs are calculated as forgone profit margin. Development of advanced manufacturing technologies also creates additional costs of αc_d. Once experience has been gained from the new production technology, unit costs are reduced by $\alpha\gamma$ in period 2. Thus profit margins, that are s for the conventional production technology, increase to $s + \alpha\gamma$ when using the advanced technology.

For the time period t we model a two stage decision process of cell producers and equipment suppliers. Equipment suppliers determine their prices for innovative equipment $p_{t,a}$, while the price of conventional technology remains fixed at p_c. Based on the price of innovative technologies, cell producers decide on which fraction of the new production line to include innovative technologies. Where cell producers finance and own the innovation, all equipment is sold at the price of conventional equipment. $p_{1,a} = p_{2,a} = p_c$.

With this framework we can now model the incentives to innovate under different market structures. In model I, one equipment supplier innovates for every step of the production process, and one cell producer decides for which section of the new production line to buy innovative equipment. While only one innovative company is competing for each production step, the threat of entry of innovative equipment suppliers at further steps of the production line creates competition in model I.

In model II, M different equipment suppliers are competing to offer innovative production technologies at every stage of the production lines. We assume that the improvement which can be achieved with the innovation, creates cost reductions that are exponentially distributed with an average improvement of γ. In the appendix we show that the cost improvement that can be achieved with the best of M improvements for a production step can be approximated by $\gamma\,(1 + \ln(M))$.

In model III M different cell producers are pursing innovative production technologies for which they retain ownership. The main difference in model III is that during the second period the innovative cell producers do not exchange information about the success of their innovation or the approach they have chosen. Hence, they all continue to produce using their own innovation.

The final model determines the optimal social level of depth and breadth of innovation. In all cases we assume that cell producers decide on their capacity expansion plans separately from the level of innovation they want to implement in new production lines. We thus take investment volumes I_t as exogenous.

The following table gives a summary of all the variables used in this paper:

Var	Description
N	number of cell producers
M	number of competing equipment innovations (depth of innovation)
I_t	Capacity increase by a cell producer in period t
α	breadth of innovation
$\gamma\alpha$	cost reduction in period two for innovative product in period 2
$\beta\alpha^2$	production downtime in period 1 with innovative technology
$c_d\alpha$	cost for developing innovative production technology
s	profit margin for conventional cell producers
$p_{t,a}$	price for advanced equipment in period t
p_c	price for conventional equipment
π_{i_e}	profit equipment company
π_{i_p}	profit cell producer

3.1 Model I - Monopolistic innovative equipment suppliers

Initially, we model a situation where one equipment supplier offers an innovative solution for each production step. In period one, equipment suppliers set the price for their innovative solution $p_{t,a}$ and the cell producer that uses innovative technology determines for what fraction of the new production line to use the innovative technology. In period two equipment suppliers can sell the new technology, now with a demonstrated track record of utilization in the first period, at a premium relative to conventional technology. Cell producers will chose the new technology in period two, if the cost improvement outweight the price margin charged. We calculate the equilibrium innovation and pricing decisions, starting in period two.

In period two, equipment suppliers price an innovative product at the level which makes cell producers indifferent to the choice between the innovative and the existing manufacturing technologies. The price that can be charged for the innovative technology exceeds the price of the conventional technology by the cost reductions that cell producers achieve with the innovative technology:

$$E\left[p_{2,a} - p_{2,c}\right] = \gamma \tag{1}$$

In period one, the cell producer buying innovative equipment decides for what fraction of the production line to use innovative approaches. He maximizes expected profits, given by the sum of investment costs in conventional and advanced technologies, and sales revenues in period one and two:

$$E[\pi_p(\alpha)] = E\begin{bmatrix} -p_{1,a}I_1\alpha - p_{1,c}I_1(1-\alpha) \\ +I_1\left(1-\beta\alpha^2\right)s + I_1(s+\gamma\alpha) \end{bmatrix}. \tag{2}$$

Note, that innovation rests with equipment suppliers and they will price innovative manufacturing equipment in period two relative to conventional manufacturing equipment. Thus, cell producers will not benefit from the overall improvement of technology and will not consider the impact of their choice of α on their future investment choices. The optimal level of innovation in period 1 follows from the first order condition of (2):

$$\frac{\partial E[\pi_p(\alpha)]}{\partial\alpha} = -p_{1,a}I_1 + p_{1,c}I_1 - 2\beta\alpha s I_1 + \gamma I_1 = 0,$$

and gives the equilibrium breadth of innovation as a function of the price of innovative manufacturing equipment in period one:

$$\alpha = \frac{-p_{1,a} + p_{1,c} + \gamma}{2\beta s}. \tag{3}$$

Equipment suppliers set the price $p_{1,a}$ at which they sell their equipment. Cell producers can introduce innovation during multiple stages of the production line. The equipment suppliers compete across these stages and thus face a competitive environment even if there is only one firm providing innovative technology for a specific production step. Thus we apply the usual assumption for competitive markets; that equipment suppliers make zero profits from selling innovative technology. Their profit consists of the sales margin in period one and period two minus the cost of innovation c_d :

$$E[\pi_e] = E\left[(p_{1,a} - p_{1,c})I_1 + (p_{2,a} - p_{2,c})NI_2 - c_d\right] \equiv 0. \tag{4}$$

Inserting the price mark up $p_{1,a} - p_{1,c}$ required to make cell producers indifferent to the choice between both technologies in period 1, (3) and the expected price mark up $E[p_{2,a} - p_{2,c}]$ to make them indifferent in the period 2 (1) in (4), gives the equilibrium breadth of innovation α_1:

$$\alpha_1 = \frac{\gamma}{2\beta s} + \frac{\gamma N E[I_2] - c_d}{2\beta s I_1} \tag{5}$$

It follows from (5) that the breadth of innovation α decreases with the cost of innovation c_d, increases with improvement γ.

With expected future market growth, the level of future investment $E\left[I_2\right]$ increases. In this case, the breadth of innovation α increases, it is profitable to explore more innovative production technologies to benefit from their lower cost with future investment in production lines.

Unexpected market growth in period 2 is not anticipated in period 1, and thus not influence $E\left[I_2\right]$ and the choice of the breadth of innovation.

Unexpected high demand in period one increases the short-term profit margin s. Would the demand increase be expected, then it would have triggered additional investment I_1. On shorter time-scales this is difficult because of financing, planning, management and supply constraints. Thus the only response is an reduction of the breadth of innovation α. This accelerates the speed at which the new line is commissioned and operating at full capacity.

The policy implications are twofold. First, it is valuable to increase market confidence in future demand growth $E[I_2]$, as this will increase the value of today's innovation and lead to accelerated cost reductions. Second, strategic deployment programs should not focus on delivering large amounts of new technologies instantly, so as to avoid unexpected short-term demand surges. Closer international cooperation on the design and timing of strategic deployment programs might be a viable approach in delivering both objectives.

3.2 Model II - Competing innovative equipment suppliers

Let us now assume we again have N cell producers. A subset M of these cell producers are buying technologically advanced manufacturing equipment for a fraction α of the production line. They buy each from separate equipment suppliers, such that M different innovations are explored for each production step with innovation. By experimenting with different advanced technologies, a wider set of approaches can be identified. We assume the cost improvements that can be achieved for the innovation are exponentially distributed, with γ describing the average improvement level. If M different innovations are explored, then the improvement level of the best innovation can be approximated by (see Appendix):

$$\gamma_{best} = \gamma \left(\ln \left(M\right) + 1\right).$$

Now we can calculate the optimal pricing decision of equipment suppliers in the second period. The most successful equipment supplier aims to capture the entire market in period 2. The price mark-up over conventional technology can therefore not exceed performance advantage relative to the second best equipment supplier. This ensures that even if the second best equipment supplier prices at the competitive price of a conventional technology, cell producers will buy the innovative technology of the best equipment supplier:

$$p_{2,a} - p_{2,c} = \left\{ \begin{array}{cc} \gamma\left(\ln\left(M\right) - \ln\left(M-1\right)\right) & \text{for } M > 1 \\ \gamma & \text{for } M = 1 \end{array} \right\} \tag{6}$$

The optimization function (3) of the cell producer remains the same as in the previous model. This is, because in period one a cell producers remains exposed to only one of the innovations for each production step and in period two all the benefits of advanced innovation is retained by the equipment suppliers. This also implies that the optimal breadth of innovation α, as a function of prices offered by equipment suppliers, stays constant.

However, the pricing function of innovative equipment suppliers changes, because the chance of capturing the benefits of innovation in period 2 is a function of the market size NI_2, and the probability of being the most innovative equipment supplier for a segment of the production line. The expected profit is:

$$E\left[\pi_e\right] = \left(p_{1,a} - p_{1,c}\right) I_1 + p(\text{best innovation}) N E\left[p_{2,a} - p_{2,c}\right] E\left[I_2\right] - c_d \equiv 0$$

The probability of having the best innovation is inversely proportional to the number of innovators, $p(\text{best innovation}) = 1/M$. Inserting the price mark-up that makes cell producers indifferent to the choice between innovative and conventional technology in period one (3) and the price mark-up the most successful equipment supplier for each production step can charge in period two (6), gives the equilibrium breadth of innovation α_2

$$\alpha_2 = \frac{\gamma}{2\beta s} + \frac{\frac{N}{M}\gamma\left(\ln\left(M\right) - \ln\left(M-1\right)\right) E\left[I_2\right] - c_d}{2\beta s I_1} \tag{7}$$

$\alpha_2$using the approximation $\ln(M) - \ln(M-1) = \ln\left(M/\left(M-1\right)\right) \approx 1/\left(M-1\right)$ this can be written as:

$$\alpha_2 \approx \frac{\gamma}{2\beta s} + \frac{\frac{N}{M(M-1)}\gamma E\left[I_2\right] - c_d}{2\beta s I_1}. \tag{8}$$

With increasing M, the breadth α_2 of innovation diminishes, while at the same time the depth of innovation α_2 increases.

In this model we have not endogenously determined M. Usually it is assumed that innovative firms price at a monopoly level, and that the equilibrium number of firms is determined such that the monopolist recovers (on average) the fixed costs c_d. We have the additional continuous dimension of the breadth of innovation α_2, which cell producers choose in response to the rebate they receive in period one. As the rebate is also set at the zero profit level we cannot use the standard 'trick'. Thus we obtain a set of combinations of M and α_2 as solutions. Perhaps policy design could be used to influence the balance between M and α_2 so as to maximize the aggregate cost improvement.

3.3 Model III - Competing innovative cell producers

Now assume cell producers, rather than equipment suppliers, pursue the innovation and retain ownership of the innovation. Not all cell producers innovate, therefore the product price in period two is still set by conventional companies. The profit function of cell producers comprises of the costs of investment in both periods, the cost of innovating, and the sales revenue in both periods.

$$\pi_p(\alpha) = -p_1 I_1 + \left(1 - \beta\alpha^2\right) s I_1 - \alpha c_d - p_2 E\left[I_2\right] + (s + \gamma\alpha)\left(I_1 + E\left[I_2\right]\right). \tag{9}$$

The optimal breadth of innovation α_3 for this cell producer follows from the first order condition of (9) with respect to α:

$$\alpha_3 = \frac{\gamma}{2\beta s} + \frac{\gamma E\left[I_2\right] - c_d}{2\beta s I_1}. \tag{10}$$

The breadth of innovation is smaller than in the case of competing innovative equipment suppliers (7) as long as the number of competitors is sufficiently large $N > M/\left(\ln(M) - \ln(M-1)\right)$, e.g. $N > 2$ for $M = 2$ and $N > 7$ for $M = 3$. In addition, the case of innovative equipment suppliers allows for the sharing of the best innovation for any step of the production line, whilst innovative cell producers only retain their innovation.

However, we have not modelled two other relevant aspects that could influence such a decision. Cell producers may find it easier to coordinate the interactions of innovation across the production line, where they own the innovation. On the other hand, equipment suppliers from other sectors might be more interested in transferring their expertise towards the production of PV cells, where they can retain ownership of the innovation.

3.4 Social optimum

In the social optimum the choice parameters are the depth of innovation M and breadth of innovation α as before. The benefits of using the best available innovative technology in period 2 across the entire industry are:

$$E\left[\pi_s\left(\alpha, M\right)\right] = M\left(-\alpha c_d - \beta\alpha^2 s I_1 + \gamma\alpha I_1\right) + N\alpha\left(\ln\left(M\right)+1\right)\gamma E\left[I_2\right]. \tag{11}$$

The first order conditions show the optimal breadth of innovation α (2nd order condition confirms max):

$$\alpha = \frac{\gamma}{2\beta s} + \frac{N\gamma\left(\ln\left(M\right)+1\right)/ME\left[I_2\right] - c_d}{2\beta s I_1}. \tag{12}$$

In the social optimum, the breadth of innovation is also determined endogenously. Differentiating (11) with respect to M gives (2nd order condition confirms max):

$$\alpha_s = \frac{\gamma}{\beta s} + \frac{NE\left[I_2\right]\gamma/M - c_d}{I_1\beta s}. \tag{13}$$

Equation (12) and (13) determine α and M and can thus be solved for M_s:

$$\frac{\ln\left(M_s\right)-1}{M_s} = \frac{\gamma I_1 - c_d}{\gamma NE\left[I_2\right]}$$

To allow for an illustration, we assume the following parameter values. In this case M also coincides with the social optimum M_s.

$$N=5,\ M=2,\ I_2/I_1=1.3,\ c_d/I_1=1,\ \gamma=.5.,$$

and obtain the equilibrium breadth and depth of innovation for the different model scenarios:

Model	breadth (α)	depth (γ_{best})	depth*breadth
I	$\frac{\gamma}{2\beta s}+\frac{\gamma NE[I_2]-c_d}{2\beta s I_1}$	γ	$\frac{1.4}{\beta s}$
II	$\frac{\gamma}{2\beta s}+\frac{\frac{N}{M}\gamma(\ln(M)-\ln(M-1))E[I_2]-c_d}{2\beta s I_1}$	$\gamma\left(\ln\left(M\right)+1\right)$	$\frac{.5}{\beta s}$
III	$\frac{\gamma}{2\beta s}+\frac{\gamma E[I_2]-c_d}{2\beta s I_1}$	γ	$\frac{.1}{\beta s}$
social opt.	$\frac{\gamma}{2\beta s}+\frac{N\gamma(\ln(M)+1)/ME[I_2]-c_d}{2\beta s I_1}$	$\gamma\left(\ln\left(M\right)+1\right)$	$\frac{1.9}{\beta s}$

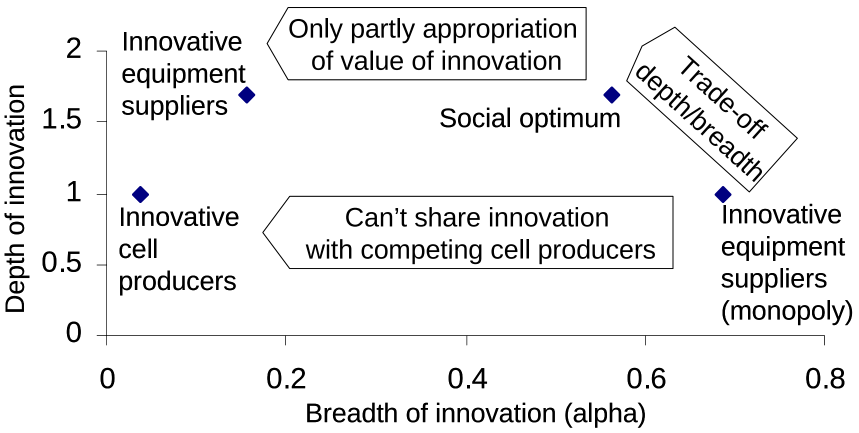


Figure 6: Innovativeness of industry for different model assumptions.

Figure 6 summarizes the results for our specific parameter assumption (we depict for $\beta s = 2$):

While the absolute values of breadth and depth of innovation in the different scenarios are obviously a function of the parameter choice, the comparison between the scenarios allows for three general results:

First , the breadth of innovation of monopolistic innovative equipment suppliers (Model 1) (5) are compared against the social optimum (12). The monopolistic companies can appropriate all the benefits of innovation. Should the optimal depth of innovation be $M = 1$, then the optimal result is achieved $\alpha_s = \alpha_1$. If the social optimal depth of innovation is bigger than $M_s > 1$, then the trade off between depth and breadth of innovation implies that the social optimal breadth of innovation is smaller than the breadth in model 1: $\alpha_s < \alpha_1$.

Second, competing innovative equipment suppliers (Model 2) (7) are compared to the social optimum (12). Assuming the number of competing innovators in any stage M equals the social optimum, then the breadth of innovation can be directly compared ($\alpha_2 < \alpha_s$). Competing innovators can not appropriate the full value of their innovation, because in period 2 they can only charge a premium corresponding to the mark up relative to the second best innovator rather than the full value of the technology improvement.

Third, competing innovative cell producers (Model 3) (10) are compared to the social optimum (12). The competing innovative cell producers bear the full cost of innovation, but do not share successful innovations. Hence society does not make full use of the innovation, and the breadth of innovation is below the optimum $\alpha_3 < \alpha_s$. This condition requires that $N > M/\left(\ln\left(M\right) + 1\right)$, which is always satisfied for competing innovative cell producers $N > 1$, $M \leq N$.

The result observed in both Model 2 and Model 3 is that the breadth of innovation is below the social optimal level of innovation. This suggests an intervention to increase the breadth of innovation should be discussed. One approach could be the provision of direct public subsidies for the cost of implementing innovative production steps. For example, Japanese technology policy offers companies relatively easy access to funds of up to a few million Euro for novel production approaches.

4 Conclusion

Photovoltaics is often expected to make a large contribution to future energy supply. This will require significant cost reductions. Past cost reductions across various sectors and technologies, including photovoltaics, suggest that learning by doing in the production process can make an important contribution. This paper analysis the incentives for innovations in the production process. Based on industry data and a survey among industry participants a two period model is developed.

Cell producers invest in both periods into new production capacity. In period one they decide for what fraction of their new production line to use innovative technology. Using innovative technology results in delays before the line can produce at full capacity, and thus creates opportunity costs of forgone production. In the second period the innovative technology offers the opportunity to build PV cells at lower costs on new production lines. The model depicts the role of equipment suppliers. If equipment suppliers pursue and subsequently own innovation, then they can leverage the benefit but also have to compensate cell producers for the initial production delays.

With this model we draw three conclusions, that might be also more widely applicable.

First, the results show that innovation in the production process depends on expectations about future investment in production capacity. While earlier studies found that firm-level growth rates affect incentives, our result is focused on the growth rate of the industry as a whole This result implies that reducing the cost of PV can be accelerated by policies that increase confidence in expected future demand for PV cells. Equipment suppliers expect that cell producers will build more production lines and that more of their technology will be required. They increase today's innovation and offer new equipment at lower prices to current users in order to gain experience with the equipment. Where cell producers have ownership of innovations, increasing future market volumes raise interest in supply into these markets at low cost, and thus increases the motivation to innovate today.

Unexpected current demand increase is not necessarily beneficial for innovation. While high profit margins generate cash flow and attract third party funding in the sector, much of the focus is on harvesting currently high profit margins. In the model this results in a lower breadth of innovation, as cell producers want to minimize production down time that is inherently linked with the use of new production technologies. This suggests that government policies should be more transparent, so as to reduce surprises, and entail longer-term technology targets. This would create market confidence in future growth. However, as this does not entail an indefinite commitment to a specific technology, this is not really credible in the first place, but mid term targets for groups of technologies. For example, the 20% renewable target of the EU by 2020, a vision of higher shares post 2020 can increase this market confidence, if they are linked with clear milestones and criteria for the ongoing evaluation of technology.

Second, production lines are mainly build with components from third party equipment suppliers. These can pursue and own innovative ideas or implement innovative ideas of cell producers. We explore the merits of competing innovative companies to the extend that they could explore multiple innovative ideas before the market selects the best production improvement.

In our interviews we identified a further advantage of an industry in which equipment suppliers innovate; several equipment suppliers entered the PV cell production market from other fields and transferred their production expertise from these fields. However, innovation lead by cell producers also has an advantage that we do not consider in the model. Many of the production steps for a PV cell are interlinked. This suggests the need for coordination of innovation across these production steps. Innovative cell producers might be able to pursue other types of innovation that requires a coordinated change across these production steps.

Finally, our models suggest that learning externalities result in cell producers using, and equipment suppliers providing, an insufficient breadth of innovations along the production chain. These results are consistent with modeling studies. Policies that can induce exploration of multiple technological alternatives when new production lines are being built can accelerate technological improvement. There is some precedence for such policies, for example funding for demonstration manufacturing plants, and also R&D specific to manufacturing.

5 Appendix - Justification for ln function to describe industry cost improvements

Explain the functional form of improvements, e.g. cost reductions ˜$1 + \ln(M)$

Assume individual cost improvements are distributed exponentially, like:

$$\rho(x) = \gamma \exp(-\gamma x) \tag{14}$$

Thus the expected cost improvement of an individual is:

$E\left[x\rho(x)\right] = \int_0^\infty x\gamma \exp(-\gamma x)dx = -\left(x + \frac{1}{\gamma}\right)\exp(-\gamma x)|_0^\infty = \frac{1}{\gamma}$

Now let us calculate what the industry cost improvement is. We use an iterative approach to calculate the distribution of cost improvements. Assume we know distribution of m player's cost improvement:

$\rho_m(x) = \sum_{i=1}^m a_{m,i} \exp(-i\gamma x)$

We can express the distribution of cost improvements of $m+1$ players as a function of the cost improvements of the known distribution of m players and the known distribution of an individual player.

$E\left[x\rho_{m+1}(x)\right] = \int_0^\infty \int_0^\infty \max(x, y)\rho_m(x)\gamma \exp(-\gamma y)dxdy$

The max function expresses that the industry will choose the better of both improvements. We can divide the integration into the cases where x performs better and where y performs better.

$$\begin{aligned}
= & \int_0^\infty x \sum_{i=1}^m a_{m,i} \exp(-i\gamma x)\left(1 - \exp(-\gamma x)\right)dx \\
& + \int_0^\infty x \sum_{i=1}^m a_{m,i}\left(\frac{1 - \exp(-i\gamma x)}{i\gamma}\right)\gamma \exp(-\gamma y)dx \\
= & \int_0^\infty x \sum_{i}^m a_{m,i} \exp(-i\gamma x)\left(1 - \exp(-\gamma x)\right)dx \\
& + \int_0^\infty x \sum_{i}^m \frac{a_{m,i}}{i}\left(\exp(-\gamma y) - \exp(-\left(i+1\right)\gamma x)\right)dx \\
= & \int_0^\infty x \sum_{i=1}^m a_{m,i}\left(\exp(-i\gamma x) + \frac{1}{i}\exp(-\gamma y) - \frac{i+1}{i}\exp(-\left(i+1\right)\gamma x)\right)dx
\end{aligned} \tag{15}$$

We could equally write the final line as a function of the distribution of $m+1$ players:

$$= \int_0^\infty x \sum_i^m a_{m,i} \exp(-i\gamma x) dx \tag{16}$$

Collecting terms we obtain

$a_{m+1,m+1} = -a_{m,m}\frac{m+1}{m}$

$a_{m+1,i} = a_{m,i} - a_{m,i-1}\frac{i}{i-1}$ for $1 < i \leq m$

$a_{m+1,1} = 2a_{m,1} + \sum_{i=2}^m \frac{a_{m,i}}{i}$

The starting value for $m = 1$ is given from (14):

$a_{1,1} = \gamma$

Iteratively solving for $m = 2, 3$ gives:

$a_{2,1} = 2\gamma \quad a_{2,2} = -2\gamma$

$a_{3,1} = 3\gamma \quad a_{3,2} = -2\gamma - 4\gamma = -6\gamma \quad a_{3,3} = 3\gamma$

For all three cases we substitute back into our initial integral and solve:

$E\left[x\rho_m(x)\right] = \int_0^\infty x \sum_i^m a_{m,i} \exp(-i\gamma x) dx = \sum_i^m \frac{a_{m,i}}{(i\gamma)^2}$

m	$E\left[x\rho_1(x)\right]$	$1 + ln(m)$
1	$\frac{1}{\gamma}$	1.0
2	$\frac{1}{\gamma}(2 - 1/2) = \frac{1}{\gamma}1.5$	1.6931
3	$\frac{1}{\gamma}\left(3 - 6/4 + 1/3\right) = \frac{1}{\gamma}1.833\,3$	2.0986

The approximation with the ln is not too bad for our purposes.

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