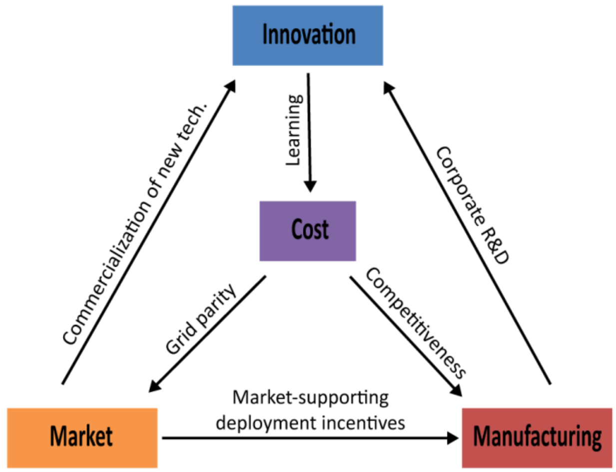
Chapter 6: Innovation-Focused Policy Framework for TW-Scale PV Deployment



6.1. Demand-Pull and Technology-Push Policy Instruments

6.2. Policy Lessons from the Rapid Development of the Global Photovoltaic Industry during 2000-2013

6.3. Policy Framework for an Innovation-Driven Photovoltaic Industry Moving Forward

Previous chapters have reviewed innovations in the photovoltaic science, manufacturing, and installation, which all have one common goal: to reduce the cost of PV technology and make it an affordable clean energy source on the global scale. These dramatic technological innovations over the past decades are enabled and supported by various policy instruments, ranging from regulation and subsidies to research & development (R&D). These policy instruments in the PV sector can be broadly categorized into two approaches: technology-push which directly supports technological progress such as public R&D funding, and demand-pull which creates or expands the market for PV installations such as tax credits.

This chapter will first review a few key policy instruments in the global PV industry, and discuss some of the important policy innovations. The second section measures the innovation pace in terms of patent applications in PV technologies over the past two decades, examines the key policy lessons from the painful turmoil in the recent few years, and highlights the role of innovation in delivering the long-term promises of PV technology in meeting growing energy demand and mitigating climate change. The last section proposes an innovation-focused policy framework in building a sustainable global PV industry [*1*].

6.1. Demand-Pull and Technology-Push Policy Instruments

PV technology was an expensive niche energy source only for satellite applications, hallmarked by the Bell Lab's launch of the Telstar satellite with PV cells in 1962. Various energy policy instruments have been devised since then to foster research and innovations in PV technology. Without these major policy innovations, it would be impossible to imagine a PV industry for terrestrial power generation with about 38 GW/year installations and over $100 billion/year market size in 2013 [2].

Net metering [3], which allows consumers to offset their electricity bill with self-generated electricity output, was first enabled in the United States by the Public Utility Regulatory Policy Act (PURPA) of 1978. This law essentially provides the regulatory assurance for the PV technology to compete with retail electricity rates, by requiring the utility companies to purchase electricity from independent generators at "avoided cost" [4]. According to the Database of State Incentives for Renewables & Efficiency (DSIRE) [5], more than 40 states, the Distribute of Columbia, and 4 territories in the United States have implemented net metering policies in 2014.

Renewables portfolio standard (RPS), which typically sets a series of milestones for the share of renewables in the electricity market, is a state-level mandate, within which a specific portion can be carved out for solar energy due to its higher cost compared with other renewables such as wind energy. For example, New Jersey has an ambitious target of providing 4.1% of retail electricity sales with PV systems by 2028 [5]. Together with net metering, RPS opens up the market for distributed PV deployment and utility-scale PV generation through regulations [6,7]. According to the DSIRE, 29 states, the Distribute of Columbia, and 2 territories in the United States have implemented RPS policies in 2014.

Financial incentives, in the form of government subsidies, have spurred the demand for PV installations dramatically in the past decade, together with the cost of PV modules declining from about $5.0/watt in 2000 to $0.70/watt in August 2014 [8]. In the United States, the most significant subsidy for PV products is the federal investment tax credit (ITC). The Energy Policy Act of 2005 enacted a 30% ITC for residential and commercial solar energy systems, where 30% of the system cost can be deducted from the federal tax, from January 1 2006 to December 31 2007. The ITC was then extended in 2006 and in 2008 to be effective till December 31 2016. However, ITC would commonly require tax equity, which could be significant cost factor of the installed PV system [9]. To stimulate the deployment of PV projects, the ITC was temporarily replaced by the cash grant enacted by the American Recovery and Reinvestment Act of 2009 for PV system constructions that commenced by 2011 [10]. The 30% tax credit could also present an unintended possibility for overstating the PV system price (for instance, there was a high-profile U.S. Treasury investigation of SolarCity in 2012 right before its Initial Public Offering [11]).

One policy innovation to discourage overstating system price is Japan's "Residential Solar Power Support Measure", which offers cash subsidy to residential PV systems (<10 kW). The subsidy rate is inversely related to the system price: a subsidy of $0.20/W for prices lower than $4.10/W, a subsidy of $0.15/W for prices higher than $4.10/W, but no subsidy for prices higher than $5.00/W [12]. Similar approaches like a moving price ceiling, which will be periodically reviewed with the market development, should be integrated with the type of subsidies, where the amount of subsidy is proportional to system price.

The incentives for purchasing more cost-effective PV system is stronger under the feed-in tariff (FiT) scheme [13,14], where the subsidy is directly tied to the electricity output ($/kWh) for a certain number of years (typically 20 years) and lower prices of PV systems will lead to a higher rate of financial return. Germany's FiT program has made Germany the world's top leader in deploying PV technology, with about 35 GW of total installed capacity by the end of 2013 [2]. The main issue with Germany's FiT program is the runaway rapid expansion in PV deployment and the associated cost burden on retail electricity prices in the form of EEG surcharge. In order to slow down the PV deployment to 2.5 – 3.5 GW/year, several EEG amendments [15,16] to reduce FiT rates for PV based on the installation volume have been passed by the German lawmakers since 2009 (**Fig. 6A-1A**), which in turn "stimulated" demand as installers expected the FiT rates to decline rapidly and rushed to take advantage of the current attractive FiT rates (**Fig. 6A-1B**).

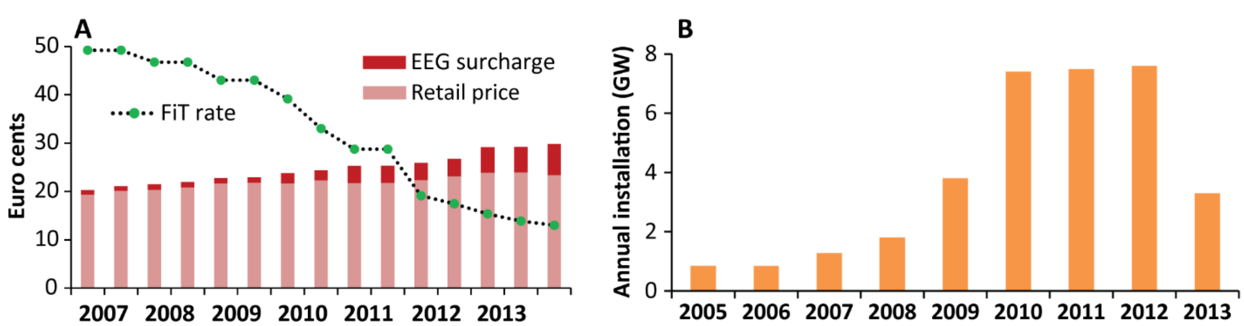


Figure 6A-1. FiT-driven PV deployment in Germany. The FiT rates have been declining while the retail electricity prices have been rising for residential consumers in Germany, where the red portion of the price is the EEG surcharge to fund the FiT payment (A). Since 2009 several EEG amendments have been made to rein in the rapid expansion in PV installations (B). Source: Eurostat and EPIA.

In terms of technology-push policies, public R&D in PV has also enjoyed innovations in the recent decade. For example, a U.S. national program, the SunShot Initiative, has been created to focus on funding the most innovative ideas in making PV technology more cost-effective. Innovative R&D models such as the U.S. PV Manufacturing Consortium was funded in 2011 to promote R&D collaboration and technology transfer among PV manufacturers, which borrowed the pre-competitive R&D model from the semiconductor industry.

In the ideal picture, private R&D can be stimulated by the "demand-pull" policies in a vibrant PV industry through market-driven innovation: PV manufacturers are thriving and re-investing their profits into R&D. An expanding market incentivizes all innovations that aim to further reduce the manufacturing cost. The fundamental long-term needs to deploy cost-competitive, low-carbon energy sources continue to attract private capital to commercialize promising innovations. All these innovation sources together drive the cost of deploying solar PV towards grid parity in a growing number of markets.

Pricing carbon emissions globally in the form of either a carbon tax or a cap-and-trade program is a direct and effective way to correct the environmental externalities comparing fossil fuels and renewable sources. In a simple theoretical framework (**Fig. 6A-2**), subsidizing renewable energy instead of pricing carbon emissions leads to overconsumption of energy and an associated deadweight loss. Moreover, a coordinated global program in pricing carbon emissions, though a challenging policy goal, may provide better sustainability and certainty than the current patchwork approaches with subsidies to renewables.

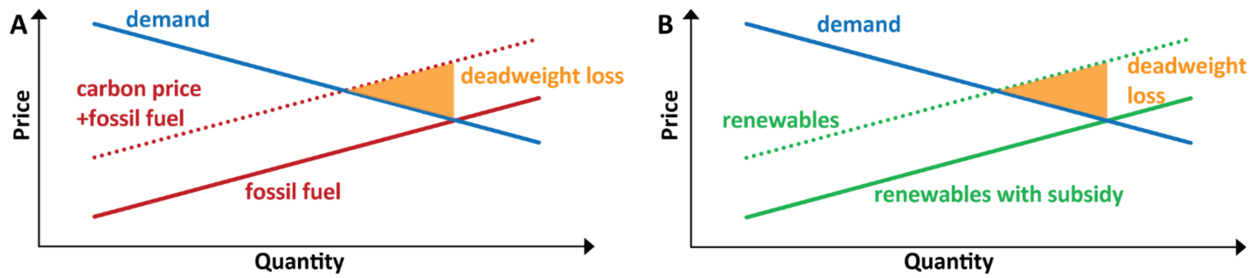


Figure 6A-2. Economic deadweight loss from carbon emissions and subsidy to renewables. In the current policy framework, overconsumption of energy (both fossil fuel and renewables) leads to a deadweight loss. The optimum operating point is to replace the patchwork subsidies to renewable energy (B) with market prices to carbon emissions (A).

6.2. Policy Lessons from the Rapid Development in the Global Photovoltaic Industry during 2000-2013

The global photovoltaic (PV) market has undergone a dramatic evolution in the recent decade, expanding from 0.3 gigawatts (GW) of annual installations in 2000 to 38 GW in 2013 [2]. This evolution has spurred manufacturing scale-up with GW-size solar panel factories. The innovation pace too has been impressive, with patent applications growing by seventeenfold between 2000 and 2011, from 138/year to 2344/year. Accompanying with the impressive scale-up and technological innovation, the inflation-adjusted prices of crystalline-silicon (c-Si) PV modules have declined from $5.0/watt in 2000 to as low as $0.72/watt in September 2013 [8].

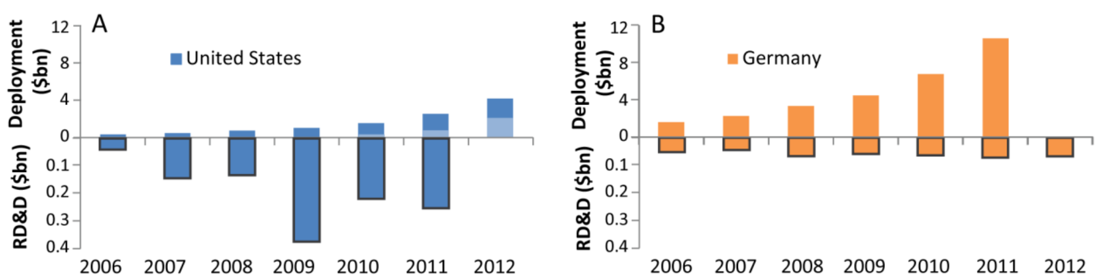


Figure 6A-3. Funding allocation between public R&D and deployment for solar PV. The cash grant (from the American Recovery and Reinvestment Act), as part of the deployment funding, is highlighted in lighter color. The R&D budget includes funding for demonstration projects. All prices are inflation-adjusted to the 2010 U.S. dollars. Source: BNetzA, IEA, LBL, and U.S. Treasury.

Billions of dollars in deployment incentives have been spent each year to support the market for solar PV (**Fig. 6A-3**), particularly in the Germany via feed-in tariffs (FiT) and in the U.S. via tax credits. These "demand-pull" policies are intended to create a vibrant PV industry through market-driven innovation. The recent overcapacity in PV module production and the resulting oversupply, however, have caused PV modules being sold at unsustainably low prices and pushed almost all major PV manufacturers into financial losses in the recent two years (**Fig. 6A-4**). There are also signs of cutback in R&D spending among these major PV manufacturers (**Fig. 6A-5**).

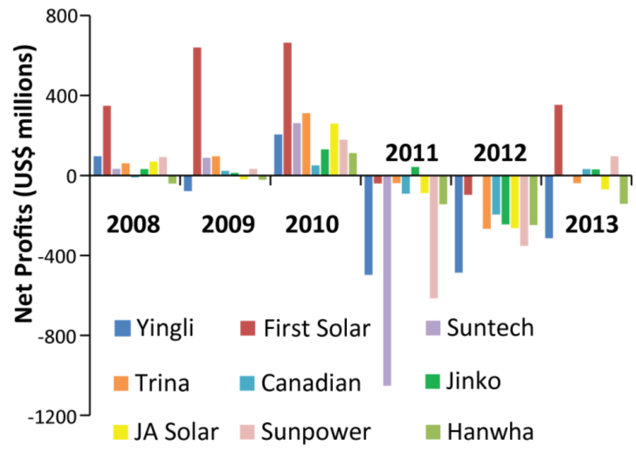


Figure 6A-4. Net profits (losses) of 9 major U.S.-listed PV manufacturers during 2008-2013. The 2013 financial results have shown signs of industry-wide recovery from the darkest periods during 2011-2012. Source: U.S. SEC.

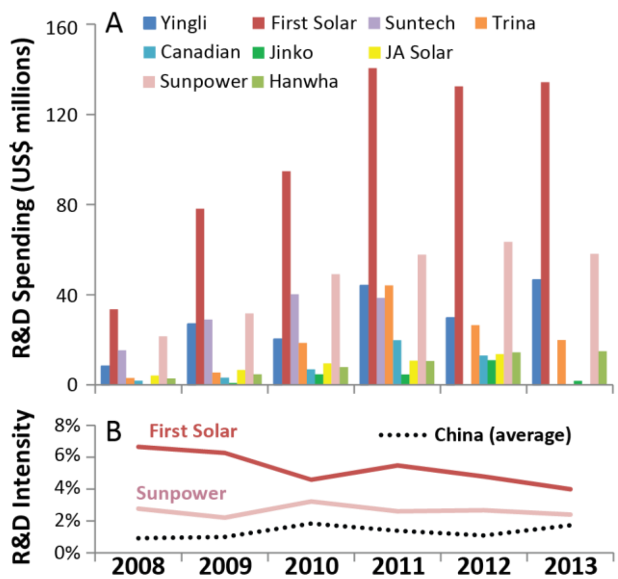


Figure 6A-5. Corporate R&D from 9 major U.S.-listed PV manufacturers during 2008-2013. The corporate R&D spending (A) is mostly increasing during 2008-2011 accompanying with increasing sales revenue, but shows signs of declining in 2012 and 2013. Different from the other 8 manufacturers, First Solar is specialized in thin film PV modules and system integration, whose business model enables First Solar to command a notably higher profit margin. The R&D intensity (B) is measured as current year's R&D expense as a percentage of previous year's sales revenue. The 7 China-based PV manufacturers on average have invested 1.33% of their sales revenue into R&D during 2008-2013. Source: U.S. SEC.

In this section we examine a set of the PV industry's key metrics on innovation, manufacturing, and market. Insights have been developed from the dataset to form a policy framework for building a sustainable PV industry.

6.2.1 Data and methods

We have assembled a comprehensive dataset from 2000 to 2013 for the global PV industry from publicly available sources, including PV installation and manufacturing, research & development (R&D), deployment incentives, and company-level financial performance for major PV manufacturers. For c-Si wafer-based PV modules, the price and market size data are obtained from the Bloomberg New Energy Finance [17] and used in the learning curve models. For First Solar's thin film PV modules, the cost and quarterly production data are obtained from the company's quarterly reports.

There are three common proxies to measure innovation: R&D spending, literature counts, and patents [18]. As we are interested to examine the relationship between innovation and cost reduction in PV technology, the patent approach is chosen to measure innovation output that is closely related to industrial applications [19]. The main limitation of patents as the proxy for innovation output is patent quality, where claims, citations, and number of protected countries have been previously explored to weight the economic value of patents [20].

Furthermore, the overall patent quality could differ significantly across major patent offices [21]. Therefore, this study measures innovation by the number of Patent Cooperation Treaty (PCT) patent applications through the World Intellectual Property Organization (WIPO), a well-established proxy for benchmarking a country's innovation capacity [22]. PCT patent application serves as a proxy for high-value innovation output, as it is a cost-effective approach for patents seeking international protection.

We collect and process the patent data from the WIPO PatentScope database. We are interested in using the same set of PV patent data to analyze the cost reduction through innovation, and to understand the dynamics among innovation, manufacturing and market forces. Therefore, we choose the keywords approach to identify patents focused on PV applications. PV PCT applications are obtained by searching keywords "photovoltaic", "solar cell", "solar module", or "solar panel" in the title and abstract of the applications. C-Si PV PCT applications are the PV PCT applications containing keyword "silicon" but no "amorphous". First Solar's PCT applications used in the learning curve model have excluded applications related to PV system installation. The patent data has been refined using the patent classes approach with technology categories defined in the International Patent Classification (IPC) Green Inventory (**Table A2.1**). All applications are sorted by country according to the applicant's address. The patent data is also sorted by year according to the priority date for quantifying innovation in the learning curve model, or according to the international filing date for measuring patenting activities.

A two-step regression procedure is then adopted to solve the co-linearity issue in the two-factor learning curve model. As both the cumulative PCT applications ($\mathrm{T_i}$) and the annual installations of c-Si PV modules (Q_i) have been increasing in our time frame, the correlations are removed by using the residual variable η_i in **Eq. 6A-1** and Q_i to explain the price (P_i) in **Eq. 6A-2**.

$$T_i = \alpha_0 + \alpha_1 \log Q_i + \eta_i \qquad \textbf{Equation 6A-1}$$

$$\log P_i = \theta_0 + \theta_1 \log Q_i + \theta_2 \eta_i + \epsilon_i \qquad \textbf{Equation 6A-2}$$

The final model is presented in **Eq. 6A-3**, or an equivalent form in **Eq. 6A-4**. The learning rate (LR) for economies of scale Q_i is defined as cost reduction per doubling in scale. The LR for innovation T_i in this study is defined as cost reduction per 100 patent applications. A summary of the key regression results can be found in **Tables A2.2** and **Table A2.3** in the appendix.

$$\log P_i = \beta_0 + \beta_1 \log Q_i + \beta_2 T_i + \epsilon_i \qquad \textbf{Equation 6A-3}$$

$$P = \left({10^{\beta_0}} \big/ {Q_i{}^{-\beta_1}} \right) \left(10^{\beta_2}\right)^{T_i} \qquad \textbf{Equation 6A-4}$$

6.2.2. Cost-effective policies for further cost reduction

We first estimate the range of cost-reduction potentials in PV modules from projections in three learning curve models. **Table 6A-1** estimates the timing and the learning investment for various c-Si PV learning curve projections. The conventional PV learning curve model (**Eq. A2.1**) for c-Si PV modules has been widely referenced to support policies that rely on a cost-reduction strategy through rapid market expansion, where the average selling price (ASP) of PV modules is projected to decline with increasing cumulative installations [*23*,*24*]. As the market grows, production of PV modules benefits from both economies of scale and "learning", where accumulated operating experience leads to innovation and cost reduction through both learning-by-doing and learning-by-searching [*25*]. However, the LR is known to vary depending on the timeframe of the regression analysis (**Fig. 6A-6A**), and this uncertainty in LR will significantly affect the projected timing and cost of reaching the cost-reduction milestones [26,27] and GHG mitigation targets. As detailed in **Table 6A-1**, "demand-pull" polices, based on this conventional learning curve model, would experience a range of learning investment with differences by an order of magnitude.

Table 6A-1. The timing and cost (learning investment) of various cost-reduction scenarios for c-Si PV modules to reach a price of $0.5/W.

	Market growth at 30%/year		No market growth	
	Timing	Cost (US$ bn)	Timing	Cost (US$ bn)
Conventional (LR=20.9%)	2023	220	2081	252
Conventional (LR=15.2%)	2034	3,576	Not within the 21st century	
Economies of scale	2043	24,837	N.A.	
Innovation (2005 level)	2031	1,616	2041	253
Innovation (2010 level)	2019	72	2019	45

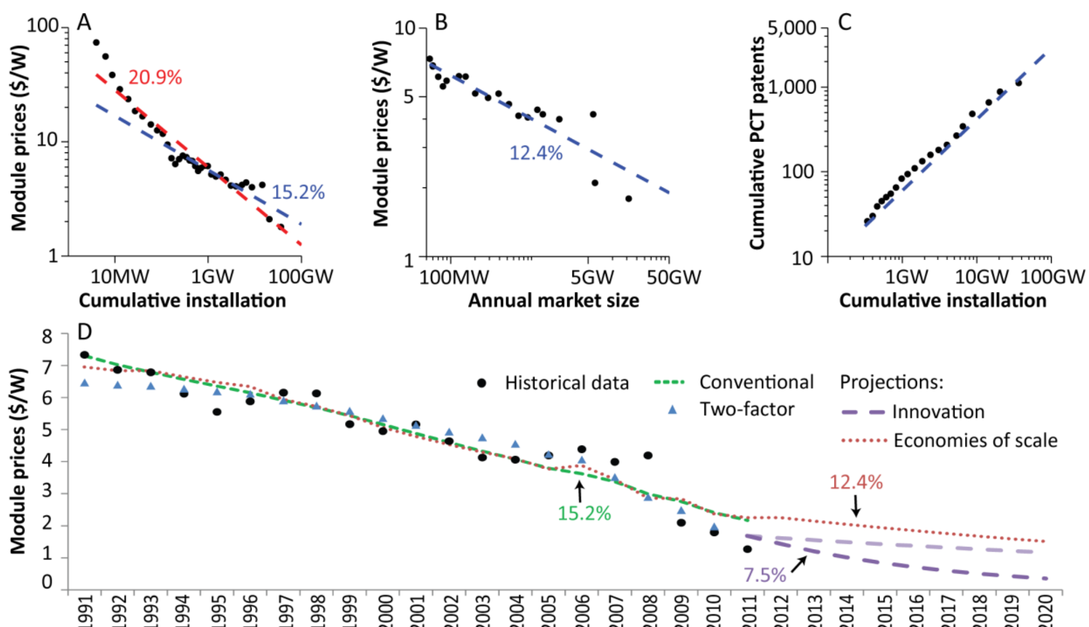


Fig. 6A-6. The effect of economies of scale and innovation in the c-Si PV learning curve. Plots A-C show the log-log linear fit of the three models: conventional, economies of scale, and learning. The various LRs are labeled in the corresponding color. The LR for the conventional model during 1976-2010 is labeled in red (A). The upper boundary of the "innovation" projections in the two-factor model (D) is based on a lower level of innovation in 2005 and assumes no market expansion beyond 2012, while the lower boundary is based on a higher level of innovation in 2010 and a market growth rate of 30%/year. See **Table A2.2** in the Appendix for detailed regression results. All prices are inflation-adjusted to the 2010 U.S. dollars. Sources: BNEF and WIPO.

Fig. 6A-6 also highlights the "economies of scale" and "learning" components of the conventional model for c-Si PV modules separately. The "economies of scale" model (**Eq. A2.2**) neglects the "learning" component, and assumes that cost reduction can be fully explained by scaling up the market size. In the projection for c-Si PV in the "economies of scale" model, a target module price of $0.5/W as set by the U.S. SunShot Initiative [*28*] would require an annual market size of 56 TW (**Table A2.2**) and an estimated learning investment of US$ 25 trillions (**Table 1**). The policy implication is that "demand-pull" policies focusing on further market scale-up is likely to be unrealistic given the total market potential and the most expensive approach to achieve the SunShot target price.

The "learning" component in the conventional model is reflected in the strong correlation between market size and innovation for c-Si PV technology (**Eq. A2.3** and **Fig. 6A-6C**). We conceptualize the overall mechanism underlying this phenomenon as market-driven innovation: besides enabling learning-by-doing, market expansion incentivizes R&D activities which are aimed at creating commercial value. An expanding market with growing revenue supports and encourages manufacturers' R&D activities, and incentivizes commercialization of important laboratory research results [*29*].

A two-factor model (**Eq. A2.4** and **Eq. A2.5**) is constructed to make explicit the cost-reduction effect of scaling from that of innovation [*25*,*30*]. Compared with the other two models, the two-factor model successfully captures the steeper decline in c-Si PV module prices during 2009-2011 (**Fig. 6A-6D**), attributing it to a notably higher level of innovation activities during the corresponding period than previous years (**Fig. 6A-7**). Among the different projections in **Table 1**, high level of innovation is not only the most promising approach to reach the SunShot goal by 2020, but also presents huge savings in required learning investment. Therefore, balanced fund allocation between R&D and deployment, with significant increases in R&D funding from the current level (**Fig. 6A-3**), is likely to be a more efficient approach in further reducing the cost of PV technology.

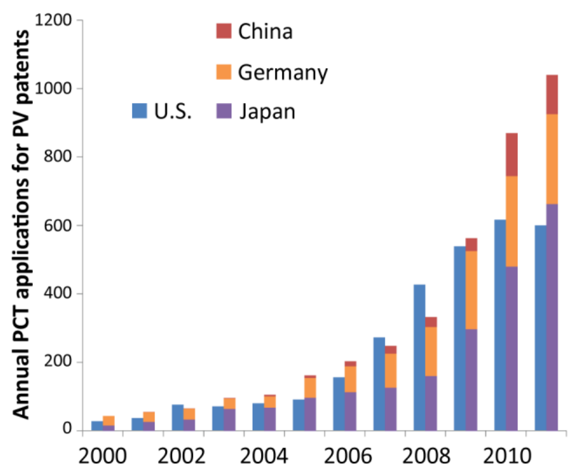


Figure 6A-7. PCT applications for PV-related patents by international filing date during 2000-2011. The patent applications are sorted by year of the international filing date (x-axis). Rapid increase in PCT applications have been observed in all four countries during 2000-2010. Together with wind, PV technology has experienced the most rapid growth in patenting activities among the renewables since the 1990s [*31*]. Slowdown in patenting activities has been observed in 2011 for the U.S., China, and Germany. Despite being the top manufacturer and the top market for PV modules, the number of PCT applications for China and Germany in 2011 were only 19% and 44% of the U.S.', respectively. The four nations together represent about 74% of the world's total PV PCT applications in 2011. Source: WIPO.

Based on similar analysis for First Solar's thin film PV modules (**Fig. 6A-8**), innovation without further expanding production scale is projected to bring the module cost to \$0.4/W (or a module price of \$0.5/W with a 20% gross margin) by 2019. Although the "economies of scale" model with a growth rate of 30%/year is also projected to achieve the cost target in about a decade, innovation in utilizing Tellurium is necessary for this scale-up [32,33].

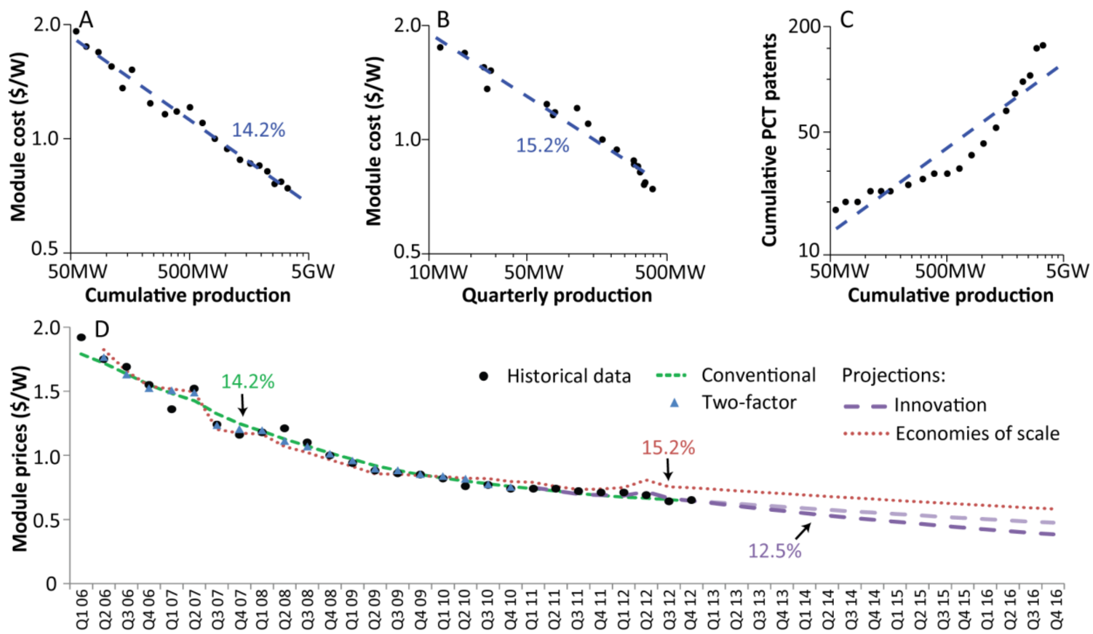


Figure 6A-8. The learning curve models for the First Solar's thin film PV modules. Plots A-C show the log-log linear fit of the three models: conventional, economies of scale, and learning. Assuming no further production expansion, the upper and lower boundaries of the "innovation" projections in the two-factor model (D) are based on the level of innovation in 2011 and 2010, respectively. See **Table A2.3** in the Appendix for detailed regression results. All prices are inflation-adjusted to the 2010 U.S. dollars. Sources: BNEF, First Solar, and WIPO.

It is important for the policy community to recognize that the primary driving force underlying the reduction in PV module prices has evolved over time, from module efficiency gains in the early stage of PV technology to economies of scale [34], which exhibits diminishing returns with scaling. The global PV market has expanded from 0.3 GW/year in 2000 to 38

GW/year in 2013, and further expanding the market size at such rates could be difficult. For example, with more than US$10 billions spent each year as deployment incentives for PV since 2011, Germany has revised its incentive programs to aim for a lower level of annual installations at 2.5-3.5 GW, which is a significant reduction compared with the annual market size during 2010-2012. For both the c-Si PV modules and the First Solar's thin film PV modules, innovation-focused cost-reduction strategies are not only more effective but also present cost-saving opportunities in terms of required deployment subsidies. The specific challenges and opportunities for innovation in PV technology have been identified in a number of previous studies [*35-39*] and in previous chapters.

6.2.3. Promoting innovation with the "technology-push" and "demand-pull" policies

The progress of developing and deploying PV technology can be greatly impeded by market failures associated with innovation and carbon emissions [*40*]. Therefore, policy intervention is necessary to account for the external cost of carbon emissions. Weather catastrophes have caused insurers an average of US$ 50 billions/year [*41*], and extreme weather events are projected to become more frequent as the global mean temperature rises [*42*]. Most importantly, any effective energy policies in mitigating energy-related CO_2 emissions will have to accommodate the developing countries' growing needs for affordable energy sources (**Fig. 1A-1**). Therefore, subsidizing the development of clean energy into cost-competitive energy sources is essential for deploying clean energy and mitigating climate change on the global scale.

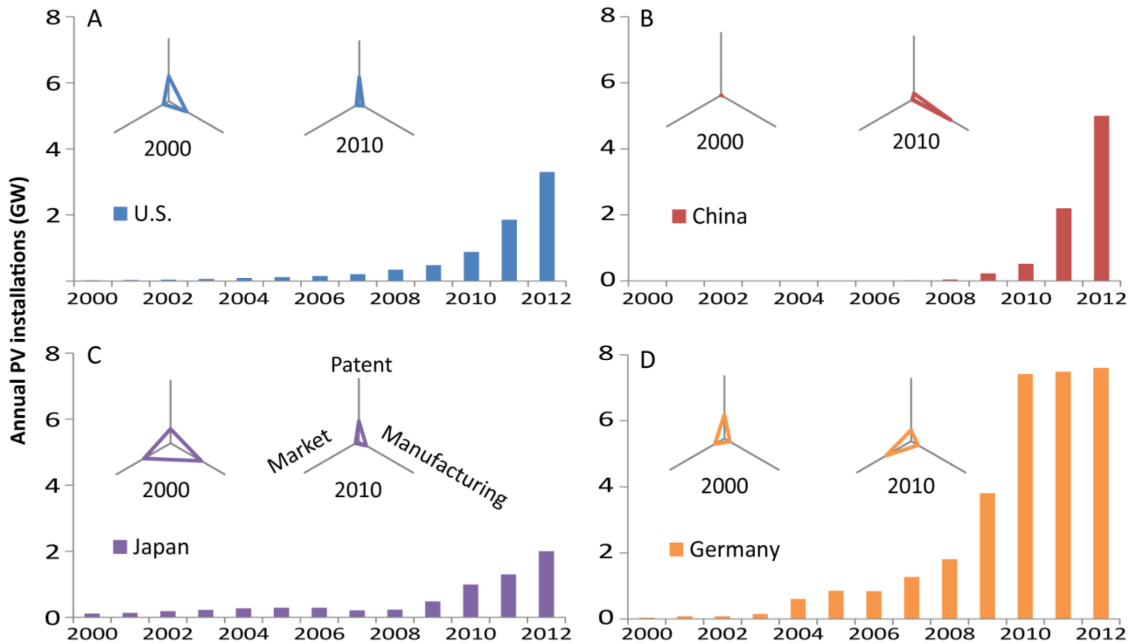


Figure 6A-9. Evolution of innovation, manufacturing, and market in four key nations in the global PV industry. The radar plot inserts show the relative shares of market size, manufacturing, and annual PCT patent applications in PV among top four key nations (**Table A2.4** in the Appendix). The PV industry has a globalized value chain with China (B) being the top manufacturer and Germany (D) being the top market. The U.S. (A) and Japan (C) are the top two innovators in PV technology, despite their diminishing share in manufacturing and market size. These dynamics suggest that Germany's "demand-pull" approach had serious leakage problem in a globalized PV industry, and failed to promote a corresponding growth in innovation and manufacturing. Sources: EPI, EPIA, and WIPO.

Public R&D spending ("technology-push") and deployment incentives ("demand-pull") are two main types of government subsidies to solar PV (**Fig. 6A-3**). In a relatively mature industry, both forms of subsidies can contribute to the technological development [29,30]. One way that deployment incentives support technological development is through subsidizing the sales of PV modules, where manufacturers use a fraction of the sales revenue for corporate R&D. However, in a globalized market for PV modules, net importing countries could face serious leakage of deployment fund in supporting domestic innovation. For example, generous deployment incentives have made Germany the world's top PV market, but Germany's innovation output still lags behind the U.S. and Japan (**Fig. 6A-9**). Focusing on the role of government subsidy on technological development, the allocation of government fund between R&D and deployment should be optimized for better efficiency in promoting technological innovation [*43*].

6.2.4. International coordination in resolving oversupply and restoring the incentives for innovation

The overcapacity situation (**Fig. 6A-10A**) across the global PV industry makes capital-intensive investment in expanding production capacity unattractive to investors. Lacking the opportunities to scale up production, early-stage PV companies with innovative technologies, many of which are based on thin film PV, are forced to compete with GW-scale manufacturers at unsustainably low module prices. Based on the economies of scale found in the learning curve for First Solar's thin film technology (**Table A2.3**), the module cost from a 1-GW production scale could be 60%-67% lower than that from a 10-MW production scale. As a result, we see waves of smaller PV manufacturers bankrupt or acquired, some of which are more innovative than most of the top manufacturers (**Fig. 6A-10B&C**).

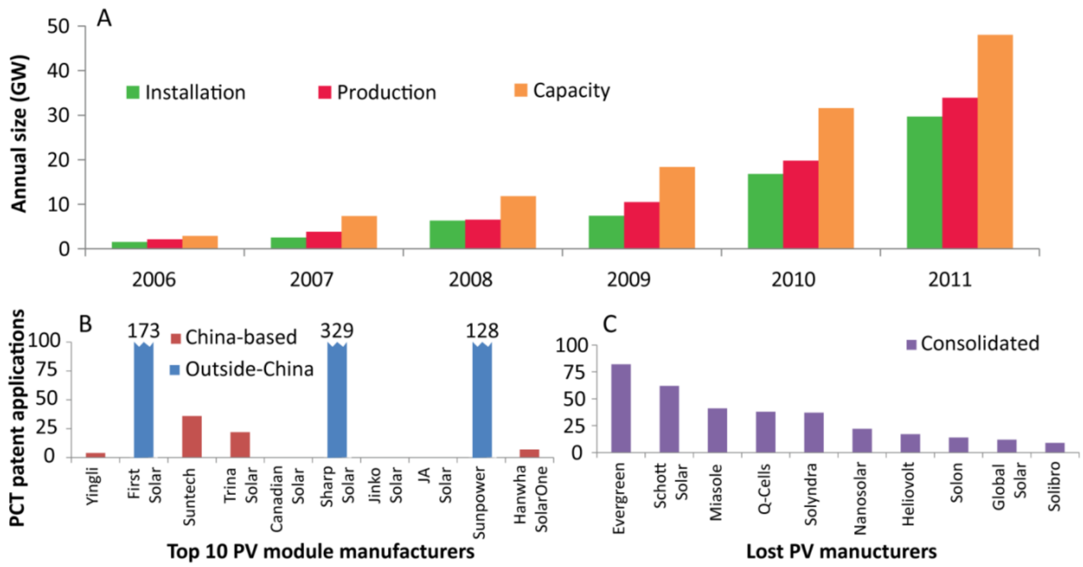


Figure 6A-10. Innovative technologies struggling under the weight of oversupply. Excess capacity has been rapidly built up in the global PV industry since 2006 (A), which leads to production exceeding installation demand despite underutilization of production capacity. The top 10 PV module manufacturers (B) capture slightly below 50% of the global demand in 2012, only 3 of which are based outside of China. Among the consolidated PV manufacturers during 2011-2013, the average PCT applications of the top 10 innovative but consolidated companies (C) is about 3 times that of the 7 Chinese PV companies. Sources: EPIA, IEA PVPS, and WIPO.

In addition to the poor financial performance of the PV industry, uncertainties associated with government incentives for deployment and long-term commitment in reducing GHG emissions also made venture capital (VC) more risk-averse towards investing in innovative solar startups (**Fig. 6A-11**).

These disparities signal serious dysfunctions of the current energy policies towards solar PV, which makes the "demand-pull" approach less effective in incentivizing innovation. Key to restoring the incentives for innovation, the oversupply problem needs to be resolved promptly and module prices can temporarily recover to a more sustainable level. An international coordination in PV deployment policies is necessary for timely response, and a binding long-term installation target for PV can help the industry adjust more efficiently. The recent market growth in the U.S., China, and Japan shows encouraging development in increasing demand (**Fig. 6A-9**). Being a hotspot in overcapacity (**Fig. 6A-12**), China's State Council pledged in 2012 to encourage consolidation among the Chinese PV manufacturers and banned local government support for failing ones.

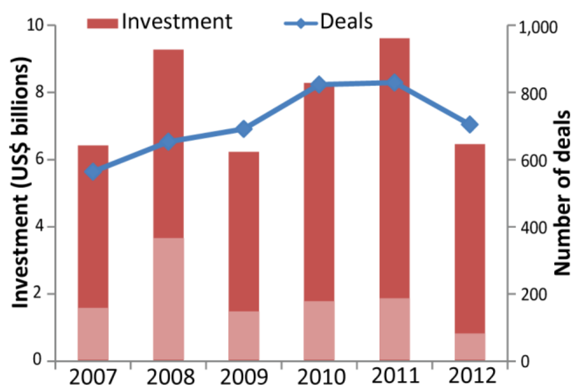


Figure 6A-11. Global VC investment in the cleantech sector. The VC funding for solar technologies (in lighter red) is heavily slashed from about $3.6 billion in 2008 to $0.8 billion in 2012. Source: MIT Tech Review.

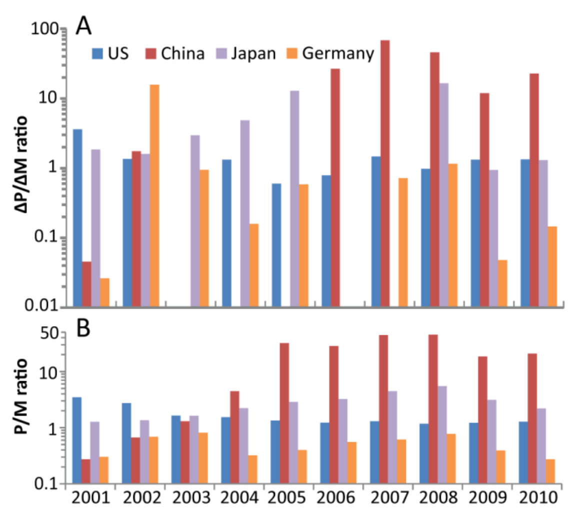


Figure 6A-12. The dynamics between module manufacturing (P) and market size (M) in the PV industry. The ratio of production expansion to market expansion (A) is indicative of how well the domestic manufacturing scales with the market size. Positive ratio shows increases in both production and installation, while negative ratio (not shown in A) is due to temporary reduction in either production or installation. Without considering the effect of inventory changes, the ratio of production to market size (B) of larger than 1.0 suggests the country being a net exporter, and vice versa. Sources: EPI and EPIA.

The need to restore innovation adds a fresh perspective to the discussion of trade issues in the PV industry. The trade tariff imposed by the U.S. [*44*] and the E.U. [*45*] would mitigate the oversupply problem in their home market and help their domestic PV manufacturing recover faster, while accelerating the supply-demand adjustment in the Chinese PV industry. From a global perspective, Chinese PV manufacturers tend to have lower R&D intensity (**Fig. 6A-5B**) and produce fewer patents (**Fig. 6A-7**). With China's dominating market share in PV manufacturing, fund through "demand-pull" policies has not been effectively channeled to the most innovative players. China could minimize the damage from an accelerated consolidation by supporting more innovative Chinese manufacturers. Largely as a casualty of the ongoing oversupply situation, the now-bankrupt Suntech was the most innovative Chinese PV manufacturer according to our metrics (R&D spending and patent applications) and established long-term R&D collaborations with leading PV research institutions such as the University of New South Wales.

6.3. Policy Framework for an Innovation-Driven Photovoltaic Industry Moving Forward

In his second inauguration speech President Obama urged the U.S. to lead and to profit from the transition to sustainable energy sources. Such opportunities for technologically advanced nations such as the U.S. may emerge as the PV industry enters an innovation-driven phase. Here we show a conceptual model (**Fig. 6A-13**) exploring the dynamics among innovation, manufacturing, and market, and use the U.S. as a case study to explain an innovation-focused policy framework for building a sustainable PV industry on the national level.

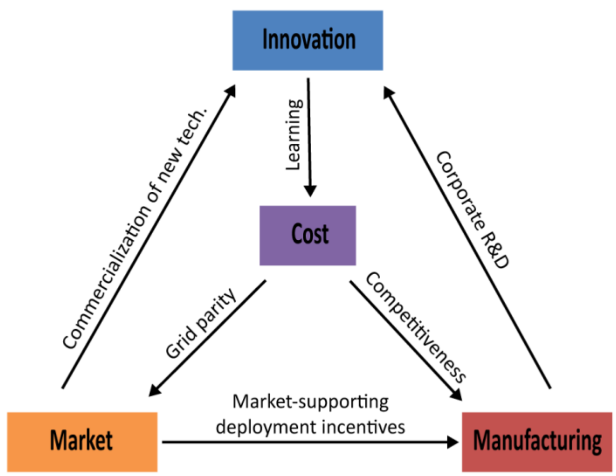


Figure 6A-13. The conceptual model for building an innovation-focused and sustainable PV industry. Utilizing the reinforcing dynamics among innovation, manufacturing, and market, a set of long-term, innovation-focused, and market-supporting policies can lead to a nation's technology leadership and help reduce the cost of PV technology for global deployment.

A set of clear-targeted and long-term deployment policies is essential in the reinforcing dynamics among innovation, manufacturing, and market. Firstly, scaling up the market can be an effective approach in fostering manufacturing base. Even without trade tariff manufacturing expansion has been observed to scale with market expansion (**Fig. 6A-12**). Secondly, as part of the market-driven innovation mechanism, a long-term and expanding market also incentivizes commercialization of important laboratory results through channels such as VC funding.

Manufacturing activities are one important source of innovation through learning-by-doing. Moreover, the corporate R&D investment from PV manufacturers (**Fig. 6A-5**) enables innovation through learning-by-searching. These R&D activities may prefer to co-locate with manufacturing base for better efficiency and rapid implementation of innovations to manufacturing lines, as highlighted by Applied Materials' largest commercial solar R&D center in China. However, another determining factor in the co-location between manufacturing and R&D activities is the nation's current innovation capacity. Despite its relatively small size in market and manufacturing, the U.S., with world-leading research institutions and talents, still leads in PV innovation, as measured by the number of PCT patent applications (**Fig. 6A-7**). As the manufacturers' competitiveness increasingly relies on cost reduction through innovation, it is also possible for a nation to use innovation to anchor manufacturing activities, and thus form a reinforcing dynamics between innovation leadership and manufacturing leadership.

The optimum structure of the PV manufacturing sector will largely depend on trade policies. Without trade barriers, surviving international competition would require economies of scale and thus a critical size of the manufacturing cluster, where a handful of giant PV manufacturers may comprise most of the market share. On the other hand, the ongoing trade tariff will ease the international competition, and policymakers could promote a national PV manufacturing sector with lower market concentration. As previously described, giant incumbent manufacturers present large cost disadvantages and risks for start-up manufacturers, whose innovative technologies are yet to be scaled up. In a segmented global PV market, a national

PV industry with low market concentration could be an additional boost to innovation during the next 7 to 10 years of an innovation-driven phase.

Elevated level of public R&D funding and focus on technological development in PV are the other central piece of this conceptual model. "Demand-pull" policies will likely face leakage problems on the national level in a globalized PV value chain (**Fig. 6A-9**). Therefore, directly injecting resources to innovation by public R&D funding should play a stronger role. The IEA study in 2010 [*46*] identified the need to more than doubling the public R&D funding, benchmarking R&D budget as 10% to 20% of deployment cost. **Fig. 6A-3** highlights the increasing R&D gap in the U.S. and Germany in the recent market scale-up. When the private sector is experiencing a difficult financial situation, it is a proper timing for increased public R&D funding to fill the gap.

Innovation itself can be made more cost-effective with innovative R&D models [*47*], such as establishing a national program aimed at promoting R&D collaboration and technology transfer among PV manufacturers. For example, the U.S. funded a shared R&D center in 2011 through the PV Manufacturing Consortium, which borrowed the pre-competitive R&D model from the semiconductor industry.

An open data model could also be adopted by the government to attract more policy and market research. Various data collection efforts (from organizations like IEA to companies like BNEF) already exist; however, variations in data and methodologies are common. It is therefore useful to compile and continue to update an official dataset for the key metrics in the PV industry with well-documented methodologies. Making this dataset publicly available will greatly reduce the cost and time for conducting policy and market research. A richer set of analyses and opinions will be valuable for decision-making in both the government and industry, and accelerating policy and business innovation that address the soft cost of deploying PV technologies [*48*].

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