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Communication

An innovation-focused roadmap for a sustainable global photovoltaic industry

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HIGHLIGHTS

- We construct a two-factor learning curve model to quantify the effect of innovation.
- We identify the industry-wide oversupply a barrier for incentivizing innovations.
- We build a conceptual framework to inform an innovation-focused roadmap for the PV industry.
- We recommend open data model for PV to accelerate policy and market innovations.

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ABSTRACT

The solar photovoltaic (PV) industry has undergone a dramatic evolution over the past decade, growing at an average rate of 48 percent per year to a global market size of 31 GW in 2012, and with the price of crystalline-silicon PV module as low as $0.72/W in September 2013. To examine this evolution we built a comprehensive dataset from 2000 to 2012 for the PV industries in the United States, China, Japan, and Germany, which we used to develop a model to explain the dynamics among innovation, manufacturing, and market. A two-factor learning curve model is constructed to make explicit the effect of innovation from economies of scale. The past explosive growth has resulted in an oversupply problem, which is undermining the effectiveness of "demand-pull" policies that could otherwise spur innovation. To strengthen the industry we find that a policy shift is needed to balance the excitement and focus on market forces with a larger commitment to research and development funding. We use this work to form a set of recommendations and a roadmap that will enable a next wave of innovation and thus sustainable growth of the PV industry into a mainstay of the global energy economy.

1. Introduction

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 31 GW in 2012 (Winneker, 2013).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 (PVXCHANGE, 2013).

This evolution has transformed the solar PV industry from being part of the "future" energy economy to an important component of the energy landscape today. As a result, the PV industry has entered the critical phase of transitioning from being a subsidy-dependent industry to becoming cost-competitive with retail electricity in a growing number of regional markets (Breyer and Gerlach, 2013). On 7 July 2013, a record 48% of the total peak electricity production in Germany was from solar energy (Fig. B1). The United States has established a goal, and an entire federal office within the Department of Energy, to reduce the PV system cost to $1/watt (approximately $0.05/kWh for the levelized cost of PV electricity and $0.5/W for the PV module) by 2020 (Margolis, 2012) that will very clearly make PV electricity cost-competitive with grid electricity rates in the United States (Fig. 1), thus reaching "grid parity" (Mileva et al., 2013).

In this paper we examined a set of the PV industry's key metrics on innovation, manufacturing, and market. Insights have

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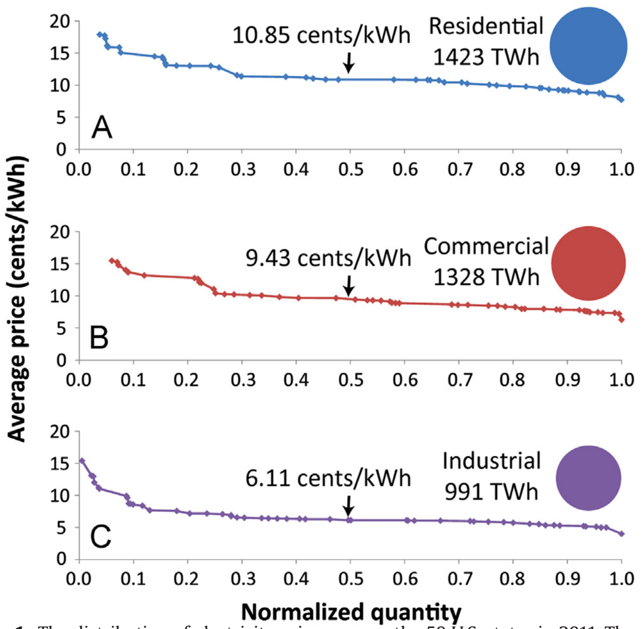

Fig. 1. The distribution of electricity prices among the 50 U.S. states in 2011. There exist a continuous range of grid parity points where the cost of solar PV electricity becomes competitive with grid electricity rates. The medium prices in the residential (A), commercial (B), and industrial (C) sectors were 10.85, 9.43, and 6.11 cents per kWh, respectively. With further cost reduction in the installed cost of solar PV system, the market size for solar PV would continue to expand, covering more states and sectors. The electricity prices in Hawaii, ranging from 27.8 to 34.0 cents per kWh, are not shown in the figure. All prices are inflation-adjusted to the 2010 U.S. dollars.
Source: EIA.

been developed from the dataset to form a policy framework for building a sustainable PV industry, and to recommend an innovation-focused roadmap which focuses on incentivizing innovation for further cost reductions in the medium term.

2. Data and methods

2.1. Time-series data for the key metrics of the global PV industry

We assembled a comprehensive dataset from 2000 to 2012 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 were obtained from the Bloomberg New Energy Finance (BNEF, 2012) and used in the learning curve models. For First Solar's thin film PV modules, the cost and quarterly production data were obtained from the company's quarterly reports.

2.2. Collection of the patent data

There are three common proxies to measure innovation: R&D spending, literature counts, and patents (Acs et al., 2002). 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 (Margolis and Kammen, 1999). 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 (Lanjouw and Schankerman, 2004). Furthermore, overall patent quality could differ significantly across major patent offices (Van Pottelsberghe de la Potterie, 2011). 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 (Schwab, 2012). 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 Patent-Scope 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 A1). 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.

2.3. Regression analysis for the two-factor learning curve model

A two-step regression procedure is adopted to solve the colinearity issue in the two-factor learning curve model. As both the cumulative PCT applications (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. (1) and Q_i to explain the price (P_i) in Eq. (2).

$$T_i = \alpha_0 + \alpha_1 \log Q_i + \eta_i \tag{1}$$

$$\log P_i = \theta_0 + \theta_1 \log Q_i + \theta_2 \eta_i + \epsilon_i \tag{2}$$

The final model is presented in Eq. (3), or an equivalent form in Eq. (4). The learning rate (LR) for economies of scale Q_i is defined as cost reductions per doubling in scale. The LR for innovation T_i in this paper is defined as cost reductions per 100 patent applications. A summary of the key regression results can be found in Tables A2 and A3 in the appendix.

$$\log P_i = \beta_0 + \beta_1 \log Q_i + \beta_2 T_i + \epsilon_i \tag{3}$$

$$P = \left(10^{\beta_0} / Q_i^{-\beta_1}\right)\left(10^{\beta_2}\right)^{T_i} \tag{4}$$

3. Results and discussions

3.1. Government subsidy for the development of cost-competitive PV technology for global deployment

To meet the long-term greenhouse gas (GHG) mitigation targets of 80% reductions from the 1990 baseline by 2050, solar energy can play a key role in decarbonizing electricity generation (EC, 2011; Williams et al., 2012). Solar PV technology with terawatt (TW)-scale deployment has long be recognized as an effective tool to mitigate climate change (Hoffert et al., 2002; Davis et al., 2010). However, the progress of developing and deploying PV technology can be greatly impeded by market failures associated with innovation and carbon emissions (Jaffe et al., 2005).

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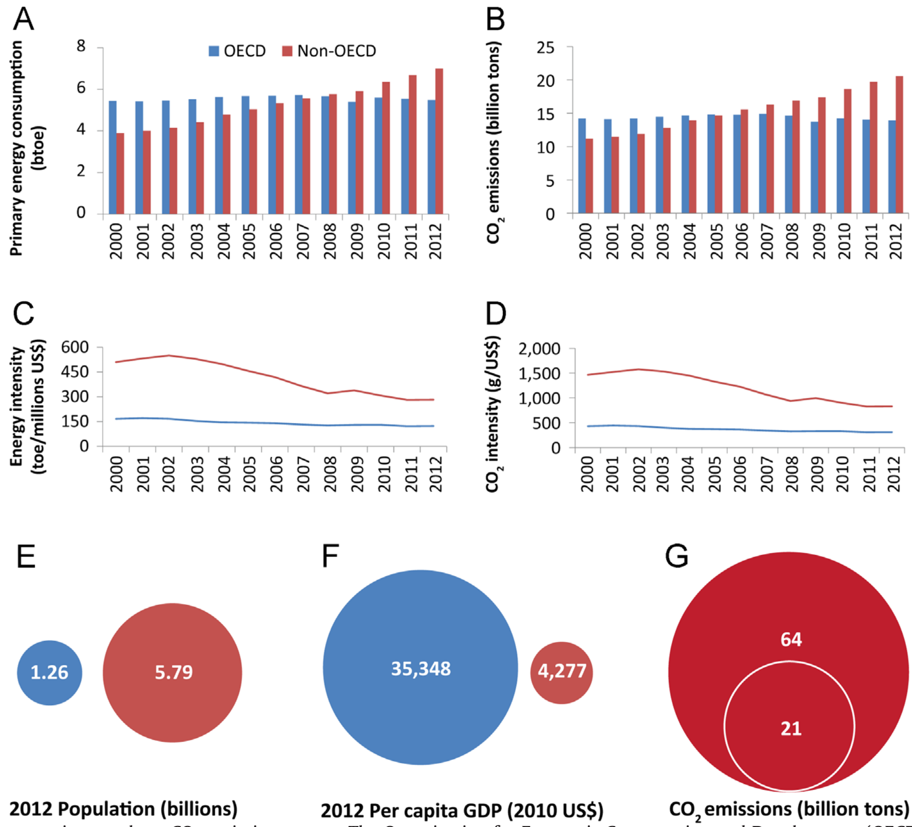

Fig. 2. Implications of global economic growth on CO_2 emission targets. The Organization for Economic Co-operation and Development (OECD) countries (in blue) and the non-OECD countries (in red) have exhibited opposite trends in primary energy consumption (A) and related CO_2 emissions (B). The primary energy consumption is measured in billion tons of oil equivalent (btoe). Both energy intensity (C) and CO_2 intensity (D) for the non-OECD countries have been declining and converging to those of the OECD countries. The non-OECD countries currently have more population (E) and less per capita GDP (F) than the OECD countries. With a population of 1.3 billion, China's energy-related CO_2 emissions have more than doubled from 3.4 billion tons in 2000 to 9.2 billion tons in 2012. If the non-OECD countries evolve to have the same per capita CO_2 emissions as the OECD countries, their CO_2 emissions could triple to 64 billion tons from 21 billion tons in 2012 (G). All prices are inflation-adjusted to the 2010 U.S. dollars. *Sources*: BP and World Bank. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

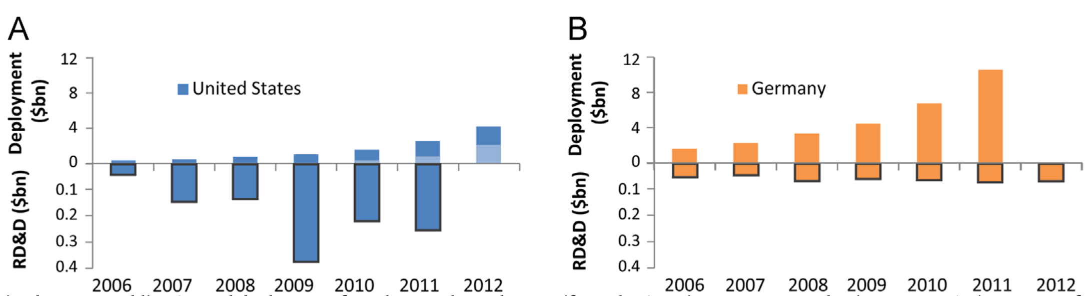

Fig. 3. Funding allocation between public R&D and deployment for solar PV. The cash grant (from the American Recovery and Reinvestment Act), as a part of the deployment funding, is highlighted in lighter color. The U.S.' public R&D funding (in 2012) and the Germany's FiT payment (in 2012) are not available at the time of preparing this manuscript. The R&D budget includes funding for demonstration projects. All prices are inflation-adjusted to the 2010 U.S. dollars.
Sources: BNetzA, IEA, LBL, and U.S. Treasury.

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 (Mills, 2012), and extreme weather events are projected to become more frequent as the global mean temperature rises (Hansen et al., 2012). Most importantly, any effective energy policies in addressing energy-related CO_2 emissions will have to accommodate the developing countries' growing needs for affordable energy sources (Fig. 2). 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.

Public R&D spending ("technology-push") and deployment incentives ("demand-pull") are two main types of government subsidies to solar PV (Fig. 3). In a relatively mature industry, both forms of subsidies can contribute to the technological development (Jamasb, 2007; Bettencourt et al., 2013). 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. 4). 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 innovation.

3.2. *Cost-effective policies for further cost reductions*

We first estimate the range of cost-reduction potentials in PV modules from projections in three learning curve models. Table 1

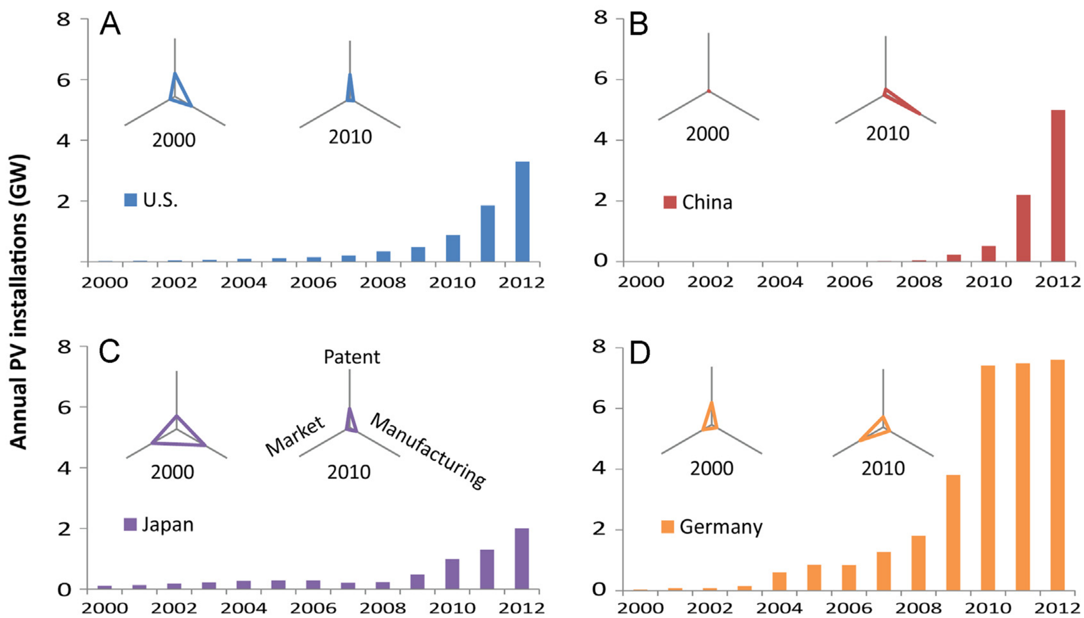

Fig. 4. Evolution of innovation, manufacturing, and market in four key nations in the global PV industry. The radar plot insets show the relative shares of market size, manufacturing, and annual PCT patent applications in PV among top four key nations (Table B1). The PV industry has a globalized value 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.

Table 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	3576	Not within the 21st century	
Economies of scale	2043	24,837	N.A.	
Innovation (2005 level)	2031	1616	2041	253
Innovation (2010 level)	2019	72	2019	45

estimates the timing and the learning investment for various c-Si PV learning curve projections. The conventional PV learning curve model (Eq. A1) 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 (Hoffert, 2010; Sagar and van der Zwaan, 2006). 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 reductions through both learning-by-doing and learning-by-searching (Qiu and Anadon, 2012). However, the LR is known to vary depending on the timeframe of the regression analysis (Fig. 5A), and this uncertainty in LR will significantly affect the projected timing and cost of reaching the cost-reduction milestones (van der Zwaan and Rabl, 2004; Ferioli et al., 2009) and GHG mitigation targets. As detailed in Table 1, "demand-pull" polices, based on this conventional learning curve model, would experience a range of learning investment with differences in order of magnitude.

Fig. 5 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) neglects the "learning" component, and assumes that cost reductions 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 (Margolis, 2012) would require an annual market size of 56 TW (Table A2) 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 goal.

The "learning" component in the conventional model is reflected in the strong correlation between market size and innovation for c-Si PV technology (Eq. A3 and Fig. 5C). 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 (Bettencourt et al., 2013).

A two-factor model (Eqs. A4 and A5) is constructed to make explicit the cost-reduction effect of scaling from that of innovation (Jamasb, 2007; Qiu and Anadon, 2012). 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. 5D), attributing it to a notably higher level of innovation activities during the corresponding period than previous years (Fig. B2). Among the different projections in Table 1, high level of

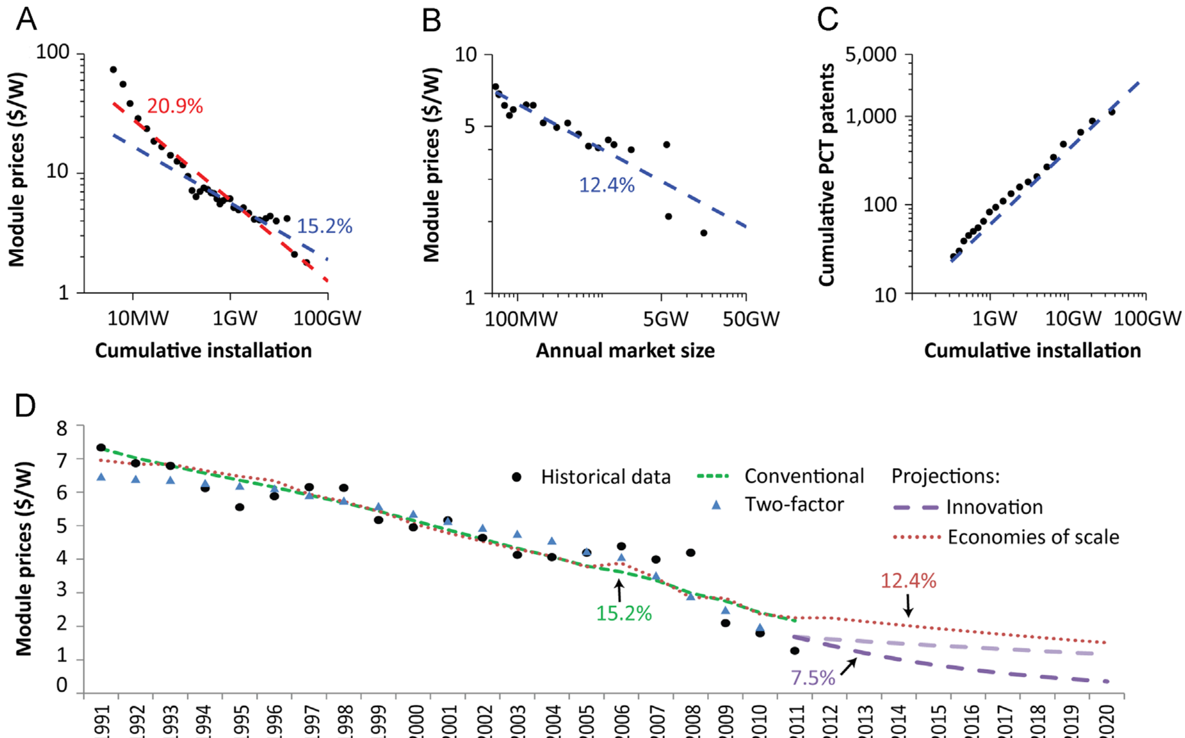

Fig. 5. The effect of economies of scale and innovation in the c-Si PV learning curve. Plots A–C show the log–log linear fit of the three models: conventional, economies of scale, and learning. The various LRs are labeled in the corresponding color. The LR for the conventional model during 1976–2010 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 Appendix A for detailed regression results. All prices are inflation-adjusted to the 2010 U.S. dollars.
Sources: BNEF and WIPO. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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. 3), is likely to be a more efficient approach in further reducing the cost of PV technology.

Based on similar analysis for First Solar's thin film PV modules (Fig. 6; Table A3), 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 (Wadia et al., 2009; Zweibel, 2010).

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 (Nemet, 2006), which exhibits diminishing returns with scaling. The global PV market has expanded from 0.3 GW in 2000 to 31 GW in 2012, 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 (Lewis, 2007; Chu and Majumdar, 2012; Goodrich et al., 2012; Powell et al., 2012; Goodrich et al., 2013).

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

Billions of dollars in deployment incentives have been spent each year to support the market for solar PV (Fig. 3), particularly in the Germany via feed-in-tariffs (FiT) and in the U.S. through tax credits. These "demand-pull" policies are intended to create 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 needs to deploy cost-competitive, low-carbon energy sources (Fig. 2) 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.

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. 7). There are also signs of cutback in R&D spending among these major PV manufacturers (Fig. B3).

The overcapacity situation (Fig. 8A) also makes the 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 A3), 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. 8B and C).

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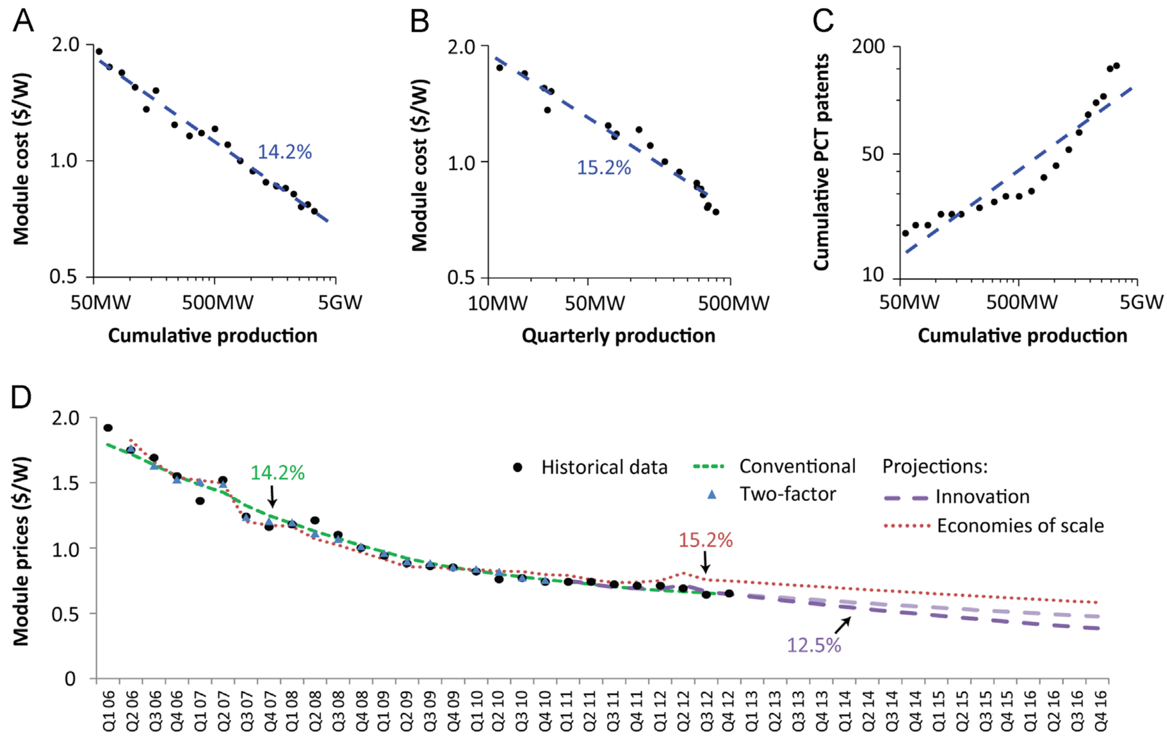

Fig. 6. The learning curve models for the First Solar's thin film PV modules. Plots A–C show the log–log linear fit of the three models: conventional, economies of scale, and learning. Assuming no further production expansion, the upper and lower boundaries of the "innovation" projections in the two-factor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

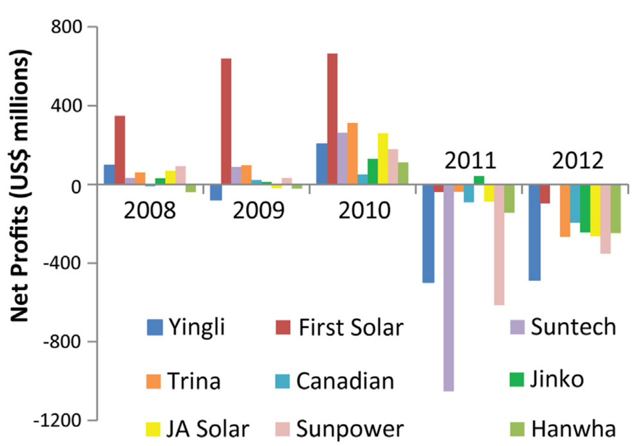

Fig. 7. Net profits (losses) of 9 major U.S.-listed PV manufacturers during 2008–2012. The 2012 financial results for Suntech Power were not available due to its bankruptcy in 2013.
Source: SEC.

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. B4).

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. 4A–C). Being a hotspot in overcapacity (Fig. 9), China State Council (2012) pledged to encourage consolidation among the Chinese PV manufacturers and banned local government support for failing ones.

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. (Deutch and Steinfeld, 2013) and the E. U. (James and Mehta, 2013) 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. B3) and produce fewer patents (Fig. 8B). 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.

3.4. Policy framework for building a sustainable PV industry on the national level

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

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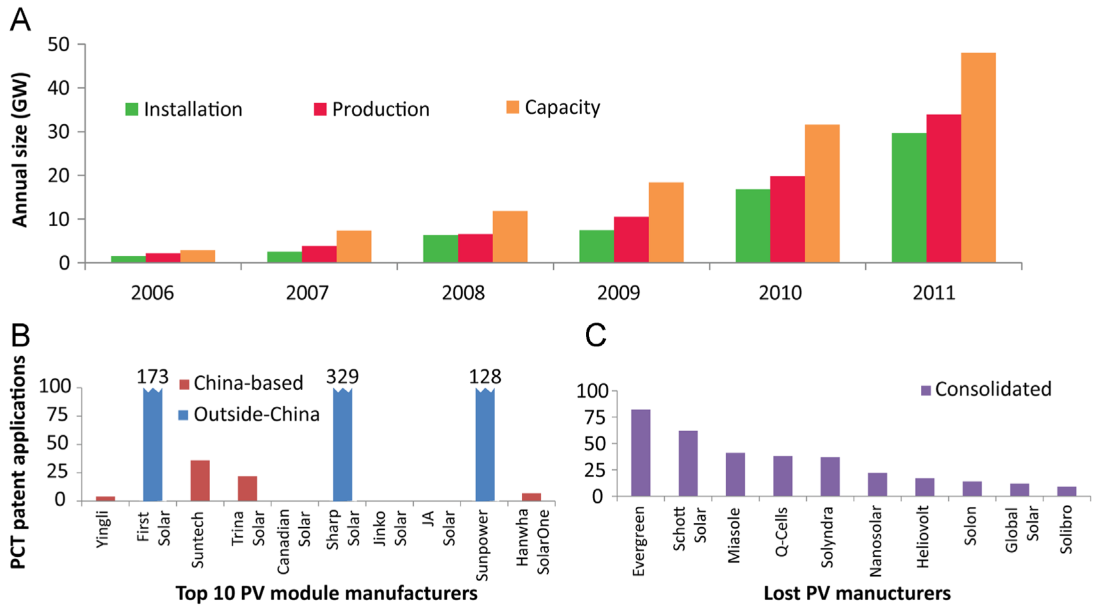

Fig. 8. Innovative technologies struggling under the weight of oversupply. Excess capacity has been rapidly built up in the global PV industry since 2006 (A), which leads to production exceeding installation demand despite underutilization of production capacity. The top 10 PV module manufacturers (B) 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.

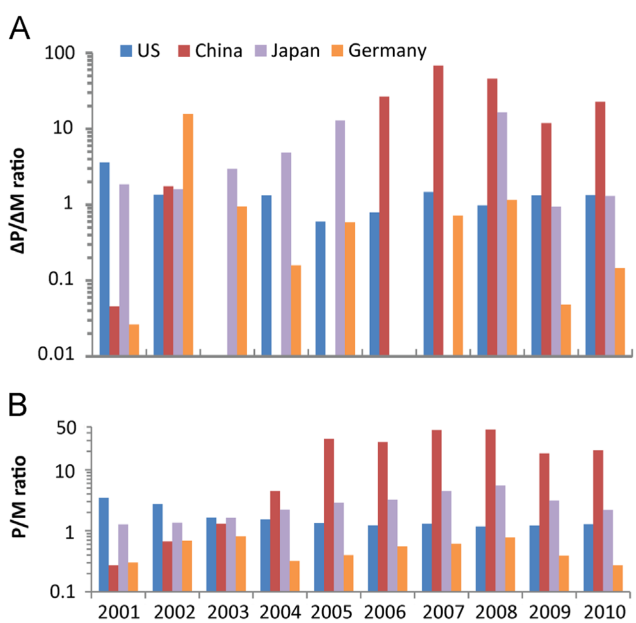

Fig. 9. The dynamics between module manufacturing (P) and market size (M) in the PV industry. The ratio of production expansion to market expansion (A) is indicative of how well the domestic manufacturing scales with the market size. Positive ratio shows increases in both production and installation, 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.

such as the U.S. may emerge as the PV industry enters an innovation-driven phase. Here we show a conceptual model (Fig. 10) 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.

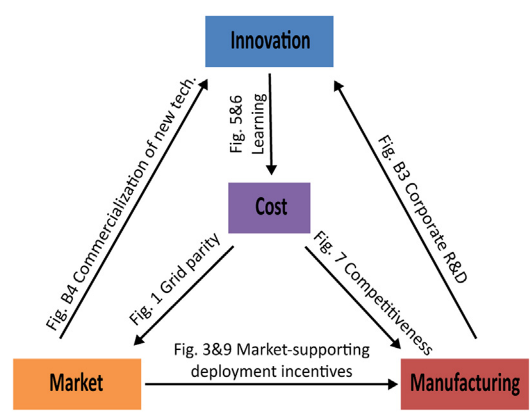

Fig. 10. The conceptual model for building an innovation-driven and sustainable PV industry. Utilizing the reinforcing dynamics among innovation, manufacturing, and market, a set of long-term, innovation-focused, and market-supporting policies can lead to a nation's technology leadership and help reduce 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. 9). Secondly, as part of the market-driven innovation mechanism, a long-term and expanding market also incentivizes commercialization of important laboratory results through channels like VC funding.

Manufacturing activities are one important source of innovation through learning-by-doing. Moreover, the corporate R&D investment from PV manufacturers (Fig. B3) 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. B2). As the manufacturers' competitiveness increasingly relies on cost reductions 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 described in Section 3.3, 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 7–10 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. 4). Therefore, directly injecting resources to innovation by public R&D funding should play a stronger role. The IEA study (Kerr, 2010) identified the need to more than doubling the public R&D funding, benchmarking R&D budget as 10–20% of deployment cost. Fig. 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, 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.

3.5. Encourage policy and market research with open access to the PV industry data

An open data model could 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 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 (Seel et al., 2013).

4. Conclusion

This study is focused on the significance of innovation and cost reduction in PV technology in mitigating climate change on the global scale, which is the fundamental driving force underlying the PV industry evolution today. By comparing a range of scenarios in different learning curve models, we find that a shift in policy focus towards innovation is needed to achieve further cost reductions timely and cost-effectively. We also find that the industry-wide oversupply and unsustainably low prices of PV modules present a barrier for incentivizing and commercializing innovation through "demand-pull" policies. The conceptual model we developed to explore the dynamics among innovation, manufacturing, and market forces leads to a set of recommendations for leaders on both the public- and private-sector sides. We find that the next era of solar PV deployment and a sustainable PV industry will rely increasingly on an innovation-focused roadmap that will focus on incentivizing innovation in the medium term. Once the PV technology is largely cost-competitive with conventional electricity sources after the next 7 to 10 years of an innovation-driven phase, the PV industry can self-expand without major policy interventions under the reinforcing dynamics among cost reduction, market growth, and economies of scale.

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Appendix A. Summary of learning curve regression

From Table A1, we note that around 10% of the PV patents are likely to be related to solar thermal technologies, which are removed from the final PV patent data presented in Fig. 4 and Fig. B2. Due to the additional keyword "silicon", only 1.5% of the c-Si PV patents are likely to be related to solar thermal technologies. After a manual inspection of these 15 patents, we find 12 of them are PV patents but have misleading IPC classes, 1 of them is about hybrid-PV-solar-thermal technology. Therefore, the c-Si PV patent data has not been refined using IPC classes to avoid introducing greater inaccuracy.

We run linear regression models (Eqs. A1-A5) for both c-Si PV and First Solar's thin film PV data. The summary of key regression results are in Tables A2 and A3.

$$\log P_i = \alpha_0 + \alpha_1 \log(CQ_i) \quad \text{(A1)}$$

$$\log P_i = \alpha_0 + \alpha_1 \log(Q_i) \quad \text{(A2)}$$

$$\log T_i = \alpha_0 + \alpha_1 \log(CQ_i) \quad \text{(A3)}$$

$$T_i = \alpha_0 + \alpha_1 \log Q_i + \eta_i \quad \text{(A4)}$$

$$\log P_i = \alpha_0 + \alpha_1 \log Q_i + \alpha_2 \eta_i + \epsilon_i \quad \text{(A5)}$$

Table A1
Summary of the PV patent data by technology. The technology category of the patent applications (PV or solar thermal) is defined using the IPC Green Inventory, which lists a range of IPC classes for a given technology.

	U.S.	China	Japan	Germany	World	c-Si PV
PV	2187	277	1969	976	7055	932
Solar thermal	341	59	93	209	1307	15
Total	3300	411	2232	1459	9987	1150

Table A2
Summary of key regression results for c-Si PV modules. Standard error of the coefficient is in parenthsis. The p-value follows the convention: $*** < 0.001 < ** < 0.01 < * < 0.05$. Minimization of the values from the Bayesian Information Criterion (BIC) suggests the best model.

	A1 (1976–2010)	A1 (1991–2010)	A2 (1991–2010)	A3 (1991–2010)	A4 (1991–2010)	A5 (1991–2010)
α_0	1.79178 (0.05238)***	1.46396 (0.08217)***	1.17325 (0.05506)***	−0.74792 (0.05948)***	−640.47 (89.08)***	1.17325 (0.04730)***
α_1	−0.33909 (0.01869)***	−0.23733 (0.02432)***	−0.19029 (0.02023)***	0.84159 (0.0176)***	326.73 (32.72)***	−0.19029 (0.01738)***
α_2						−0.0003402 (0.0001252)*
R^2	0.9089	0.8411	0.8310	0.9922	0.8471	0.8822
BIC	−45.38	−46.29	−45.06	−59.22	250.5	−49.28
LR	20.9%	15.2%	12.4%			
Q at $0.5/W	1.5 TW	27 TW	56 TW			

Table A3
Summary of key regression results for First Solar's thin film PV modules.

	A1 (2006Q1–2010Q4)	A1 (2006Q1–2012Q4)	A2 (2006Q2–2010Q4)	A3 (2006Q1–2010Q4)	A4 (2006Q2–2010Q4)	A5 (2006Q2–2010Q4)
α_0	0.644524 (0.02080)***	0.61933 (0.01605)***	0.51882 (0.0.02416)***	0.30092 (0.1222)*	−62.7 (24.52)*	0.51882 (0.01763)***
α_1	−0.22054 (0.007514)***	−0.20998 (0.005222)***	−0.23822 (0.01156)***	0.48395 (0.04415)***	54.54 (11.74)***	−0.23822 (0.00844)***
α_2						−0.0006956 (0.0001744)**
R^2	0.9795	0.9842	0.9615	0.8697	0.5595	0.9807
BIC	−94.43	−135.97	−80.21	−23.59	183	−90.38
LR	14.2%	13.5%	15.2%			13.0%
Q at $0.4/W	53 GW	70 GW	7 GW			

Table B1
The importance of the U.S., China, Japan, and Germany in the global PV energy landscape in 2010. Source: EIA, EPI, EPIA, WIPO, and World Bank.

	U.S.	China	Japan	Germany	World	The top four's world share (%)
GDP (2010 US$ billions)	14 419	5931	5488	3284	63 195	46
PV market size (GW)	0.88	0.52	0.99	7.41	16.82	58
Cumulative PV capacity (GW)	2.53	0.89	3.62	17.19	40.02	61
PV manufacturing (GW)	1.12	10.85	2.17	2.02	24.05	67
Annual PCT patent applications (#)	685	142	492	306	2198	74
National electricity consumption (TWh)	3886	3634	1002	549	18 466	49

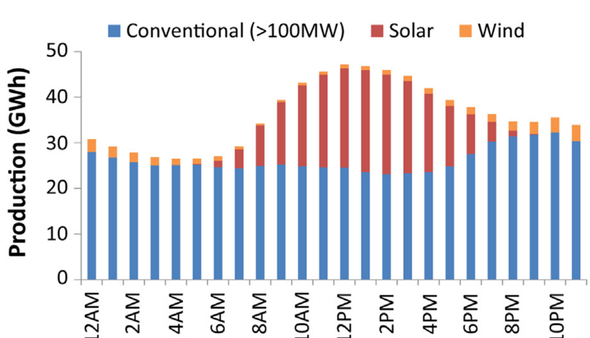

Fig. B1. Actual power curve in Germany on 7 July 2013. About 48% of the total electricity around 1:30 PM was produced from solar energy at 22.4 GW. The daily solar electricity production was 197 GWh, or 23% of the total daily production. *Source*: EEX.

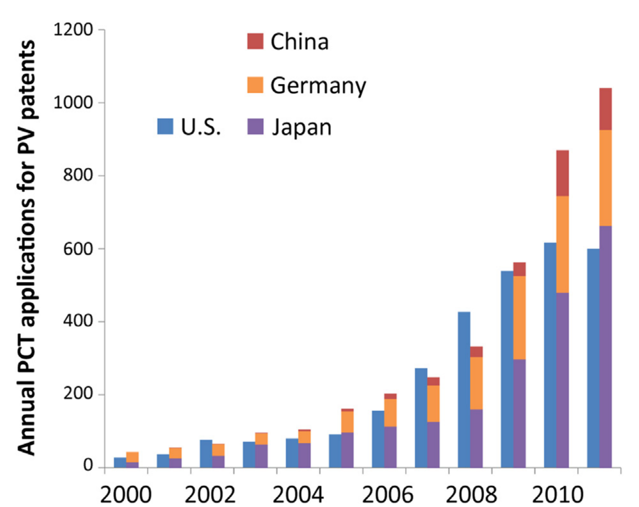

Fig. B2. PCT applications for PV-related patents by international filing date during 2000–2011. The patent applications are sorted by year of the international filing date (x-axis). Rapid increase in PCT applications have been observed in all four countries during 2000–2010. Together with wind, PV technology has experienced the most rapid growth in patenting activities among the renewables since the 1990 s (Hafner, 2010). 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.

The coefficients of the two-factor learning curve model (Eq. 3) can be derived from Eqs. A4 and A5, yielding Eqs. A6–A8.

$$\beta_0 = \theta_0 - \theta_2\alpha_0 \quad \text{(A6)}$$

$$\beta_1 = \theta_1 - \theta_2\alpha_1 \quad \text{(A7)}$$

$$\beta_2 = \theta_2 \quad \text{(A8)}$$

Based on the BIC values, the conventional model during 1991–2010 is a better fit to data after adjusting for the fact that the conventional model during 1976–2010 has 75% more data points, yielding a better R-square value. The two-factor model (Eq. A5) is a further improvement, with a lower BIC value and better R-square value than both the the conventiaonal model (Eq. A1, 1991–2010) and the "economies of scale" model (Eq. A2).

See Tables A1–A3.

Appendix B

See supplementary materials for a list of the data sources used in all the figures and tables.
See Table B1 and Figs. B1–B4.

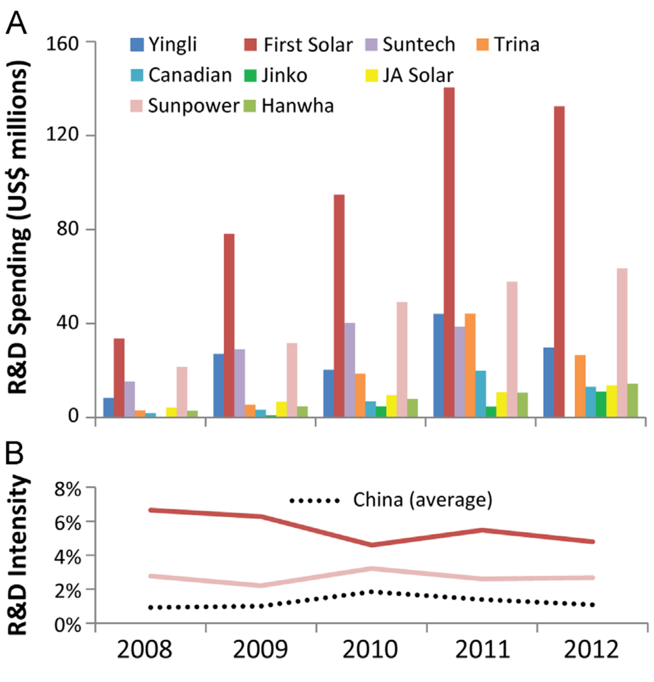

Fig. B3. Corporate R&D from 9 major U.S.-listed PV manufacturers during 2008–2012. The corporate R&D spending (A) is mostly increasing during 2008–2011 accompanying with increasing sales revenue, but shows signs of declining in 2012. Different from the other 8 manufacturers, First Solar is specialized 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 1.25% of their sales revenue into R&D during 2008–2012.
Source: SEC.

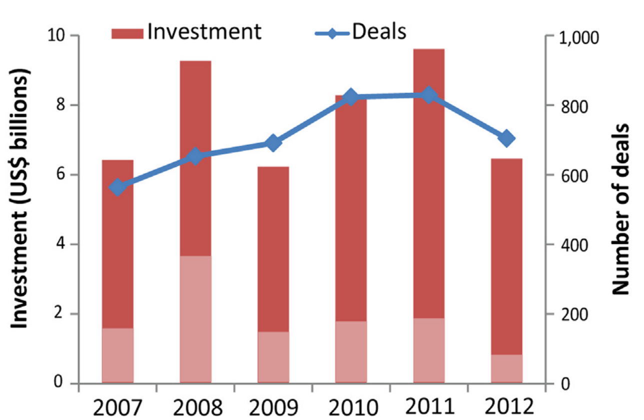

Fig. B4. Global VC investment in the cleantech sector. The VC funding for solar technologies (in lighter red) is heavily slashed from about $3.6 billion in 2008 to $0.8 billion in 2012.
Source: MIT Tech Review.

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