Working Paper Series

WP 10-6 MAY 2010

Toward a Sunny Future? Global Integration in the Solar PV Industry

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Abstract

Policymakers seem to face a trade-off when designing national trade and investment policies related to clean energy sectors. They have pledged to address climate change and accelerate the large-scale deployment of renewable energy technologies, which would benefit from increased global integration, but they are also tempted to nurture and protect domestic clean technology markets to create green jobs at home and ensure domestic political support for more ambitious climate policies. This paper analyzes the global integration of the solar photovoltaic (PV) sector and looks in detail at the industry's recent growth patterns, industry cost structure, trade and investment patterns, government support policies and employment generation potential. In order to further stimulate both further growth of the solar industry and local job creation without constructing new trade and investment barriers, we recommend the following: (1) Governments must provide sufficient and predictable long-term support to solar energy deployment. Such long-term frameworks bring investments forward and encourage cost cutting and innovation, so that government support can decrease over time. A price on carbon emissions would provide an additional long-term market signal and likely accelerate this process. (2) Policymakers should focus not on solely the manufacturing jobs in the solar industry, but on the total number of jobs that could possibly be created including those in research, project development, installation, operations and maintenance. (3) Global integration and broader solar PV technology deployment through lower costs can be encouraged by keeping global solar PV markets open. Protectionist policies risk slowing the development of global solar markets and provoking retaliatory actions in other sectors. Lowering existing trade barriers—by abolishing tariffs, reducing non-tariff barriers and harmonizing industry standards—would create a positive policy environment for further global integration.

JEL Codes: F14, F18, F23, H23, Q27
Keywords: Solar PV, climate change, renewable energy, government support, green protectionism, green jobs, global integration

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Note: The authors would like to thank numerous solar industry experts and colleagues for assisting us in writing this working paper, in particular Matthiah Larkin, Trevor Houser, Jennifer Morgan, Letha Tawney, Sarah Forbes, Jenna Goodward, Alexander Perera, Deborah Seligsohn, Brian O'Hanlon, Sam Newman, Bill Rever, Bianca Barth, and Sebastian Meyer. The conclusions and any remaining errors are, of course, the authors' responsibility. This working paper contains preliminary research, analysis, findings, and recommendations. The World Resources Institute and the Peterson Institute for International Economics welcome reviews and suggestions, which can be sent to Jacob Kirkegaard at *jkirkegaard@piie.com* and Lutz Weischer at *lweischer@wri.org*. This working paper was supported by a grant from the Doris Duke Charitable Foundation.

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I. INTRODUCTION

The development of clean energy industries has initially been limited to individual countries with strong supportive policy frameworks for selected sectors. However, as more and more countries join the global effort to tackle the climate change challenge and new multibillion-dollar markets emerge, renewable energy sectors are rapidly expanding beyond national boundaries. Pioneer firms are growing into multinational companies with globally integrated value chains and new entrants from emerging economies are fostering global competition. This ongoing process of global integration offers the opportunity to increase the worldwide deployment of clean energy technologies and find low-cost solutions to the climate change challenge.[1] At the same time, such a realignment of value chains also increases global competition and changes the outlook for many countries' domestic businesses and employment patterns.

Policymakers thus seem to face a trade-off in designing national trade and investment policies related to clean energy sectors. On the one hand, they have pledged to address climate change and accelerate the large-scale deployment of renewable energy technologies. Policies that foster global integration could help to reduce the price of related goods and services and make this undertaking less costly. On the other hand, they are tempted to nurture and protect domestic clean tech markets in order to create the promised "green jobs" at home and ensure domestic political support for more ambitious climate policies.

Against this background, this paper analyzes globalization in the fastest growing renewable energy sector, the solar photovoltaic (PV) industry. While still a dwarf among the traditional fossil fuel giants, the solar PV industry has been growing at a rapid pace in recent years and the industry's value chain increasingly spans the globe. As policymakers decide on how to support the deployment of solar power at scale in the years ahead, they face the critically important question of how to best tap into the potential a globalized solar PV industry offers for lower-cost climate change mitigation while still creating solar jobs "at home." The high local employment potential makes solar PV an attractive sector for policymakers interested in promoting renewable energy and combating high domestic unemployment. Our goal is to provide the necessary background for related policy debates and offer some policy recommendations based on our findings on globalization patterns in the industry.

Our analysis starts with a brief summary of various solar PV technologies and their applications (section II). In section III, we then map out the current and future global demand for solar PV systems and the role of government support. Next, section IV analyzes the cost structure and competitiveness of solar PV power. We then show how the solar energy sector has developed into a truly global industry

1. Following Slaughter and Scheve (2001), we will take "global integration" to mean the increased integration of product and factor markets across countries through cross-border trade and foreign direct investment (FDI), i.e., the increase in cross-border flows of goods and services, as well as capital linked to multinational companies. Analysis of increased global flows of people (immigration) and financial capital (portfolio investment flows) are outside this analysis.

characterized by high levels of growth, trade flows, innovation spillovers, and competition before we assess the future globalization potential of different segments of the value chain (section V). Then we proceed to analyze existing barriers to further global integration such as tariffs, nontariff barriers, or investment obstacles in section VI. Finally, we discuss the consequences of greater globalization for green job creation along the solar PV value chain in section VII before we conclude with a set of recommendations to policymakers who want to optimize both local job creation and climate change mitigation.

Our principal findings and recommendations are:

1. The solar PV sector has grown very rapidly over the past years in response to the demand created by strong political support in four key markets: Germany, Spain, Japan, and the United States. Global demand will continue to grow and expand into other countries, including emerging economies, as solar support policies become more widespread. Technological advances, improved production and installation processes, scale, and shift of production to lower cost areas have led to sharp price declines in the past decade. However, the solar industry will remain dependent on government supply policies in the years ahead until cost competitiveness with conventional sources of power (grid parity) is reached in major markets sometime between 2012 and 2020. Policymakers can best support the further development of the solar industry with policies that create strong and predictable demand for solar power, complemented by a price on carbon emissions that would provide a broader, more long-term market signal than incentive or mandates.
2. The industry is in the midst of a globalization process that is likely to further increase the efficiency of production and the global deployment of solar technology. Global competition has especially intensified in the midstream manufacturing of wafers, cells, modules, and components due to the entry of new players from emerging economies and higher levels of cross-border trade. We expect this globalization trend to continue and expand to other segments, especially the downstream business. In light of growing global competition, firms in OECD economies will likely have to focus on high-quality and highly automated manufacturing, downstream activities such as project development and installation, and areas in which they possess a competitive advantage such as upstream silicon production, research and development or other high value-added services.
3. The job generation potential of solar PV over the lifecycle of an installation is very high compared to both fossil fuels and other renewable energy sources. Distributed generation solar PV creates more jobs per unit of electricity produced than any other energy source. The net employment impact of globalization on the solar PV industry in OECD countries is difficult to assess, however. Whereas their share in global solar manufacturing employment is shrinking, globalization can also contribute to a lower price for solar installations, which increases the overall demand for solar installations and thus increases local jobs in development and installation. In designing their support policies, policymakers should ensure that programs exist

for both centralized and distributed segments of solar PV markets in order to promote total market growth.

4. Solar firms have faced relatively low barriers in globalizing their value chains in the past. Tariffs are comparably low in all major markets and direct investment was not met with any major resistance. However, in light of growing global competition, there are certain political pressures for protectionist measures in some of the major markets including Germany and the United States, as well as in some of the newly emerging solar markets such as Canada and India. Such policies would come at the cost of jeopardizing the potential cost savings from a globally integrated industry structure. Protectionist measures in the clean tech sector would also inhibit the risk of retaliation and trade frictions in other areas and could negatively affect global initiatives to tackle climate change. Conversely, keeping global solar PV markets open will be conducive to future cost reductions and help to broaden the global deployment of solar technology. In addition to refraining from new protectionist measures, governments could take steps to lower existing trade barriers, such as abolishing remaining tariffs and harmonizing solar industry standards. As the majority of global solar PV demand is currently concentrated in just three economies—the European Union, Japan, and the United States—the unilateral implementation of such policies in these markets would be an important signal for the global market.

II. SOLAR ENERGY TECHNOLOGIES AND APPLICATIONS

The sun is an abundant, free, and nonpolluting source of energy with multiple possible applications. The sun's energy potential may be harnessed naturally through the photosynthesis of biomass production or through the design of buildings that maximize room heating/cooling and illumination. Alternatively, two groups of so-called active solar technologies exist. Solar thermal technologies can be used to produce heat or electricity through steam-powered turbines (concentrated solar power: CSP).[2] Alternatively, solar PV technologies generate electricity from solar radiation when sunlight photons are absorbed by the semiconducting material of a solar PV cell. The photons cause electrons to be released and flow through the semiconducting material generating electricity.[3] This working paper focuses on solar PV systems, which is the most important segment of the market in terms of installed capacity. This section will briefly map out the variety of solar PV technologies and their applications.

Solar Photovoltaic (PV) Technologies

In many ways, solar energy remains an energy technology cluster in its infancy with numerous different applications, high levels of R&D spending and venture capital (VC) funding,[4] new breakthrough

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2. Also see Barclays Capital (2009, 364ff) and Staley et al. (2009) for an elaboration on commercial CSP technologies.

3. For a detailed description of different end-use applications of solar energy on which this section builds, see Abdelilah (2009).

4. UNEP SEFI (2009, figure 10) shows how solar energy received over 40 percent ($5.5 billion) of the total venture

technology applications, and continuing high levels of efficiency improvements in existing technologies. In the solar PV industry, three generations of technologies exist:

First generation solar PV technologies are known as crystalline silicon. The cells are cut from a silicon ingot, casting, or grown ribbon. So far, this generation dominates the market because of its high conversion efficiency, defined as the percentage of sunlight that is converted into electrical energy, as well as its extensive manufacturing base. Monocrystalline PV cells today have an efficiency of 16 to almost 20 percent, while the cheaper-to-produce multicrystalline PV cells achieve a slightly lower 14 to 15 percent.[5] Crystalline solar PV cells are usually interconnected and encapsulated between a transparent front (typically glass) and insulating back cover material to form a solar PV module, which is usually mounted in an aluminum frame (also see figure 10 for the different steps of the production chain) .

Second generation solar PV technologies are referred to as thin film because thin layers of PV materials are deposited on low-cost substrates like glass, stainless steel, or plastic. Their advantage is that they are significantly cheaper to produce, but they have much lower efficiency levels. The oldest and most prevalent thin-film technology is "amorphous silicon" with a conversion efficiency of just 6 to 7 percent, while hybrid "amorphous/micro-silicon technologies" achieve about 8 percent. Other thin-film technologies, using compound semiconductors, such as Germanium (an amorphous silicon thin-film), cadmium telluride (CdTe) or copper iridium di-selenide (CIS), have achieved commercial conversion efficiencies of up to 11 to 12 percent (Barclays Capital 2009 and IEA PVPS 2009a). These improvements in thin-film efficiencies have led to a very rapid expansion of this segment of solar PV technologies in recent years; their market share has risen from less than 5 percent in 2004 to over 22 percent by 2008.[6]

Third generation solar PV technologies are not yet being deployed on a large scale. They are the focus of current R&D efforts using various organic and nanotechnologies to achieve higher efficiency and/or much lower cost.

Individual solar PV modules typically range from 50 watts to 300 watts in capacity. Multiple solar

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capital/private equity investment in eight renewable energy sources in 2008. See Jennings, Margolis, and Bartlett (2008) for a historical assessment of private sector investment in the solar PV industry.

5. Monocrystalline PV cells are usually cut from a single grown silicon ingot while multicrystalline PV cells are manufactured using a process of multi-ingot casting, where wafers cut from those cast blocks are made up of multiple crystals. See IEA PVPS (2000) for a detailed description.

6. These percentages represent the share of thin-film modules in total module production by members of the International Energy Agency's Photovoltaic Power Systems (IEA PVPS) Program. Production in other countries, including China, Taiwan, and India, is not included. The PVPS members are the European Union, 21 individual developed and emerging countries (Australia, Austria, Canada, Denmark, France, Germany, Israel, Italy, Japan, Korea, Malaysia, Mexico, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States), and one industry association (the European Photovoltaic Industry Association). The increase has been accelerating in recent years from less 5 percent in 2004 to over 6 percent in 2005 to 9 percent in 2006 to 14 percent in 2007 and finally over 22 percent in 2008. See IEA PVPS annual reports 2000–09.

modules can subsequently be connected and configured to generate the desired power load level. Solar PV systems can therefore range in scale from just a few watts in small separate applications powering streetlights or small consumer electronic equipment to hundreds of megawatts in utility-scale solar power plants. In addition to the cell/module, a PV system includes balance of system components, including the module mounting structure, the wiring and other switchgear and an inverter, which converts the direct current (DC) electricity produced by the semiconducting material to the alternate current (AC) suitable for applications and the electricity grid.[7]

Solar PV Applications

The large degree of flexibility in the assembly and installation of solar PV applications means that several distinct categories of solar PV power generating applications exist. The standard classification, described in IEA (2009, 16), demarcates based on application type and size and distinguishes between four different solar PV categories:

> **Consumer products**: small applications of less than 10 watts. Includes small items like solar calculators, watches, garden lighting, or camping-related equipment.
>
> **Distributed PV,[8] off grid:** applications between 10 watts to 100 kilowatts. The modular flexibility of PV makes it ideal for production of electricity close to the point of consumption. Off-grid systems operate as stand-alone systems without access to the electricity network. They are well suited for power consumers located in remote areas subject to very high transmission costs, but who in such areas require electricity for essential services like lighting, telecommunication, infrastructure signaling, refrigeration, water pumping, or irrigation. Typical off-grid residential PV systems produce around 1 kilowatt and are most widely used in large countries with vast rural hinterlands or in developing countries to provide rural infrastructure.
>
> **Distributed PV, grid connected:** applications between 10 watts to 100 kilowatts. As with distributed off-grid PV applications, PV's modular adaptability enables the production of electricity at residential or industrial premises. Grid-connected solar PV applications are located at the power consumer's premises as for instance rooftop applications or so-called Building Integrated PV (BIPV), where solar PV panels form an architecturally integrated part of a building or broader built-up environment. Distributed grid-connected PV applications first aim to cover the consumer's own power demand, while feeding any surplus electricity into the local grid. If net metering standards or a feed-in-tariff are in place, this creates an additional benefit

7. Solar PV mounting structures vary widely in design, but are generally designed to maximize the level of direct sunlight that can hit the solar PV cell. They may include motorized directional mounts, but can also include a wide array of products designed to install solar PV modules on building façades and roof tops. Off-grid solar PV applications also include batteries and charge controllers.

8. "Distributed generation" generally covers "decentralized power systems." In solar PV, this typically includes off-grid and small grid-connected systems. See Abdelilah (2009).

for the PV system owner. Most residential rooftop PV systems are smaller than 100 kilowatts, but installations on commercial rooftops may be larger and reach several megawatts.[9]

Centralized solar PV power stations: applications from more than100 kilowatts to multi-100 megawatt utility scale. Like ordinary power plants, centralized PV power stations produce electricity for distribution to consumers through the regular electricity network. As large ground-located structures, the scale of solar PV plants is limited only by space constraints. While some centralized plants (typically 5 to 30 MW) can be located near distribution centers, the largest centralized PV plants are usually located in remote areas with high solar irradiation (e.g., desert-like locations), but often far away from centers of power consumption. This can create significant challenges for grid transmission and balancing that is exacerbated by the fact that solar power is "forecastable but variable" and only produces electricity during daytime.

This diversity of applications and scales has important implications for the analysis of the solar PV sector. It makes an accurate measurement of installed solar PV power production capacity, as well as the amount of solar power actually produced, very challenging. It is likely that the real total level of solar PV application is being significantly underestimated and global aggregates and most national-level solar PV capacity and production data must be regarded as merely indicative of the actual situation. This paper will therefore principally focus on on-grid PV installations, for which the data situation is most reliable. We largely exclude small solar PV applications in consumer goods from our analysis and are cautious about the analysis of off-grid data.[10]

III. SOLAR PV DEMAND AND THE ROLE OF GOVERNMENT SUPPORT MEASURES

The global demand for solar PV installations has grown rapidly over the past decade, mainly driven by the support policies for grid-connected installations in four lead markets. The following section summarizes

9. Distributed grid-connected installations located on top of corporate warehouses, offices, or government buildings can range in size from 500 kilowatts to 3 megawatts, depending on available roof space. An emerging business model for commercial rooftop PV development is to locate solar assets on a roof with a low power load (i.e., an empty warehouse) and sell the majority of the electricity back to a contacted utility.

10. The principal depository of official solar PV statistics is the PVPS Program, which since 1993 has analyzed the sector in the program's member states. However, the rapid expansion of solar PV production in countries outside the IEA PVPS, especially in China and other emerging economies, raises new data concerns. Large, centralized power stations provide the most accurate data because capacity and production are published, metered, and reported to national authorities. Yet much solar PV capacity comes in the form of smaller distributed systems, where power production is consumed directly onsite. Off-grid solar PV systems are not monitored by utilities, and national statistics typically only cover installations over a certain threshold size (often close to the megawatt level). Countries such as Germany or Spain, where utilization of government incentives for small and off-grid solar PV installations require ongoing consumer registration, have the most reliable solar PV data. Alternatively, solar PV capacity and production data can be estimated from sources such as surveys or industry reports. They often provide data on total shipments of different PV system types during a year. However, such data will invariably differ from the amount of solar PV capacity actually installed and operational during the same. See UN et al. (2002) for a general discussion of data survey coverage difficulties of small entities in official balance of payments (BoP) statistics.

trends in demand for solar PV technology and identifies the relationship between demand and government support policies.

Global Solar PV Demand

Solar PV technology today remains a relatively minor component of total installed renewable energy capacity for power generation, while for heat generation solar sources are a larger component, as illustrated in figure 1. However, solar PV was by far the fastest growing source of renewable energy globally during both 2008 and 2009 with an annual increase of over 70 and 45 percent respectively, resulting in approximately 5.4 and 7.2 gigawatts of added grid connected capacity.[11]

A group of just four countries—Germany, Spain, Japan, and the United States— has long accounted for the overwhelming majority of the rapidly expanding global solar PV market. The data from the International Energy Agency's Photovoltaic Power Systems Program (IEA PVPS) presented in figure 2 illustrates this. Today, apart from these four countries only Italy (in 2009) has reached a cumulative installed solar PV capacity of more than 1 gigawatt. New installations of solar PV reached a record about 7.2 gigawatts in 2009 globally, with Germany alone accounting for more than half of the global market in 2009 with 3.8 gigawatts of new capacity added last year alone.

Figure 3 compares cumulative installed solar PV capacity data for all countries for which reasonably comparable data exist. Aside from Germany, Spain and "emerging" Czech Republic, Italy and France, no other European countries have yet developed large markets for solar PV applications. Similarly, solar PV energy has a very low penetration in developing countries. Even in large emerging economies in Asia such as China or India that have successfully established large markets for other renewable power sources like wind, the domestic solar PV market size remains dwarfed by the top four OECD markets. However, large markets outside the OECD world are rapidly emerging. In 2009, China announced a very ambitious goal of deploying 20 gigawatts of solar power by 2020, more than the total global solar PV capacity in 2008 (Solar Plaza 2009a). Similarly, India's National Solar Mission outlines policy mechanisms and targets to reach 20 gigawatts or more of solar power generation by 2022 (Renewable Energy World 2010).

The rapid rise in installed solar PV capacity in recent years has exclusively been concentrated in grid-connected solar PV. Figure 4 shows how on-grid installations overtook off-grid capacity in 1999 and

11. Large hydropower sources have been excluded from figure 1, but remain by far the largest renewable source of energy with 860GW of installed capacity at the end of 2008. Including more uncertain estimates for off-grid solar PV capacity estimated at about 4GW globally in 2008 raises the total estimated solar PV capacity at the end of 2008 to about 17GW. Note that the Renewable Energy Policy Network for the 21st Century (Ren21) data for off-grid solar PV capacity include all countries in the world and are therefore larger than IEA PVPS data for off-grid solar PV data utilized elsewhere in this paper. Source: www.Ren21.net and EPIA (2010). Note that 2009 data for all the types of energy supply included in figure 1 is not available.

have since grown to 95 percent of the total IEA PVPS member state installed capacity.[12] The increased importance of grid-connected capacity is directly related to their far larger scale and government policy support that overwhelmingly targeted grid-connected PV installations.[13] As such, so long as this situation continues, grid-connected solar PV applications can be expected to drive aggregate demand for solar PV for the foreseeable future.[14]

Another way to illustrate this issue is to relate the relative importance of grid-connected installed capacity to overall national solar market depth measured in installed watts per capita. Figure 5 shows how most countries in 2008 retain a very limited solar PV penetration with just a few watts of installed capacity per capita. Only three geographically large countries with substantial rural areas have more than 2 watts of installed solar PV capacity per capita and less than 90 percent of their total solar PV consisting of grid-connected capacity: France (87 percent), Australia (30 percent), and the United States (68 percent). Figure 5 further shows how the two global market leaders in Germany and Spain have far higher solar PV market depths than all other nations and are almost wholly reliant on grid-connected applications.

Government Support as Main Driver of Demand

Until the late 1990s, off-grid solar PV installations accounted for the majority of what was a relatively modest sized global market. This early importance of small-scale off-grid solar PV applications was a result of their ease of use in desolate areas with no or only very expensive alternative power supply options, such as diesel-fueled power generators or extensions of the public electricity grid. As such, off-grid solar PV applications were already fully cost competitive with alternate power supply options, especially on a lifetime cost comparison basis that includes the alternatives' variable cost of (diesel) fuel.

For grid-connected solar PV applications, which essentially accounted for the entire dramatic growth of the solar PV market in recent years, the cost comparison is very different than for off-grid applications. Rather than merely offering electricity at specific locations cheaper than generators or expanded public grids, the cost of grid-connected solar PV produced power must be compared to the cost of power generated by standard sources of supply—namely fossil fuel, nuclear, and large hydro plants.[15] However,

12. Given the noted data validity concerns especially regarding off-grid solar PV applications, the data in figure 4 must be taken as approximate figures. However, these data concerns do not materially affect the conclusions drawn here.

13. As will be elaborated below, unless a solar PV installation is grid-connected, it cannot, for instance, receive feed-in tariffs.

14. Rapid future expansion of the off-grid solar PV market cannot be ruled out in especially rural areas, but currently seems dependent on significant improvements in (declines in prices of) battery capacity and increases in the price of power generator fuels, such as diesel.

15. This comparison will be different for centralized and distributed grid-connected installations. For the owner of a grid-connected distributed solar PV system what matters are retail electricity rates, as he decides whether to install solar panels or to purchase power from his utility company. The cost of centralized solar PV generation, on the other hand, is directly measured against the cost of other plants—that is, against wholesale electricity rates.

the point at which solar PV power becomes fully competitive with other sources of power—known as "grid parity"—has not yet been reached in any large power markets (see below in section IV).[16] Against this backdrop, the dramatic increase in grid-connected solar PV application installations in recent years seems surprising. This is even more so as the rapid rise was not coincidental with similar declines in the price of solar PV applications over this period (see figure 9, IV). In addition, countries with relatively low solar radiation, such as Germany, have been able to develop large PV markets. These patterns illustrate that instead of price considerations, the main driver for the development of global demand for grid-connected PV systems was national or regional support policies in four key markets: Germany, Spain, Japan, and the Unites States. Figure 6 illustrates how the annual installed grid-connected solar PV capacity in these countries reflects the introduction of key government support measures.

Japan

Japan got a head start in the mid-1990s with its Residential PV System Dissemination Program (RPVDP), which provided varying investment rebates (initially up to 50 percent) for installed solar PV capacity, depending on recipient category and system size (Ikki and Matsubaba 2008). Consequently, Japan became the world's largest solar PV market in the late 1990s.[17] However, due to the type of installations supported by the RPVDP, Japan's solar PV market has remained dominated by relatively small-scale (3 kilowatts to 5 kilowatts) grid-connected private residential solar PV applications, with some expansion into medium-sized PV systems for public commercial buildings. As a result, the size of Japan's solar PV market has been relatively stagnant in recent years in terms of total new megawatts installed.[18]

United States

The United States—as a very large country with vast rural areas—retains a relatively large share of off-grid solar PV capacity (figure 5) but nonetheless has added over 100 megawatts annually of new grid-connected solar PV capacity since 2006. The state of California, which accounts for the vast majority of new installations, began its Emerging Renewables Program (ERP) in 1998, making it the first US state with a large-scale support program for solar PV applications. The ERP provided a fixed (although over

16. It should be noted that although solar PV power may not be directly cost-competitive with other power sources, it can still be an attractive option as part of a utility's or large industrial user's broader portfolio of different power sources. This is due to its zero variable fuel costs, minimal operating and maintenance costs, and corresponding cost predictability. Unlike fossil fuel derived power, where up to 70 percent of total costs consists of highly variable fuel costs, the principal cost of solar power is up-front capital cost, which is known in advance. This facilitates investment planning and can be an important hedge against fossil fuel price volatility.

17. Data from IEA PVPS (2009b). Japan also in 1994 introduced a smaller voluntary net billing system, in which utilities can buy back surplus PV power from consumers at the same rate as retail power.

18. Ibid, page 9ff.

time declining) rebate per kilowatt of installed capacity to offset capital cost associated with installation.[19] Today, state-level financial support programs for solar PV in America have become more numerous. In 2008, 27 major financial incentive programs existed in 16 states (Wiser et al. 2009).[20] State-level support programs don't only include direct rebates, but also solar set-asides under state Renewable Energy Standards (RES). An RES sets a goal for renewable energy generation for utilities and requires them to purchase the necessary amount of Renewable Energy Certificates (RECs) from producers of renewable energy in order to demonstrate they achieve the goal. Because RECs from other renewable energy sources such as wind are cheaper than those generated by solar power plants, 16 states and the District of California have defined a solar set-aside, that is a certain percentage of the goal that must be met by solar RECs (DSIRE 2010). On the federal level, the main support mechanism is an investment tax credit of 30 percent for solar power projects that was introduced in its current form in 2005 and extended through 2016 in 2008. The American Reinvestment and Recovery Act of 2009 created the possibility to receive the same amount as a grant, rather than a tax credit, to make it more attractive for investors without large tax liabilities (DSIRE 2009).

Germany

Germany's long-term commitment to solar PV energy began in 1999 with the 100,000-roof program and was scaled up in 2004, when the Erneuerbare-Energien-Gesetz (EEG—Renewable Energy Sources Act) was revised to include generous feed-in rates for solar PV (see box 1).[21] The EEG locked in the level of the solar PV feed-in tariff for any given project for a 20-year period. However, the tariff also declines annually, meaning a project built in the following year will also be guaranteed a set tariff over 20 years, but at a lower level. Feed-in tariff rates for different renewable energy sources were determined on an industry-specific basis. This allowed the government to set the rate at a level that would allow for profitability, but only if the most efficient technology available for the specific project type was used. Correspondingly, solar PV electricity, with production costs far higher than other renewable sources such as wind or small hydro, secured by far the highest feed-in tariff, initially €0.51 per kilowatt hour produced. As can be seen in figure 4, the 2000 EEG law, and particularly its 2004 revision, set in motion the rapid solar PV market expansion that during the 2000s made Germany the largest market in the world.[22]

19. Initially the ERP rebate was up to $3,000 per kilowatt. In 2006 the rebates were reformed and set at $2,600 per newly installed kilowatt, declining by roughly $200 each every six months. IEA PVPS (2009c) and IREC (2009).

20. The more inclusive Database of State-level Incentives for Renewables and Efficiency (DSIRE) even lists approximately 500 state and local government financial incentive programs for renewable energy, including solar PV applications, for December 2009. DSIRE is available at www.dsireusa.org/.

21. The EEG was originally introduced in 2000. Its predecessor, the Stromeinspeisungsgesetz (StrEG), was introduced in 1990 and principally targeted small hydro plants and wind turbines.

22. The 2004 EEG revision maintained very high—up to 10 times value for wind energy—feed-in tariffs for solar PV

Spain

Spain has recently emerged as a major solar PV market. Explosive demand growth was triggered by the government's 2006 decision to separate solar PV feed-in tariffs from average electricity tariffs and to guarantee solar PV feed-in tariffs for the duration of application life (reduced after the first 25 years). In 2008, Spain surpassed Germany to become the fastest growing solar PV market in the world in absolute terms with over 2.6 gigawatts of newly installed solar PV capacity (figure 2), though Germany still has the largest cumulative capacity. However, in 2008 the Spanish government, in a cost-controlling response to the market's swift growth, introduced an annual cap on eligibility for guaranteed feed-in tariffs. In 2009 the cap was set to an aggregate 500 megawatts of for newly installed solar PV capacity.[23] The immediate market impact was dramatic. Preliminary data for 2009, shown in figure 6, reveals that other leading solar PV markets were hardly impacted by the global recession at all, while the Spanish solar PV market collapsed, due to the policy change.

In sum, global demand for solar PV applications has been highly dependent on the policy decisions of just a few countries, especially Germany and Spain, and has exhibited noticeable volatility as a result. Spain's sudden volte-face has clearly had a disruptive effect not only on the country's domestic solar PV industry, but on the entire global sector. To a certain degree the impacts of sudden changes in political priorities are part of the risk of doing business for any industry that remains as dependent on government financial support as the solar PV industry. Global deployment of solar PV power in a large number of countries would make for a more liquid market and reduce the vulnerability to government decisions in just a few countries. In the long run, only full grid parity for the principal solar PV market segments will abate the risks of this type of politically induced market disruption.

Global Demand Outlook

Political support of grid-connected solar PV applications can be expected to drive aggregate demand for solar PV for the foreseeable future.[24] The examples of Germany and Spain illustrate how diversified feed-in

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energy in Germany. The latest revision of the relevant EEG provisions for solar PV in 2008 put in place a system with diversified 20 year feed-in tariffs for different solar PV applications—<30kW/30-100kW/100-1000kV/>1MW sized rooftop and ground-mounted applications. Moreover, guaranteed feed-in tariffs automatically decline by a preset schedule every year for new solar projects. The rate of degression in guaranteed feed-in tariffs is adjusted up or down, depending on the rate of market expansion, such that a very large increase in year t (above a determined market growth corridor) leads to a larger decline in the guaranteed feed-in tariff in year t+1 and vice versa. See EPIA (2009b).

23. Similarly to feed-in tariffs in Germany, Spanish regulation distinguishes between different solar PV applications—<20kW/>20kW rooftop and ground-mounted applications. Spanish rules also have a size maximum on feed-in tariff eligible PV systems. As in Germany, Spanish regulation stipulates varying feed-in tariffs and cap sizes depending on the previous period's market developments. Hereby, gradual reductions in the feed-in tariffs are introduced if more than 75 percent of the cap is reached during the previous period, with inversely proportional increases in the cap in the following period. Source: EPIA (2009b).

24. Rather than by government support policies, future expansion of the off-grid solar PV market would be driven by

Box 1 Government support considerations for solar PV

Solar PV can be described as an emerging, transitional, or imperfect market.[1] Such a market is different from a mature or fully competitive market, as individual buyers and sellers can affect the market price. Higher demand expands total market size and leads to price decreases in the long run, due to industry learning rates, economies of scale, and increased competition. This development continues until the emerging market transitions into a mature market. As such, government financial support for solar PV demand is crucial to support market growth and the emergence of a competitive market with lower prices.

At the same time, as described in section II, solar PV consists of several distinct product categories and has highly diverse sources of final demand ranging from individual consumers looking to cut their power bills to large sophisticated utilities aiming to add hundreds of megawatts of new grid-connected power production capacity. Governments therefore need to tailor support programs toward specific market segments, both to ensure program success, as different groups will respond to different incentives structures,[2] and to prevent policy driven market excesses.

In principle, governments can achieve the desired stimulative effect on individual solar PV market segments through a large number of different types of promotional drivers, as illustrated in the table below (box table 1). In recent years, there has been a shift toward increased reliance on stratified feed-in tariffs for solar PV support, especially in the large markets such as Germany and Spain and, in coming years, also China. Such differentiated feed-in tariffs are seen as a particularly effective support mechanism, partly because they tend to provide very high support levels, but also because they provide long-term price visibility and simplicity for investors and allow for differentiation by project type and continued price decreases (EPIA 2009b and IEA-PVPS 2009b).

One common feed-in tariff program feature is that most financial incentives decline with the scale of the solar PV installation, such that individual consumers looking to add a small rooftop application can usually get a higher level of government support per kilowatt of installed new capacity than large utilities intent on building large grid-connected solar PV plants. Indeed, the recent solar PV boom in Spain in 2007–08 can largely be attributed to large solar PV developers figuring out how to circumvent the "declining scale adjustment" of Spain's feed-in tariffs. The government had intended to limit its generous solar PV feed-in tariff to small-scale projects of up to 100 kilowatts. However, utility-scale solar PV developers realized that their far larger projects would also be eligible for the high "small project feed-in tariff" if they simply installed individual sections of less than 100 kilowatts next to each other (The Economist 2009).

Another often seen feed-in tariff feature in longer-term solar PV support programs is a built-in gradual decline in support levels. A preannounced annual "X percentage point" reduction in available levels of long-term financial support for solar PV projects serves to bring investments forward in time. For example, a small 25 kilowatt rooftop solar installation built in Germany in 2007 and connected to the grid at a feed-in tariff rate of €0.4921 per kilowatt hour guarantees the owner that rate for 20 years. The 5 percent decline stipulated by the German legislation affects anyone who builds a project in 2008 when he or she will receive a feed-in tariff of €0.4921—5 percent = €0.4675 per

continued on next page

1. See IEA PVPS (2009b) and Haass (2002) for a detailed discussion.

2. Some commentators suggests that individual demand for rooftop solar PV appliances responds more to nonfinancial incentives, such as appearing "environmentally aware and eco-friendly" in the neighborhood. See for instance Schuant (2009).

Box 1 Government support considerations for solar PV *(continued)*

kilowatt hour for 20 years. Similarly, built-in future declines in government support levels maintain the incentives on solar PV producers to continue innovation to bring down production and installation costs, despite high initial levels of government support.

Sophisticated long-term programs, as in Germany, directly link government support levels to previous years' market developments. If new installations are above (or below) a fixed government target, the next year's tariff level will be decreased (or increased) more than had originally been planned. The objective of such an approach is to align solar PV market developments with government policy targets. A similar dynamic was at play in Germany in January 2010, when the government announced, following continued explosive growth of solar PV during 2009 (see figure 6), that in the second half of 2010 solar PV feed-in tariffs would be cut by an additional 16 percent for rooftop, 15 percent for ground-mount and 11 percent for ground-mount project on conversion sites, on top of the scheduled 9 percent decrease, and completely abolished for farmland installations.[3] However, Germany—unlike Spain in 2008—has not imposed any new megawatt cap on future solar PV market expansion, thus managing a market slowdown rather than precipitating a collapse.

3. See Bloomberg, April 23th, 2009, "German Solar-Park Aid Cut Less Than Expected in Draft", www.bloomberg.com; and CDU/CSU-Fraktion im Deutschen Bundestag, April 23th, 2009, "Koalition einigt sich auf Reform der Solarförderung", www.cducsu.de.

tariffs of varying duration and generosity can have an immediate and powerfully stimulating effect on solar PV markets. Correspondingly, it is a positive signal for global solar PV demand that a host of potentially large markets—including France, Israel, Italy, Japan, Korea, the Netherlands, Portugal, China, and India—have in recent years announced the introduction of national feed-in tariffs for solar PV applications (IEA PVPS 2008, 2009a). These clear commitments of support should both provide a robust aggregate stimulus to global solar PV demand and, through the greater number of countries engaged, act as a stabilizing factor in demand growth over the next three to five years. Various forecasts put the estimated global annual growth for solar PV installations at around 20 to 30 percent over the coming years, with the level of political support across markets as a crucial variable (IEA PVPS 2009a).

For the medium- and long-term market outlook, direct policy support for installations is expected to decrease in importance and the deployment of solar PV energy will increasingly depend on its price competitiveness with traditional power generation systems and other renewable energy sources. Climate policies that reflect the social cost of greenhouse gas emissions by putting a price on carbon will further help solar power become competitive. If this is achieved, most scenarios forecast a massive expansion of installed solar PV capacity over the next two to three decades, especially if strong global commitments to greenhouse gas reductions are made. The IEA's Blue Map scenario, which targets reducing global greenhouse gas emissions

rising costs of power generator fuels, such as diesel, and technological advances, such as improvements in battery capacity.

by 50 percent, includes a 300-fold expansion of installed capacity by 2050, with grid-connected residential panels accounting for the major share of installations (figure 7). Under this scenario, the annual market for solar PV would increase to 34 gigawatts as early as 2020 and reach more than 140 gigawatts in 2050. This would imply an increase in the share of solar PV in total electricity generation from virtually zero today to around 5 percent in 2030 and more than 10 percent in 2050 (IEA PVPS 2008). The following section briefly analyzes the past and current cost structures of solar PV energy to present the most important determinants of its future competitiveness before we explore the global integration of the industry's value chains.

IV. COST STRUCTURE AND COMPETITIVENESS OF SOLAR PV POWER

Although solar PV has experienced high industry learning rates and associated cost reductions in the past, it remains an expensive way to generate power.[25] The overall cost of power generated from a solar PV system over its lifetime (levelized cost) still lingers between $0.15 to $0.40 per kilowatt hour, two to three times the level for other currently available large-scale grid-connected electricity sources. Industry analysts estimate that it is possible to further bring down the costs for solar systems by improving technology, expanding economies of scale, and streamlining production processes. This projected reduction of upfront installation costs, which represent the lion's share of levelized solar PV cost, in combination with rising world market prices for fossil fuels and carbon pricing would make solar PV–generated electricity commercially competitive in many regions of the world within the next 5 to 10 years.

Current Competitiveness of Solar Power

Although grid parity also depends on several external and regional factors, such as grid electricity prices, fossil fuel prices, or the amount of solar radiation, the most important determinant of future competitiveness will be the price of solar electricity itself and thus the total lifecycle costs of solar PV installations. The total costs over a lifecycle of 20 to 30 years can be divided into fixed capital costs that occur as a one-off investment at the time of installation and variable costs that occur every year. Taken together and spread over the lifetime of a project, these make up the levelized costs.

Over the past decades, the levelized costs of grid-connected solar electricity dropped from over $2.00 per kilowatt hour in the 1970s to $0.15 to $0.40 per kilowatt hour in 2008, depending on the application and the geographic conditions. Even under a scenario where carbon pricing would increase the price of fossil fuels, the levelized cost of solar PV energy would still be among of the highest of all currently available energy technologies. Broadly speaking, the price for solar energy would have to further decline by

25. The learning rate (and its inverse the progress ratio) is a standard tool for understanding long-term cost trends and relates cumulative installation/production and associated costs. For every doubling of cumulative installed capacity/production, the learning rate indicates the associated reduction in costs. See Arrow (1962), Boston Consulting Group (1972), and Abell and Hammond (1979).

30 to 50 percent to around $0.10 per kilowatt hour in order to reach grid parity and be competitive with other forms of grid-connected energy generation (figure 8).

A more detailed analysis of the cost structures of solar PV applications helps to illustrate the most important cost drivers and suggest where future strategies to bring down overall costs need to focus. Table 1 breaks down the cost structure of a typical 5 megawatts ground-mount field project in Europe. The initial installation expenses account for about three-quarters of total lifetime costs. Variable costs such as operation, maintenance, lease, and insurance fees only account for around 25 percent of total costs. Within upfront costs, solar modules and the rest of the system ("balance of system" or BOS) roughly account for 40 percent each. Project permits and development fees, which are highly variable by installation and country, account for the rest. Within variable costs, two-thirds are made up of operation and maintenance costs; the remaining third is evenly split between land lease expenses and insurance fees.

The cost structure varies slightly for other solar PV applications. For example, the composition of the initial capital costs is somewhat different for smaller-scale systems, but the proportion of upfront capital cost to variable costs remains similar. Grid-connected rooftop systems require fewer approval fees and a smaller investment in interconnections than field projects do. However, smaller-scale rooftop projects can have higher transaction costs per watt, since the sales and due diligence process for multiple rooftop projects is often more expensive. Large-scale greenfield projects (often referred to as utility-scale projects) typically have higher associated environmental permitting and interconnection fees, as well as permitting risks that increase the cost of capital. Simultaneously, economies of scale often allow for lower equipment and installation costs on a per watt basis for utility-scale projects. The cost structure for off-grid systems is also different from grid-connected systems, as BOS components play a more important role. They can account for up to 70 percent of total PV system costs (IEA PVPS 2009).

The Road to Grid Parity

Constituting 75 percent of total expenses, it is clear that upfront capital costs are the major determinant of the price of solar PV power. The industry's steep learning curve over the past two decades led to significant reductions in average project costs per installed megawatt, which in turn led to falling prices for solar PV generated electricity. Figure 9 shows how prices for solar PV modules and complete PV systems in the three historically dominant solar PV markets—Germany, Japan, and the United States—declined rapidly in the 1990s. The nominal price decrease then slowed down somewhat during the rapid market expansion in the 2000s. The relative increase in US module prices after 2003 can largely be attributed to limited supply, as there were bottlenecks in polysilicon production and most modules were shipped to Europe at that time. Average costs for commercial systems declined from approximately $10.00 per installed megawatt in 1998 to $4.50 in 2009.

The main variables of this trend were price improvements for key components such as modules, inverters, or the mounting structure,[26] combined with a better conversion efficiency of solar cells. As figure 9 shows, the major contribution in 2003–07 did not come primarily from cheaper solar modules but rather from cheaper nonmodule components. In fact, around 60 percent of overall decline in the cost for solar PV projects over the past decade can be attributed to nonmodule components (Wiser et al. 2009). In contrast, module prices were relatively stagnant over the period of 2003–07, mostly due to dramatic increases in the price for silicon, the major input material for solar cells. In that period, spot market prices climbed from around $30 per kilogram to as high as $400 per kilogram as a result of an acute global shortage. In 2008–09, prices fell again to around $60 to $80 per kilogram as the financial crisis hit and new silicon production capacity came online. Additionally, slackening demand in the semiconductor industry contributed to the recent correction in silicon prices.

Looking forward, most industry experts estimate that solar PV can reach grid parity between 2012 and 2020 in most markets, if the existing potential to bring down total lifecycle costs further is fully exploited.[27] In order to reach retail grid parity in many markets, analysts estimate that the cost for solar systems must fall from $4.50 to below $2.50 per installed watt.[28] At that level, the cost of solar electricity will be comparable to the current level of the retail rate of electricity produced in combined cycle natural gas plants, which provide marginal generation capacity in many parts of the world.[29] While measures to level the playing field vis-à-vis fossil fuels, such as a price on carbon and an elimination of fossil-fuel subsidies, would still be needed, direct support mechanism such as feed-in-tariffs could be phased out at this point, Compared to the experiences over the past decade, falling module costs will likely contribute more to the overall drop in prices for solar PV installations than in the past.

Nonmodule Cost Trajectory

The target for achieving grid parity of solar power is to reduce total nonmodule costs—currently $1.75 to $2.00—to $1.00 per installed watt. Table 2 maps out a scenario for "balance of systems" (BOS) components[30] and module costs up to 2015, based on various industry reports and interviews with

26. Inverters transform the DC power generated by the solar PV modules into AC electricity useful in most appliances and all grid-connections. Mounting structures refer to the different structures into which solar PV modules are fastened or placed to ensure maximum sunlight exposure.

27. IEA's technology roadmap for solar PV estimates that broad grid parity will be reached by 2020; industry analysts such as Barclays Capital (2009) paint an even more optimistic picture of grid parity during 2012–15.

28. These and the following numbers in this section are authors' estimates based on interviews with industry experts and research reports such as Barclays Capital (2009) and others.

29. The analysis in Lazard (2009) assumes a gas price of around $8MMBtu (British thermal unit).

30. A precise definition of BOS components does not exist, but can best be thought of as everything in a solar PV system except the solar cells/panels.

industry executives. Many experts expect that the industry will succeed in further reducing the costs for BOS components such as inverters[31] and mounting structures. In such a scenario, BOS costs may fall by another 30 percent over the coming five years. Major drivers of further cost improvements will be global competition, cheaper manufacturing, technological improvements, and greater economies of scale. One area with large BOS cost reduction potential is the further standardization of mounting and installation techniques. Large-scale installations, in particular, will also benefit from improvements in inverter technology, as fewer inverters are required in large projects, effectively lowering the inverter cost per watt. Additionally, inverters are becoming more efficient at converting electricity from DC to AC, and this efficiency will also bring down solar costs per kilowatt hour in the future. Both large- and small-scale installations may benefit from the effective implementation of microinverters, which could greatly simplify the installation process and create AC solar panels (instead of the current DC panel, which must then be fed into a central inverter). In addition, cost savings might be possible through lowering the currently high administrative expenses and project approval fees.

Module Cost Trajectory

For modules, the learning curve and associated cost improvements are likely to be even more pronounced in the years ahead. All types of solar development will benefit from increasing silicon conversion efficiency (measured in grams per watt) and from yield improvements due to the implementation of automation procedures in Asian production facilities. In 2009, module prices have already fallen significantly faster than in prior years to around $2.00 per watt. The goal is to bring average module cost to around $1.00 through a combination of cheaper input materials, technological innovation, economies of scale, and more cost efficient manufacturing. Analysts broadly agree that the single most important driver of future cost improvements will be the falling price of polysilicon, the input material that currently accounts for more than 50 percent of total module costs. There has long been a pricing oligopoly and supply bottlenecks in the silicon market (see section V), which is now eroding due to new entrants and increasing competition. The fast-growing demand from solar cell producers pushed the spot price for silicon, which was originally mostly used by the semiconductor industry, up to $400 per kilogram in 2008. In 2009, spot prices fell to around $60 to $80 per kilogram and most analysts expect them to further drop to about $40 to $50 per kilogram due to new capacity, coupled with near-term slackened demand in the semiconductor space. Technological innovation in the form of thinner wafers, increased conversion efficiency or technological breakthroughs in thin-film technology will also drive down the costs per installed watt.[32]

31. As field projects grow larger, the trend in inverters is to also grow increasingly larger. This leads to a lower cost per watt for inverters.

32. The IEA technology roadmap puts out the following efficiency targets: 21 percent by 2015 and 23 percent by 2020 for single crystalline cells; and 17 percent by 2015 and 19 percent by 2020 for multicrystalline cells (IEA PVPS 2009a).

At a more fundamental level, the price of solar electricity will continue to decrease as the industry transitions from a small-scale market—where the support mechanisms at the system level are feed-in tariffs or other incentive programs—to competing directly on price with fossil-fuel electricity generation. Hereby it will achieve mass production scale and the cost-plus margin driven model seen in most mature manufacturing industries. This transition needs to occur for solar electricity to reach higher levels of cost efficiency and be competitive on an unsubsidized basis. The following section maps out the structure of the solar PV industry and analyzes how the cross-border integration of supply chains can contribute to making both modules and nonmodule components cheaper and thus facilitate a breakthrough for the commercial competitiveness of solar PV power.

V. STRUCTURES AND GLOBAL INTEGRATION OF THE SOLAR PV INDUSTRY

The solar PV industry currently is in the midst of a global integration process. Initially dominated by local firms in European pioneer markets, all segments of the solar PV value chain have experienced fast globalization over the past years, through cross-border investment flows, new market entrants from developing countries, and especially through high levels of cross-border trade in raw materials and intermediate and finished products.

Industry Structure

The solar PV industry can roughly be broken down into three separate value chains—upstream, manufacturing, and downstream—as illustrated in table 3 and figure 10. The following analysis focuses on crystalline silicon PV, as this technology still accounts for more than 80 percent of the global market.

The Upstream Segment

The most important part of the upstream segment is the production of the main input material, polysilicon. The world has abundant reserves of metallurgical-grade silicon but its refinement and production are very capital and energy intensive and require high-tech equipment. Historically, the silicon industry was dominated by a handful of firms from Germany, the United States, and Japan that supplied the global semiconductor industry with high-purity silicon. In 2009, around 10 incumbent companies were able to supply large quantities of high- and lower-grade silicon to both the semiconductor and the solar industry. However, several new entrants, mostly from Asia, are now reshaping the industry. They had been attracted by very high profit margins in 2006–08, caused by fast-growing demand from solar cell manufacturing that had led to supply bottlenecks. These new entrants are often competing at the lower end of the market with lower grade silicon that can only be used for solar cells. Most suppliers exclusively focus on the production of silicon and sell to producers of wafers through long-term contracts or on the spot market. However, several silicon manufacturers such as MEMC or Wacker have also expanded their business into the making of wafers. Similarly, some integrated solar companies such as SolarWorld or LDK have also expanded into the upstream business in recent years.

Wafer, Cell, Module, and BOS Component Manufacturing

The first step in the manufacturing segment is to pull or cast silicon in big furnaces before it can be squared and sliced into wafers. Ingots (and subsequently, wafers) can be produced through different manufacturing processes. Despite slightly lower conversion efficiency, the multicrystalline process is currently the most common method because of its cost advantage and higher throughput levels. Then, wafers are turned into solar cells through a five-step process: etching and polishing, cleaning, diffusion, antireflective coating, and screen printing. After the individual cells have been created, they are soldered together in series and encapsulated in multiple layers of glass and plastic to form a solar module.

In general, solar cell and module manufacturing are much more fragmented than other renewable energy industries. For example in wind turbine manufacturing, the top 5 players in each segment account for at least half the total market. Business concentration and competition vary significantly between the wafer, cell, and module manufacturing segments. Wafer production is relatively sophisticated and only about 50 firms are active in their manufacture. Cell manufacturing has slightly lower entry barriers as most processes are highly automated so that production lines can be installed without much experience in the firm. On the other hand, this automation means that the cell production is relatively capital intensive. In 2009, there were around 100 firms in the cell manufacturing business. By contrast, module manufacturing has very low entry barriers given its reliance on labor and relatively low capital requirements. Thus, this segment has seen many new entrants from all over the world in recent years, particularly from China and other emerging markets. In 2009, around 500 firms were competing globally for market share (Barclays Capital 2009). Some smaller firms focus on a specific segment of the value chain only, while others strive to integrate their value chains. Leading industry firms such as Suntech or SunPower have the capacity to rely on their own facilities for the whole manufacturing process from wafer production to the final module.

Within the solar PV thin-film market, manufacturing is not quite as fractured as it is in the crystalline world. Typically the thin-film panel manufacturer either owns the intellectual property (IP) for the production equipment and produces the complete panel in house (First Solar), or buys turnkey production equipment from a third-party vendor (such as Applied Materials or Oerlikon) and then manufactures the panel at its own production facility.

The category of balance of system components includes a wide range of goods such as solar panel mounting equipment, PV charge controllers, PV current monitoring devices, inverters, cables and wiring, connectors, overcurrent protection, combiner boxes, grounding hardware, and lightning protection equipment. System integrators do not produce these components themselves but overwhelmingly source them from external suppliers.

The Downstream Segment

Finally, the solar PV system integration part of the value chain varies greatly between the different applications. Some vertically integrated firms, such as Conergy or SolarWorld, are active in the full range of downstream activities, from system integration to installation and maintenance. Other players in the market include big developers, smaller independent firms, or utilities that have large enough installations to run their own development operations. As national markets incentivize different applications in different ways, the industry structure varies greatly across countries. Developers and financiers typically target installation types that yield the highest return on investment, and they normally "follow the incentives." As a result, countries like Germany and Japan have a higher percentage of rooftop installations, while installations in a market like the United States are more evenly mixed.

Current State of Global Integration

Whereas the silicon industry has long been of global scope, the manufacturing of solar cells and modules and especially the downstream business of system integration were initially located close to the local market. This has fundamentally changed over the past decade through new entrants increasing competition and cross-border trade flows. Today, the upstream and manufacturing segments show high levels of integration across national borders and regions and downstream business is also getting attention from firms operating across borders.

The Upstream Segment

The production of silicon was historically concentrated in the OECD. Table 4 illustrates that these incumbent suppliers still dominate the global market and that most of them have significantly increased their production in 2007–09. Most of these firms already operate across borders and often have production facilities in multiple countries. Table 4 also shows that new players started to enter the market in 2006 and 2007, many of them from China and other emerging markets. By 2009, these new entrants had captured around one-third of the total global market. China alone increased its market share from zero in 2005 to around 17 percent in 2009. The suppliers of silicon to the solar industry have also had increasing competition from lower-grade metallurgical silicon suppliers. New silicon capacity in emerging economies can mostly be attributed to new entrants rather than overseas subsidiaries of incumbent firms. Cross-border foreign direct investment (FDI) only played a minor role in financing new capacity. While incumbent firms can rely on their own technology and in-house expertise, new entrants need to acquire the equipment for silicon manufacturing from globally operating OECD firms such as GT Solar or Applied Materials.

Wafer, Cell, Module, and BOS Component Manufacturing

This industry segment has experienced even more pronounced globalization over the past few years. Although there are serious data issues,[33] it is clear that production patterns have shifted dramatically. Table 5 captures the most important trends using cell and module production data from the IEA.[34] For a long time, manufacturing was mostly concentrated in countries with high local demand so that the global industry structure mirrored the installed capacity displayed in figures 2 and 4. Early in this decade, Japan was by far the largest producer of solar PV cells and modules, reflecting the country's status as the world's largest solar PV market. The rapid expansion of especially the German and Spanish solar PV markets after 2004 and 2007, respectively, is similarly reflected in the very rapid expansion of European solar PV production after 2004. Compared to European developments, both US market and production growth in the solar PV sector has been relatively modest. The data also show that the trend of local production radically changed in recent years: the production of solar cells and modules is no longer exclusively concentrated in advanced economies with large solar markets but has shifted to emerging economies without large domestic installations. The latest data from 2008 indicate that perhaps as much as half of the world's PV solar cells are now produced outside of IEA PVPS countries. In just a few years China has developed into the world's largest producer of PV solar cells and modules and production growth in Taiwan and the Philippines has also been rapid. The majority of equipment for wafer, cell, and module production is still supplied by European or American firms such as Roth & Rau (Germany), Applied Materials (United States), GT Solar (United States), Meyer Berger (Switzerland), or Centrotherm (Germany).

Table 5 illustrates that the value chain from wafer to module is already spread across borders. Some countries, such as Japan, produce more cells; other particular European firms emphasize module manufacturing. The relative shift of manufacturing activities throughout the value chain to Asia is evident.

Module production can further be broken down by technology (table 6). Polysilicon-based PV remains the dominant technology globally and is increasingly dominated by producers in Asia. Production of the newer thin-film PV technology is dominated by Germany- and US-based producers. Thin-film technologies initially captured a very low market share but have grown quickly in recent years. Their share in total solar production in PVPS member countries increased from 6 percent in 2005 to 22 percent in 2008. Across all technologies, Germany in 2008 was the largest PVPS-member solar PV producer with 1.5 gigawatts of solar cells, over 900 megawatts of wafer-based modules, and almost 300 megawatts of thin film–based modules. The presence of three developing countries—China, Malaysia, and the Philippines—

33. Significant variation exists between reported solar PV industry consultants' estimates for annual production data. In addition, no commonly agreed upon verifiable official data source exists for this type of data. Detailed data analysis of solar PV production should consequently be approached with caution.

34. The IEA PVPS reports annual approximate production data provided by member states, as well as in recent years reputable industry consultant estimates of nonmember state solar PV production.

among the top eight global producers in 2008 is noteworthy. Whereas the strong position of the latter two is related to FDI inflows, China's expansion mostly came from domestic market entrants.

All major markets (greater than100 megawatts) for solar PV applications in 2008 also had substantial domestic production of solar PV products. As such, domestic market demand for solar PV products of a certain magnitude seems to spur local production facilities, either through the formation of new domestic suppliers or via FDI. In this regard, solar PV is similar to wind energy, another major commercially available renewable energy source (Kirkegaard, Hanemann, and Weischer 2009). However, table 6 also illustrates that a large domestic market is not a prerequisite or a domestic solar PV industry. Asian countries, noticeably China, with very small domestic solar PV markets in 2008 produced large numbers of solar PV applications. This implies that a large domestic market is not a requirement for participation in the global solar PV market with some countries exporting essentially their entire production of solar PV products. This again suggests that the solar PV sector is relatively trade intensive when compared to, for instance, the wind industry.

The production patterns of highly standardized BOS components are difficult to track and strongly depend on the structure in the related sectors. However, given the characteristics of most related light manufacturing industries, we can assume that the production of BOS components will today be almost exclusively carried out at low-cost locations.

The shift of production of cells, panels, and BOS components to export-intensive Asian countries is in many ways similar to developments in the information technology (IT) hardware industry and can be expected to continue to drive prices down in a similar way (box 2).

System Integration and Other Downstream Activities

The final steps of system integration and installation need to happen close or at the final location so these segments are still mostly dominated by local service providers and construction firms, with very limited participation of international players. While several significant developers such as Spain's Fotowatio or Iberdrola, integrated multinationals such as SolarWorld or small and medium sized service providers such as Sgurr Energy do operate across borders, this segment of the value chain has the lowest degree of globalization to date.

Cross-Border Trade and Investment Flows

The described globalization patterns along the value chain suggest that the solar PV sector is relatively trade intensive when compared to, for instance, the wind industry. The analysis of available data confirms that high levels of trade were the major characteristic of global integration in the solar PV industry whereas the cross-border flow of direct investment remained comparably low to date.

Box 2 The link between open, globally integrated markets and lower solar PV product prices—lessons from the IT hardware industry

Precisely how does globalization work to lower prices for goods and services in developed OECD countries? In low-tech, labor-intensive production such as, say, apparel or toy manufacturing, the answer is straight forward: Places such as Bangladesh, Mexico, or China have far lower wage costs. When wage costs account for the majority of total costs of a product, reducing them substantially by offshoring production to a low-cost manufacturing location obviously lowers the total cost the product.

Subsequently, when the cheaper good is then imported duty-free from the low-cost production location into the United States, the European Union, or other OECD markets, consumers in these countries get access to lower-priced goods, lower inflation, and lower interest rates. Everyone in the import market gains a little bit from this (as does the exporter). There are also some losers, for example laid-off US textile workers, but with the right institutions in place, they can get retrained and find jobs in other sectors.

However, it might seem that the production of sophisticated, highly capital-intensive products like solar PV panels and other key renewable energy products is quite different from toys, textiles, and other low-tech, labor-intensive sectors. Certainly, as has been described elsewhere in this paper, labor costs play just a minor role in the total costs of solar PV cells and panels and hence the "lower total costs through lower labor costs through globalization" explanation above does not apply. Yet, that does not mean that globalization does not work to lower final product costs for capital intensive products, such as solar PV panels, merely that it works in another way.

What drives down final prices of capital-intensive goods in open competitive global markets is expanding global production capacity, not labor costs. This is an application of the basic principle that global supply and demand determine the price. When new entrants to the global solar PV market in, say, China or Taiwan rapidly scale up their production capacity, the global supply of solar PV products will increasingly surpass global demand, and the final price for such products will subsequently decline in all global markets.

To understand how important this process of global integration is for product prices even in a sector continuously characterized by rapid technological innovation such as solar PV, it is instructive to look at the example of the IT hardware sector. IT hardware is both the most globally integrated sector with guaranteed free trade through the Information Technology Agreement, and the industry that has been characterized by the most rapid innovation in history under Moore's law, which says that the number of transistors that can be placed on an integrated circuit has doubled approximately every two years.

Undoubtedly, the single most important factor in cutting the cost of computers has been innovation itself, which through Moore's law consistently has made last year's product obsolete and hence caused its price to collapse. However, global competition was the second most important factor—accounting for 10 to 30 percent of total price declines in IT, depending on which particular hardware component is analyzed (for instance dynamic random access memory [DRAM], semiconductors, or personal computers [PCs]).

As laid out in Mann and Kirkegaard (2006), regression analysis shows how, for instance, global DRAM prices have declined beyond the usual rate of decline explained by Moore's law at times when global DRAM production capacity has exceeded supply, that is when actual production was low compared to production capacity.

DRAM production is an industry that was originally pioneered by US firms, but since the 1980s local Asian firms—first in Japan, then in South Korea, then in Taiwan, and now in China—have massively invested in DRAM

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Box 2 The link between open, globally integrated markets and lower solar PV product prices—lessons from the IT hardware industry *(continued)*

production capacity (so-called chip fabs). While shifting the majority of the world's DRAM production capacity out of the US to Asia, this has dramatically helped push down prices of DRAMs and computers in the US market. This has in turn helped promote the post-1995 IT productivity revolution in the broader US economy.

While it is not immediately possible due to a scarcity of data to determine precisely how large this impact will be in the solar PV sector, there is no doubt that today's rapid investments in new solar PV production capacity in China and elsewhere in Asia will have the same directional impact on solar PV product prices in the United States and other OECD markets, if open markets are retained. Chinese investments in solar PV production capacity therefore will make it easier to expand solar PV capacity in the United States and elsewhere.

Cross-Border Trade

As illustrated in table 7, trade volumes have generally mirrored the trend in installed capacity in the world's top four markets. Germany and particularly Spain's trade volumes grew very rapidly in recent years, while the United States and Japan showed more moderate growth trends. Spain in 2007–08 ran substantial trade deficits in solar PV goods, while Germany and the United States had relatively balanced solar PV trade. The table shows available data for approximate US, German, Spanish, and Japanese imports and exports of solar PV goods (cells, modules, and panels) from 1996–2008, based on a detailed classification analysis of national trade data that provide more information than aggregate international data (see box 3 on data issues).[35]

35. It is important to emphasize here that national sub-six-digit trade data for solar PV cells and/or modules are not immediately compatible and that direct comparisons of absolute magnitudes of imports and exports are not necessarily meaningful. Nonetheless, national sub-six-digit trade data can yield useful approximate indicators of trends in international solar PV goods trade. For the United States, such sub-six-digit solar PV trade flow analysis must include only the two 10-digit harmonized tariff schedule (HTS) categories shown in table 8, i.e., solar PV cells, modules, and panels. Available sub-six-digit data for Germany and Spain is slightly less detailed, but the eight-digit Eurostat Combined Nomenclature (CN) data from the COMEXT database (COMEXT database is available at http://epp.eurostat.ec.europa.eu/newxtweb/) do allow for separation of solar PV goods from light-emitting diodes within HS85410.40. We will correspondingly here present German and Spanish data from CN category 8541.40.090 "Photosensitive Semiconductor Devices, [Including] Photovoltaic Cells" (CN8541.40.090 is an aggregate category, which includes three CN eight-digit categories: CN85410.40.091 "Solar Cells Whether or Not Assembled in Modules or Made Up Into Panels ([excluding] Photovoltaic Generators)"; CN8541.40.093 "Photodiodes, Phototransistors, Photothyristors, or Photocouplers ([excluding] Solar Cells)"; and the residual category CN8541.40.099 "Photosensitive Semiconductor Devices ([excluding] Photodiodes, Phototransistors, Photothyristors, Photocouplers, and Solar Cells)." Regretfully, COMEXT data is not available for CN8541.40.091 separately and the EU data is therefore less accurate than the US HTS data. As a result of this inclusion of additional goods trade in the reported German and Spanish data, reported values for these countries will be biased upward and inflated relatively to reported US and Japanese values. The magnitude of this bias cannot be immediately discerned. However, detailed analysis for earlier periods reveal trade in CN8541.40.093 and CN8541.40.099 as relatively stable, indicating that at least any large change in the trend for CN8541.40.090 is likely to originate with developments within CN8541.40.091 and hence be relevant for this analysis of solar PV goods trade. Due to differences in the detailed nine-digit national tariff schedule for Japanese imports and exports, only import data are available for

Table 8 displays imports into the top four global solar PV markets by country of origin. It is noteworthy how China has in recent years emerged as by far the most important exporter to Germany, Spain, and Japan. US imports of solar PV goods are more diverse in origins, with Japan just edging out China as the largest exporter to the US market in 2008. Table 8 also highlights how China is now the largest global exporter of solar PV goods by a significant margin.

Tables 7 and 8 illustrate a considerable international trade in solar PV equipment that has risen rapidly in broad tandem with the increase in global installed capacity. Table 8 also shows significant levels of "two-way trade" in solar PV goods with the United States, Germany, and Japan all serving as both major import destinations and exporters to other principal solar PV markets. As such, available approximate international trade (import) levels for solar PV goods in the four dominant markets, when compared to levels of global solar PV investments and total market size suggest a trade intensity of between 60 to 90 percent during the 2006–08 period.[36] The solar PV trade intensity is thus substantially higher than in the other main renewable source of power, wind energy, where Kirkegaard, Hanemann, and Weischer (2009) found global trade (import) intensities of only about 10 percent.

Higher trade intensities in solar PV goods indicate that countries experiencing large sudden increases in market demand, such as Spain in 2007–08, are likely to be able to access global sources of supply and hence avoid the most extreme cases of localized price inflation.[37] Table 8 also suggests that countries that maintain a large domestic solar PV market for longer periods of time tend to become important exporters of solar PV goods. At the same, however, China's and Taiwan's important positions in several markets show how a large domestic market is not required to become a large exporter of solar PV goods. China's recent announcement of large domestic investments in solar PV generation capacity (Solar Plaza 2009b and Watts 2009) indicates a shift away from its initial focus on exports alone. China now intends to build its domestic market and develop a solar PV industry more akin to that in the United States, Germany, and Japan. This trend toward a fully developed Chinese solar industry is also highlighted by a recent announcement by leading Chinese solar PV manufacturers Suntech and Yingli Solar to invest in both the US and EU markets (see below).

Japan, where we will present data for nine-digit category CN8541.40.020 "Photovoltaic Cells Whether or Not Assembled in Modules or Made Up Into Panels." A detailed description of the Japanese tariff schedule is available at http://www.customs.go.jp/toukei/sankou/code/code_e.htm. The detailed 2009 import tariff schedule relied upon for this analysis is available at http://www.customs.go.jp/english/tariff/2009_6/data/200910e_85.htm. The presented Japanese import data corresponds relatively closely to the presented US 10-digit HTS data totals.

36. According to UNEP/SEFI (2009: figure 4) global investments added up to $10.3 billion, $22.5 billion and $33.5 billion respectively in 2006, 2007 and 2008. Trade data similar to the German and Spanish data is available from Eurostat for the EU-27 block as a whole. However, as Germany and Spain account for by far the largest market shares including the remaining EU trade does not add substantially to the aggregate. Recorded combined US, EU-27, and Japanese imports of solar PV goods accounted for 89, 62 and 81 percent of global solar PV investments in 2006, 2007 and 2008 respectively.

37. In Spain's 2008 case, however, the sudden demand growth was so large that it clearly caused also global market prices to increase (and subsequently decline).

Cross-Border Investment

In contrast to high levels of merchandise trade, the overall level of cross-border investment remains relatively low. Figure 11 summarizes cross-border investment patterns in the solar industry in recent years and categorizes transactions by industry segment. Evidently, cross-border FDI in the solar industry has been dominated by investment in new facilities (greenfield projects) whereas mergers and acquisitions (M&A) have a comparably low profile to date.

Greenfield investment was initially directed toward manufacturing activities. Since 2006, investments in solar field installations and downstream activities such as sales and maintenance services have expanded rapidly. Since 2007, the share of greenfield investment in research and design facilities has also gradually increased. Initially most of the greenfield projects were investments by European and US firms in production facilities in Asia: SunPower's facilities in the Philippines in 2003 were the beginning and many European and American manufacturers followed, including SolarWorld in South Korea, Aleo Solar in China, and First Solar and Q-Cells in Malaysia. However, the overall level of manufacturing FDI stayed relatively low compared to the rapid growth of global production capacity. Most new manufacturing capacity in Asia resulted from new local market entrants rather than outsourced production facilities from established firms in the OECD countries.[38] The regional patterns of greenfield investment in manufacturing facilities show that FDI is not only flowing to export production facilities in Asia but also to smaller-scale manufacturing operations in countries with high demand or promising future markets. The example of Arizona-based First Solar, the world's leading thin-film PV manufacturer, illustrates this strategy: Despite the transfer of its major manufacturing capacity to Malaysia, it retained manufacturing operations in the United States and also set up facilities in the largest and most promising markets. In 2007, the firm opened a 212 megawatt facility in Germany; in 2009, it announced a joint venture with Électricité de France (EDF) Energies Nouvelles, a subsidiary of the French public utility EDF, to build a factory in France with a capacity of over 100 megawatts; and in 2009 it signed a memorandum of understanding with the Chinese city of Ordos in Inner Mongolia to develop the world's largest utility-scale PV project in connection with local manufacturing facilities.[39]

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38. Of course financial globalization was important for these local entrants as many of them were able to raise funds through listings at overseas stock exchanges and other channels of international capital markets. See UNEP SEFI (2009).

39. First Solar will act as project developer and supply the panels. The agreement with Ordos also stipulates that First Solar will explore opportunities to build panel manufacturing in China. The project will be part of the "New Energy Industry Demonstration Zone" in Ordos, combining solar, wind, hydroelectric, and biomass installations to generate a steady supply of renewable energy. See First Solar (2009a, 2009b).

Box 3 Data issues

Mapping out trade flows and trends for the solar PV industry raises several data issues. International trade data are classified according to so-called Harmonized Commodity Coding and Classification System (HS) codes, which are used principally for customs and tariff rate identification purposes and are internationally uniform down to the six-digit product code. However, the HS system does not have separate categories for solar PV products, which makes accurate estimating world trade in solar products problematic. Typically the six-digit HS category most frequently associated with solar PV products is HS 8541.40, which the UN ComTrade database defines as "Photosensitive semiconductor devices, including photovoltaic cells whether or not assembled in modules or made up into panels; light-emitting diodes (LEDs)."[1] However, even at the detailed six-digit level, HS 8541.40 is a highly misleading indicator for solar PV trade because it also includes light-emitting diodes, for which the world market is also substantial, but unrelated to solar PV products (Steenblik 2005, 9–10 and Wind 2008).

The potentially misleading effect of lumping LEDs together with solar PV trade can be illustrated utilizing country-specific US HTS[2] 10-digit trade data for the United States, which, with its more detailed product category specification, makes precise identification of solar PV goods possible. This is done in the table below for US imports from 1996–2008 (Box Table 2). It shows how US imports of HS 8541.40 category goods increased more than three-fold from $739 million in 1996 to over $2.7 billion by 2008. Looking, however, at the more detailed 10-digit HTS data for the two relevant solar PV goods categories—HTS 8541.40.6020 and HTS 8541.40.6030—it can be seen how US imports over the period rose explosively by more than 27-fold to about $1.25 billion in 2008. The share of solar PV–relevant goods in the total US imports of HS 8541.40 rose from a minuscule 7 percent to 46 percent from 1996–2008, as imports of these goods rose much faster than other subcategories of HS 8541.40 (e.g., light-emitting diodes). Hence researchers who rely on HS 8541.40 trade data as a proxy for "solar PV goods trade data" will vastly underestimate the increase in solar PV trade in recent years and possibly reach erroneous conclusions concerning solar PV goods trade.

With regard to BOS parts such as inverters, batteries, mountings, and other electrical components, the aforementioned problem of HS six-digit categories being "too large" is even more intractable. BOS components are generally standard electrical goods for which utilization in the solar PV industry accounts for just a tiny part of the total market demand. Wind (2008) provides two telling examples: (1) solar PV inverters, which are part of the HS 8504 heading defined as "Electrical transformers, static converters (for example, rectifiers), and inductors" and the six-digit HS 8404.40 category of "Static converters" and (2) solar PV mounting equipment, which is recorded under HS heading "Structures (excluding prefabricated buildings of heading 94.06) and parts of structures (for example, bridges and bridge sections, lock-gates, towers, lattice masts, roofs, roofing frameworks, doors and windows and their frames and thresholds for doors, shutters, balustrades, pillars, and columns) of iron or steel; plates, rods, angles, shapes, sections, tubes and the like, prepared for use in structures, of iron or steel."[3] In either case, solar PV end use of these products account for a trivial share of total world trade.

1. See UN ComTrade website at http://comtrade.un.org/db/mr/rfCommoditiesList.aspx?px=H3&cc=854140.

2. HTS stands for "Harmonized Tariff Schedule" and is equivalent to internationally uniform HS codes down to the six-digit level, but significantly more detailed with 10-digit product categories specified and frequently updated. See http://www.usitc.gov/tata/hts/index.htm for details.

3. HS definitions from http://comtrade.un.org.

The biggest emerging Asian producers of solar PV components seem to follow this strategy as well and have started to invest in manufacturing facilities in the European Union and especially the promising US market. Suntech, the leading Chinese manufacturer of crystalline silicon panels, recently announced plans to build a plant in Goodyear, Arizona. Production is scheduled to begin in September 2010 with a capacity of 30 megawatts and the potential to expand beyond 120 megawatts (Suntech 2009, 2010). Yingli Green Energy, a large, vertically integrated Chinese producer of solar PV products, announced in early 2010 its intention to build a 100 megawatt capacity module manufacturing facility in the United States. This facility is envisioned to also serve as Yingli's North American headquarters for operations and R&D (Yingli Solar 2010).

In sum, large producers from all parts of the world appear to be following the strategy of investing in small-scale manufacturing operations in key markets in order to be closer to consumers and more flexible. Our analysis of cross-border projects from 2003–07 supports this finding as the three most important solar PV markets in terms of annual added capacity (Spain, Germany, and the United States) were also the leading destinations for greenfield investment in manufacturing facilities.[40] The pattern that the promise of fast-growing local demand attracts manufacturing FDI by globally operating producers can also be observed in the wind industry, albeit the scale and scope of investment in local production are much higher (Kirkegaard, Hanemann, and Weischer 2009).

Greenfield FDI in downstream-related activities such as distribution, marketing, project development, or maintenance was broadly distributed among all major markets. Fast-growing markets that formerly only had a low solar PV exposure such as Spain, the United States, Greece, or Italy accounted for the most investment projects in this segment. The ongoing erosion of margins in the manufacturing segment will likely force more producers to expand into the downstream business in order to capture higher margins and diversify risks. Being present in overseas downstream markets will require investment in local operations, which will likely lead to an increase of cross-border investment flows in this segment.

Finally, greenfield FDI in electricity generation was mostly targeted toward markets promising foreign investors high returns due to attractive support schemes, a high sun radiation, or a combination of both. Not surprisingly, Spain was the major target for foreign investment in solar electricity generation assets in the period of 2003–08, followed by other European countries such as Italy, Greece, and Germany. While mostly an intra-European story in earlier years, investors from emerging economies have entered the stage in recent years and are now playing a more prominent role in the financing of solar power plants. Especially Chinese investors have announced plans to expand their activity in European and US installations: in December 2009, China's biggest developer China Energy Conservation Investment Corporation (CECIC) announced the goal to expand into utility-scale solar projects in Spain, Italy, and Germany with the help

40. Our dataset is based on number of projects, not investment value.

of local partners and a $3 billion credit line from China Development Bank (CDB). The stable and comparably high returns of government-supported renewable energy projects could also increase the attractiveness of large-scale solar plants for sovereign investors from oil-exporting countries with a large pile of foreign exchange reserves.

Compared to greenfield projects, M&A did not yet play a major role in global solar investment flows thus far as M&A activity remained mostly of domestic nature. The few cross-border transactions in recent years were mostly intra-European deals involving assets of solar power plants. Since 2008, the number of M&A deals is on the rise and their scope is broadening from power production to manufacturing and downstream services, suggesting a beginning consolidation of the industry. Acquisitions in the downstream sector such as the February 2010 purchase of European project developer SunRay by US manufacturer SunPower for $277 million are likely to gain importance in the years ahead. Aside from greater downstream competition, the consolidation of the manufacturing segment could also contribute to lifting the currently low weight of cross-border M&A in the Solar PV's cross-border investment profile.

FUTURE OF GLOBALIZED SOLAR PV VALUE CHAINS

Although it is impossible to accurately predict the future of the solar PV industry, an analysis of the sector's current structure and the cost composition of components allows us to draw several conclusions about possible globalization patterns in the future. The production of cell, modules, and BOS components will likely continue to shift toward countries in Asia and other low-cost production centers that possess a comparative advantage in flexible light manufacturing of tradable goods. This trend could be mitigated by higher shipping rates, lower labor intensity due to greater automation, and the tendency toward larger-scale projects, which could strengthen the competitiveness of OECD countries in manufacturing. Segments in which OECD countries are likely to retain a strong position include upstream silicon production as well as high value–added upstream services such as R&D. Downstream system integration and related construction and development services will also remain local, but with stronger participation of foreign firms via direct investment, acquisitions, or partnerships.

Upstream

Given the high capital costs, technological sophistication, and low labor input, the silicon industry is likely to remain dominated by current incumbents located in Europe, the United States, and Japan. New suppliers outside the OECD and especially in China might enjoy some advantages such as access to cheap financing or preferential electricity rates, but currently still lack the expertise needed to successfully compete head-to-head with incumbent firms. Given the investment rates and learning curves, China will likely emerge as a very significant global silicon supplier in the future, but OECD firms will likely continue to dominate the market in the short and medium term.

Wafer, Cell, Module, and BOS Component Manufacturing

Table 9 breaks down the principal solar PV components by factor input costs. The comparative advantage of Asian manufacturers for the production of electronics and similar products is rooted in the availability of relatively high-skilled but low-cost labor. Another advantage is their ability to flexibly expand production capacities and react quickly to changes in demand, through their faster project approval, shorter construction periods, and their comparative advantage in "speed intensive" manufacturing sectors.[41] Other advantages include access to cheap financing, light manufacturing clusters that allow local sourcing of key components, and strong support from local governments.

As long as relevant parameters such as freight rates remain unchanged, these patterns in manufacturing of wafer, cells, module, and components cannot be expected to fundamentally reverse in the future. However, the decreasing labor intensity of production due to a greater degree of automation could increase the competitiveness of production facilities in Europe or the United States in the medium and long term. The chances to keep existing manufacturing capacities and attract investment in cell and module manufacturing are greatest for OECD countries that provide an incentive for firms to build fully integrated local production lines. Several industry experts also believe that the trend toward utility-scale solar PV plants will make it more likely that at least some of the module manufacturing will happen close to the plant site to exploit economies of scale and bring down transportation costs.

Downstream Segment

While system integration and installation are currently in the hands of local operators, it is likely that foreign firms will increase their participation through greenfield investment, partnerships, or cross-border acquisitions. Experienced European firms in this segment are expanding into lucrative new markets in North America and Asia, and firms from emerging economies want to expand into the segment to capture higher margins. Chinese firms want to escape low-margin manufacturing and are actively looking for opportunities to participate in the downstream segment of the solar value chain.

VI. BARRIERS TO GLOBAL INTEGRATION IN THE SOLAR PV SECTOR

In streamlining their value chains, firms today face various barriers to investment and trade in goods and services, which we analyze in the following section. While tariffs are only a minor barrier to international trade in solar PV technologies, a number of nontariff barriers inhibit the full global integration of the industry. Additional charges and taxes, burdensome customs procedures, and the lack of universal mutual recognition of certification for the industry—let alone globally harmonized standards—make global trade more expensive. Domestic politics are another source of friction for international trade as policymakers

41. Olds (2009) argues that Chinese business networks have had a comparative advantage in markets that are in constant flux due to changing fashion or technology throughout the twentieth century.

often expect direct benefits for their domestic economy from solar support policies, leading to formal local-content requirements or informal expectations for local manufacturing job creation. On balance, however, barriers to global trade and investment are relatively low at the moment. Current debates in major PV markets such as Germany suggest that this status of relatively free flows of goods, services, and capital might be at risk.

Tariffs

Many goods along the value chain are being traded internationally, including silicon, wafers, cells, modules, and BOS components such as batteries, mounting structures, and inverters. An assessment of tariff levels for the different components required for solar PV and CSP systems by the International Center for Trade and Sustainable Development (ICTSD) found that the average tariff level on solar energy components is around 15 percent. However, this represents a nonweighted average of all countries, while tariffs in all the major solar markets are lower. Major developing country importers were found to apply tariffs at around 8 percent, while major developed country importers have very low or zero tariffs (Jha 2009).

The data in Tables 10 and 11 confirm this assessment. The major raw material, silicon, is subject to a tariff between zero and 5 percent in the leading cell and module producer countries. In the major PV markets, there are no tariffs on the import of solar cells and modules. Tariffs for these products are low across the world, often at zero and usually not surpassing 10 percent. Of 121 WTO member countries reporting tariffs for this group of products, only 13 had applied tariffs above 10 percent, none of which were significant solar markets. Tariffs for balance of system components, namely mounting structures and static converters, are slightly higher, between zero and 20 percent with most countries applying tariffs below 10 percent. In conclusion, tariffs seem to be only a minor barrier to international trade in solar PV technologies in the most important markets.

Nontariff Trade Barriers

A number of nontariff barriers inhibit the full global integration of the industry, with industry experts and earlier surveys naming customs procedures and surcharges, diverging industry standards, and political quid pro quo expectations as the major culprits.[42]

Nontariff Surcharges and Taxes

According to one estimate from the OECD, additional charges, taxes, or countervailing duties levied at the border can lead to an additional 15 percent on top of import costs in many countries in Africa, South Asia, and Latin America. However, more developed solar markets, such as the European Union or the United

42. The following paragraphs draw from a study prepared by the OECD (Steenblik, Matsuoka, and Hight 2009) as well as interviews with industry experts in the second half of 2009.

States, generally do not apply such charges. Other countries have applied them as temporary measures; for instance, Korea introduced a 19 percent surcharge on foreign PV equipment in 2008 that has since been removed (Steenblik, Matsuoka, and Hight 2009, 22).

Customs Procedures and Inspection

Customs procedures and preshipment inspection can be burdensome and increase the final price of solar PV components—including BOS components, cells, and modules—as the additional costs are passed on to consumers. Issues identified include long and/or costly procedures, misclassification of PV products leading to higher tariffs, or the need for import licenses (Steenblik, Matsuoka, and Hight 2009, 22). Even in mature economies such as the United States, there can be uncertainty about the tariff classification. For example, importers assumed that new generation modules would be classified under subheading 8541.40.6020 of the Harmonized Tariff Schedule of the United States, which would qualify them for duty-free import. But US customs ruled in January 2009 that they would be classified as generators, once the modules contained a diode that diverted electric current away from shaded areas of the panel, making them subject to a 2.5 percent tariff. This diode is now standard in most solar panels and required by US safety regulations. While this is not a particularly high tariff level, such reclassifications unexpectedly change developers' cost calculations.

Divergent Standards and Costly Certification Procedures

Standards are an important tool to facilitate trade. They lower information costs and assure consumers about the quality of the product. Certification makes it easier to compare different products and reduces the risk of buying goods of inferior quality. In a market heavily dependent on government support, standards are needed to determine which installations should benefit from support. A lack of standards can therefore be an important factor disturbing fair international competition. On the other hand, standards can also act as barriers to international trade, especially if different countries use different standards.

In the solar PV industry, many manufacturers find certification requirements burdensome and costly and the fact that different countries use different procedures further complicates matters. Estimates provided by a European manufacturer to the OECD indicate that staff costs to manage the European, US, and Canadian certifications of modules and related products were around $750,000 annually, plus certification costs of $25,000 to $30,000 per module series (Steenblik, Matsuoka, and Hight 2009, 21). For example, the United States requires projects to be certified according to Underwriter Laboratories (UL) standards, while European projects require International Electrotechnical Commission (IEC) certification. While manufacturers recognize the need for certification, certifying agencies have been accused of unnecessarily increasing the burden on manufacturers by charging more than necessary. The potential revenue from providing certification tends to lead countries to develop requirements that favor their domestic certifiers (Steenblik, Matsuoka, and Hight 2009, 22). In addition, certification procedures do not only cost money, they also consume time. Industry experts highlight that the time foreign producers have to wait until their products are certified according to the national standards leads to foregone market-share. Authorities in some countries and the industry are undertaking efforts to streamline testing and certification procedures, including increased equivalency recognition between testing laboratories and a number of testing bodies offering simultaneous UL/IEC testing. Nonetheless, testing and certification issues remain one of the most important nontariff barriers to trade, according to industry sources.

Political Quid Pro Quo Expectations and Explicit Local Content Requirements

As the solar power market heavily relies on government support, policymakers often expect direct benefits for their domestic economy in terms of local job creation in the PV manufacturing industry. These expectations can lead to local-content requirements for projects benefitting from government support. Even if no such formal requirements exist, foreign manufacturers frequently perceive procedures for government tenders as nontransparent. The tenders are often set up in manner that directly or indirectly favors domestic manufacturers. (Steenblik, Matsuoka, and Hight 2009, 24).

Political expectations are not restricted to projects directly commissioned by the government. Solar PV projects benefit from political support, for instance in the form of feed-in tariffs or stimulus money and some countries have also put in place local content requirements, so that the entire domestic solar PV market is effectively covered. For example, any developer wishing to take part in the Canadian province of Ontario's feed-in tariff program must show that the equipment and labor used to install the system consists of 40 percent Ontario content for projects less than 10 kilowatts in size. Above that threshold the required local content is 50 percent. The local content requirement for all project sizes will rise to 60 percent starting January 1, 2011 (Legislative Assembly of Ontario 2009).

Although United States federal policy does not explicitly state such a requirement, PV projects that apply for stimulus funding have to indicate where the contained content originates, which is a factor in the final decision. The US government announced in reference to the funds provided by the American Recovery and Reinvestment Act that preference would be given to projects that create the most American jobs.[43] According to industry analysts, most large Chinese projects are implemented at the provincial level with the implicit expectation that they will lead to manufacturing in that region. Companies hoping to receive government approval for large PV projects therefore often agree to locate manufacturing assets near the project site.

43. Renewable energy projects receiving stimulus funding and using foreign parts have been met with political opposition, as exemplified by Senator Charles Schumer's strong reaction to a projected wind park in Texas that would use Chinese turbines, see Schumer (2009). For a discussion see Kirkegaard, Hanemann, and Weischer (2009).

Investment Barriers

So far, cross-border investment in the solar PV industry has encountered few barriers. Announcements to locate manufacturing in a foreign country have generally been received very positively by the respective host country government. However, there is a certain risk that the maturing of the industry and the emerging patterns of direct investment in the downstream segment might change this status quo.

From a national security perspective, energy projects are part of a country's critical infrastructure, which puts such projects under special scrutiny in countries that regulate inward investment. National security is one of the central criteria in the investment review process of many countries, for example the Committee on Foreign Investment in the United States (CFIUS).[44] Aside from the formal process, media and the public in the United States and elsewhere are prone to protectionist sentiments in such cases. The debate surrounding the investment of a Chinese wind turbine producer in a Texas wind farm in 2009 hints at the potential backlash that developing country investors could face when expanding their downstream presence in the OECD world.[45] The same could apply to OECD developers expanding to overseas growth markets. China in February announced to exclude foreign companies from certain investments in the offshore wind sector, which might be followed by similar constraints in other renewable energy markets such as solar PV (Environmental Finance 2010).

Another potential field of conflict could be M&A. To date, cross-border investment in the solar industry was mainly directed toward new facilities (greenfield FDI) but the share of M&A transactions is gradually growing. M&A transactions can provoke stronger protectionist reactions. Thus far, there is not much evidence for protectionist reactions to foreign acquisitions in the renewable energy space. Most cross-border acquisitions of electricity generation assets in the OECD have gone through without major problems and even sovereign investment vehicles from emerging economies could receive approval for the purchase of such assets in OECD economies.[46] However, it remains to be seen if the cross-border investment remains open when M&A activity reaches other sectors of the industry. In segments such as manufacturing and R&D, it is possible that governments decide to defend the clean tech industries they subsidized for years against foreign takeovers. In the case of industry consolidation and restructuring—for example in Europe—foreign takeovers that include employment cuts or technology transfer to emerging economies could spark hostile reactions as well.

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44. For a survey of investment review practices in the OECD, see OECD (2008). For a discussion of critical infrastructure in the context of national security from a US perspective, see Graham and Marchick (2006).

45. For a critical discussion of the reactions to A-Power's announced investment in Texas, see Kirkegaard (2009).

46. See for example the stake of China's sovereign wealth fund (China Investment Corporation, CIC) in the wind power operations of the American AES Corporation. See EAS News Release, March 15, 2010: AES Announces Close of Transaction with China Investment, available at: Corporationhttp://investor.aes.com/phoenix.zhtml?c=76149&p=irol-newsArticle&ID=1402516&highlight=

Intellectual Property Rights—A Barrier to Globalization?

Historical experiences with industries such as pharmaceuticals have shown that strict intellectual property rights (IPR) enforcement can be a barrier to global competition by cementing the market position of incumbents and restricting the entry of new players. In the ongoing climate change negotiations, many developing countries have taken the position that current IPR regimes are an impediment to their access to renewable energy technology. However, in the solar industry, such claims seem unwarranted because technology is widely available and IPR is not a major cost driver.

First, mainstream solar technology is relatively mature and widely available. Firms such as Applied Materials provide turn-key production lines and most of these lines were delivered to developing countries in the past years. Second, the share of IPR-related outlays in total costs is small and will likely remain on a comparably low level. The solar PV industry continues to experience rapid technological innovation and large venture capital investments.[47] As the third generation of nano-based and organic solar PV technologies is developed, the weight of IPR in total project costs of this type can correspondingly be expected to increase in the years ahead. However, as is the case in other renewable industries such as wind (Kirkegaard, Hanemann, and Weischer 2009), the growth of IPR-related project costs will occur from a very low base and it is unlikely that IPR costs would become a noteworthy part of total costs in the foreseeable future. Solar PV will most likely not develop into an industry comparable to, for instance, pharmaceuticals, where IPR costs make up for the majority of total product cost. Absent disruptive and patented innovations in solar PV technologies, the existing solar PV technologies that are mass produced today and contain only very little IPR cost will remain relatively close to the "innovation frontier" in efficiency terms.

On balance, barriers to both global trade and cross-border investment are relatively low. However, as the solar industry becomes more globalized and global competition grows more intense, there is an increasing risk that countries might resort to protectionist moves. Producers in some of the most important markets, notably Germany, have begun calling for trade restrictions (see box 4). So far, these calls have not been successful. However, they highlight that, as the solar industry relies heavily on government support, there are high expectations for domestic economic benefits, in particular the creation of "green collar jobs." The next chapter takes a closer look at the employment potential of the solar PV industry and the impact of globalization on job creation.

VII. GLOBAL INTEGRATION AND LOCAL JOB CREATION

The debates in Germany and other countries illustrate that local job creation is at the heart of calls for a more protectionist configuration of national trade and investment regimes. Policymakers see newly created

47. See UNEP SEFI (2009, figure 10) for estimates showing the solar PV industry as the largest recipient of venture capital among all renewable energy industries.

Box 4 The German debate about trade protection for solar producers

Prior to the German federal elections in September 2009, the future of feed-in tariffs for solar energy was intensely debated. Germany is both the world's largest aggregate solar PV market among the countries in the world with the most generous domestic feed-in tariffs, and possesses a substantial local solar PV industry. Some participants in the debate claimed that that most of the public support provided for solar installations actually profited Chinese manufacturers and endangered the German manufacturing sites that had successfully been established in recent years.

Representatives of the solar industry subsequently proposed to impose protectionist measures. The CEO of German manufacturer and project developer Conergy was most vocal in proposing additional tariffs on imports from China, which he classified as dumping. The provision of cheap land and production subsidies by Chinese authorities and favorable financing by Chinese banks for projects using Chinese panels were mentioned to support this claim. BSW-Solar, the German solar industry association, announced in August 2009 that it would begin an investigation into the price structure of Chinese panels and would decide, based on the results, whether it would officially request the European Commission to establish antidumping tariffs (Steitz, Palmen, and Holmes 2009).[1] So far, that decision has not been taken.

The CEO of another large manufacturer, SolarWorld, also proposed several protectionist measures, including a "buy European clause" for all projects supported by the feed-in tariff. He declared that he would support a lowering of the feed-in tariff, only if it was linked to the introduction of stricter technical standards in the legislation (Palmen, Steitz, and Loades-Carter). This proposal was seen as a move to make market access more difficult for Asian and American producers (Zheng 2009).

More recently, the president of European Photovoltaic Industry Association—which represents more than 90 percent of European solar firms—also asked European policymakers to consider import quotas or local content requirements.[2]

Analysts outside the industry in Germany are more skeptical of such measures, however. They highlight the fact that the strong and stable support for the solar industry has allowed Germany to build a unique infrastructure for the sector with strong research institutions and networks of manufacturers. While the production of standardized components might move to Asia, they expect research and development as well as more technically sophisticated manufacturing to remain in Germany. Furthermore, they highlight the fact that grid parity might be reached as early as 2012 or 2014, also with panels produced in Germany. Some analysts recommend that, instead of calling for protectionist measures, German manufacturers should invest more in marketing and in building strong brands in order to highlight their products' quality and reliability.[3] From their perspective, stronger international competition only contributes to a necessary consolidation of the sector, but does not endanger its long-term prospects.[4]

continued on next page

1. Wirtschaftswoche: Solarbranche verlangt Schutzzölle, August 28, 2009, available at: http://www.wiwo.de/unternehmen-maerkte/solarbranche-verlangt-schutzzoelle-406426/

2. Reuters, Solar sector needs defense to German cuts: EPIA, February 8, 2010, available at: http://www.reuters.com/article/idUSTRE6172IM20100208?feedType=RSS&feedName=GCA-GreenBusiness

3. Photovoltaik Guide: Deutsche Solarindustrie muss stärker auf Markenbildung setzen, August 26, 2009, available at: http://www.photovoltaik-guide.de/deutsche-solarindustrie-muss-staerker-auf-markenbildung-setzen-5358.

4. Wirtschaftswoche: Solarindustrie—Kunden sind die Gewinner der Krise, July 15, 2009, available at: http://www.wiwo.de/technik-wissen/solarindustrie-kunden-sind-die-gewinner-der-krise-402606/

Box 4 The German debate about trade protection for solar producers *(continued)*

This debate has died down since the German elections in September 2009 and no such protectionist measures have actually been introduced to date. Instead, the government has announced that it will seize the opportunity that falling global prices present to lower the feed-in tariff. In addition to the regular annual 9 percent decrease in the feed-in tariff, the government announced its intention to implement one-time cuts of 11 to 16 percent for rooftop installations and field installations on industrial sites, while the support for field projects on agricultural sites would be abolished, making solar power less expensive for the German rate payer.[5]

5. CDU/CSU-Fraktion im Deutschen Bundestag, April 23t, 2009, Koalition einigt sich auf Reform der Solarförderung, available at: www.cducsu.de.

jobs in the solar PV sector at risk in light of the emergence of new players in developing countries. This section analyzes the employment potential of solar PV in comparison with other energy sources and looks into current and future employment patterns in a globalized industry.

The Employment Potential of Solar PV

Comparative studies have shown that the total job generation potential of solar PV over project lifecycles is generally very high. As illustrated in table 12, solar PV, due to its distributed nature, generates up to 10 times the employment per gigawatt hour of power produced than traditional fossil fuel power plants. Solar PV is also much more labor intensive than other forms of renewable energy. It creates four times more jobs on average than wind farms or biomass power plants.

However, the nature of solar PV technology means that some of these jobs do not have to be located in the domestic market. Compared to, for example, wind turbines, solar panels and other parts of solar PV systems are much easier to ship and do not require the same organizational sophistication in production, which means a higher degree of "potential outsourcing" to countries with relatively low-cost labor and other cost advantages in the manufacturing of these goods.

Local Job Creation in a Globalized Industry

Although there are no comprehensive estimates for global employment in solar PV manufacturing, the shift in global production patterns described above implies a relative shift of jobs in cell and module production from Europe to Asian countries without significant domestic demand, most importantly China. However, while it is likely that light manufacturing will continue to shift to countries that possess a comparative advantage, the United States and EU countries retained a large number of solar PV jobs in manufacturing and other areas following a surge in domestic demand for solar PV systems (see summary of estimates in table 13).

In addition, a jobs debate that is solely focused on the manufacturing segment of the solar industry misses one important point: The majority of jobs along the solar value chain are not created in production but in the downstream stages of system integration, installation, and construction—activities that inherently must happen domestically. Figure 12 presents estimates of manufacturing and installation jobs per installed megawatt of solar industry by segment. In 2009, around 60 percent of the jobs related to small-scale installations and 40 percent of the jobs related to field installations were created in the downstream segment. Adding jobs in operation and maintenance (O&M), which are not included in figure 12, more than 50 percent of jobs created by solar installations are not "outsourceable" but bound to the region where the solar system is installed.

As with all types of construction sector jobs in temperate climate countries, installation and construction jobs in the solar PV sector are subject to high seasonality. Activities pick up during the spring, remain high over the summer and decline again during the fall and are limited during wintertime. Most local jobs of this kind created in the solar PV sector can therefore not be characterized as "year-round full-time jobs," and will correspondingly command relatively lower total annual wage sums. The solar PV industry with high labor intensity in construction and installation matched against other sources of energy will be relatively more affected by job seasonality than other energy-producing industries. As such, the job generation capacity of the solar industry will, when compared to other energy industries on a "full-time equivalent jobs" basis, be relatively lower. At the same time it is important to stress that not all jobs that are likely to remain local are seasonal in nature. High value-added project development services, and operations and maintenance services, are perennial activities.

Looking forward, the job intensity of the various segments and the ratio of locally bound versus outsourceable jobs are hard to predict as they depend on the technological learning curves, the degree of automation in production, scale effects in O&M and other factors. Leading solar industry consultants currently have contradictory views on this issue.[48]

On balance, it is hard to adequately calculate or even predict the net impact of globalization on jobs in solar industry in OECD countries. On the one hand, the evident outsourcing patterns and respective migration of employment certainly lead to lower manufacturing employment in developed countries. On the other hand, this trend has also contributed to an overall lower price for solar installations, which is an important determinant for the price competitiveness of solar PV overall and thus the local demand for solar installations. The lower prices made possible by globalization can lead to higher overall demand for installations and result in local employment in construction and other installation-related sectors. As

48. Navigant Consulting (2009) estimates that the employment intensity of installation will fall faster than the employment intensity of production. Others, such as the European Photovoltaic Industry Association (EPIA), predict the opposite patterns.

solar installations create a large number of these "non-outsourceable" jobs, higher demand might offset the relative job losses in manufacturing.

VIII. FINDINGS AND RECOMMENDATIONS

Our analysis of the development of the solar PV industry and its ongoing global integration yields the following key findings:

The solar PV sector has grown very quickly over the past years, driven by government support policies rather than cost considerations or availability of a strong solar resource. Growth has been strongest in countries with generous long-term support mechanisms such as Germany, Spain, Japan, and parts of the United States.

In the future, the four leading OECD markets will continue to play an important role. However, demand can be expected to be less concentrated as more and more countries both in the developed and the developing world are introducing support schemes for solar power generation to bridge the time until grid parity is reached.

The industry has seen steep learning curves and price reductions over the last decades. Further technology improvements, expanding economies of scale, streamlined production processes, rising costs of fossil fuels, and a price on carbon emissions will make it possible to reach grid parity between 2012 and 2020 in most markets, depending on the local characteristics such as sunlight and grid power prices.

The globalization of the value chain has helped to increase the efficiency of production and the deployment of solar technology. The degree of global integration is highest in the middle part of the value chain, the manufacturing of wafers, cells, modules, and BOS components and is lowest in the downstream segment, which includes system integration, installation, operation, and maintenance. New entrants outside of established markets and cross-border trade, rather than FDI, were the major characteristics of globalization.

Manufacturing will likely continue to shift toward Asian countries that possess a comparative advantage in flexible light manufacturing of tradable goods. However, OECD countries that enact policies guaranteeing strong and stable long-term demand will likely retain some manufacturing as well. Firms in OECD economies will have to further focus on highly efficient midstream manufacturing, upstream silicon production, and high value–added services such as R&D. Downstream system integration and related construction and development services will also remain local, but with stronger participation of foreign firms.

Firms currently face comparably low barriers in operating globally. Tariffs for solar panels and other components are at a low level in all relevant markets and firms did not face any significant investment barriers. However, firms had to deal with a range of nontariff barriers such as import charges and taxes, burdensome customs procedures, divergent national standards, and local content requirements in key markets. Additionally, current debates in key markets such as Germany as well as in new markets such as Canada and India, and changes in the industry structure point to the risk that countries might enact more trade and investment barriers in the future.

The job generation potential of solar PV over the lifecycle of a project is very high. Several studies have found that solar PV generates up to 10 times the employment per gigawatt hour of power produced as compared to conventional fossil fuel based power plants and four times as many jobs as other renewable energy sources. The majority of jobs along the solar value chain are not created in production but in system integration, installation, operations, and maintenance. Overall, more than 50 percent of jobs created by solar installations are locally bound.

It is evident that global integration has caused a relative shift in manufacturing employment away from developed countries. At the same time, globalization also contributes to an overall lower price for solar installations and thus to an overall higher demand for solar installations. Given that manufacturing only accounts for a smaller share of total jobs over the total lifecycle of a solar installation, the net impact of globalization could well be positive by creating incentives for a higher level of installations and resulting in additional employment in system integration, installation, operations, and maintenance. However, an adequate calculation of the net impact of globalization on solar industry employment in OECD countries is beyond the scope of this paper.

Policy Recommendations

Based on our findings, the following policies are recommended to policymakers aiming at stimulating further growth of the solar industry and local job generation without erecting new trade and investment barriers:

1. **Long-Term Government Support Policies:** The most important contribution policymakers can make to create solar PV–related jobs is to provide a sufficient and predictable framework for investment in solar energy deployment. Direct or indirect financial support policies for solar PV will remain necessary until full grid parity is achieved. Historical experience from all major solar PV markets has shown that stable long-term policy designs, such as multi-year feed-in tariffs, provide private industry and investors with the required incentives to rapidly expand the solar PV market. Preannounced decreases in support levels bring forward investments and create incentives for cost cutting and innovation. A pricing mechanism for carbon emissions applied to all power producers would level the carbon playing field and bring forward the point in time at which solar PV grid parity is achieved.
2. **Employment-Maximizing Policy Design:** When designing solar PV support policies aimed at job creation, policymakers should bear in mind the total number of solar PV associated jobs instead of focusing on manufacturing jobs only. As in other capital-intensive industries, manufacturing

jobs will invariably decline through productivity increases. A large majority of job generation in the solar PV industry will be in installation and other segments of the service sector such as project development, research, or consulting, which implies that growing the total installed solar PV capacity should be a priority. While utility-scale centralized solar PV projects can be expanded more rapidly and have a larger potential for cost reductions, smaller distributed solar PV applications will typically have a larger localized job creation potential. When designing solar PV support policies, governments can therefore promote total market growth in a labor-intensive manner by ensuring that programs for both segments of solar PV market development exist.

3. **Investment and Trade Policies:** Policymakers can encourage global integration and broader deployment of solar PV technologies by keeping global solar PV markets open. Protectionist policies would not only slow the development of global markets for solar PV related goods and services but could also provoke retaliation measures in other clean technology sectors. Such an outcome would not only harm the global trade system but also increase the risk of hurting collective political action against climate change. If governments want to promote global integration, they could take steps to lower existing trade barriers, for example abolishing remaining tariffs, addressing nontariff barriers and harmonizing solar industry standards. The OECD economies that account for the majority of solar PV demand—the European Union, Japan, and the United States—could send a strong signal for their commitment to both climate change mitigation and an open trading system by implementing such measures unilaterally and without delay.

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Table 1 Lifecycle breakdown of a solar PV investment project

5 MW field project in Europe

Upfront capital costs (in euros)						
			Percentage composition			
	Per watt	**Total**	**BoS** (percent)	**N.Mod** (percent)	**Sys** (percent)	**Tot** (percent)
Inverters	0.21	1,050,000	14	11	6	6
Module mounting structure	0.19	950,000	12	10	6	5
Transformer	0.05	250,000	3	3	2	1
Other electrical devices	0.03	125,000	2	1	1	1
DC cables and string connectors	0.03	125,000	2	1	1	1
AC cables and underground connectors	0.10	500,000	6	5	3	3
Civil work	0.11	550,000	7	6	3	3
Labor cost	0.18	900,000	12	10	6	5
Construction management	0.35	1,750,000	23	19	11	10
Other administrative fees	0.30	1,500,000	19	16	9	8
Total balance of system installation	1.54	7,700,000	100	81	48	43
Project permits	0.35	1,750,000		19	11	10
Total non module cost	1.89	9,450,000		100	58	53
Solar modules	1.35	6,750,000			42	38
Total system installation cost	3.24	16,200,000			100	90
Assorted development fees	0.35	1,750,000				10
Total system financing price	3.59	17,950,000				100
Variable costs						
	Per watt	**Total**	**BoS**	**N.Mod**	**Sys** (percent)	**Tot**
Solar farm annual O&M costs	0.04	200,000			67	
Annual site lease	0.01	50,000			17	
Annual site insurance	0.01	50,000			17	
Total annual variable costs	0.06	300,000			100	
20 Year variable costs		6,000,000				
Overall lifetime costs						
Total system financing price		17,950,000				75
Total 20 year variable costs		6,000,000				25
Total lifetime cost		23,950,000				100

Note: These are approximate estimates for capital and variable costs.

Sources: Authors' estimates based on project data and expert interviews.

Table 2 PV system price evolution scenario (2009–2015) (in dollars)

	2009	2010	2011	2012	2013	2014	2015
Silicon price per kg	70 .00	60.00	50 .00	50 .00	50 .00	50 .00	50.00
Silicon grams per watt	6.80	6.50	6.10	5.80	5.50	5.00	4.00
Silicon cost per watt	0.48	0.39	0.31	0.29	0.28	0.25	0.20
Ingot (multi) processing cost	0.12	0.11	0.10	0.09	0.09	0.08	0.08
Wafer processing cost	0.33	0.30	0.28	0.26	0.24	0.22	0.22
Cell processing cost	0.20	0.18	0.17	0.16	0.14	0.13	0.13
Module processing cost	0.40	0.37	0.34	0.31	0.29	0.26	0.26
Module cost	1.53	1.35	1.20	1.11	1.03	0.94	0.89
Module margin	15%	15%	15%	15%	15%	15%	15%
Module price	1.80	1.59	1.41	1.30	1.21	1.11	1.05
BOS components							
Inverter cost per watt	0.30	0.28	0.25	0.23	0.21	0.20	0.20
Mounting structure	0.35	0.32	0.30	0.27	0.25	0.23	0.23
Junction box	0.08	0.07	0.07	0.06	0.06	0.05	0.05
Monitoring system	0.04	0.04	0.03	0.03	0.03	0.03	0.03
Cables and other materials	0.36	0.33	0.30	0.28	0.26	0.24	0.24
Labor and construction	0.35	0.34	0.34	0.33	0.32	0.32	0.32
Other BOS costs	0.22	0.20	0.19	0.17	0.16	0.14	0.14
BOS cost	1.70	1.59	1.48	1.38	1.29	1.21	1.21
BOS/installation margin	15%	15%	15%	15%	15%	15%	15%
BOS price	2.00	1.86	1.74	1.62	1.52	1.42	1.42
System cost	3.23	2.94	2.67	2.49	2.32	2.15	2.10
System price	3.80	3.46	3.15	2.93	2.73	2.53	2.47

Notes: BOS is German field installation. Inverter and mounting structure account for 25 percent each of BOS costs, labor 20 percent (Europe and US), cables 15 percent, other costs 11 percent.

Sources: Authors' estimates based on project data, industry reports, and expert interviews.

Table 3 The solar PV industry value chain

Value chain segment		Key characteristics
"Upstream"	**R&D**	Mostly inhouse at integrated solar firms and component suppliers.
	Polysilicon production	Global supply dominated by 8 OECD firms but many new entrants; most producers focus on silicon production (Hemlock) but some also produce wafers (Wacker) and some integrated solar firms have expanded to silicon production (REC, Solarworld); high entry barriers.
	Other materials	Materials other than silicon such as glass, aluminum, etc. for panels or other components.
"Manufacturing"	**Wafer manufacturing**	Around 50 companies globally: integrated solar firms (REC, Solarworld), silicon suppliers (Wacker, MEMC), and wafer-module manufacturers (Schott, BP, Yingli); relatively high entry barriers.
	Cell manufacturing	More than 100 companies globally: Cell manufacturers only (Q-Cells, JA Solar), wafer-module manufacturers and integrated solar firms; relatively low entry barriers.
	Module manufacturing	More than 400 companies globally: integrated solar firms, wafer-module manufacturers and cell-system manufacturers (Suntech, Sunpower); very low entry barriers.
	BOS components manufacturing	Production of inverters, mounting structure, batteries and other electronic equipment.
"Downstream"	**System design**	Design of rooftop and field installations: integrated solar firms, system integrators and external service firms.
	System integration	Final manufacturing of BOS components: integrated solar firms and system integrators (Phoenix, Sekisui).
	Project development	Development of larger-scale projects: integrated solar firms, system integrators, external service firms.
	Financing	Integrated solar firms and project developers with banks and other financial services providers.
	System installation and construction work	Local providers of construction and installation services.
	O&M	Integrated solar firms, system integrators, external service firms.

Sources: Authors' interviews with industry experts, Barclays Capital (2009), and industry reports.

Table 4 Global Polycilikon supply, 2003–2009 (million tons)

	2003	2004	2005	2006	2007	2008	2009E
Incumbent suppliers	25,740	26,825	29,125	32,952	35,220	42,843	55,991
Hemlock semiconductors (US)	6,100	6,450	7,250	8,850	10,000	12,325	17,850
REC (US, Norway)	4,400	4,600	5,050	5,600	5,270	5,950	8,203
MEMC (US)	3,700	3,700	3,850	4,200	3,465	3,800	4,800
Mitsubishi polysilicon (US)	1,200	1,200	1,200	1,250	1,148	1,254	1,339
Wacker (Germany)	4,200	4,600	5,250	6,200	8,175	11,800	15,150
Tokuyama (Japan)	4,080	4,165	4,335	4,548	4,803	5,143	5,865
Mitsubishi Materials (Japan)	1,360	1,360	1,360	1,424	1,551	1,700	1,870
Sumitomo (Japan)	700	750	830	880	808	871	914
New entrants non-China	0	0	0	0	1,050	7,555	12,329
New entrants China	0	0	0	250	1,500	5,685	14,715
Total	25,740	26,825	29,125	33,202	37,770	56,083	83,035
Metallurgical silicon	0	0	0	125	1,150	3,000	8,200
Total	25,740	26,825	29,125	33,327	38,920	59,083	91,235

Source: Barclays Capital (2009).

Table 5 Production of solar PV cells and modules 2000–2008, by country

Country	Solar PV technology	2000	2001	2002	2003	2004	2005	2006	2007	2008
Japan	Cells	128	170	244	365	604	824	920	923	1,228.0
	Modules	136	182	260	402	590	773	645	422	569.0
United States	Cells	75	104	121	102	138	156	201	266	429.7
	Modules	56	74	81	71	139	198	201	266	428.7
Europe	Cells	37	62	134	192	329	479	730	1,152	17,98.9
	Modules	41	56	133	183	420	515	750	1,758	2,483.8
Other PVSP members	Cells	4	10	21	27	38	41	54	61	276.4
	Modules	6	7	8	11	11	46	72	69	316.1
Approximate reported IEA PVSP total	Cells	244	346	520	686	1,109	1,500	1,905	2,402	3,733.0
	Modules	239	319	482	667	1,160	1,532	1,668	2,515	37,97.6
Non-PVSP country estimates										
China	Cells						150	380	1,090–1,200	1,790–2,550
	Modules							510	1,300	
Taiwan	Cells						60	170	430	830–900
	Modules								55	
Philippines	Cells						12	63	100	237
	Modules									
Thailand	Cells						11			
	Modules							20		
Czech Republic	Cells									
	Modules							42	55	
South Africa	Cells									
	Modules							30		
India	Cells									
	Modules							65	100	
Approximate reported non-IEA PVSP total	Cells	n.a.	n.a.	n.a.	n.a.	n.a.	233	613	1,675	3,272
	Modules	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	667	1,510	n.a.

n.a. = not applicable

Source: IEA PVSP (2000–2008).

Table 6 Reported solar PV production 2008 megawatts, by technology; and 2008 cumulative installed capacity

	Solar PV production by technology			
		Modules		
Country	Cell Production (All Types)	Multi-cell (wafer) based	Thin film	2008 Cumulative installed capacity
Denmark		0.5		3.3
Switzerland	0.5	11.5	0.5	47.9
Canada		26.0	0.4	32.7
Portugal		28.4		68.0
Australia	42.0	8.0		104.5
Austria		65.4		32.4
Italy	28.4	144.0		458.3
France	60.0	120.0	0.7	179.7
Korea	67.4	106.1	8.3	357.5
Sweden		185.0		7.9
Britain	2.5	225.5	2.5	22.5
Philippines	237.0			n.a.
Malaysia	167.0		167.0	8.8
Spain	195.0	498.0		3,354.0
US	429.7	161.7	267.0	1,168.5
Japan	1,227.5	468.0	100.3	2,144.2
Germany	1,513.0	914.0	289.0	5,340.0
Taiwan (1)	865.0	n.a.	n.a.	15.0
China (1)	2,170.0	n.a.	n.a.	130.0

n.a. = not available

Note: Mid-point of two different estimated production volumes from different primary sources cited in IEA PVSP (2009)

Source: IEA PVSP (2009) and JRC (2009).

Table 7 US, German, Spanish and Japanese solar PV goods (cells, modules, and panels) trade 1996–2008 (millions of US dollars)

	1996	2000	2004	2005	2006	2007	2008	Change 2004–2008
US exports	146.1	199.4	267.3	389.7	460.2	670.6	1,051.4	784.1
US imports	49.0	73.1	116.9	229.3	434.5	670.2	1,240.8	1,123.8
US NX	97.1	126.2	150.3	160.4	25.7	0.5	–189.4	-339.7
Germany exports	169.9	225.4	441.8	788.0	1,612.4	3,268.8	6,391.5	5,949.7
Germany imports	188.0	374.5	1,564.7	2,807.6	3,521.4	4,631.7	8,377.7	6,813.1
Germany NX	–18.1	–149.1	–1,122.8	–2,019.7	–1,909.0	–1,362.9	–1,986.3	-863.4
Spain exports	14.5	54.3	283.1	266.7	258.2	190.0	363.6	80.4
Spain imports	19.7	31.3	62.8	198.5	942.1	3,126.3	7,946.5	7,883.6
Spain NX	–5.2	23.0	220.3	68.2	–683.9	–2,936.3	–7,582.9	–7,803.2
Japan imports	88.7	152.2	164.2	225.9	316.4	282.0	393.7	229.4

Note: US data equal sum of HTS categories 8541.40.6020 "Solar Cells Assembled Into Modules or Made Up Into Panels" and 8541.40.6030 "Solar Cells Not Assembled Into Modules or Made Up Into Panels." German and Spanish data equals CN category 8541.40.090 "Photosensitive Semiconductor Devices, Including Photovoltaic Cells." Japanese import data equal 8541.40.020 "Photovoltaic Cells Whether or Not Assembled in Modules or Made Up Into Panel." Euro- and Yen-denominated trade values converted into $US at annual average exchange rates.

Source: US ITC, Eurostat, and Japan customs.

Table 8 Solar PV goods (cells, modules, and panels) imports, by country of origin (millions of US dollars)

United States				Germany			
Country/year	**1996**	**2002**	**2008**	**Country/year**	**1996**	**2002**	**2008**
Japan	33.4	57.8	248.1	China	2.3	11.8	3,085.1
China	1.6	9.7	247.1	Japan	56.5	118.4	807.1
Mexico	3.9	23.0	213.2	US	37.9	108.6	524.8
Taiwan	0.3	1.2	175.6	Taiwan	0.9	2.8	525.7
Germany	1.1	4.0	171.7	Malaysia	36.9	29.9	313.2
Philippines	0.2	0.0	138.6	India	0.0	12.9	202.8
Other	8.5	31.6	46.5	Other	53.4	251.1	2,918.9
Spain				**Japan**			
Country/year	**1996**	**2002**	**2008**	**Country/year**	**1996**	**2002**	**2008**
China	0.0	0.4	4,055.9	China	4.0	8.8	241.1
Germany	4.3	6.1	1,788.6	Germany	0.6	14.5	60.4
Taiwan	0.1	0.4	555.1	US	29.1	4.7	28.3
India	0.0	5.7	227.7	Philippines	0.1	8.3	14.3
US	3.2	16.3	187.1	Taiwan	5.7	0.9	13.3
Japan	1.9	2.2	139.4	South Korea	42.8	14.6	9.0
Other	10.2	20.5	992.7	Other	6.4	27.5	27.3

Source: US ITC, Eurostat, and Japan customs.

Table 9 Principal solar PV component costs

	Polysilicon	Ingot/wafer	Cell	Module	BOS
			Cost (percent of total)		
Fixed costs	38	10	10	2	9
Bulk raw material costs	10	73	60	90	75
Electricity costs	35	6	12	1	4
Labor costs	4	5	12	6	10
Other costs (incl. IP)	13	6	6	1	2
Total cost	100	100	100	100	100

Note: Ingot/wafer through module represent Asia-based manufacturing costs and are a hybrid of manual labor and automation. Polysilicon costs are based on global best practices.

Source: Authors' industry expert interviews, September/October 2009.

Table 10 Silicon tariffs in major cell/module producing countries

Country	Applied tariff (percent)	Bound tariff (percent)
European Union	0	0
China	4	4
Japan	0	0
Taiwan	0	0
United States	0	0
Malaysia	0	5
Phillipines	3	20
Korea	3	5.5
Australia	0	10
Canada	0	5.5

Note: Table represents last reported MFN applied and bound tariff levels for HS 280461 "Silicon, >99.99% pure." Bound tariffs refer to the level beyond which tariffs cannot be raised without compensating the affected parties, according to WTO law.

Source: WTO tariff download facility; HS code short title according to UN COMTRADE.

Table 11 Tariffs for select PV components in major markets

Countries (by installed capacity)	Cells and modules		Mounting structures (iron/steel)		Mounting stuctures (aluminum)		Static converters	
	applied	**bound**	**applied**	**bound**	**applied**	**bound**	**applied**	**bound**
European Union	0	0	0	0	6–7	6–7	0–3.3	0–3.3
Japan	0	0	0	0	3	3	0	0
United States	0	0	0	0	5.7	5.7	0–1.5	0–1.5
Korea	0	0	0	0	8	13	0–8	0–13
India	0	0	10	40	10	unbound	0–10	0–40
China	0	0	4	4	6	6	0–10	0–10
Australia	0	0	5	7.7	5	5	0–5	0–16

Note: The table gives applied MFN and bound tariff rates for the last year reported. All HS codes mentioned include more than solar PV components, i.e., only a small fraction of trade under each HS code is related to solar PV projects. HS codes included are HS 854140 ("Photosensitive/photovoltaic/LED semiconductor devices"), 730890 ("Structures and parts of structures, iron or steel, not elsewhere specified"), 761090 ("Aluminium structures and parts not elsewhere specified, for construction"), and 850440 ("Static converters, not elsewhere specified"). Short HS code titles according to UN COMTRADE.

Source: for tariff information: WTO Tariff Download Facility.

Table 12 Average employment generation over the lifespan of facility (jobs per gigawatt hour of power produced)

Energy source	Manufacturing, construction, and installation	Operations and maintenance/ fuel processing	Total	Project average
Solar PV	0.16–0.84	0.07–0.57	0.23–1.42	0.87
Biomass	0.01–0.03	0.16–0.21	0.19–0.22	0.21
Wind Power	0.03–0.14	0.05–0.13	0.1–0.26	0.17
Coal-Fired	0.03	0.08	0.11	0.11
Natural Gas-Fired	0.01	0.1	0.11	0.11

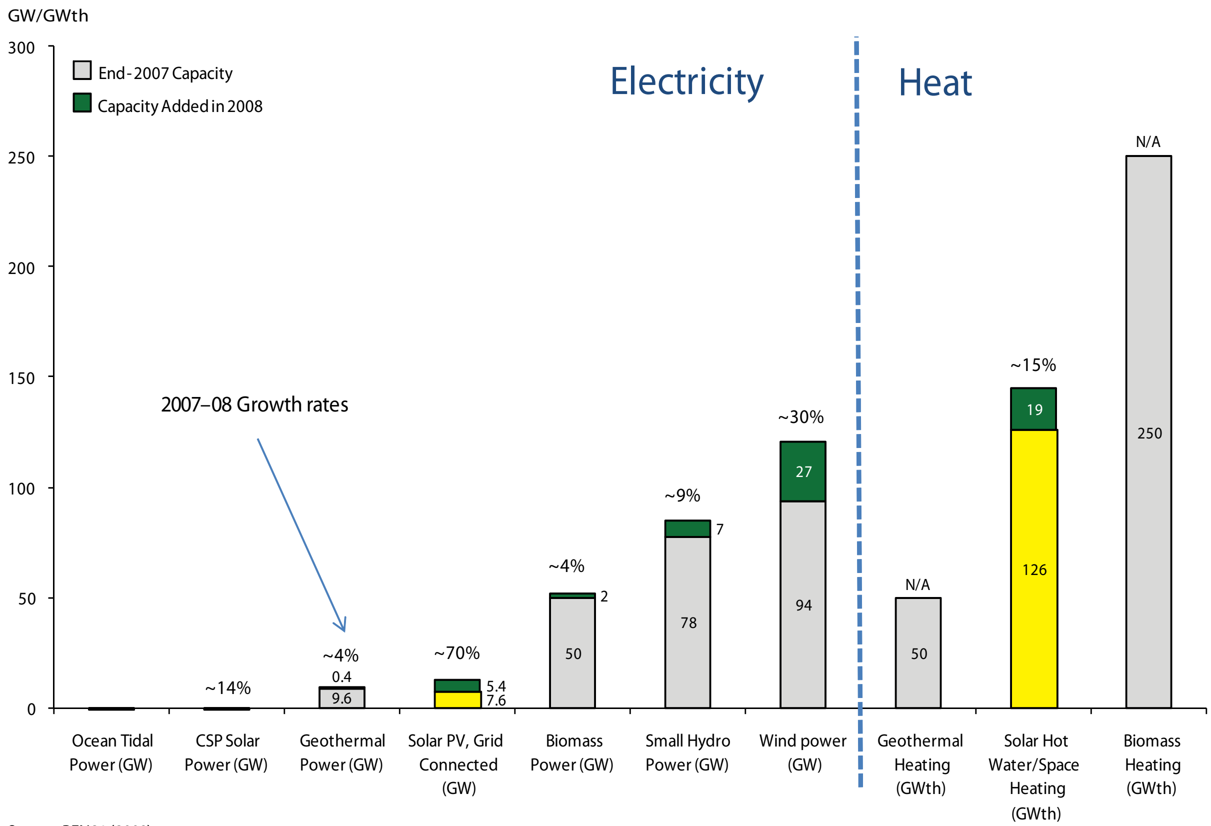
Note: The data are average annual employment numbers distributed over the lifespan of an installation and takes into consideration the very different factor capacities of renewable (low factor capacities) and fossil fuel (high factor capacities) energy sources.

Source: Wei, Patadia, and Kammen (2009).

Table 13 Estimates for national employment in the solar industry

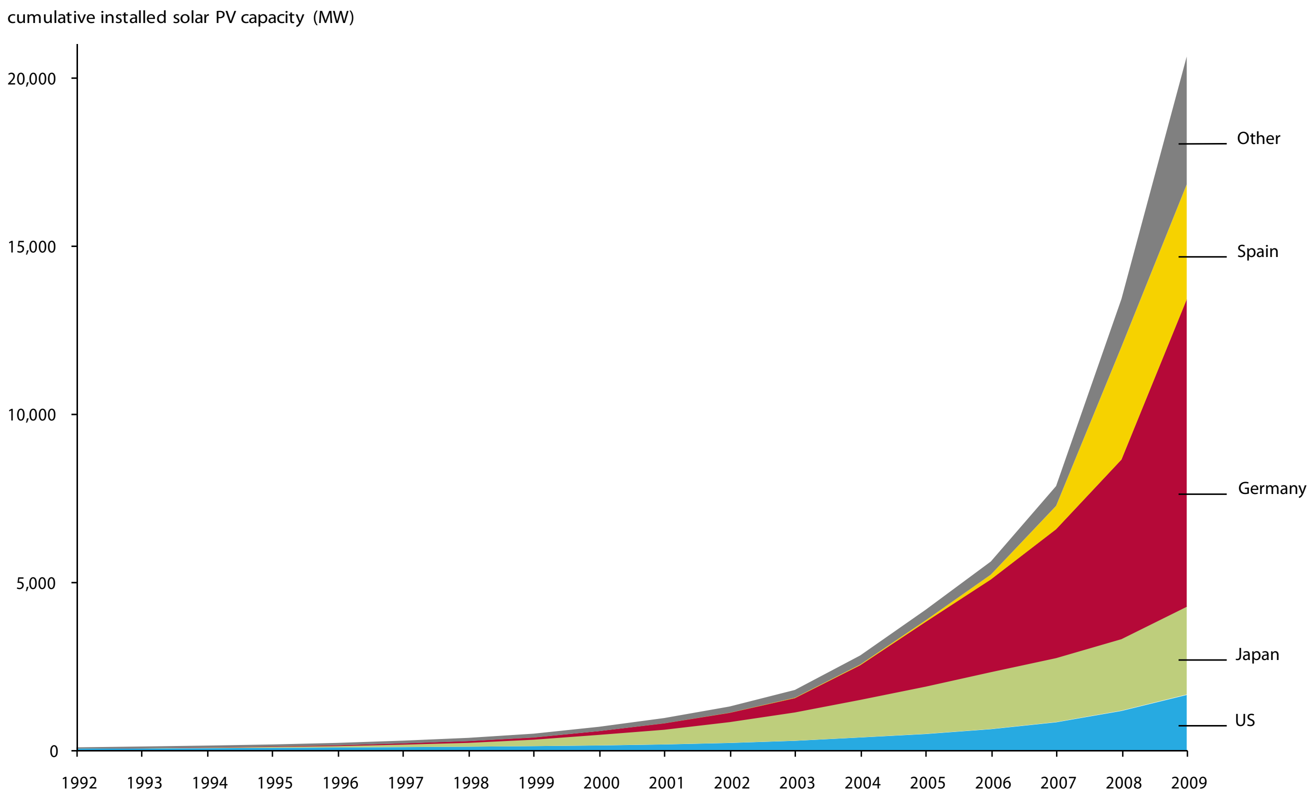
Year	Area	Estimate	Source
2009	Germany	Solar PV industry: 64,600; solar CSP industry: 15,000; all solar industry: 79,600	German Federal Environment Ministry, Renwable Energy Employment Report, March 2010
2007	Spain	Solar PV industry: around 26,500; CSP: around 9,000	Nieto Sáinz (2008)
2008	Europe	Solar PV industry: 130,000 directly and 60,000 indirectly employed; 190,000 total employment	EPIA, Solar PV Employment, 2009, www.pvemployment.org
2009	United States	All solar industry: 24,000 directly and 22,000 indirectly employed; 46,000 total employment	SEIA, US Solar Industry Year in Review 2009, April 2010

Figure 1 Renewable energy capacity 2007–08, GW (electricity) and GWth (heat)



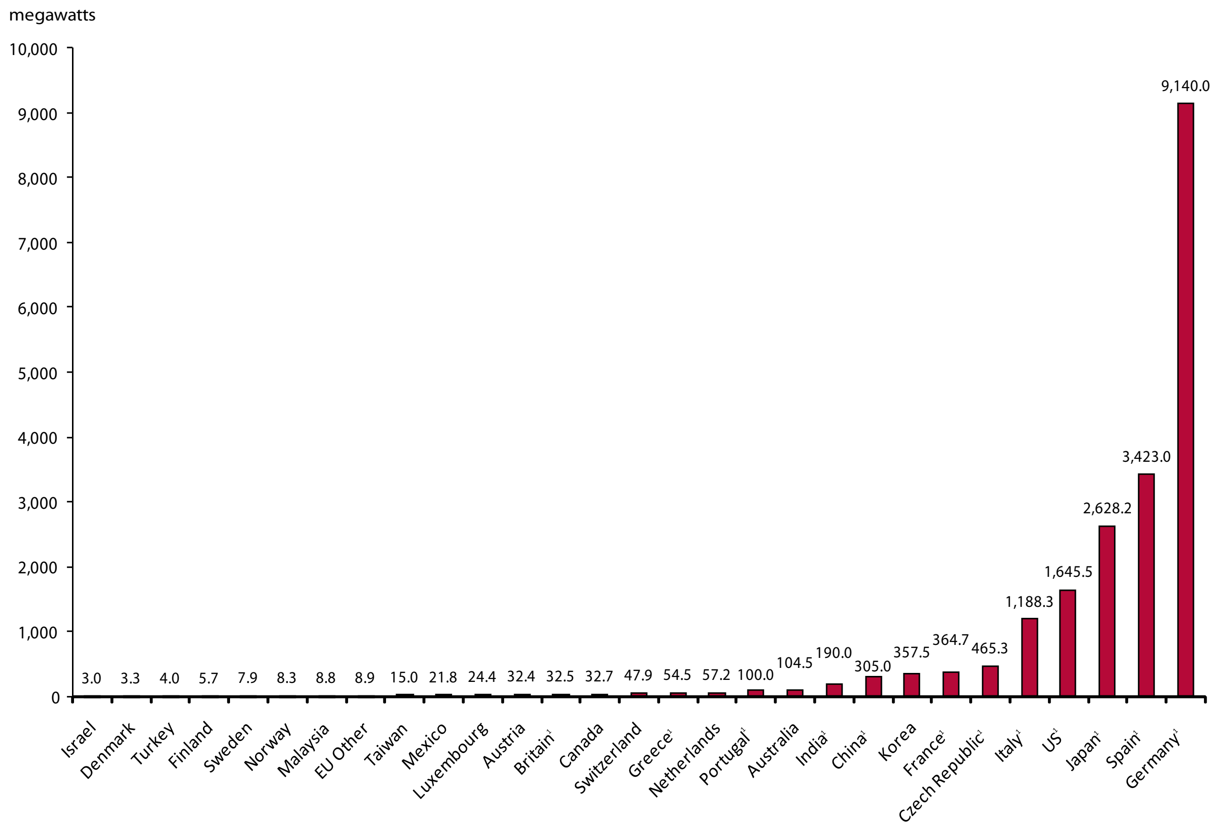
Source: REN21 (2009).

Figure 2 Cumulative installed solar PV capacity, IEA-PVSP members 1992–2009, all types of solar PV



Source: IEA - PVSP (2009); EPIA (2010).

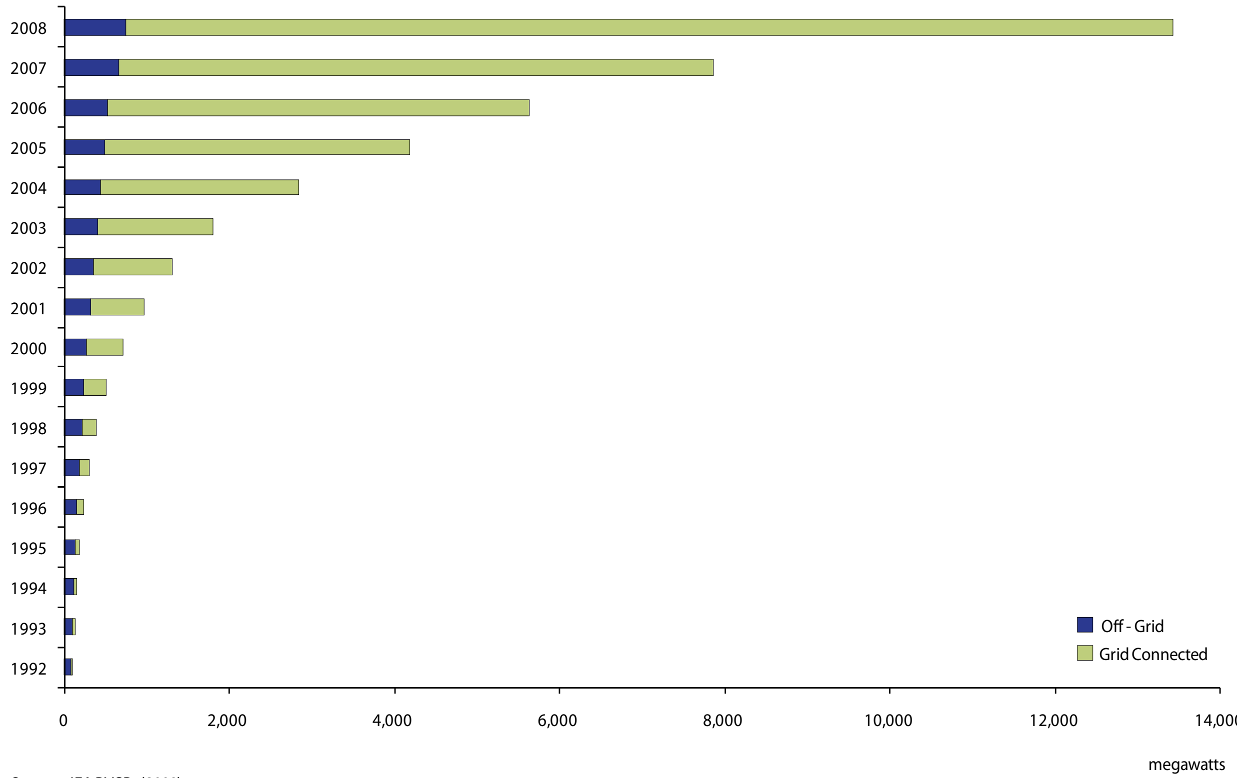
Figure 3 Cumulative installed solar PV capacity 2008–09 all types of solar PV



1. 2009 Data.

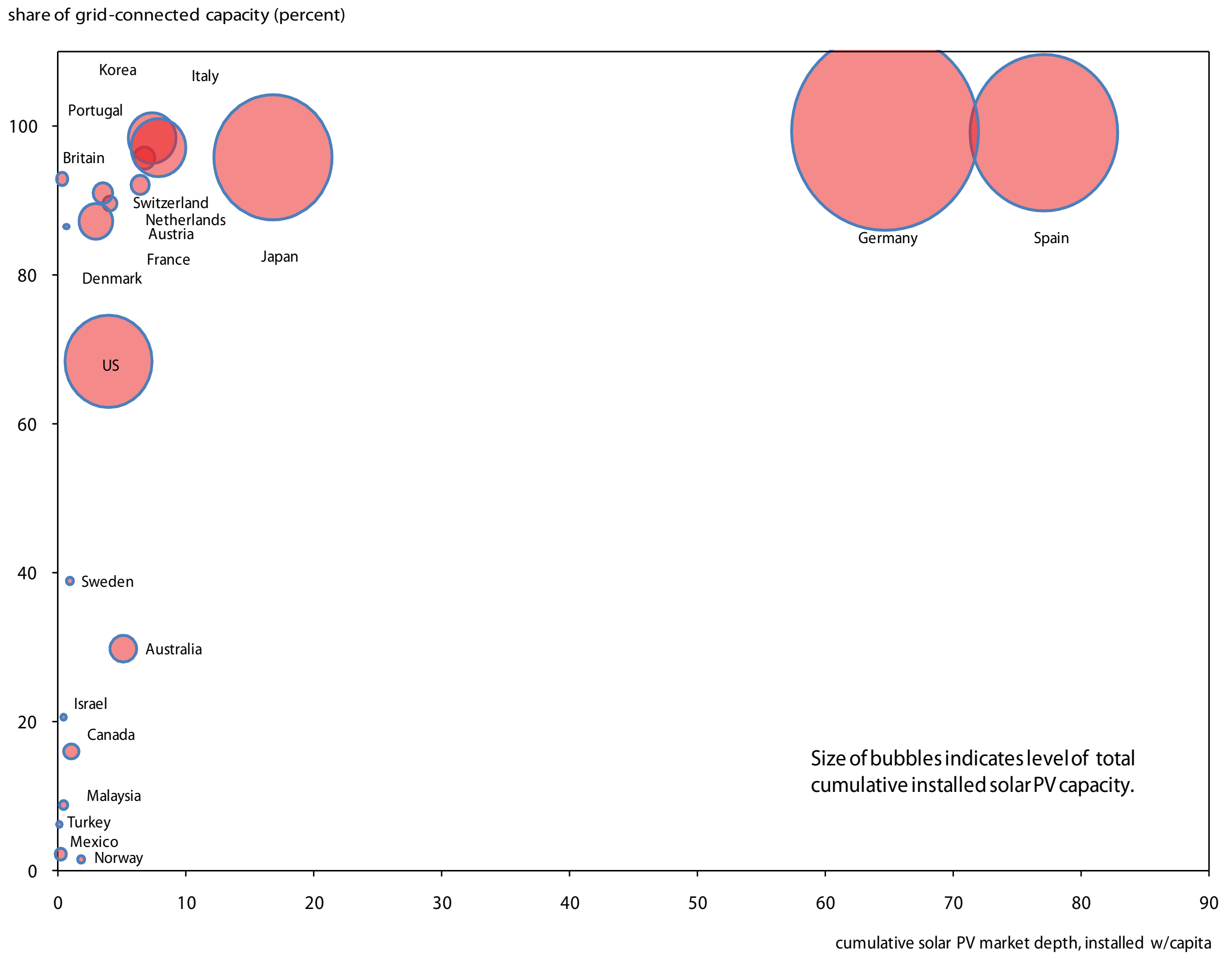
Source: IEA PVSP (2009); JRC (2009); EPIA (2010).

Figure 4 Cumulative IEA PVSP solar PV installed capacity, by grid connectivity 1992–2008



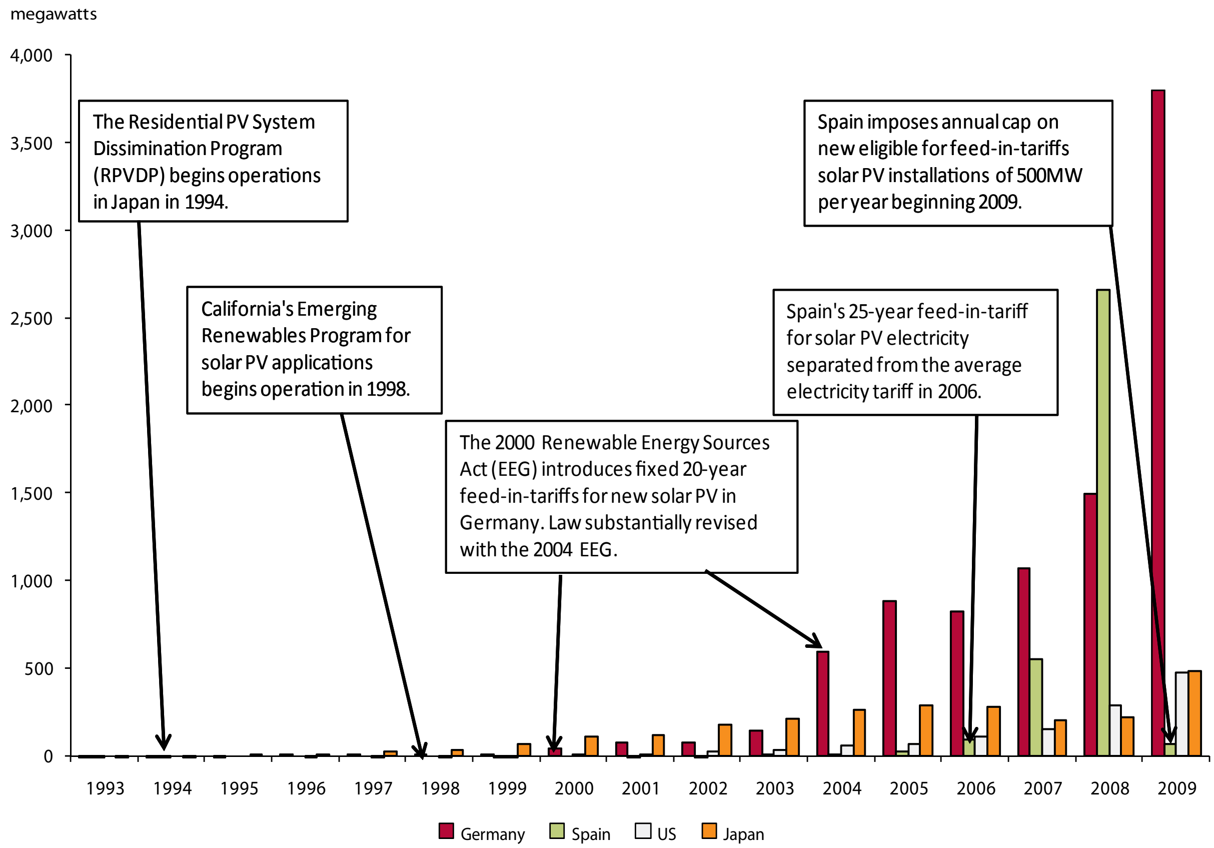
Source: IEA PVSP (2009).

Figure 5 Solar PV market depth and share of grid-conected capacity, 2008



Source: IEA PVSP (2009).

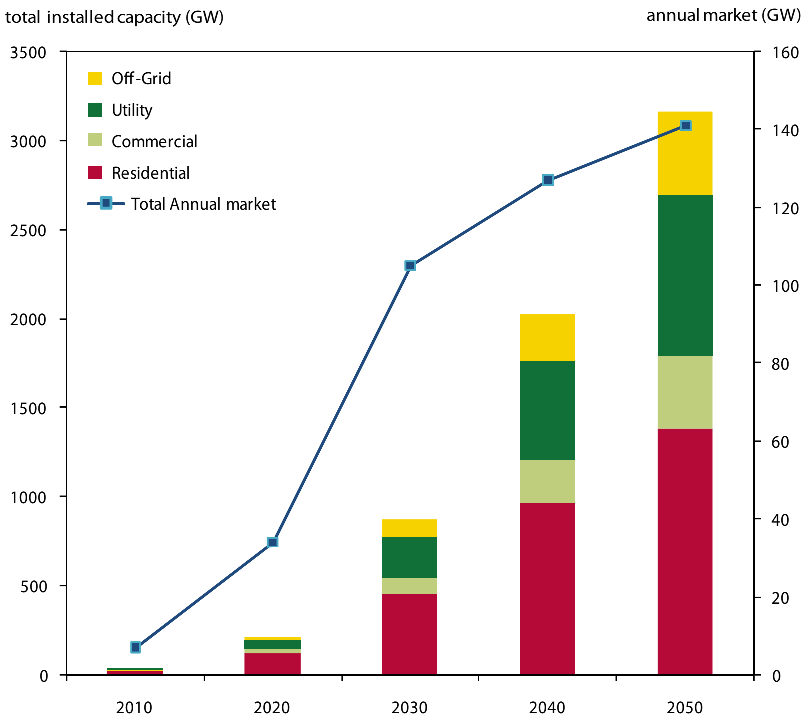
Figure 6 Annually installed grid-connected solar PV capacity, 1993–2009[1]



1. 2009 Data refers to all types of solar PV.

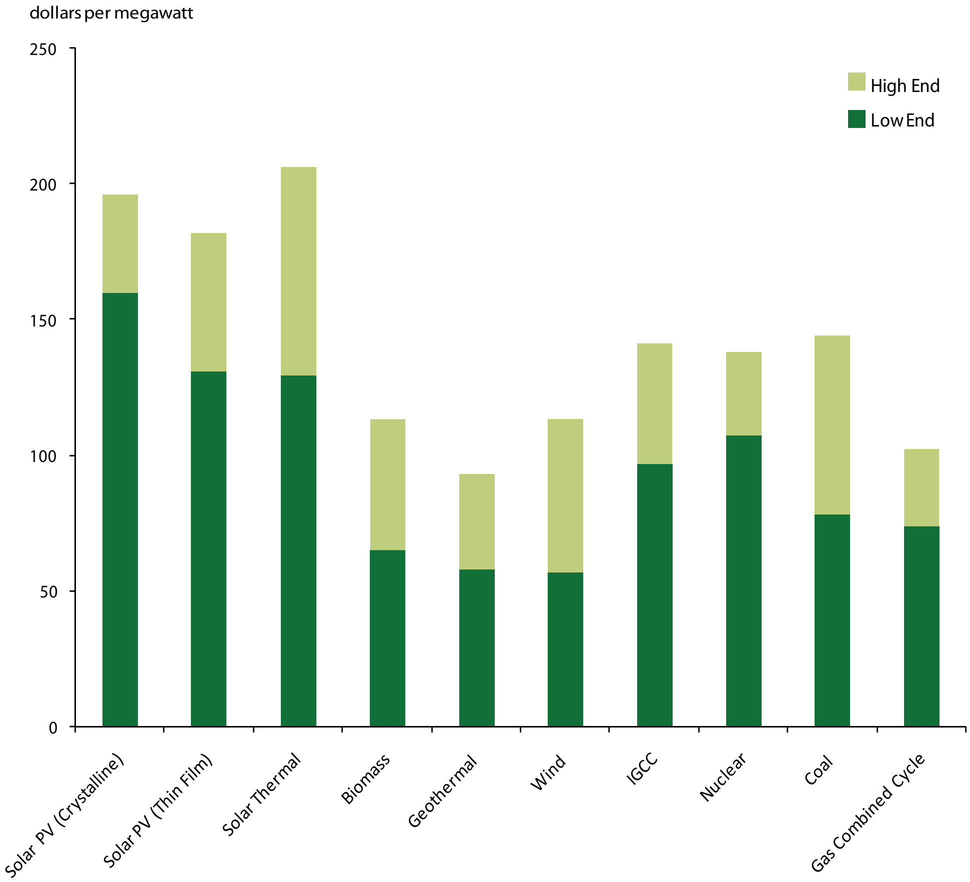
Source: EPIA (2009 and 2010); IEA PVSP (2009 and 2009c).

Figure 7 Solar PV in the IEA blue map scenario, 2010–50



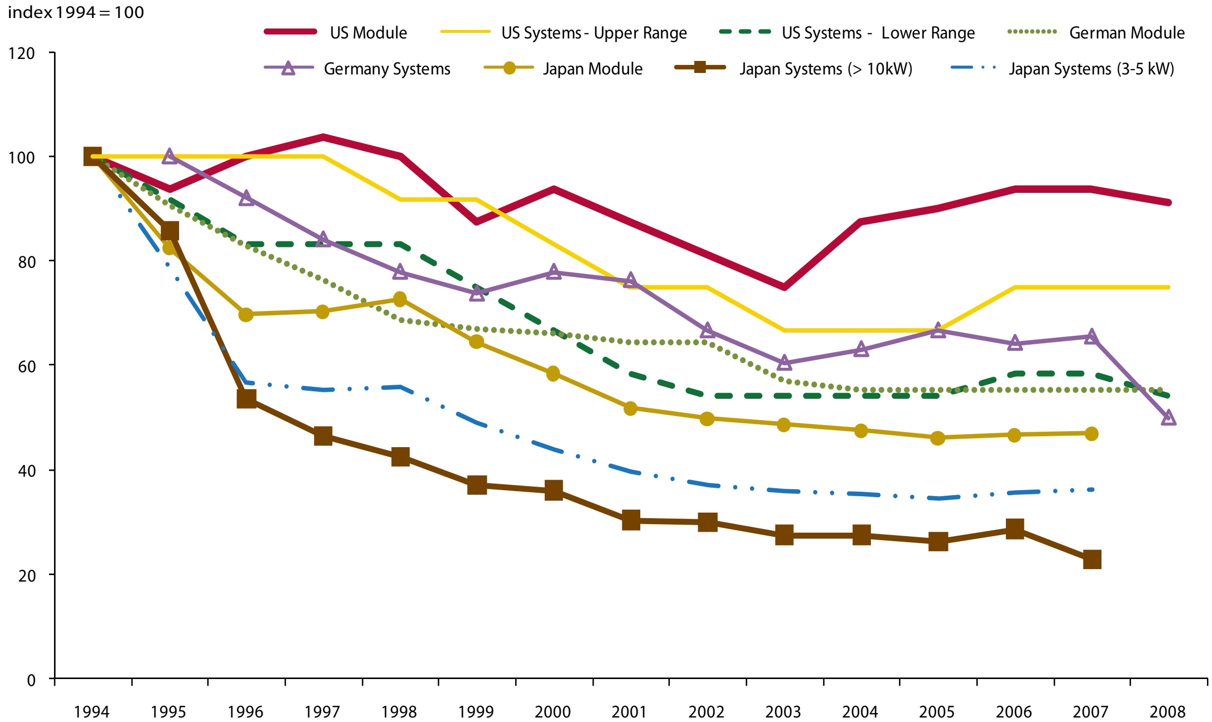
Source: IEA.

Figure 8 Levelized cost of energy: solar versus other energy sources in 2009



Source: Lazard Ltd., Levelized Cost of Energy Analysis 3.0, February 2009; the analysis assumes incentives such as tax credits as they are currently applied in the United States, for detailed assumptions and methodology see Lazard (2009).

Figure 9 Historical major markets' solar PV module and systems prices 1994–2008



Note: German systems 1995 = 100.
Source: IEA PVSP National Reports.

Figure 10 Solar PV production chain (polysilicon and thin film)

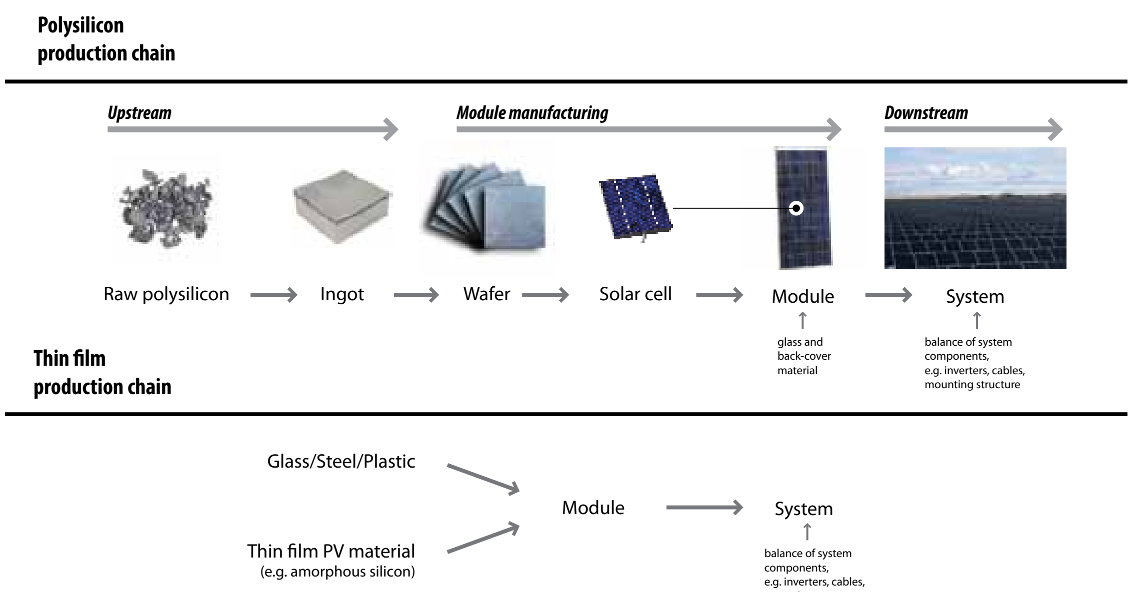
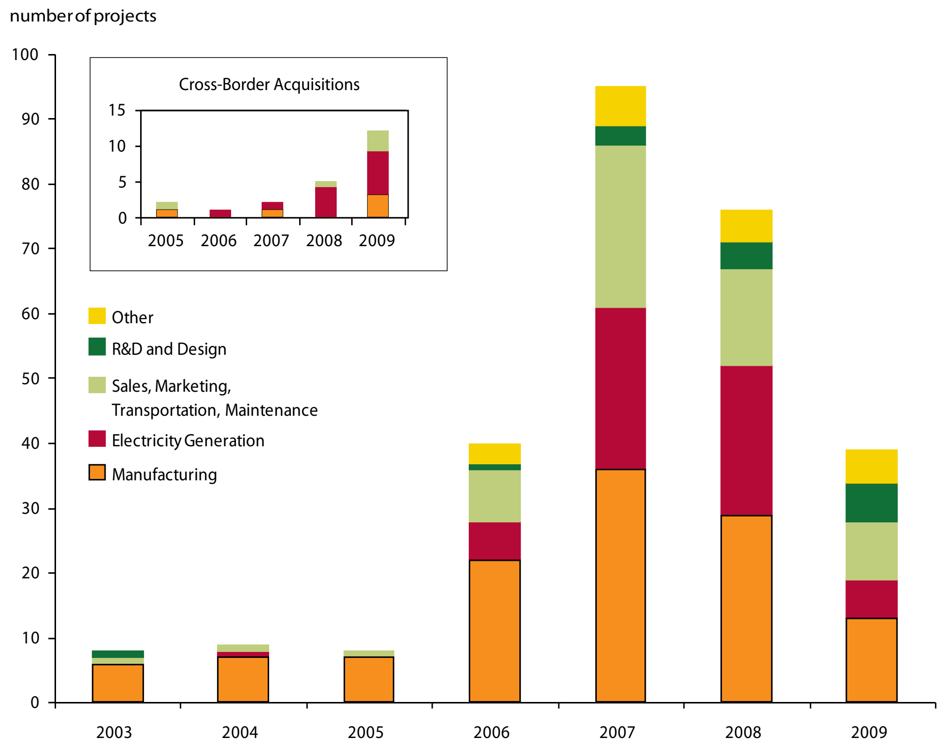
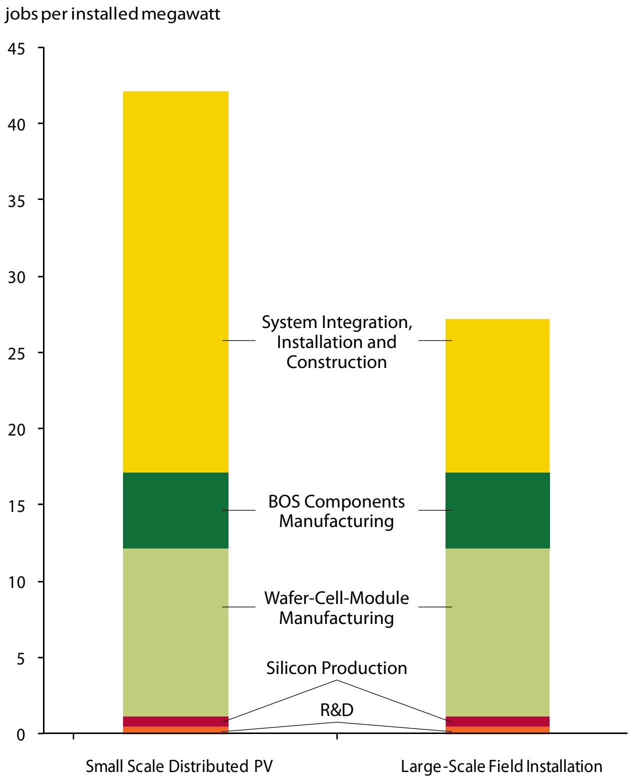


Figure 11 Greenfield FDI in the Solar Sector*



*All solar sector (including CSP) and related sub-sectors; includes cross-border investment with final stakes classified as direct investment under the OECD Benchmark Definition of FDI, available at: http://www.oecd.org/document/33/0,3343,en_2649_33763_33742497_1_1_1_1,00.html.
Source: FDIntelligence and Thomson ONE.

Figure 12 Direct jobs per installed megawatt of solar PV capacity, 2009



Source: Estimates based on authors' interviews with industry experts and external estimates from NREL's JEDI database, Navigant Consulting, New Energy Finance.